Technology Roadmap: Materials and Manufacturing

CENTER FOR AUTOMOTIVE RESEARCH

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Acknowledgments

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CAR's mission is to conduct independent research and analysis to educate, inform and advise stakeholders, policymakers, and the general public on critical issues facing the automotive industry, and the industry's impact on the U.S. economy and society.

Introduction

The automotive, transportation, and mobility industries have experienced transformative changes due to advancements in connectivity and automation technologies, data analysis, and the rise of new mobility services. With such rapid changes in the industry's landscape, an understanding of where technological development is at present and where it is likely headed is helpful to guide future decision-making.

With funding from the Michigan Economic Development Corporation (MEDC), the Center for Automotive Research (CAR) has prepared this technology roadmap based on internal research and a thorough analysis of available industry reports. CAR researchers vetted the study conclusions with critical input from a group of subject matter experts. This white paper updates CAR's previous Technology Roadmap (Smith, Spulber, Modi, & Fiorelli, 2017) published in 2017.

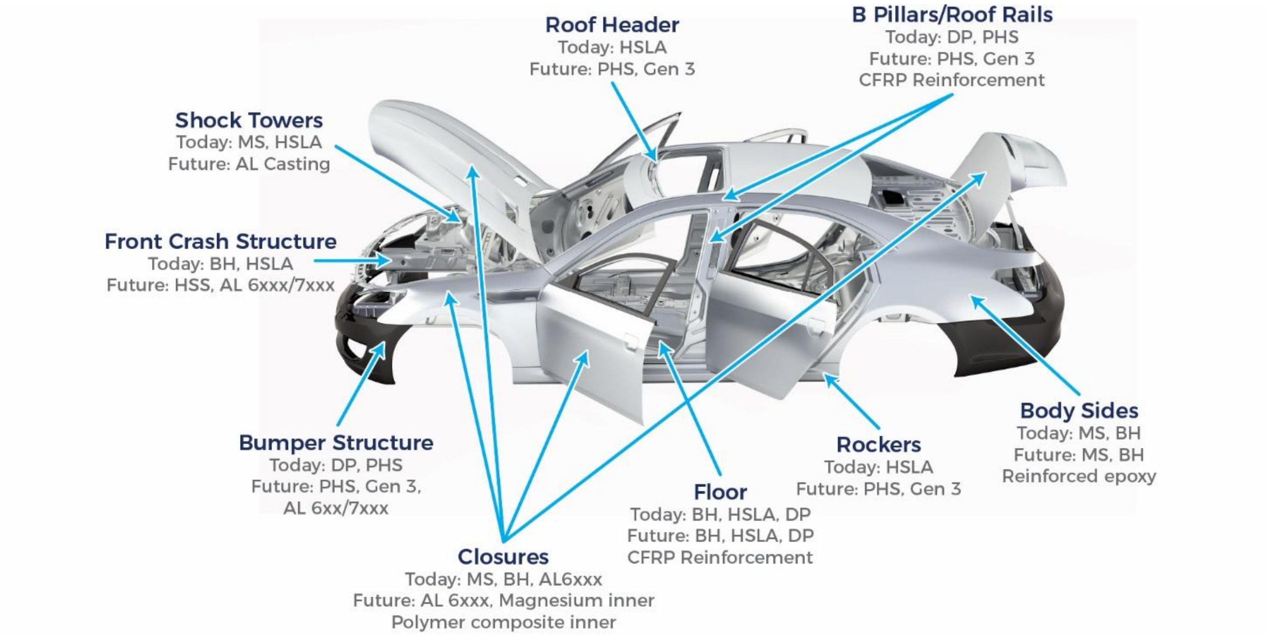
The World We Know

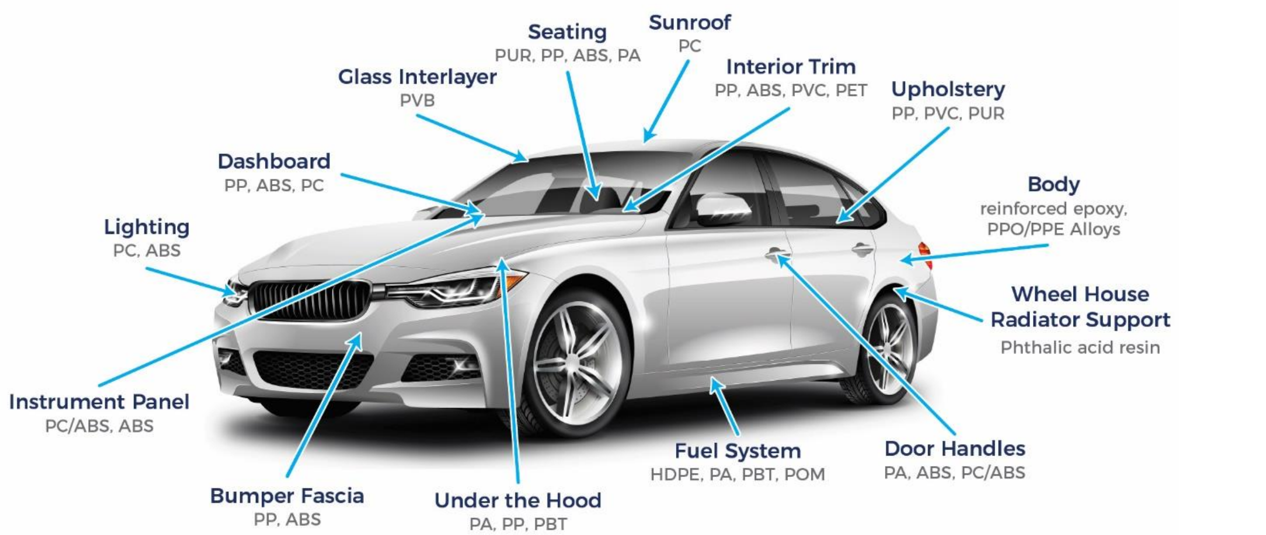
Materials

Materials are the core competence of any manufacturing industry. No matter how high-tech the final product is—production always starts with basic raw materials. In the last 100 years, the automotive industry has mastered the mass production of vehicle bodies (body-in-white and closures) made predominantly from steel with occasional use of aluminum, magnesium, plastics, polymer composites, and even wood. An average vehicle body in the U.S. fleet today is 65 percent steel, 13 percent aluminum, 4 percent magnesium, 6 percent plastic and polymer composites, and rest are