ROADMAP for AUTOMOTIVE ADDITIVE MANUFACTURING

USCAR
UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH LLC

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

Additive manufacturing (AM) has many potential benefits for automotive production. AM can enable greater design flexibility, functional prototyping, light weighting opportunities, and cost advantages. AM can produce intricate designs that are difficult to achieve through traditional methods and enable better performance, and parts consolidation. AM can also eliminate tooling requirements and increase speed to deliver components.

The automotive sector has been using AM processes for decades, but it has yet to become integrated into high volume production processes. Challenges exist due to high cost of materials, equipment and operations. The speed and reliability needed for high volume applications are not possible with current AM systems, which are used mostly in low-volume batch production. The large number of raw materials used today in automotive manufacturing is a challenge for AM equipment designed for one or a few materials. Interoperability with traditional systems and standardization of equipment pose further barriers.

The Roadmap for Automotive Additive Manufacturing represents an automotive voice on what is needed to enable additive manufacturing to become a commonly accepted part of the production of automotive components and vehicles. The overall objective is to accelerate development of AM systems and materials that will work best in automotive – opening the doors wide to using AM in this industry. Collaboration and awareness are critical – automotive OEMs want to work closely with the AM industry to build reliable, fast machines; help the industry understand the key requirements and specifications for automotive grade materials, equipment and production quality; and build awareness of the potential opportunities for AM suppliers – which are enormous.

Call to action for the AM industry

- Partner with automotive OEMs to design, build and deploy reliable, fast AM machines
- Work with automotive OEMs to better understand requirements and specifications for high volume production and quality controls
- Ensure supplies of automotive grade materials with optimized potential for recycling and reuse

The global automotive parts market is projected to reach $466 billion in 2025, with AM potential growth projected of $10-12 billion over the next decade. This makes a strong business case for the AM industry to accelerate and strengthen its position in the automotive sector – with mutual benefit for suppliers and OEMs.

The major themes and goals of this Roadmap are illustrated in Figure E-1 by segment – Materials, Manufacturing, Design, and Operations/Workforce. This Roadmap explores the current challenges to reaching these goals and recommends actions and pathways to address them. It is hoped that this call to action will create greater awareness, not only of the needs but of the potential opportunities, for all stakeholders.

Figure E-1. Goals for Additive Manufacturing in the Automotive Sector

GOALS for AUTOMOTIVE ADDITIVE MANUFACTURING

Materials

Automotive grade agnostic AM materials, standards, and specifications – open-source, characterized materials

Robust, available material supply – existing/new feedstocks with standard properties

Lower cost – cost-effective and readily available chemistries and materials systems

Sustainability and recycling – capture of full value of recycling and reuse of AM materials

Materials characterization and validation – advances in methods for assessing materials

Manufacturing

Machines – cost-effective AM equipment with needed speed, robustness, throughput, repeatability, and size

Automated, integrated processes and digital workflow – interoperable systems compatible with plant-floor automation

Quality control and testing – inspection/methods sufficient for plant floor product quality control

Post-processing – optimized parts with minimal post-processing

Sustainability and recycling – low-waste and emissions processes

Design

Design workforce – designers/engineers versed in both AM and traditional design

Design methods and tools – accessible digital AM design tools with common formats and machine language, for end-to-end design

Business-integrated front-end design – integration of design with the value proposition and business case for AM

Plant floor layout – effective right sizing and facility design around AM equipment and production

Operations & Workforce

Factory connectivity – machine connectivity integrated, interoperable machines, unified Manufacturing Execution Software (MES)

Material and equipment safety – common global standards for safety

Equipment maintenance – expedited, fully-staffed operational support for AM machines

Worker Safety – machines that prioritize safety, ergonomics, and minimize operator exposure and touch-time during turnover

Skilled, diverse, next generation AM workforce – workforce to handle current/next-generation AM equipment and processes

INTRODUCTION

Current State of Additive Manufacture in Automotive

Additive manufacturing, also referred to as 3D printing, has been used in the automotive sector for at least three decades.[1] It has been reported that the auto industry was in fact among the earliest adopters of the technology and helped to facilitate its role in production.[2]

Automotive manufacturers have applied AM technology mostly for prototyping or low-volume batch parts—but would like to incorporate it more broadly. There is a strong role for manufacture and assembly of both functional prototypes and functional production parts in automotive based on potential benefits in performance.[3]

Examples of performance benefits can be found across industries that are adopting AM to enhance design flexibility, functional prototyping, lightweighting, and cost advantages. AM can eliminate tooling requirements and increase speed to deliver components by reducing delivery time for prototypes or tooling—achieving many cost benefits. The ability to produce parts without a tool cost-effectively enables variants in low-volume niche products, allowing for more customer-focused products and personalization.

According to an AM equipment producer, one automaker produced 30 distinct production tools within the first three months of having obtained its AM equipment.[4] Ford has noted that, whereas the use of traditional methods took up to four months to construct an intake manifold prototype, applying AM towards this process reduced this time to about four days. In addition, the cost to produce the intake manifold prototype was reduced by greater than 99 percent.[5] GM has reported that no less than 40,000 "prototype parts" are produced on an annual basis (via AM) at their Warren, MI facility.[6] At the Stellantis Product Development center of excellence in Turin, engineers are creating lightweight grills and other parts using AM and forging ahead with a multitude of design ideas and prototypes.[7]

Weight reduction has been long gaining ground in automotive, first for improved fuel efficiency and now for electric vehicles (EVs). GM produced an AM steel seat bracket that is 40 percent lighter and 20 percent stronger than the traditional part.[8] Ford engineers have printed a plastic electric parking brake bracket that is 60 percent lighter than the stamped steel version.[9] BMW

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[1] Brooke, Lindsay. (2020, August 5) *Directing 3M's 3D-printed future.* Retrieved from https://www.sae.org/news/2020/08/directing-gm%E2%80%99s-3d-printed-future

[2] Delic, M. & Eyers, D. "The effect of additive manufacturing adoption on supply chain flexibility and performance: An empirical analysis from the automotive industry." *International Journal of Production Economics* **228** (2020). https://www.sciencedirect.com/science/article/abs/pii/S0925527320300815

[3] Beamler (2018) *Business cases: 3D printing in the automotive industry.* Retrieved from https://www.beamler.com/3d-printing-in-the-automotive-industry/

[4] Pearson, A. (2020, March 26). "3D printed thermoplastics versus metal: why Volvo Trucks chose additive manufacturing." [Blog post]. Retrieved from https://www.stratasys.com/explore/blog/2015/volvo-trucks-additive-manufacturing

[5] Lizotte, C. (2014, June 6). *A View Inside Ford's 3D Printing Lab.* Retrieved from https://3dprint.com/5318/ford-3d-printing/

[6] Brooke, Lindsay. (2020, August 5) *Directing 3M's 3D-printed future.* Retrieved from https://www.sae.org/news/2020/08/directing-gm%E2%80%99s-3d-printed-future

[7] *Manufacturing Ideas in 3D*. Retrieved from https://www.fcagroup.com/en-US/media_center/insights/Pages/additive_manufacturing_3d.aspx

[8] *How major automakers use AM for production today, part 2: General Motors additive manufacturing*. Retrieved from https://www.3dprintingmedia.network/general-motors-additive-manufacturing/

[9] *Automakers Turn to Production-Ready Printable Parts* (March, 2019) https://www.assemblymag.com/articles/94784-automakers-turn-to-production-ready-printable-parts

has started using AM to develop hand tools that are part of the vehicle development and assembly processes, in one case achieving a weight reduction of more than 70 percent.[10] The lightweighting advantage could potentially play a role in helping automobile manufacturers achieve increasingly strict fuel economy regulations and an improved EV range.

Additive manufacturing processes can produce geometric shapes that might otherwise require production and/or assembly of multiple parts—enabling parts consolidation. Component consolidation can dramatically decrease costs, increase production speed and heighten functional performance on the factory floor. For example, General Electric Aviation was able to replace 900 parts with 16 using AM technology for a helicopter engine build.[11] AM can produce intricate designs that are difficult to achieve through traditional methods, with cost and performance advantages.

