Quadrennial Technology Review 2015

Chapter 8: Advancing Clean Transportation and Vehicle Systems and Technologies

Technology Assessments

Connected and Automated Vehicles

Fuel Cell Electric Vehicles

Internal Combustion Engines

Lightweight Automotive Materials

Plug-in Electric Vehicles

U.S. DEPARTMENT OF ENERGY

Lightweight Automotive Materials

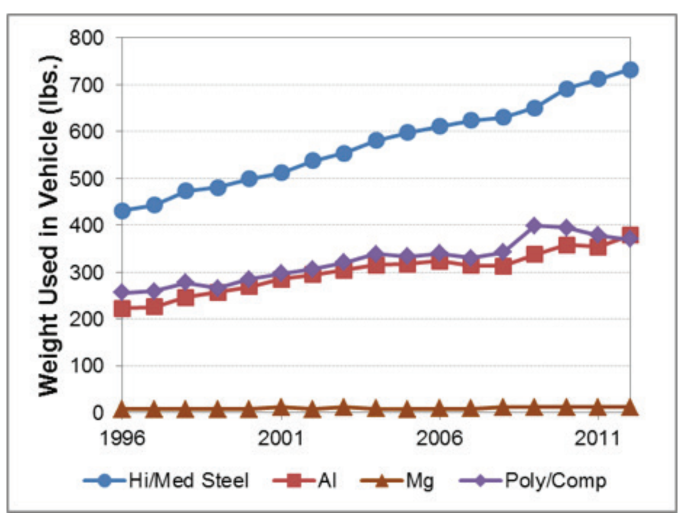
Chapter 8: Technology Assessments

Introduction to the Technology/System

Overview of vehicle lightweighting

Reducing vehicle weight affects transportation energy consumption by improving efficiency. Upwards of 85% of the energy in fuel is lost to thermal and mechanical inefficiency in the drivetrain[1] while the remaining 12-15% is used to overcome the tractive forces that resist forward motion.[2] Of these tractive forces, vehicle weight most significantly affects inertial (acceleration) and rolling resistance forces while aerodynamic forces are not closely related to mass. While the specific relationships between mass and inertial and friction forces is well understood, calculating the exact impact of vehicle weight reduction on energy efficiency is complicated by factors such as fleet mix, mass decompounding (i.e., a mass reduction in one component such as the body enables the use of lighter weight systems such as brakes and suspension), and vehicle design decisions. Several studies have explored the relationship between mass and fuel consumption using empirical techniques. A linear regression analysis of the curb weight versus carbon dioxide (CO_2) emissions (a measure of efficiency that is correlated with fuel consumption) for the model year 2008 vehicle fleet suggests that a 10% reduction in vehicle weight is associated with an 8% reduction of CO_2 emissions.[3] A model that combines curb weight and fuel consumption data with a technique for normalizing vehicle performance indicates that a 10% reduction in vehicle weight yields a 5.6% reduction in fuel consumption for cars and a 6.3% reduction in fuel consumption for light trucks.[4] Other studies have used more complicated (though still empirically based) models. A detailed physics-based model of vehicle performance as a function of mass across several driving cycles shows a 6.8% improvement in fuel economy for a 10% reduction in vehicle weight when the engine is "re-sized" to maintain the performance characteristics of the original vehicle;[5] simulation using a different detailed modeling technique indicates that a 10% reduction in weight provides a 6.9% reduction in fuel consumption for cars and a 7.6% reduction in fuel consumption for light trucks.[6] Modeling work sponsored by the Department of Energy at the National Renewable Energy Laboratory (NREL) also uses a detailed model to understand vehicle efficiency and predicts a 6.9% improvement in fuel economy for a 10% reduction in weight when the engine is resized. Despite the varied approaches summarized here,

Figure 8.D.1 Trends of Lightweight Materials use in Vehicles[8]



the results are quite similar. In general, a 10% reduction in vehicle weight provides a 6-8% improvement in fuel economy when vehicle performance characteristics are maintained.[7]