comprised of other materials such as glass, adhesives, sealers, and foam Powertrain components are around 58 percent iron and steel, 29 percent aluminum, 8 percent plastics and rubber, and rest is other materials. Engines are mostly aluminum. Other vehicle components such as interiors trims, seats, carpets, bumper, headlamps, engine cover, and hoses are made from plastics or polymer composites.

Further investigations reveal specific grades of metals and types of plastics and polymer composites used in vehicles today. Steel grades range from mild steel and dual-phase steels to strategic use of hot-stamped and gen-3 steels. Aluminum is either 5000 or 6000 series and used mostly in closures (doors, hood, liftgate, and fenders) and powertrain components with few structural applications. (Khemka, 2019). Figure 1 illustrates various materials used in vehicles today.

Figure 1: Materials used for key vehicle components





Source: CAR Research, Nexant, American Chemistry Council

Metals								
HSLA	High-strength low-alloy steel		**DP**	Dual-phase steel		**Gen 3**	Generation three steel
BH	Bake-Hardenable Steel		**PHS**	Press Hardenable Steel		**MS**	Mild Steel
Plastics and Polymer Composites							
ABS	Acrylonitrile Butadiene Styrene		**PET**	Polyethylene terephthalate		**PUR**	Polyurethane
HDPE	High-density polyethylene		**POM**	Polyoxymethylene		**PVB**	polyvinyl butyral
PA	Polyamide		**PP**	Polypropylene		**PVC**	Polyvinyl Chloride
PBT	polybutylene terephthalate		**PPE**	Polyphenylene Ether		**CFRP**	Carbon Fiber Reinforced Composite
PC	Polycarbonate		**PPO**	Polyphenylene Oxide			

Manufacturing

Fast, cost-effective manufacturing processes is one of the top priorities in making profitable, good quality vehicles. Since steel and aluminum are currently the predominant materials, stamping, forging, extruding, CNC machining, and welding are the critical manufacturing processes. For plastics and polymer composites, injection molding, vacuum forming, and autoclave are the critical processes.