A shift towards AM technology is not without its practical challenges across the full spectrum of automotive operations – materials, manufacturing, design, and workforce training. For example, challenges include speeds needed for high-volume applications. The breadth of raw materials used for traditional automotive manufacturing can also be a challenge for AM equipment that is typically designed for one or a few materials.[12] Incorporating AM early in design is currently complicated due to the lack of good data and unified methods. In addition, a well-trained workforce is lacking to effectively maintain, trouble-shoot and operate AM equipment during high-speed operations.

Speed and cost of AM are critical in automotive, where millions of parts are produced sharing the same shapes and geometries.

Metal model makers check on 3D printers in the GM Additive Industrialization Center at the GM Tech Center in Warren, Michigan.

[10] Stratasys. (2018) *The Road Ahead: Rapid Prototyping in the Automotive Industry.* Retrieved from https://www.stratasys.com/explore/whitepaper/the-road-ahead
[11] *GE Team Secretly Printed a Helicopter Engine, Replacing 900 Parts with 16*. Retrieved from https://www.additivemanufacturing.media/articles/ge-team-secretly-printed-a-helicopter-engine-replacing-900-parts-with-16
[12] FutureBridge (2020) *Additive Manufacturing in the Automotive Industry* (2020) Blog post. Retrieved from https://www.futurebridge.com/blog/additive-manufacturing-in-the-automotive-industry/

Future AM Automotive Markets and Applications

The global auto parts manufacturing market is substantial. In 2017 the value was estimated at about $350 billion, with an anticipated market valuation of around $466 billion by 2025.[13]

While the focus of this Roadmap is on AM production parts (i.e., identifying and addressing the challenges to deployment of AM production parts in vehicles), predicted growth in the overall AM automotive market is impressive. Recent reports project the AM automotive market to reach as much as $5 billion in revenues in 2023 and grow to $10 to $12 billion toward the end of the decade.[14,15,16] While automotive AM today centers around prototyping and tooling, predictions show materials and parts production could potentially become major market segments by 2028. Figure 1 illustrates segment differentiation in 2028, based on approximate data from recent projections.

While considered a revolutionary technology, it is reported that AM is more likely to thrive as a compliment to traditional practices in the automotive sector and its supply chain, i.e., as an augmentation of existing processes rather than a total replacement.[17]

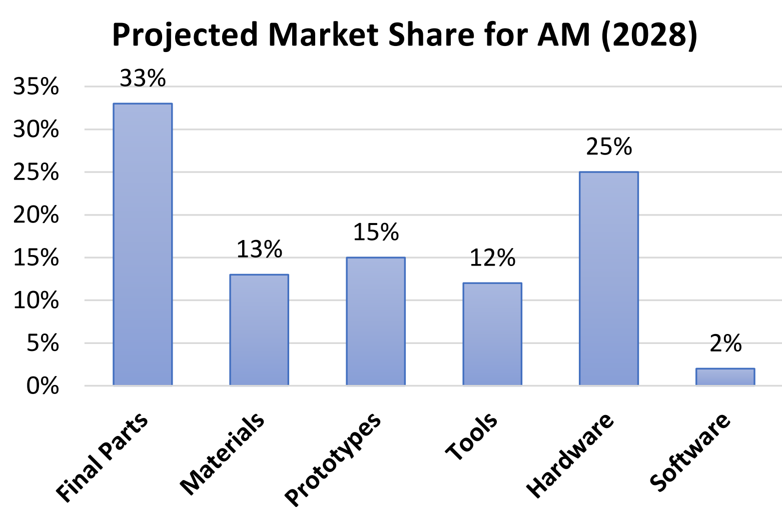


Figure 1. Approximate Projected Distribution of AM Automotive Markets in 2028[15]

[13] *Global Auto Parts Manufacturing Market: Dynamics Influencing Revenue Growth*. Persistence Market Research. (2018, November 2018) https://www.openpr.com/news/1370826/global-auto-parts-manufacturing-market-dynamics-influencing-revenue-growth.html

[14] Robert, Nolan. (2018) *Smartech Issues New Report on Automotive Additive Manufacturing Market, Sees $5.3 Billion Market in 2023*. https://www.smartechanalysis.com/news/smartec-report-automotive-additive-manufacturing-market/

[15] Sher, Davide. (2020, January 2) *AM for automotive production set to become $10 billion business by 2030.* Retrieved from https://www.3dprintingmedia.network/who-will-make-the-most-automotive-am-end-use-parts-and-where/

[16] Robert, Nolan. (2018) *Smartech Issues New Report on Automotive Additive Manufacturing Market, Sees $5.3 Billion Market in 2023*. Retrieved from https://www.smartechanalysis.com/news/smartech-analysis-issues-new-automotive-additive-manufacturing-report/

[17] *Directing GM's 3D-printed future*. (2020, August 5). SAE International. https://www.sae.org/news/2020/08/directing-gm%E2%80%99s-3d-printed-future

The potential future opportunities for automotive AM components are diverse. Today, AM is primarily used in the automotive sector for prototyping; small, low-volume batch or customized parts; and production of manufacturing tools. This includes automation tools, hand tools, large forming tools, dunnage, jigs, rapid response tooling, and others. Emerging applications for AM generally fall into three categories: 1) functional prototyping; 2) serial production; and 3) manufacturing tools. In serial production, AM could enable a move to island production rather than long assembly lines using small AM cell units. Mass-customization via AM also has great potential to change supply chain dynamics in automotive.

There is significant motivation for automakers to increase the use of AM and take advantage of design and cost benefits. The overall market potential for automotive AM and the breadth of potential parts and components is enormous. Many opportunities for automotive AM could be realized through advances in machinery and AM processes that enable greater production speed, quality, reliability, and lower cost—and meet higher volume manufacturing requirements. An accessible and reliable supply of quality materials at larger scale would be needed to ramp up to meet these higher production volumes.

The unique capability of AM for producing parts with complex geometries without the need for tooling and its potential for designing for parts consolidation makes it especially applicable for a wide range of automotive components. Eliminating tooling development lead time enables manufacturers to use AM to design and build parts and products fast – and in new ways that were not possible before.

This Roadmap is a call to action – supplier engagement is needed to realize automotive market opportunities for AM.

The advantages of AM also lend to the design and production of EVs, which are rapidly beginning to populate the highways.[18] EVs have many heavy power electronic systems that can benefit from AM, such as power management and distribution systems, charging systems, and traction inverters. Designing such systems for AM could help optimize cost and assembly configurations, with potential light-weighting. The ability to embed networking, sensing, and smart device capabilities into a vehicle structure via AM also reduces fabrication and manufacturing steps.

In the aftermarkets, while technical challenges exist,[19] there are promising opportunities for AM production of spare parts on-demand at locations in close proximity to customers, such as

[18] *Applications of Additive Manufacturing in Automotive Electronics: 3 Key Innovations*. Nano Dimension (2019, April) https://www.nano-di.com/blog/2019-applications-of-additive-manufacturing-in-automotive-electronics-3-key-innovations#:~:text=Additive%20manufacturing%20systems%20may%20also,vehicles%20with%20a%20wireless%20network.
[19] Delic, M. & Eyers, D. "The effect of…" (Ibid. 2)

dealer service facilities. This would be an ideal application for smaller batch AM production of parts, if reductions in cost and advances in quality and reliability can be achieved.

Figure 2 illustrates the typical distribution of materials in a vehicle today.[20] While this is an indication of how materials are utilized today—it does not limit AM to reproduction of the same types of materials used in vehicle parts. The flexibility of AM lends to material substitutions as well as parts consolidation and entirely new designs. As automakers look to include more AM processes to manufacture parts, they will likely explore a variety of materials with a focus on performance and functionality. For example, an AM material could produce a part with the same or better functionality – but not necessarily be the same grade or even type of material used today. The AM process itself opens opportunities to design parts specifically for AM—with similar or even better performance than those produced with conventional processes.