Today's average passenger vehicle weighs 3350 pounds without passengers or cargo, and consists of the following materials as a percentage of total vehicle mass: 54% iron or mild steel, 10% first generation high strength steel, 9% aluminum, 7% plastic, 4% glass, 1% magnesium, and the remaining 15% a mixture of copper, paint, carpeting, padding, insulation, and rubber (see Table 10.3 in the QTR main report). The amount of high strength steel, aluminum, plastic, and magnesium has been steadily increasing. As shown in Figure 8.D.1, since 1996 lighter weight materials have shown significant increased use in production vehicles: aluminum has increased by 70%; magnesium has increased by 64%; medium and high strength steel has increased by 70%; and the use of composites has increased by 45%. In today's car, the use of these materials represent a 10% weight reduction and a 7% improvement in fuel economy (based on a 3600 lbs car including passengers, using 330 lbs aluminum, 35 lbs magnesium, 350 lbs of high strength steel, and 280 lbs of composites and plastics).

Challenges

Despite this increased use of lightweight materials, vehicle weight increased throughout this period until 2004, probably due to weight increases from other content changes such as increased safety system requirements, increased vehicle size, greater consumer content, or higher output drivetrains.

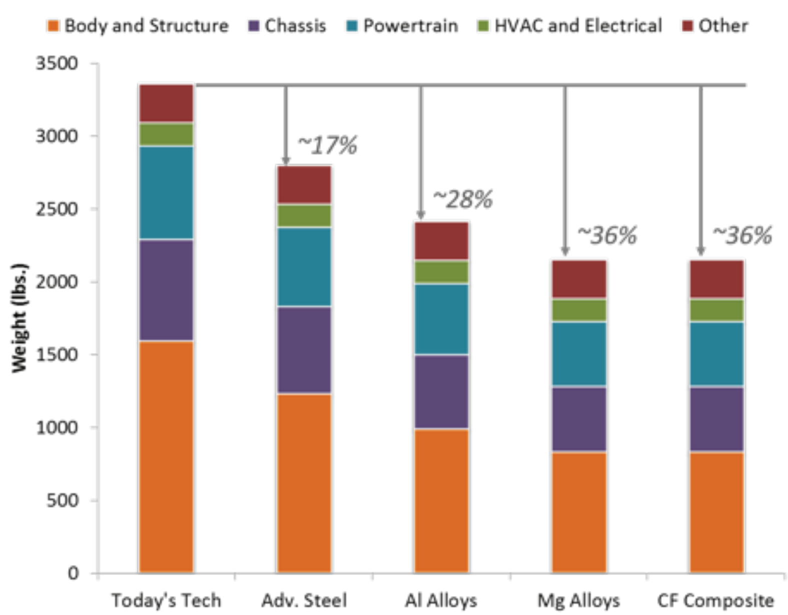
Table 8.D.1 Vehicle Weight in a Typical Mid-size Passenger Car Without Passengers or Cargo (representative values determined from various sources and interaction with automotive industry members). Weight is distributed across different subsystems in the vehicle (DOE calculations).

System	Baseline Weight (lbs.)	Percent of Total
Body and Structure	1591	47%
Chassis	696	21%
Powertrain	645	19%
HVAC and Electrical	158	5%
Other	268	8%
Total	**3358**	

Materials substitution in the body, structure, and some chassis systems directly reduces weight with a range of effectiveness based on material type as summarized in Table 8.D.1. Weight reduction in the powertrain and in certain parts of the chassis is achieved mostly through mass decompounding, for example, by reducing the size of the engine and brakes to accommodate a lighter body structure, rather than through direct savings. Finally, the weight reduction potential for many systems, such as the HVAC or many electrical components, is essentially zero. Based on these results, the weight reduction potentials for vehicles that make the greatest reasonable use of each material system discussed here are shown in Figure 8.D.2. Each bar in the chart represents the estimated weight of a vehicle if the indicated material was applied to the greatest extent possible.