Almost all processes in the automotive industry embody some form of automation. Body shops are generally fully-automated, requiring very little human intervention. However, the trim and final assembly departments use mostly manual processes (Automotive News, 2018). Most modern machines have sensors to record critical data such as temperature, pressure, humidity, etc. However, the data is currently stored and analyzed in the machine offline. Automation is a rapidly changing arena, and there are many changes on the horizon.

Technology Drivers

The automotive industry is facing record disruptions from technologies such as automated, connected, shared, and electric vehicles (ACES), additive manufacturing (3D printing), Internet of Things (IoT), increasing personalization, and lower rates of vehicle ownership among younger consumers. Significant changes in technology affect vehicle design and engineering, which in turn affect the material selection. Figure 2 shows the major trends driving material change in vehicles.

Figure 2: Major Trends Driving Material Change

Fuel economy regulation and customer expectations for their new vehicles to be more efficient than their last vehicle are the biggest drivers of change in materials. In the U.S., Corporate Average Fuel Economy (CAFE) and greenhouse gas (GHG) regulations put pressure on automakers to increase vehicle efficiency. Lightweighting is an important tool used by automakers to meet these standards and consumer expectations. The Trump Administration is reviewing CAFE and GHG regulation and is expected to set less stringent regulatory standards through 2026. If enacted, less stringent standards could temporarily reduce pressure to lightweight vehicles sold in the U.S. However, regulators in many countries and regions are moving forward with increasingly stringent fuel economy and GHG policies. Since most automakers design vehicles to sell in global markets, changes to current U.S. regulations may not drastically alter automaker's lightweighting strategies.

The second relevant trend driving materials usage is the increasing penetration of battery-electric vehicle (BEV) technology. Batteries are significantly heavier than the internal combustion engines (ICE) that have similar performance characteristics. Ten gallons of gasoline contains approximately 337 kWh of energy embodied in the fuel (33.70 kWh = 100 percent of the energy of one gallon of gasoline) (US DoE, 2014). A vehicle with 10 gallons of fuel onboard weighs an additional 63 pounds, and it gradually drops that weight as the fuel is combusted. A BEV battery pack may contain 100 kWh of energy and weigh 1,400 pounds but does not need many additional powertrain components to propel the vehicle.

Overall, BEVs are heavier than ICE vehicles. For example, the Chevrolet Bolt EV weighs 300 pounds more than the similar size Volkswagen Golf (UBS, 2017). Similarly, BMW announced that the 2020 Mini EV would weigh 284 pounds more than a base Mini Cooper. Therefore, BEVs are forcing automakers to look for innovative ways to lightweight their vehicles.

The third important driver is advanced driver assist systems (ADAS) and consumer demands for better comfort, infotainment, and productivity features. The push for autonomous vehicles will lead to increased use of sensors and supporting systems that are expected to add significant weight to the vehicle. Automakers have anecdotally claimed 300-400 pounds of future weight additions due to the installation of ADAS. Studies have shown that the content in the vehicles for comfort, infotainment, and production features has grown almost every model year (Zoepf, 2011). This trend is likely to continue for personal vehicles and may become more prevalent for shared vehicles. ADAS and consumer demand for more content will increase the pressure on that automakers' lightweighting targets.

Mobility-as-a-Service (MaaS) is a disruptive trend that may also alter vehicle design and engineering requirements. Shared vehicles are projected to accumulate five to seven times more miles per year than personally owned vehicles and experience higher use of components such as doors, seats, and suspension systems (Modi, 2018). These increased demands for shared vehicles will necessitate improvements in structural durability, higher fatigue targets, robust joint design, better thermal management, and vehicle end-of-life management. These requirements demand materials that perform better under more stringent engineering targets.