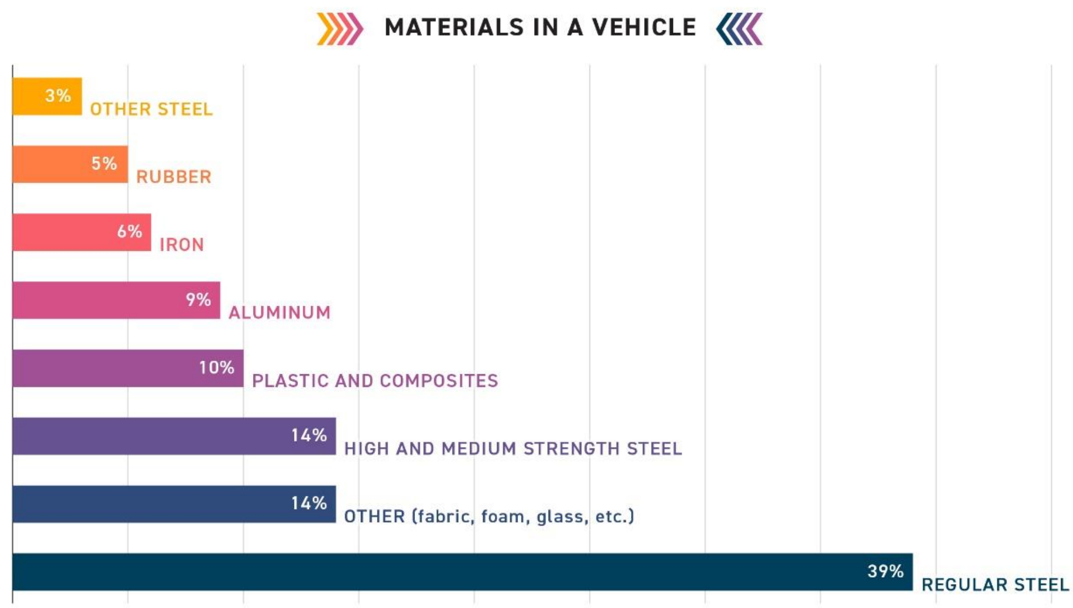


Figure 2. Typical Distribution of Materials in a Vehicle

The AM Supply Chain

Automakers rely on a strong network and ecosystem of suppliers. These supply chain organizations are vital to manufacturing, delivering quality and high-performance parts to the OEMs and customer base. The majority of parts used in automotive are produced by this network of suppliers.

The automotive production supply chain includes suppliers of components or modules suppliers (Tiers 1-3), distributors, and retailers. Automotive OEMs have thousands of suppliers—every OEM job creates up to seven additional jobs in the economy.

Continuous improvement and responsiveness in supply chain execution is a core supply capability for automotive OEMs – AM suppliers must rise to the challenge for this key technology to expand.

[20] NIST. (2014, July). *New NIST Research Center Helps the Auto Industry 'Lighten Up'* [Blog Post]. Retrieved from https://www.nist.gov/featured-stories/new-nist-research-center-helps-auto-industry-lighten

The effectiveness of suppliers is measured in part by 1) the ability to ensure on-time delivery at the highest level of quality and lowest possible cost; 2) connectivity, i.e., expedient lines of electronic communication between suppliers and customers with little lag time; and 3) responsiveness to potential issues in meeting demand requirements.

Recent studies have shown that adopting AM can improve the performance and flexibility of both OEMs and their supply chains.[21] At present, the AM industry is slow to change; technology and materials will need to advance more quickly to realize the enormous potential for AM in the automotive sector. This Roadmap is a call-to-action and action plan for AM supplier engagement and adoption with mutual benefits to OEMs and their suppliers through production of parts with greater flexibility and performance.

The real opportunity for automotive is moving beyond prototypes – using AM for production parts at levels not seen before.

[21] Delic, M. & Eyers, D. "The effect of…" (Ibid. 2)

Roadmap Purpose and Objectives

The purpose of the roadmap is to better understand and communicate the opportunities and pathways for more widespread, efficient, and sustainable use of AM in automotive production facilities. The scope includes all aspects of the manufacturing life cycle, from design to materials, manufacturing processes, operations and maintenance, and workforce.

This roadmap was developed in part to encourage and enable the greater use of AM in the automotive sector. A number of objectives in support of that overarching goal are outlined below.

- Impart to industry partners an understanding of the most important pathways to accelerating development and opening doors to adopting AM technologies in automotive
- Provide a voice from automakers regarding AM and expectations for reliability, quality, and scale-up
- Raise awareness of and prioritize the challenges of doing AM at scale in automotive and focus efforts to overcome them
- Encourage a dialogue about mutually beneficial business models to incentivize AM industry partners to develop bulk materials and large-scale, high-volume equipment
- Identify automotive criteria, requirements, and standards needed for AM – and influence industry partners to discuss and embrace them as they are developed
- Identify mutually beneficial approaches for the AM community to support automotive, i.e., an understanding of what OEMs as well as industry partners can bring to the table to enable broader use of AM

Purpose

Understand opportunities and pathways for the more widespread, efficient, and sustainable use of AM in automotive production

Scope

Integrate AM into automotive sector, starting with materials and manufacturing processes, and including design, operations and maintenance, and workforce development

Objectives

Identify and prioritize challenges to be overcome and spur action by AM community to accelerate deployment of AM in automotive applications

A ROADMAP FOR AUTOMOTIVE AM

Greater adoption of AM in automotive production applications will require innovations across many aspects of additive manufacturing, including materials, manufacturing equipment and processes, operations and maintenance, design, and workforce. While opportunities abound, there are a number of challenges that need to be overcome in each of these areas to realize the potential of AM.

AM Materials

Materials are foundational to the successful use of AM for automotive parts and represent the greatest area of opportunity. While a variety of metals, ceramics and polymers are available for AM processing, not all are readily suitable for automotive parts or available in the volumes needed. Table 1 illustrates some of the materials that are currently being used for automotive component manufacturing and rapid design prototyping, and the processes employed.[22]

New materials for AM have been emerging regularly as research continues and the use of AM becomes more widespread. As is evident from Table 1, AM is an umbrella term encompassing a wide variety of technologies and materials. Metals and polymeric systems are the most commonly used materials in automotive applications and represent unique materials challenges.

On the metals side, the two most common feedstocks are powders and wires – both produced by a mature supply base primarily for use in other industries (e.g., powdered metal and metal injection molding industries, welding industry). Most alloy development that has occurred to accommodate the feedstock needs of AM has been conducted to support the aerospace and medical/dental industries (Titanium, Ni-based alloys, Co-based alloys, and Stainless Steel). Less attention has been focused on alloys of specific interest to the automotive industry such as tool steels, low alloy steels, copper, and aluminum alloys.

On the polymers side, the most common feedstocks include thermoplastic filaments, thermoplastic powders, and photopolymer resins. The most commonly used polymer AM materials were first developed for prototyping applications (polyamide 12, acrylates, and polylactic acid for PBF, VPP, and ME, respectively), followed by those to support the aerospace and medical industries (including carbon filled powders, polyether imide, and polyether ether ketone). These materials are either insufficient to meet automotive requirements for performance and durability or are overengineered for automotive needs. Materials that possess a balance of thermal capability and ductility, UV stability, and durability—while meeting a competitive price point—drive polymer material needs more than developing AM versions of conventional materials.