A single material is not the optimal solution for a complex system such as a vehicle, and additional weight can be removed from a vehicle through the use of multi-material structures. Material substitution at the component level can reduce weight through the application of materials with improved specific properties (i.e. properties per unit density) or by consolidation of parts and functions. Examples of component-level material substitution include an advanced high-strength steel (AHSS) rear chassis structure[9] and magnesium engine cradle,[10] both of which reduce considerable weight while maintaining the specific packaging and performance requirements of the original steel components. Examples of multi-material structures include the European Union Super Light Car which is about 50% aluminum by weight but also includes significant use of magnesium, steel, and composites.[11] The recent Multi-Material Lightweight Vehicle (MMLV) program sponsored by the Department

Figure 8.D.2 Weight Reduction Opportunities (DOE calculations)



of Energy in conjunction with Magna International and Ford Motor Company demonstrated the potential for a 50% weight reduction through the use of multi-materials, although substantial reduction in content and function was required for this level of weight reduction.[12] Implementing multi-material solutions introduces an additional layer of technology challenges associated with multi-material joining, corrosion prevention, design tools, and performance predictions.

R&D has focused on the most promising materials (advanced high strength steels, aluminum alloys, carbon fiber reinforced composites, and magnesium alloys), and then developed the technology needed to overcome barriers that impede the use of these materials in automotive structural applications, while continuing to evaluate other material options as new information becomes available. These R&D activities can be partitioned into three broad areas:

- Properties and manufacturing: reducing the cost of raw materials and processing, while improving the performance and manufacturability
- Multi-material enabling: evaluation and development of multi-material joints and structures, taking best advantage of the properties of each of the materials
- Modeling and simulation: the development of commercially available design tools and predictive models which incorporate validated data and computational processes for lightweight material options, and making the validation data available to the community

Lightweight materials also face non-technical considerations from consumers, manufacturers, and suppliers. From the consumer perspective, substituting lighter weight materials for steel in vehicle structures will result in an increase in production cost, which will ultimately be reflected in an undesirable increase in vehicle price. From the manufacturer's perspective, vehicle weight reduction involves risk, such as uncertainty in structural performance and repair concerns. Further, while there are supply chain capacity concerns with all the lighter weight material options, material supply is of particular concern with magnesium and carbon fiber, where minor increases in use of these materials across a wide section of the automobile fleet would overwhelm the available supply.