Safety is another critical consideration in material selection. Governments around the world enforce driver and passenger safety regulations, but the automakers often strive to do better than the standards. A long-held belief that heavier vehicles are safer than lighter-weight vehicles in a crash is not universally true. Improvements in vehicle design, smart engineering, and load path optimization using materials with a high strength-to-weight ratio can lead to safer as well as lightweight vehicles.

Manufacturing technology is both an enabler and a barrier to new materials. Innovative manufacturing technologies such as additive manufacturing can disrupt the material supply chain by favoring AM-specific materials such as powdered metals and plastics. However, substantial capital investments in current manufacturing processes such as stamping and injection molding tend to curtail the rapid transition to new materials and processes. Another factory technology which might act as a catalyst for innovative materials and fabrication processes is Industry 4.0. It refers to the concept of factories in which machines are augmented with wireless connectivity and sensors, connected to a system that can visualize the entire production line and make decisions on its own. Important Industry 4.0 technologies include robots and cobots (collaborative robots) that work side-by-side with humans, big data, and artificial intelligence that help factory managers predict equipment maintenance schedules to reduce downtime and improve productivity and quality.

The last but business-critical driver is material cost. Cost is an important variable in the overall design optimization process. The automotive industry is highly competitive, with consumers always looking for value. Therefore, the cost is one of the critical components of material design optimization. Any material that might replace steel must fit within those optimization boundaries.

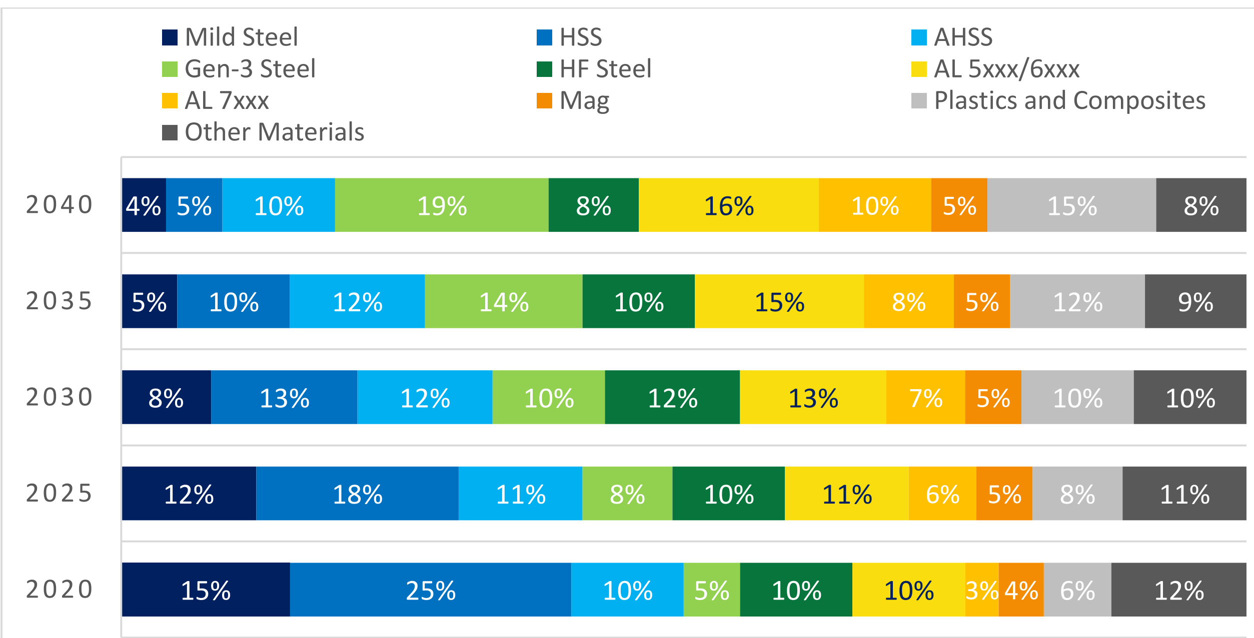
The World on the Horizon

As addressed earlier, the direction and speed of advancements in material and manufacturing technologies depend on whether the specific application of it fits within the design optimization space for the vehicle or family of vehicles.