[22] Based on ASTM F2792; and *7 Families of Additive Manufacturing*. Hybrid Manufacturing Technologies, https://www.additivemanufacturing.media/cdn/cms/7_families_print_version.pdf

Table 1. Common Uses of Materials and AM Processes for Automotive Applications			
Names	**Materials**	**Description**	**Applications**
Powder Bed Fusion			
Laser Powder Bed Fusion (LPBF), Selective Laser Sintering (SLS), HP Metal Jet, Direct Metal Laser Sintering, Electron Beam Melting	Metal alloys, polymers, ceramic, and carbon fiber materials	Achieved layer by layer using a heat source such as a laser or electron beam to consolidate material into 3D objects. As each cross-section is fused the powder bed lowers by a layer and another is applied until part completion. Overhangs and unconnected islands are supported by the surrounding unfused powder bed. Any fusible material can be processed but some metals may be problematic.	Strategic for tooling, prototyping of low volume parts, components (grills, fenders, small engine parts, fuel tanks, etc.); filled/unfilled materials, functional prototyping
Materials Extrusion			
Fused Deposition Modeling (FDM), Fused Filament Fabrication (FFF)	Thermoplastic filaments/pellets (acrylonitrile butadiene styrene, poly-carbonate, polyetherimide), can contain metal particles	Melt extrusion is used to deposit filaments and pellets of thermoplastics in a specific pattern. Materials are extruded through an orifice along tracks or in beads and then combined into multiple layers. An inexpensive, easy to use process, although supports may be needed, and parts may be susceptible to temperature fluctuations.	Lower-volume components (headlight bezels, floorboard mounts, wheel space covers, etc.) and design prototyping
Vat Polymerization			
Stereolithography, Digital Light Processing, Continuous Liquid Interface Production	UV curable photopolymer resins	A process used to create models, prototypes, patterns, and production parts layer by layer fashion using photochemical processes. Chemical monomers and oligomers are subjected to light and then cross-link together into polymers to form a three-dimensional solid. While fast (functional parts can be manufactured within a day), the cost is high.	Rapid prototyping (pneumatic/hydraulics, headlight lamps and lenses, etc.) and components (gear shift knobs, etc.)
Binder Jetting			
HP Multi Jet Fusion, 3DP™ Printing	Powdered polymers, polypropylene, metal, ceramics, sand	Binder is selectively deposited on powdered material to bond areas and form a solid part, layer by layer. Binders can be organic/inorganic materials; metal or ceramic parts are fired in a furnace. Used for producing large sand casted cores and molds and low-cost metal parts. Lends to a variety of materials.	Functional prototyping/ production of polymers; high productivity metal printing; casting operations
Directed Energy Deposition			
Laser Metal Deposition, Laser Engineering Net Shaping, Direct Metal Deposition	Metal wire and powder, ceramics	During this process, melted material is deposited on a surface and solidifies. The material (powder or wire) is melted using either a laser or electron beam, where it then adheres to the underlying part or layers. The material is melted at the same time as it is being deposited via a nozzle. The process repeated until the layers have solidified and created or repaired the part. For repair, it is a type of automated build-up welding.	Limited uses; automotive die repair, repairing complex parts
Material Jetting			
Smooth Curvatures Printing, Multi Jet Modeling, Multi Material Jetting	Photopolymers, polymers, ceramics, metals, wax	Material droplets (polymers, photopolymers) are deposited layer by layer to create a 3-dimensional part. The droplets of a photosensitive material solidify under exposure to an ultraviolet (UV) light. The process uses either a continuous or Drop-on-Demand (DOD) approach. Material jetting produces parts with an exceptionally smooth surface but are photosensitive and mechanical properties can degrade over time.	Potential use for multi-material functional prototypes (limited experience)
Sheet Lamination			
Selective Deposition Lamination, Ultrasonic Additive Manufacturing	Paper, plastic sheets, metal foils/tapes	Objects are formed by stacking and laminating sheets of material; lamination is accomplished using adhesives, chemicals, ultrasonic welding, or brazing (of metals). Overhangs/excess material is cut away after the part is built.	Limited use in prototype or production; low fidelity prototypes
Other Processes			
Additive Friction Stir, Selective Thermoplastic Electrophotographic Process (STEP)	Metal powders, wires, metal matrix composites, polymers	Hybrid processes that combine different methods. Additive friction stir, for example, combines friction stir welding concepts with a material feeding process.	Currently limited use

Assuring sustainable supplies of AM materials continues to be a challenge at higher volumes. For AM to become more widely adopted in automotive facilities, reliable supplies of materials will be needed that are comparably priced, of consistent quality, and well-characterized. While supplies are often adequate for rapid prototyping and low-volume parts, they are not readily available in sufficient volumes to supply high-throughput or just in time operations.

In addition to the broad technology categories identified by the ASTM F42 Committee on Additive Manufacturing, technology and materials applications are continuously emerging. Additive friction stir is a low-temperature, solid-state, large-area metal additive process that has been used in the fabrication of Al-based alloys.[23] Selective Thermoplastic Electrophotographic Process (STEP) is another new process that aligns layers and bonds them into final parts (similar or equal isotropic properties to injection molding) with potential for higher volume production. Hybrid processes are also emerging, such as the combination of machining or sheet lamination and 3D printing.

Table 2 illustrates some of the specific material families and possible requirements of interest to automakers. There are many unexplored opportunities to utilize the unique attributes of a variety of materials and apply these to AM processing approaches. Low alloy steels, for example, can exhibit the mechanical properties of existing materials such as cast, wrought or metal-injected metal steels. Breakthroughs in additive powders can provide materials that can potentially better meet requirements for cost effective and scalable production, such as that typical in automotive. Although not well-studied for automotive AM, the conductive characteristics of copper make it ideal for aerospace parts such as heat exchangers, engine parts, and electronics.

Table 2. Materials of Unique Interest to Automotive at the Component Level

Steel	Heat treatable low alloy steels, tool steels, electrical steels, other steels that are well-studied for conventional applications and could be applied to AM
Aluminum	Alloys with high temperature, structural and strength capabilities; weight reduction
Copper	Copper parts in high conductivity applications, electric motors, with thermal or electrical conductivity requirements; applications where copper is currently not well-studied but has potential
Composites	Composites to replace metal parts – lighter but with the same strength or other properties
Polymers	Polymers with improved UV and temperature resistance

[23] R. Joey Griffiths, Mackenzie E.J. Perry, Jennifer M. Sietins, Yunhui Zhu, Nanci Hardwick, Chase D. Cox, Hunter A. Rauch, and Hang Z. Yu. “A Perspective on Solid-State Additive Manufacturing of Aluminum Matrix Composites Using MELD.” (2018, July) https://www.researchgate.net/profile/Hang-Yu-16/publication/327926186_A_Perspective_on_Solid-State_Additive_Manufacturing_of_Aluminum_Matrix_Composites_Using_MELD/links/5bae304da6fdccd3cb7950ea/A-Perspective-on-Solid-State-Additive-Manufacturing-of-Aluminum-Matrix-Composites-Using-MELD.pdf

Goals for AM Materials

The goals shown below illustrate the major milestones that must be met to accelerate and significantly grow the use of AM in automotive components. These goals are driven by the need to assure quality parts production at higher production volumes, which will enable the greater use of AM beyond rapid prototyping or low-volume, one-off applications.

Automotive grade agnostic material, standards, and specifications— development of open-source materials that meet functional requirements for automotive applications as defined by AM technology-specific specifications and inclusive of post-process (e.g., heat treatment) capability; accompanied by standards for producing and testing AM specimens and components.

Usability and availability—development of existing and new feedstock supply base for standardization of materials and AM manufacturing parameters to support efficient production, including high productivity processing and feedstock recycling/reconstitution.

Lower cost—cost-effective and readily available chemistries and materials systems to enable use of AM materials in high throughput applications, including innovative lower-cost methods for feedstock production.

Sustainability and recycling—capture of full value stream for recycling and reuse of AM materials, both polymers and metals; sustainable materials that are recyclable and lend to low or zero waste processes, with planned materials recycling and downstream value propositions through end-of-life (EOL).

Materials characterization and validation—advances in methods for characterization and assessment of materials and reliable materials properties and material card databases to enable design for automotive applications (e.g., aluminum, wires).

Reliable supplies of high quality, automotive-grade materials are essential to enabling the use of AM in high-volume applications.

3d-printed components for U.S. Army M781 munitions.

Challenges and Opportunities for Materials

Materials are an important first step in the design and production of quality parts. While opportunities abound in automotive, there are still a number of obstacles to overcome for widespread adoption. Table 3 highlights the major opportunities and challenges identified.