Technology Assessment and Potential

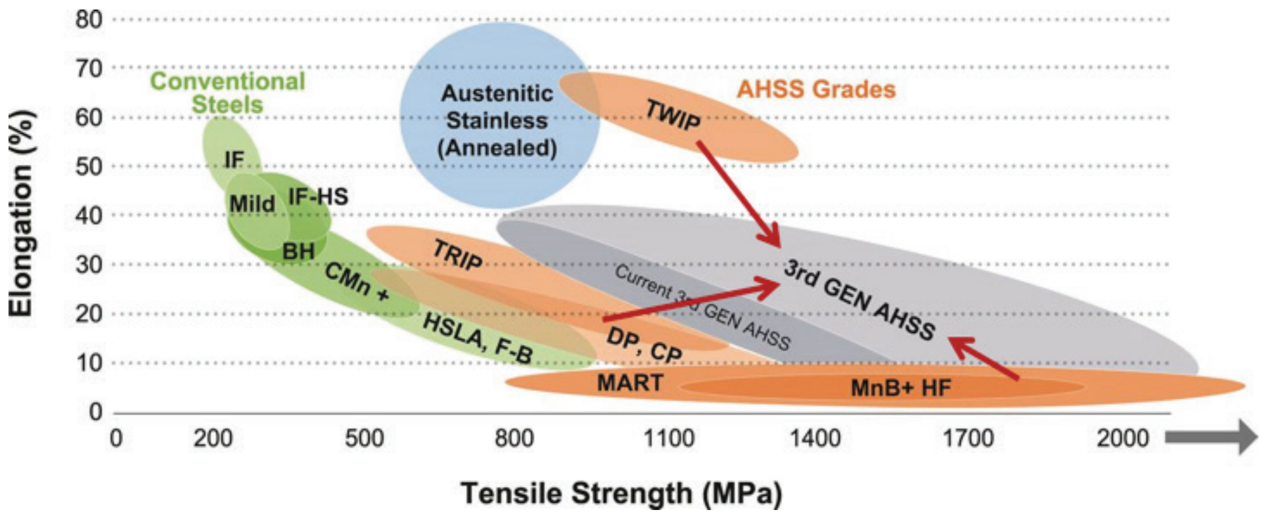
Advanced High Strength Steel

Conventional iron and steel alloys are prominent in existing vehicle architectures, making up about 45% of the weight of a vehicle. Despite the relatively high density of iron-based materials, the exceptional strength and ductility of advanced steels offers the potential for efficient structural designs and reduced weight. Application of a new generation of advanced high strength steels has the potential to reduce component weight by up to 25%, particularly in strength limited designs. Steel components are also generally compatible with existing manufacturing infrastructure and vehicle materials, making them a likely candidate for near-term weight reduction. Promising pathways towards improved steel performance include quench-and-partition (Q&P) steel,[13] medium-manganese transformation induced plasticity (TRIP) steel, and a range of other metallurgical and processing options.[14] Further, the complicated chemistry and microstructure of steel alloys presents many opportunities for improved performance and is well suited to the application of computational materials science and integrated computational materials engineering (ICME) techniques.[15]

Figure 8.D.3 summarizes the tensile mechanical properties of the current generations of advanced high strength steel along with the target properties for "3rd GEN AHSS" which offer up to 25% weight reduction potential against conventional steels. The very high strength of these steels enables weight reduction by reducing sheet gauge (thickness) while the very high ductility enables room temperature forming and lower manufacturing cost, along with increased energy absorption and resistance to fracture. Figure 8.D.3 also indicates some of the development paths available to the community in pursuing these properties. For example, significant increase in TRIP steel strength, significant increase in martensitic/hot-stamped (MART) steel ductility, or significant reduction in twinning induced plasticity (TWIP) and austenitic stainless steel cost are all viable paths for further development.

Figure 8.D.3 Tensile Strength Versus Elongation to Failure for Various Grades of Sheet Steel.[16] Acronyms are defined in the acronym/glossary section at the end of this technology assessment.