Materials

Steel is the primary material in current light vehicle structures. Interior components utilize metals for safety-critical components such as seats, and plastics and polymer composites, fabrics, leather, and vinyl for trims, upholstery, headliners, and carpet. To capture the most critical future material and manufacturing technology trends of the industry, the CAR team compiled the findings from multiple academic, industry, together with CAR's knowledge base to project future materials usage in light vehicle manufacturing. CAR researchers validated these projections in discussions with industry subject matter experts. Figure 3 shows the material percentage distribution of an average vehicle structure today to 2040.

Figure 3: Average Vehicle Structure (Body-in-White and Closures) - Material Percentage by curb weight per vehicle



Other materials include dampeners, static sealers, adhesives, and glass

Note: 100% includes Body-in-White and Closures Only. Not included are powertrain/chassis, interiors, windshield, and dynamic sealers
Source: CAR Research

CAR projects that future vehicle structures will be a mix of materials including high-strength steel (HSS), high-strength aluminum, some magnesium, as well as plastics and polymer composites for reinforcement. While the overall percentage of steel in the vehicles is expected to decrease, the number of steel grades is expected to increase. Aluminum will most likely replace mild steel for closures (doors, hoods, liftgate, and fenders), roof panel, and body sides. Polymer composite (primarily carbon and glass fiber composites) use in structural components as reinforcement will increase with advancements in processing technology and lower costs. Increased use of polymer composites will drive more use of epoxies and other thermoset resins. Automakers are also experimenting will thermoplastics for polymer composite applications to improve recyclability *(American Chemistry Council, 2015)*. Polycarbonate use may increase due to the increased installation of panoramic sunroofs and sensors for ADAS. The use of polyamides and engineering plastics may also increase due to their application in the battery tray and other structural parts.

Vehicle interiors will continue to use predominantly plastics and polymer composites because of the advantages in lightweighting, personalization, and customization. The emphasis on recyclability, especially for ACES vehicles, may drive greater use of bio-based resins and fibers. Bio-based polymers are produced from a variety of sources—including soybeans, castor beans, corn, and sugar cane—all of which can be fermented and converted into polymers. Bio-based composites may be reinforced or filled using natural fibers such as hemp, flax, or sisal. The use of these plant-based materials may reduce reliance petroleum-based polymers and fibers *(Hill, Cregger, & Swiecki, 2012)*.

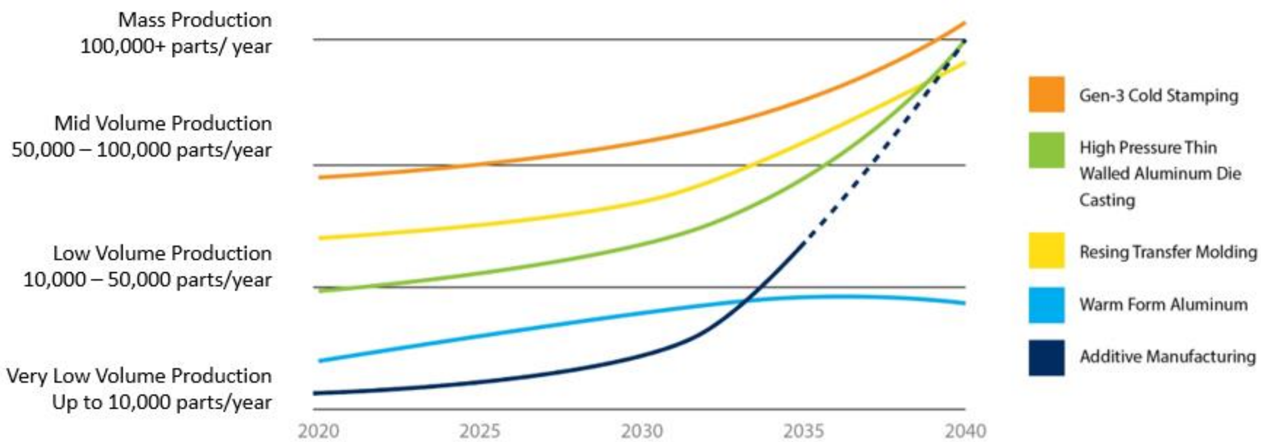
The vehicle propulsion system and related components are made from both metals and plastics. Metal applications include engine blocks, engine heads, pistons, crankshafts, camshafts, connecting rods, transmissions gears and case, electric motor cases, exhaust manifold, and others. The majority of these components are made from ferrous alloys and aluminum. Plastic and elastomer applications include hoses, air induction systems, engine covers, cooling piles and pumps, and the skid plate. The ferrous metal content of internal combustion engine vehicles (ICEVs) and hybrid electric vehicles (HEVs) is slowly decreasing and is being replaced by aluminum, plastic-based materials, and HSS.