Table 3. Challenges and Opportunities for AM Materials	
Agnostic Automotive Grade Materials	Machine agnostic, automotive grade materials are important for expansion of AM. This translates to AM materials that are not specific to a machine (open material systems) to avoid the potential for single supplier failures on a high throughput assembly line. As automakers identify the opportunities for AM in automotive, AM materials must be developed that meet the functional requirements of the applications (e.g., many polymeric materials used in AM do not meet mechanical or physical property performance requirements for many automotive applications). Functional requirements include mechanical and durability requirements, surface characteristics, environmental stability, and chemical compatibility with other materials in the vehicle including joining areas, coatings, and fluids.
Common Material Specifications	An important objective is common specifications for all feedstocks. Standards specific to AM or updating of existing standards to include requirements for AM technologies are needed – processes from 'old' or conventional materials may not work. Standards should include chemical composition and ranges, allowable impurity and defect levels and feedstock characteristics required for a particular AM technology (e.g., powder size, morphology, and particle distribution for technologies involving spreading of powder layers). Allowable ranges for batch-to-batch variation should be addressed. End-users and machine manufacturing OEMs should provide input to feedstock suppliers on material requirements so that key material families can be developed and evaluated. For post-processing, redefinition may be needed around some specifications for AM parts (e.g., surface quality, heat treatment protocols). Lot acceptability procedures are needed, along with specifications or guidelines for reuse qualification and acceptance. Functionally graded materials, both polymer and metals, should provide gradated mechanical properties that would help to achieve desired engineer objectives.
Lower Cost Materials	To drive greater use of AM, the cost of materials needs to be near the competitive range for traditional materials (e.g., polymer cost similar to dollar/pound for bulk polymers; metal powder cost closer to PM or MIM powder cost). Innovative techniques or approaches to feedstock production and use (e.g., atomization innovation, using recycled feedstock, using greater size distribution of particles) are needed to lower powder production costs while maintaining quality. Feedstock chemistries should be optimized for cost.
Materials Data and Testing	Reliable, statistically significant mechanical, physical, and chemical data are required for materials, particularly those of automotive interest. Data needs to include the effects of processing (including directional anisotropy) and post-processing. Common test procedures for products are required either through development of new procedures unique to AM technologies or by validating existing testing procedures (e.g., current material testing procedures for materials already available through agencies such as ASTM, MPIF, or AWS). Material behavior models and requisite datasets should be developed for implementation into current automotive CAE performance simulation analysis (e.g., material behavior models, material input decks to finite element of multi-physics/structural models such as LS_DYNA, Radioss, Opti-struct, etc.).
Sustainable Materials Supply	Availability of feedstocks at scale needed for high volume parts is a challenge. Powders in particular are currently produced in a batch and sized for the application, scaling up to large volumes could be expensive with today's production equipment. A large enough, stable, guaranteed market is needed to incentivize producers to scale up for high throughput. Some feedstock components are also controlled, i.e., subject to export controls or national security policies. Clarity around these issues or development of substitutes is required. Established recycling streams for in-plant and end-of-life feedstock scrap are limited or non-existent. These streams need to be developed and feedstocks and handling procedures need to be validated to ensure they comply with capability. Feedstocks that are sustainability produced as well as the capability for reuse/recyclability of unused powders is also an important objective.

Manufacturing

As noted, AM is used today in automotive for prototyping, design, tooling, and production of batch parts in relatively low volumes (Table 1). While AM processes have been steadily assimilating into automotive manufacturing, a number of challenges limit their more widespread use. While AM materials are foundational, the capabilities of the machines designed for producing AM parts are equally important.

One of the challenges with today's AM machines is meeting acceptable process capability for repeatability while maintaining the desired throughput of production. Machines that are working well for producing prototypes or low volume parts are not readily adaptable or proven for higher throughput production volumes. Scaled production capable processes are needed. Some of the processes shown in Table 1 (SLS, binder jetting) are more scalable for production than others such as FFF or DED processes which are better suited for prototype or tooling/fixturing or other niche applications. Investment required is also a key consideration.

In the future, the automotive manufacturing factory model could be quite different. It can be envisioned as a more distributed model, with printing of parts conducted not just in an assembly plant, but also at a service center or dealership. Managing a distributed model for parts will be more complex and virtual—requiring assurance that locations are meeting the same quality standards for parts. In this scenario, AM machines will need a higher degree of interoperability, standardization, and connectivity. Open platform machines and the ability to adjust parameters for material development will be needed. Broader awareness, comfort with, and acceptance of standard automotive terms and conditions versus other industries, i.e., warranty, etc. is also needed.

Little transformational change has occurred with laser powder bed fusion printing of metals over the last decade. Automakers need partners to build new machines that address the capability of current systems and their limitations. Robust AM machine design is needed (i.e., a cast base like the machine tool industry), where supplier resources are invested in rigorous development and there is collaboration with machine tool builders.

Quality is a primary concern from both a cost and performance perspective. Current methods for producing AM parts are smaller batch operations, and lack the process monitoring, inspection, and control systems typical of high throughput, continuous operations. Testing and inspection, as well as certification of parts will be important as AM moves into higher volume production. The automotive industry has higher volume production than aerospace and medical, making it difficult to do 100% inspection. While not as high volume as consumer goods, automotive often has higher durability and functional requirements, necessitating built-in quality in processes and materials to successfully apply to scaled production.

Automakers need partners who will build new AM machines with expanded capabilities.

Each type of AM technology has unique post-processing requirements and approaches, some requiring specialized equipment. Machining, handling of rejects, or unusable powders or waste are examples. While many improvements have been made, post-processing is still a challenge with today's AM technology post-processing. Post-processing is often more challenging for complex parts. Automated solutions, or minimization of post-processing at the front end, are needed to facilitate cost-effective, sustainable use of

AM in automotive. The manufacturability, printability, and ease of post-processing or functional optimization should all be considered during the design of a part for AM.

Size of machine build volumes is another factor limiting automotive applications. AM parts on the order of one cubic meter are needed for grilles, interiors, and substitute body panels used during pre-production tune-in.

Goals

The goals shown below illustrate the major objectives to be met to successfully integrate AM more widely in automotive components. These goals support the production of quality parts at higher volumes and a new manufacturing paradigm where AM is effectively integrated with systems on the factory floor.

Manufacturing/machines—cost-effective equipment for AM with speed, robustness, throughput, repeatability, and size adequate to meet automotive production needs; open platforms to allow for development of automotive grade materials and optimization of process.

Automated, integrated processes and digital workflow—interoperable systems that are compatible with plant-floor automation and can integrate with other manufacturing processes and systems (physical as well as data systems) and allow for ability to use machine learning (ML); higher degree of machine automation and integration; adequate cybersecurity protocols.

Quality control and testing—inspection and methods sufficient for plant floor AM product quality control; reliable testing procedures for part compliance with tolerance and other performance requirements, both in production and prototypes.

Post-processing—optimization of parts with minimal post-processing or machining requirements and sustainable recycling/reuse protocols.

Sustainability and recycling—low-waste and reduced hazardous waste processes, to achieve 10% or less waste by 2035; plans for recycling and downstream value proposition.

Faster, interoperable AM systems that provide reliable and repeatable performance will accelerate use of AM in new applications.

3D print facility for Ford Mustang parts.

Challenges and Opportunities for Manufacturing

Given the potential benefits in productivity and the potential for innovation, automakers are highly motivated to adopt AM in a wide spectrum of high-volume applications. Table 4 highlights the top areas of opportunity and major challenges for automotive AM.