Credit: United States Council for Automotive Research LLC

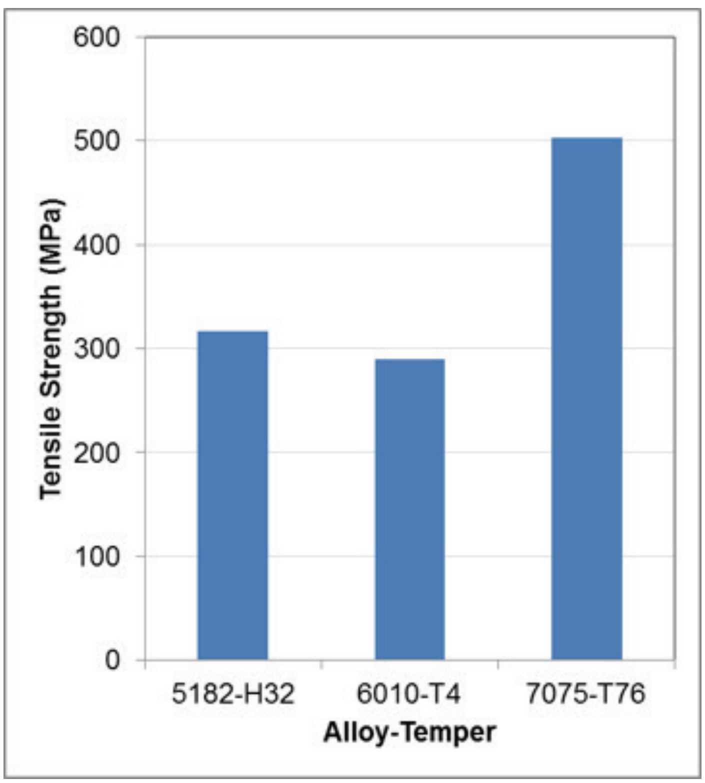


Aluminum Alloys

Aluminum alloys represent a middle-ground in the structural light metals spectrum. Years of development within the aerospace, construction, and automotive industries have led to a well-developed and reasonably well understood alloy and processing set. Applications of aluminum within automotive design include hoods and panels, power train components, and even entire vehicle body-in-white structures. There are several barriers to the increased use of aluminum in vehicle weight reduction applications such as material cost, room temperature formability, and limitations within the existing manufacturing infrastructure. As with magnesium, the addition of significant amounts of aluminum to the automotive manufacturing stream presents added multi-material challenges in joining, corrosion, paint and coatings, repair, and recycling. Aluminum sheet from the 5000 and 6000 alloy series is applied across a wide range of structures in today's vehicles; further, use of sheet aluminum is expected to grow from about 4% of vehicle weight in 2015 to about 16% of vehicle weight in 2025.[17] Increased application of this important lightweight metal system could be supported by optimization of 5000/6000 series alloys for improved strength, formability, and recyclability.

Introducing high strength aluminum with properties comparable to today's 2000 and 7000 series aerospace alloys could enable significant weight reduction in strength-critical systems; however, alloy cost and compatibility with automotive manufacturing infrastructure must be addressed. Figure 8.D.4 provides typical tensile strength for common 5000, 6000, and 7000 series alloys and tempers, demonstrating value of 7000 series for vehicle structures.

Figure 8.D.4 Typical Tensile Strength of Three Common Aluminum Alloys and Tempers.[18] Both 5182 and 6010 alloys are applied in vehicles today, while despite excellent strength, 7000 series alloys such as 7075 are not used in high volume vehicle due to high cost and long cycle time for heat-treatment.



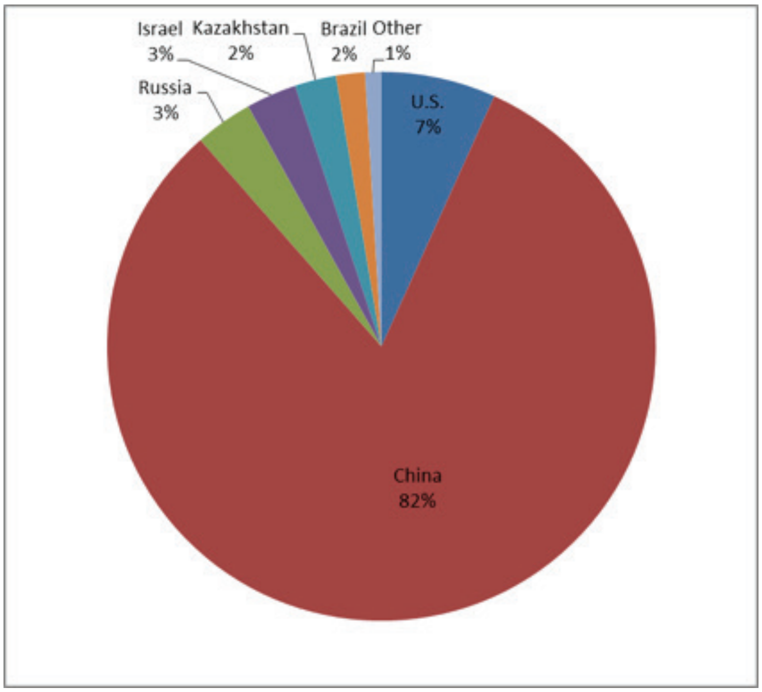
Use of Al alloys for entire vehicles is possible; however, the associated material cost and supply chain disruption creates a large commercial barrier. Incremental addition of Al to existing platforms would lower this barrier, but requires significant advancement in dissimilar material joining, corrosion protection, repair protocol, and end-of-life handling. New developments in these areas would be of great benefit to vehicle lightweighting.