Given that most powertrain metals are either castings or forgings, HSS use is minimum *(Sullivan, Kelly, & Elgowainy, 2018)*. This trend is expected to continue for ICEVs and HEVs. However, in a BEV powertrain, ferrous use is expected to decrease drastically, while aluminum will also decrease slightly, and plastics content will be similar to ICE. BEVs will use more copper due to its use in batteries and wiring harnesses, and there will be greater use of other essential materials such as lithium, cobalt, and rare earth elements until innovations in battery technology reduce or eliminate the reliance on these materials *(Petit, 2017)*.

Manufacturing

Innovative manufacturing technologies are needed to implement new materials strategies. Figure 4 shows emerging manufacturing processes in the automotive industry and the maturity of these processes at various vehicle production volumes. CAR considered additive manufacturing, high-pressure thin-walled aluminum die casting, resin transfer molding, warm forming aluminum, and press-hardened steel (PHS) in this research. CAR researchers selected these technologies due to their expected advancement and availability by 2035. Several manufacturing processes are already considered mature (currently used in mass production) and, therefore, not mentioned. These processes include cold stamping, roll forming, hydroforming, forging, casting, powdered metal technology, extrusion, and injection molding. The additive manufacturing curve beyond 2035 is unknown, but this technology could be deployed in mass production if it follows a similar trajectory to other developing manufacturing processes considered for this research.

Figure 4: Emerging Manufacturing Processes in the Automotive Industry



Source: CAR Research

Future vehicle structures will rely on a mix of different materials, and joining dissimilar materials is one of the significant challenges to multi-material usage strategies. Resistance Spot Welding (RSW) is the most popular joining method for steel-to-steel in the automotive industry. RSW is fast and cost-effective (as low as $0.03 per spot), but RSW does not work well with dissimilar materials. Table 1 lists popular automotive joining technologies and their applicability for different material combinations.

Table 1: Popular joining methods for automotive applications
S; Steel, A: Aluminum, M: Magnesium, C: Composite, P: Plastic, All: All Materials