Table 4. Challenges and Opportunities for Manufacturing	
Fast, Affordable, Reliable AM Machines	The cycle time of most AM machines needs to be increased by as much as 10 times faster than those currently available through innovation in process parameter development, increasing thermal sources, hardware upgrades, faster powder spreading technology/innovative packing strategies, and optimized build areas, i.e., taking rate-limiting steps offline. Standards can also be developed for the acceptability criteria of part performance through the use of high productivity processing (e.g., larger layer thickness). Machines are needed that are certified by suppliers for use with multiple types of materials, i.e., an ability to use material X with machine Y. Common specifications around feedstock testing and validation are needed for AM-specific processes (e.g., a common standard for measuring and reporting powder flowability). Technology advances are needed to achieve cost reductions. This includes, for example, affordable five-axis machines for filament and stick-based raw stock, that will orient the part for deposition to eliminate the need for supports (used today for some direct deposit systems).
Machine Automation, Inter-operability, and Digital Flow	Standard (APIs) and language between machines and secondary automation type processes are lacking and need to be developed. Proprietary software needs to be able to interface with plant operations and provide required outputs in standard forms. A higher degree of automation and integration is needed across the entire value stream from CAD to near net part and possible beyond, minimizing non-value-added labor. AM automation and material handling are currently immature and do not have the seamless integration needed to meet the needs of serial production. Models that are standardized, translatable, and customizable are needed. Integration of all process steps is important for wider AM use. This includes integrating printing with powdering and all of the process steps necessary to fully industrialize AM within the automotive plant – from part to vehicle. AM product life cycle management is now offline and should become part of the digital workflow.
Part/Process Repeatability	Part-to-part dimensional variation with one-off machines remains an issue. Dimensional tolerance for AM technologies as a function of direction and part size needs to be optimized and standardized. Machine-to-machine variation should be minimized, i.e., all 20 machines from the same vendor should perform in an identical way. Techniques are needed to identify parts for assurance of provenance and standard criteria for part history should be instituted. Automotive manufacturers and machine vendors need common understanding on expectations for AM technology performance and part quality (defined using current process control metrics). Making hundreds of parts in an automated process will require assurance that each part will be the same.
Part Quality Control and Testing	Accurate, in-situ monitoring techniques will be required for process control. Research will be required to identify controlling factors to monitor and quick, real-time techniques should be developed to determine anomalies (e.g., defects or control factors) that fall outside prescribed control plans. Common supplier qualification standards are need, to IATF 16949. More experience with testing is needed to understand the capability of AM and how to achieve realistic tolerances in high throughput production. Geometric tolerance, for example, is not easy to achieve. If a part will be 3-D printed – what actual tight tolerances are needed (i.e., some tolerances are process-specific, such as injection molding)? In some industries, extra parts are printed in case some are rejected – an expensive approach and not practical at high volumes.
Post Processing/ Recycling	Ideally, AM produced parts should be of first quality with minimized (predictable level) of rejects and post-processing requirements (right geometry, tolerance, porosity, etc.). Many different AM technologies can produce similar types of parts; the challenge is to determine the different capabilities for each to provide optimized builds. Master models are needed for every portion of the build so it can be scaled properly. Minimization of waste with respect to sustainability is a key objective; this requires methods of recycling and handling of excess materials. Recycling streams need to be developed for in-plant scrap.

Operations and Workforce

Operations encompass the facility as well as the key functions underlying an efficient and continuous manufacturing factory, such as maintenance of equipment, health and safety, and infrastructure (information technology, networks, software/hardware, etc.). Workforce and associated functions are included as a critical element of effective, productive operations.

Industry needs to develop integrated, compatible software solutions. Machines should be deployed in a heterogenous 3D printer 'ocean' where they meet standard interfaces and operational workflows, in contrast to their current software solutions and operational models acting as 'islands'.

Quality control and monitoring for AM equipment is currently insufficient to meet higher volume production requirements. Assurance of machine uptime, accessibility and other key variables is critical. Quality control and monitoring needs to go beyond in-situ part quality, with better monitoring of key parameters such as machine uptime/downtime and process variables. In this respect, current AM systems fall far short of competing equipment in established industries, such as stamping and injection molding. AM equipment analytics must support calculation of overall equipment effectiveness (OEE) and other common maintenance parameters, for the entire manufacturing stream not just printing.

Damage during maintenance and operation can create challenges. When machines are turned over (cleaned between builds) systems can be damaged (e.g., scratching protective lenses, hitting/touching heat lamps, scratching ink jet nozzles, etc.). AM machines need to be designed to be less prone to accidental damage. Clearances for lifts needs to be more forgiving; tubing, plumbing, and electrical should be routed to eliminate exposure to lift forks.

Safety is a top concern, not just for equipment but for materials and other resources or chemicals needed for the AM process. The Underwriters Laboratory (UL) and others have researched safe use of AM and together with industry developed guidance for facilities using AM equipment (i.e., safety and code compliance).[24] Global standards need to be adopted for both bulk AM materials safety and for safety in working around AM machinery.

Additive manufacturing uses innovative technologies and novel materials that may have new or uncharacterized safety and health concerns. In January 2019, the National Institute for Occupational Safety and Health (NIOSH) established an Advanced Manufacturing Initiative to investigate potential worker safety and health concerns in AM. NIOSH has made progress investigating and contributing to engineering controls and best practices for AM inhalation exposure.[25] NIOSH also announced a partnership with the America Makes non-profit to further support advances in workplace safety and health AM.[26] Work is needed in the area of safety. Workers can be exposed to pinch points, crushing points, and hot areas (i.e., potential for burns). There are also potential ergonomic hazards while loading, unloading, and maintaining AM tools depending on the machine and mass of feedstocks.

[24] UL 3400, Outline of Investigation for Additive Manufacturing Facility Safety Management (2018) https://www.ul.com/news/ul-certifies-first-additive-manufacturing-facility-ul-3400 https://www.ul.com/news/uls-3d-printing-additive-manufacturing-equipment-compliance-guideline

[25] NIOSH provides update on Advanced Manufacturing initiative. J.J. Keller and Associates. (2019, May) https://www.jjkeller.com/learn/news/052019/NIOSH-provides-update-on-Advanced-Manufacturing-initiative

[26] NIOSH announces partnership aimed at enhancing safety and health in 3D printing. (2020, February). Safety and Health Magazine. https://www.safetyandhealthmagazine.com/articles/19406-niosh-announces-partnership-aimed-at-enhancing-safety-and-health-in-3d-printing

While making investments in AM equipment is relatively straightforward, it is only a first step. The process may need to be refined, and staff must be trained and available to program, troubleshoot, and adjust equipment if needed. In addition, OEMs should be able to purchase, own and operate equipment, rather than via lease or subscription service. The continuously evolving nature of AM equipment has created significant uncertainties and challenges for capital investment; purchased machines could be obsolete or require upgrades in a relatively short time.

Goals for Operations

Factory connectivity—machine connectivity and unified Manufacturing Execution Software (MES); integrated, interoperable machines that have standard interfaces and operational workflows, rather than 'island' software and operational models.

Monitoring and control of equipment—Effective, affordable, in-situ and dynamic digital monitoring and control for AM equipment, incorporating innovative solutions possible through artificial intelligence and machine learning; dynamic hybrid control systems that allow for statistical process control (SPC) and six sigma decisions.

Material and equipment safety—common global standards for safety, including bulk AM materials safety and handling; intrinsic machine safety for those working around and with equipment; and others as needed.

Equipment maintenance—expedited, fully-staffed operational support for AM machines for trouble-shooting and maintenance, i.e., OEM technicians that are fully trained for trouble-shooting, repair, and maintenance.

Cost-effective business models—AM equipment that can be purchased, owned, and operated by automotive OEMs.

Safety, maintenance and factory integration are all important operational challenges for automotive AM.

Stellantis 3D printing prototype facility.

Challenges and Opportunities for Operations

For AM to become more widely used in automotive, improvements and innovations will be needed to ensure systems integrate with those on the factory floor, are safe, and well-monitored. Table 5 highlights the top areas of opportunity and major challenges for AM in automotive operations.