Magnesium Alloys

Magnesium alloys, with the lowest density of all structural metals, have the potential to reduce component weight by greater than 60%. However, significant technical barriers limit the use of Mg to approximately 1% of the average vehicle by weight. These barriers include high raw material cost and price volatility, relatively low specific stiffness, difficulty in forming sheet at low temperatures, low ductility of finished components, and a limited alloy set, among others. Production of primary magnesium occurs mostly in China, as summarized in Figure 8.D.5; supply chain and price stability could be supported by developing and deploying new processes for extraction of primary magnesium in the United States.

In addition, using Mg in multi-material systems introduces joining, corrosion, repair, and recycling issues that must be addressed. Promising paths towards increased use of magnesium alloys include alloy development for improved strength and ductility, demonstration of production-ready corrosion coating and paint systems, and implementation of new alloys and processes to improve fatigue, creep, and high temperature performance in magnesium castings.

Figure 8.D.5 Worldwide Primary Magnesium Production, 2013 (U.S. value reports capacity)[19]

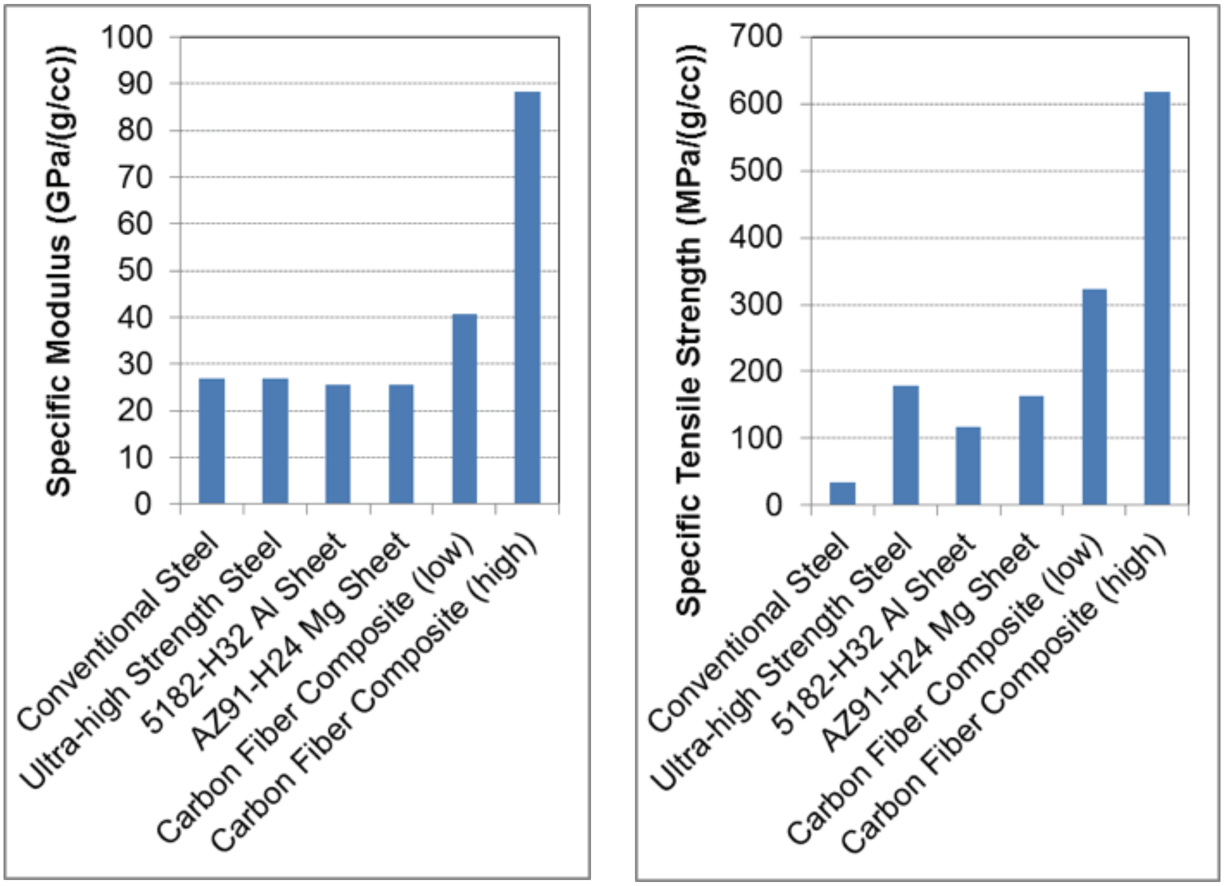


Carbon Fiber Composites

Carbon fiber reinforced polymer composites have the potential to reduce component weight by more than 60%; however, there are significant technical and cost barriers to their widespread introduction onto vehicles. Figure 8.D.6 compares the specific elastic modulus and strength (per unit density) of several metal alloys and representative carbon fiber composites, indicating