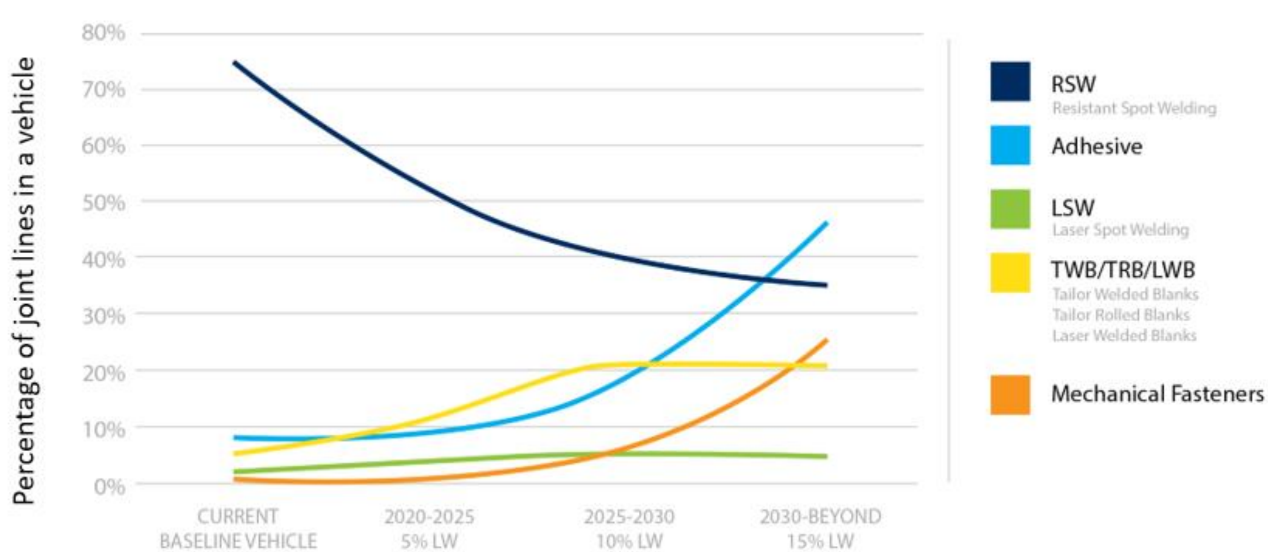
Type	Joining Method	Abbreviation	Material Combinations
Liquid Phase Welding	Resistance Spot Welding	RSW	S-S, A-A, S-A
	Laser Welding	LW	S-S, A-A, S-A
	Gas Metal Arc Welding	GMAW	S-S, A-A
	Tungsten Insert Gas Welding	TIG	S-S, A-A
	Electron Beam Welding	EBW	
	Magnetic Pulse Welding	MPW	S-S, S-A, A-A, A-M
	Resistance Element Welding	REW	S-A
	Element Arc Spot Welding	EASW	S-S, A-A, S-A
Solid-State Welding	Friction Stir Welding	FSW	S-S, A-A, S-A
	Friction Stir Spot Welding	FSSW	A-A, S-A
	Friction Welding	FW	A-A, S-A
	Ultrasonic Welding	UW	A-A, S-A
	Friction Element Welding	FEW	A-A, S-A
Mechanical Joining	Self-Piercing Riveting	SPR	A-A, S-A, M-M
	Clinching	CLN	A-A
	Blind Riveting	BR	S-S, A-A, S-A
	Flow Drilling	FD	S-S, A-A, S-A
	Punch Nailing	PN	S-S, A-A, S-A

Type	Joining Method	Abbreviation	Material Combinations
Threaded Fastening	Bolts and Nuts	B & N	All
	Metal Screws	MS	All
Adhesive Bonding	Adhesive Bonding-Epoxy	AB-E	All
	Adhesive Bonding-Polyurethane	AB-PU	All
	Adhesive Bonding-Acrylic	AB-A	All
Mixed or Hybrid Joining	Weld Bonding	W-B	S-S, S-A, A-A
	Rivet Bonding	R-B	S-S, A-A, S-A
	Clinch Bonding	C-B	S-S, A-A, S-A
Other Methods	Laser Brazing	LB	A-A, S-A
	Insert Molding	IM	C-C, C-S, C-A
	Hemming	HM	S-S, A-A, S-A
	Clipping	CL	All
	Snap Fitting	SF	P-P, P-S, P-A

Source: CAR Research

Adhesive bonding is one method that can join most material combinations. Adhesives also provide increased structural rigidity since they produce a continuous bond, unlike RSW. In automotive applications, adhesives are often used with mechanical fasteners because the parts need to be held together until the adhesive cures. Fasteners also provide added safety in case the adhesive fails in the field. Automakers are increasingly using adhesives for joining, and this trend is expected to continue with the introduction of mixed-material body structures (see Figure 5).

Figure 5: Trends in Joining Processes



LW: Lightweighting as a percentage of curb weight
Note: Percentage of joint lines do not add up to 100 because of overlapping applications. For example, adhesives and fasteners used concurrently
Source: CAR Research

Automotive factories already have high automation, but in the future, machines will be connected and communicate with one another to ultimately make decisions without human involvement—an advancement commonly known as Industry 4.0. A combination of cyber-physical systems, IoT, and the Internet of Systems will make Industry 4.0 possible, and the Smart Factory a reality. As a result of the support of intelligent machines that keep getting smarter as they get access to more data, factories will become more efficient and productive, and more ecologically friendly. The industry is investing in digital factory technologies such as smart sensors, cloud computing, and artificial intelligence (AI). Figure 6 shows the current investment in smart factory technologies and the forecast.