Table 5. Challenges and Opportunities for Operations	
Connectivity with Enterprise Systems	Connectivity and plug-and-play communication with factory floor systems that govern operations will be needed. Standards for interoperability and interconnectivity are currently lacking to enable interoperability and integration. Being able to interpret machine communication, send jobs efficiently, maximize time and materials, and optimize resource planning is key. Integrated, compatible software solutions are needed. OEMs need machines that are connected to Enterprise Resource Systems (ERPs), MES, and CAD archives – and controlled as part of a globally distributed solution space. Supplier-specific slicers should be eliminated and replaced with integrated plug-in solutions to provide an end-to-end compatible, seamless, consistent, and efficient to use systems that is free of duplicate data entry.
Data Protection/ Security	Data protection agreements need to be established to protect, establish ownership, and properly monetize data sent offsite to OEMs. Control software needs to run embedded intellectual property protection to allow an organization to control the encryption of the build volume, the number of copies to print, the timeframe to make prints, lock down build parameters, specifically identify the printer of use, and many other parameters. USB and other portable drive mechanisms need to be eliminated; printers should be network devices following the 802.1x and latest cyber security protocols and best practices.
Equipment and Materials Safety	Challenges for handling of AM materials in large volumes include storage in inefficient powder drums which have greater potential for spills and are not suitable for larger volumes. Operators need to be able to easily load machines and avoid spillage; new storage options are needed. Safety for normal machine operation and standard maintenance should limit the need for PPE and material handling should be enclosed from the operator as much as possible.
Monitoring/ Control and Maintenance of Equipment	Effective operations with AM require in situ monitoring that is compatible with current processes. Ideal systems could self-correct or flag issues early-on (e.g., simple sensors to flag issues rather than requiring a full inspection). There is a need for machine builders to better understand OEM expectations for operating efficiency, uptime and the basic metrics associated with reliable manufacturing operations. Mean time to failure (MTTF), mean time to repair (MTTR), and overall equipment effectiveness (OEE) standards are needed. Monitoring of machine uptime, downtime, alarm logs, and key process variables needs to improve and be visible to manufacturing teams. Digital traceability and control are needed, including traceability procedures down to position in the build volume. Machines should be configured for ease of operation and troubleshooting at the plant site by the operator (e.g., log files should be accessible). Affordable in-situ monitoring and dynamic hybrid control systems are needed to allow for statistical process control (SPC) and six sigma decisions to occur in real-time on a layer-by-layer basis so the appropriately sized sample set statistics can be gathered to support SPC and in-situ quality control rework. This could reduce the need for costly post-processing to acquire non-destructive test data for build quality control. Current monitoring is not real-time, is data-intensive and lacks timely access. Better understanding is needed of what to sense and control in AM equipment. External monitoring is currently via vendor cloud-based systems; a 'local cloud' enterprise version (behind the local firewall) for in-house monitoring is needed.
Synchronization with Manufacturing Requirements	A matrix approach could be used to help educate suppliers, machine builders, and software developers about OEM plant floor requirements in operational areas. Machine builders are commonly used to working with a prototype process or batch builds rather than continuous, high-volume environments, where factory acceptance requirements are quite different. Maintenance operations need to be developed for automation where possible. Operating conditions should be compatible with a plant environment for factors such as changes in temperature and humidity. Operational partnerships with vendors could be beneficial for increasing understanding and awareness of this environment

Goals for Workforce

Worker Safety—machines that prioritize safety, ergonomics, and minimize operator exposure and touch-time during turnover; improved best practices, PPE, and guidelines for inhalation and health and safety issues; elimination of potential personal safety areas, such as pinch or crushing points, and hot processing spots.

Skilled, diverse, next generation AM workforce—a skilled workforce to handle current and next-generation AM equipment and processes; continuously developed and enhanced through targeted education as well as non-traditional pathways; fully integrated and effective, ongoing training programs for use of AM on the automotive production floor, to include both vendors and union partners.

Challenges and Opportunities for Workforce

For AM to become more widely used in automotive, improvements and innovations will be needed to ensure systems integrate with those on the factory floor, are safe, and include a workforce or resource capability for expedient troubleshooting and repair. Table 6 highlights the top areas of opportunity and major challenges for AM in automotive workforce.

Table 6. Challenges and Opportunities for Workforce	
Worker Safety	Worker safety and emissions inhalation are serious considerations in continuous AM operations with cleaning between builds, which requires personal protective equipment (PPE). Safe handling equipment is needed for metal powders, photopolymer resins, solvents, binders, inks, and other materials. Published, up-to-date guidelines covering many types of AM materials are needed. Machines should be designed to avoid ergonomic hazards while loading, unloading, and maintaining AM tools; these vary depending on the machine and mass of feedstocks. NIOSH and OSHA guidelines and best practices for working around AM machines and processes need to be improved and incorporated. Current filter systems are inadequate and new designs are needed. Safety around equipment is another concern that needs to be addressed, due to potential pinch and crushing points, and hot areas.
Workforce and Training	Targeted education at universities and vocational/technical schools is needed to produce diverse skilled graduates and workforce. In addition, there are opportunities to take advantage of the diverse community of experts working in 3-D printing, including hobbyists and the next generation or non-traditional AM workforce. As AM becomes more widely used, training programs which cover the nuances of AM high volume operations may be needed, as well as general training for equipment technicians and union workers in operations, safety, and various other AM aspects. Union workers will need training to ensure proper use of PPE and handling of powders.

Design

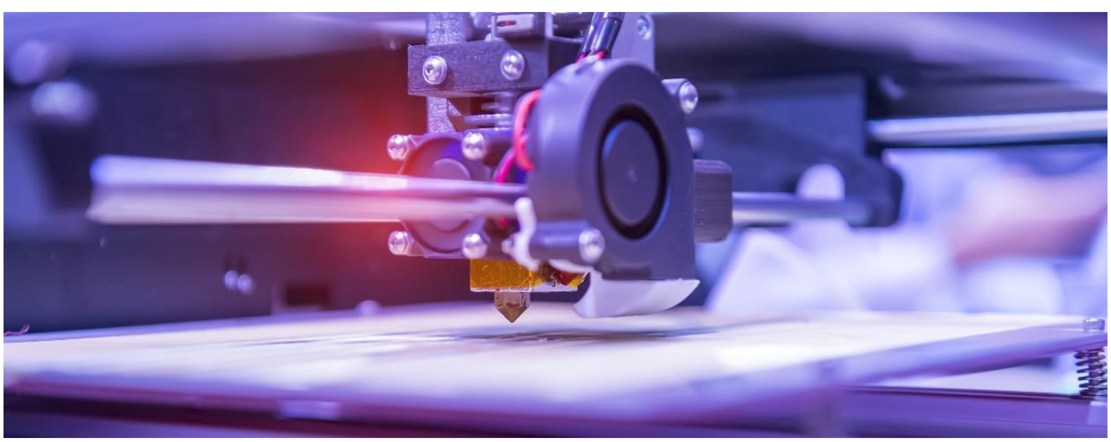
Design is an especially important element of AM and differs from traditional paradigms in several ways. There are advantages in designing a part specifically for the AM process, including more design freedom and the capability for part consolidation. AM parts can be designed with more intricate shapes, reduced weight, and less overall material use. AM can provide more design freedom—but part design should consider functional performance, manufacturability, post processing, and other key factors. Highly customized features can also be designed and produced. Many benefits (parts consolidation, complex geometries, bespoke parts and customization, faster speed to market, quick iterations, enables low volume production) result from not having a tool or mold requirement, and therefore enable greater design freedom.

Jigs, manufacturing tools, and fixtures, critical components of parts manufacture, can be designed and produced much quicker. Reducing the need for multi-component jigs and fixtures also saves time and costs in continuous operations.

The availability of good computer-aided design (CAD) models is vital to support the design process for AM. CAD lends to digital transfer of design and enables more rapid prototyping as well as product creation. However, a gap still exists between 3D CAD models and design capabilities for printed parts. This is due in part to the lack of tools to prepare and optimize CAD models for AM parts. Iterating between design optimization tools and the CAD environment is challenging; most optimization tools require going back/forth to CAD to yield the final part design. Generative design and topology optimization tools are just starting to incorporate design guidelines specific to each modality; these guidelines for casting, extrusion, and injection molding have long been incorporated into topology optimization tools.

Another challenge is that designers and engineers are not fully experienced and familiar with designing parts specifically for AM rather than traditional processes. This capability gap also limits opportunities to truly optimize and innovate designs.

The value proposition for AM parts can be impressive— but a clear business case needs to be developed and backed up by data and predictive cost models. For the automotive industry, the case for AM prototyping and low-volume or custom batch operations has become relatively established. The business case for high-throughput parts production is less clear and needs to be integrated with design models and cost-benefit analysis.



Goals

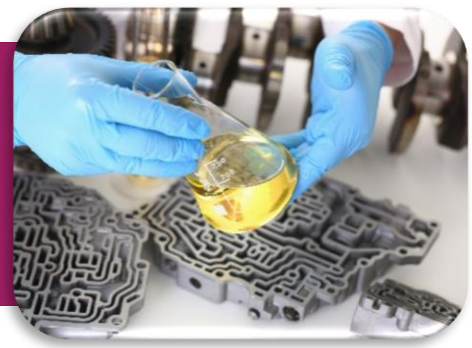
Design workforce—designers and engineers well-versed in both AM and traditional design paradigms.