the potential for high structural efficiency in composite vehicle structures. It is, however, important to note that composite properties are highly anisotropic and vary considerably with fiber precursor, fiber process, fiber form (e.g. mat, weave, chopped, etc.), resin, and many other characteristics.[20] The many degrees of freedom in carbon fiber composite design and manufacturing simultaneously provide great challenges and great opportunities for the lightweight materials community.

Among technology and commercial challenges, high material, manufacturing, and integration cost is a major barrier to widespread use of carbon fiber composites. The cost of input material (precursor) and the carbonization process contribute significantly to the total cost of carbon fiber, hence significant focus has been provided to these areas. Focus on low cost carbon for both the precursor (polyacrylonitrile/lignin) and the advanced processing (plasma oxidation) show progress in both lower cost precursors as well as in lower cost oxidation of the precursor and conversion of the oxidized precursor to carbon fiber. The process improvements continue to enable validation of successfully converting larger volumes (tows) of precursor to carbon at faster rates. Continuing effort to reduce the cost of carbon fiber, develop predictive tools for component design using composites, and demonstrate composite manufacturing technologies compatible with automotive volumes and cycle times will enable wider adoption of carbon fiber and polymer composites.

Figure 8.D.6 Typical Specific Modulus (Per Unit Density) and Specific Strength (Per Unit Density) of Selected Steel, Al, Mg, and Carbon Fiber Composites[21]