Figure 6: Smart Factory Investments

	Current	2020-2025	2025-2030
Investment in Digital Technologies (as % of total annual revenue)	2.60%	3.70%	4.70%
AI and Data Analysis (as % of digital technology investment)	34%	38%	43%
Use of Smart Sensors[1] (as % of all shop floor machines)	35%	52%	76%
Cost Savings with Digital Tech	11%	21%	30%

[1] A smart sensor is a device that takes input from the physical environment and uses built-in compute resources to perform predefined functions upon detection of specific input and then process data before passing it on.

Source: CAR Research, PWC, KPMG, Imperial College London, Machine Design, Various Others

Enablers and Threats

Technological availability and adoption can be affected by multiple factors, such as the availability of enabling technologies and the costs, consumer acceptance, and the supply chain and infrastructure required to support them. This section considers the primary barriers to the adoption of new materials and new manufacturing technologies.

Risk of part failure and vehicle recalls

New materials used in new applications have the potential to fail. Material failure in the field is a constant risk that automakers have when introducing new materials into a vehicle. The industry has implemented stringent material qualification procedures to safeguard consumers and to try to prevent such a scenario. However, these procedures also hinder the greater use of new, innovative materials. Often new materials are tested in the niche, low-volume vehicles, e.g., BMW uses CFRP extensively in its "i-series" vehicles.

Supply Chain

Due to unforeseen circumstances, the material supply chain may not be able to produce the required quantity of material or products, which can cause delays in vehicle production. For this reason, automakers make sure that materials have a robust global supply chain before qualification for use in mass production. Single sources of supply are often not acceptable for materials used in high-volume parts as an element of an automaker or supplier's risk-management strategies. Countries and companies need to invest in local production, the supply of materials, and infrastructure to drive innovation.

End-of-Life Recycling and Environmental Concerns

With the growing awareness around climate change and waste management, automakers need to manage the vehicle's end-of-life better. In a few countries, automakers and suppliers have a legal obligation to manage their product's lifecycle through end-of-life mandates. Therefore, criteria material's recyclability is an increasingly important factor in material qualification. Materials or manufacturing technologies that could cause environmental harm are not favored.

Cost versus Benefit

A change in the material may improve the performance of the product, but the cost may far exceed the benefits. For example, carbon fiber is lightweight material providing significant strength but is roughly ten times more expensive than steel (Rocky Mountain Institute, 2011). The automotive industry is very cost-sensitive because consumers have many options, and many segments of the market are price-sensitive. Therefore, any material or manufacturing technology needs to meet the vehicle program's design optimization and cost targets, which can vary significantly according to production volumes.

Customer Expectations

Market forces often play a significant role in material choices, especially for interior trim materials. For example, if consumers prefer leather interiors, an automaker may be hesitant to try out new materials even if the new materials are superior and cost less. Customers are increasingly demanding greater personalization and customization of their vehicles. Technologies that enable customization, such as additive manufacturing, have an advantage since there is no hard tooling, which is costly and time-consuming.

Conclusion

This report forecasts materials and manufacturing trends based on the CAR team's research findings as well as input from subject matter experts. The results show that several factors can affect the industry's progress on material technology in the coming decades, including fuel economy regulations, added weight due to batteries, ADAS, comfort features, increasing durability requirements for shared vehicles, and safety. CAR researchers found that vehicle lightweighting will remain a top priority for the industry as automakers strive to use the right materials for the correct application promoting mixed-material body structures. The use of advanced HSS, high strength aluminum, plastics, and polymer composites will continue to increase.

To enable the production of lightweight parts, the use of advanced manufacturing technologies such as additive manufacturing, thin-wall casting, resin transfer molding, and structural adhesives are all expected to increase. To increase productivity, improve part quality, and reduce waste, automakers are investing in Industry 4.0 technologies such as smart sensors, cloud computing, and AI. Industry 4.0 investments are expected to double in the coming decade.

Finally, the future of materials and manufacturing technologies will depend on multiple factors, such as the availability of enabling technologies and the cost, consumer acceptance, recyclability, and supply chain and infrastructure required to support them. Design optimization is the key to balancing performance and cost requirements.

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