Design methods and tools—accessible digital tools for AM with common formats and machine language, and capability for end-to-end AM design consideration and optimization, from materials to part.

Cost-effective front-end design—integration of design with the value proposition and business case for AM.

Plant floor layout—effective right-sizing and facility design around AM equipment and production.

Accessible CAD-integrated tools are needed to enable cost-effective up-front design of AM parts.



Testing of AM motor oil automatic gearbox and hydraulic booster.

Challenges and Opportunities for Design

Designing for AM can have multiple cost and productivity benefits for automotive parts and components, while enabling new part configurations with increased functionality. Taking advantage of AM opportunities on a broad scale will require overcoming some fundamental design challenges. Table 7 highlights the top areas of opportunity as well as major challenges impacting design of automotive AM parts.

Table 7. Challenges and Opportunities for Design of AM Parts	
AM Design Knowledge Base	Limited education and familiarity with how to design for AM and design allowables[27] constrains ability to optimize AM parts. Design rules for most AM parts differ from those for traditional manufacturing methods such as stamping, casting, or injection molding. Instead, designers need to understand and design around structures, down-facing surfaces, self-supporting structures, and other design features for both process build and post-processing. Designers need to understand a new set of rules and be familiar with traditional and AM design paradigms (including design software).
AM Design Tools and Methods	AM design guidelines specific to AM technologies are needed in CAD and finite element analysis (FEA) software to aid in design; design rules for AM should reside in native CAD to avoid need for multiple software packages and add-ons. Quick, in-process estimates are needed for time and cost, and the ability to quickly compare design A vs. design B.
	Current commercially available process simulation software is in its infancy and needs to be further developed to accurately simulate different AM processes and outputs (e.g., distortion and design changes to minimize). Design best practices and manufacturing requirements by process are needed. Modeling also needs to deliver results quickly. Parameterization still represents an issue for complex design translation from topology optimization to usable CAD. This is a particular issue with lattices. Moving from CAD to the AM part and maintaining digital quality is an issue, i.e., loss of quality with Standard Triangle Language (STL) format.
	FEA models lack the ability to compute complex geometry or models don't exist (e.g., slicing of layers). The actual product structure may not be represented if part is highly complex. Being able to model the final product accurately is desirable. Better ways are needed to incorporate design changes and iterations – today this requires going all the way to the front end to redo the CAD.
	Currently methods are lacking to conduct digital design and understand total cost of producing a part (including design hat can optimize processing and post-processing). Tools are needed to integrate the business case more fully into design software.
	Optimizing material utilization can be constrained by existing designs or automated nesting. When nesting is carried out at the design stage, there is a better chance to optimize these issues for AM. Nesting routines are being developed but not necessarily working.
Material Cards	Material cards define the specifications for AM material inputs for FEA software evaluations and other purposes. For example, material properties and how they behave under certain load cases are not available for AM materials and feedstocks for performance evaluations during the design process.

[27] Statistically determined materials property values, such as limits of stress, strain, or stiffness allowed for a specific material, part, application, or environmental condition.

A PATH FORWARD

Additive manufacturing has the potential to find use in many new applications in the automotive sector. This roadmap lays out some of the critical challenges to moving forward as well as some of the greatest opportunities.

For AM to become more widely used in automotive, technology advances will be needed to bring down the cost of both materials and machinery. This translates into machines that can use different types of materials, are more interoperable, and expediently maintained. Safety and environmental considerations will continue to be important, as well as the sustainability of the materials of use and ability for reuse.

Production equipment will need to provide reliable and repeatable quality parts at higher volumes. Batch operations will be always be needed – but the greatest market potential is for high throughput production lines with millions of potential parts. In the future, AM could be providing parts at remote locations, close to customers, such as dealer service centers. The opportunities are enormous.

All stakeholders need to work together to find solutions that are mutually beneficial. Recommendations for some of the next steps and actions that could follow from this Roadmap are outlined in Figure 3.

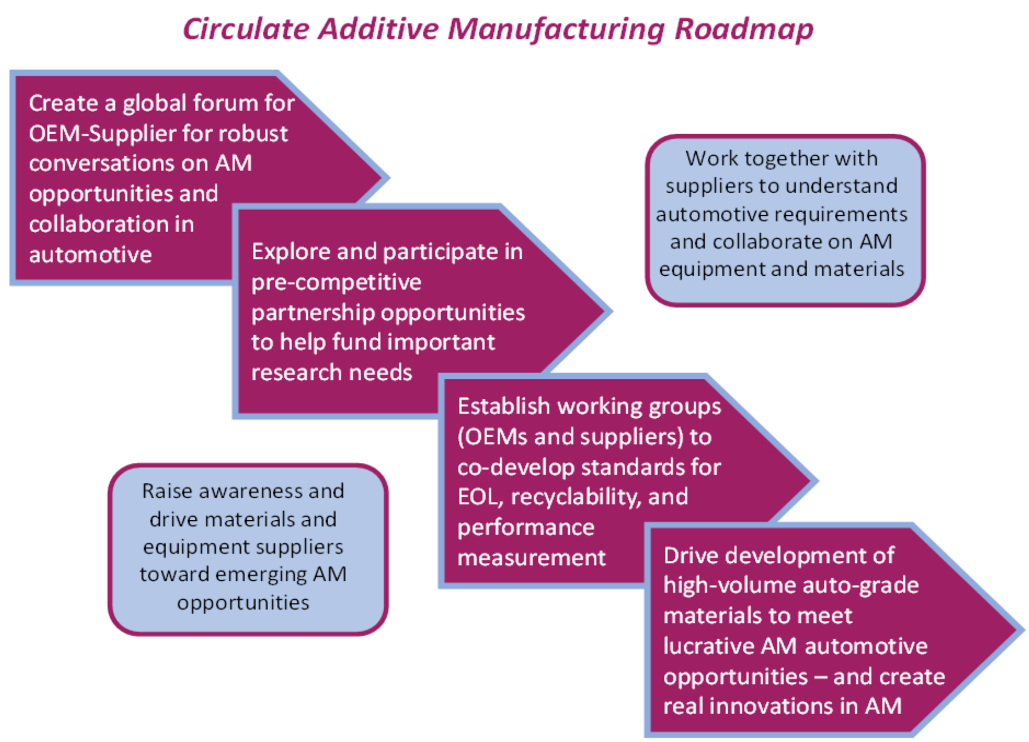


Figure 3. Recommendations for Future Actions

Cover photos (from top to right)

Wheel: Airless, 3D, puncture-less tire prototype, GM-Michelin project https://www.3dprintingmedia.network/general-motors-additive-manufacturing/

Manifold inlet: Ford aluminum manifold inlet printed by GE XXL additive printer https://www.3dnatives.com/en/ford-3d-printed-metal-part-050220195/#!

Lightweight aluminum 3D suspension system component with combined wheel carrier and brake caliper. Fraunhofer-Fiat-Chrysler research project. https://3dprintingindustry.com/news/fraunhofer-researchers-develop-3d-printed-suspension-part-for-fiat-chrysler-sports-car-179242/

GM Additive Innovation Center. From Corvette To COVID-19 Response: How 3D Printing Transforms Technology for General Motors (gm.com)

Stellantis Product Development center of excellence in Turin. Grill component prototypes. https://www.fcagroup.com/it-IT/media_center/insights/FiatGallery/gallery/additive_manufacturing_3d/FCAGroup_Additive_Manufacturing_3D_gallery_13.jpg

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Page 14. Courtesy of U.S. Army

Page 17. Courtesy of Ford Motor Company. https://3dprintingindustry.com/news/ford-opens-advanced-manufacturing-center-and-3d-prints-ford-shelby-mustang-gt500-parts-144889/

Page 20. Courtesy Stellantis (former Fiat Chrysler Automotive) https://www.fcagroup.com/en-US/media_center/insights/Pages/additive_manufacturing_3d.aspx#

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