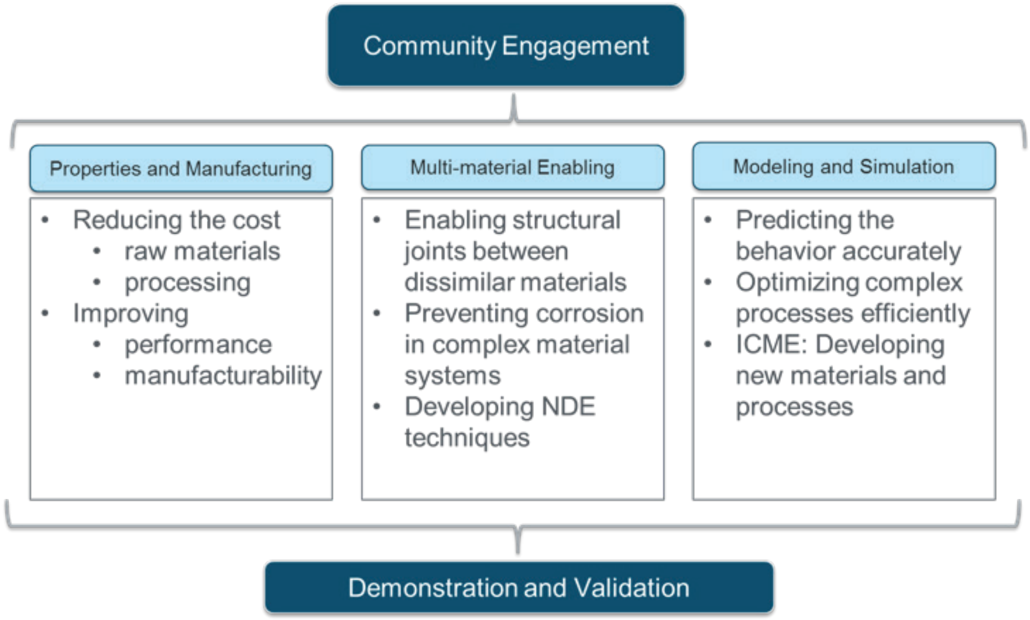


Program Considerations to Support R&D

Lightweight Materials

In order to implement a new lightweight material technology into commercial manufacturing, three main capabilities must be demonstrated: (1) the material technology must exhibit suitable properties and manufacturability, wherein single components can be manufactured with adequate mechanical properties and acceptable cost/cycle-time; (2) joining and integration technology must allow integration of the individual components into a complete vehicle structure; (3) validated tools must predict behavior of the material technology using modeling and simulation. Lacking any of these capabilities, a newly developed material technology will "sit on the shelf" without potential for commercial implementation in high-volume vehicle manufacturing. To address these needs, R&D support into these three main areas is structured as described in Figure 8.D.7.

Figure 8.D.7 DOE lightweight materials program structure addressing three key capabilities for new lightweight material technologies: (1) Properties and Manufacturability; (2) Joining and Integration; and (3) Modeling and Simulation



The three-capability architecture of the program is complemented by outreach, workshop, and analysis activities to provide program targets and guide towards the most promising R&D. Demonstration and validation programs, which tend to be large, mixed-material, cross-supply chain efforts, bring low technology readiness level (TRL) concepts to prototype stage while providing detailed mid-TRL technology gaps and program guidance. R&D support is primarily provided through competitive, cost-shared, fixed-term contracts.

Multi-material Systems

While each of the material systems described above reduces weight in automotive structures and provides associated efficiency improvements, multi-material vehicles may represent the most promising path forward for fleet-wide weight reduction. Application of mixed-materials through the vehicle structure offers tremendous design flexibility for using each material type where it is best suited. Large, planar, stiffness-limited structures such as hoods benefit from the low density of Al alloys; safety-cage structures such as B-pillars and roof-rails benefit from the exceptional strength of high-strength steels; cross-members and transverse structures benefit from the high specific stiffness of carbon fiber composites. By integrating mixed-materials into a single structure, design engineers can better optimize structural performance as well as total vehicle cost, supply chain utilization, and compatibility with existing infrastructure. In addition to pursuing the technology and performance objectives for each material system described above, lightweight materials R&D support must include multi-material technologies. Of particular note are joining, corrosion protection, paint/finishing, and end-of-life challenges specific to multi-material structures.

Public-Private Partnerships

Fundamental research and pre-competitive activity are needed to improve properties and demonstrate revolutionary manufacturing processes, while applied research and technology demonstration is required to reduce incremental cost and more rapidly introduce technology into the supply chain. The private sector has demonstrated interest in reducing vehicle weight; however, significant technology barriers and risks prohibit rapid development and adoption of the necessary technology. Public-private partnerships in vehicle lightweighting offer a path towards overcoming these barriers, reducing risk, and ultimately delivering improved vehicle efficiency.

Endnotes

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[7] It is important to note that a 7% reduction in fuel consumption (gallons per mile) is not the same as a 7% increase in fuel economy (miles per gallon). For changes on the order of 10% the improvements are similar and the terms can be used somewhat interchangeably.

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Acronyms/Glossary

AHSS	Advanced high-strength steel
Al	Aluminum
BH	Bake-hardenable
CMn	Carbon-manganese
CO_2	Carbon dioxide
CP	Complex phase
DP	Dual-phase
FB	Ferritic-bainitic
HSLA	High-strength low-alloy
HVAC	Heating, ventilation, and air conditioning
lbs	Pounds
HF	Hot-formed
ICME	Integrated computational materials engineering
IF	Interstitial-free
IFHS	Interstitial-free high strength
MART	Martensitic/hot-stamped
MMLV	Multi-material lightweight vehicle
Mg	Magnesium
Mn	Manganese
MnB	Manganese-boron
NREL	National Renewable Energy Laboratory
R&D	Research and development
Q&P	Quench and partition
TRIP	Transformation induced plasticity
TRL	Technology readiness level
TWIP	Twinning induced plasticity