U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

VEHICLES TECHNOLOGIES OFFICE

WORKSHOP REPORT:

Light-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials

February 2013

FINAL REPORT

EXECUTIVE SUMMARY

The Vehicles Technologies Office (VTO) hosted a workshop on Lightweight and Propulsion Materials in March 2011 in Dearborn, Michigan. The Materials area of the VTO focuses on developing lightweight materials for structures and propulsion materials for more efficient power train systems. The purpose of this meeting was to gain industry's perspective on the out-year material requirements of light-duty vehicles. In addition, this meeting focused on current technology gaps that contribute to delays in adoption of designs utilizing these lighter weight materials and those that improve propulsion efficiency. The industry experts who participated in this workshop included original equipment manufacturers (OEMs), tier-one suppliers, and materials suppliers to the light-duty vehicles value chain. The output from this workshop will serve as the foundation for the Vehicles Technologies Office Materials Roadmap for light duty vehicles. The driver for obtaining this updated input is to support the Administration's goals for reducing greenhouse gas emissions and U.S. dependence on petroleum. In support of these goals, the mission of the VTO is to develop more energy-efficient and environmentally friendly transportation technologies while meeting or exceeding drivers' performance expectations and environmental requirements.

Following is a list of the primary objectives of this workshop:

- To understand industry's needs with respect to out-year requirements and quantitative metrics
- To understand technology gaps that inhibit development of materials that will help the industry attain the following objectives (the vehicles community could significantly accelerate the adoption of these technologies by expanding capabilities for modeling and design tools):
    - Develop the next generation of high-efficiency power trains
    - Minimize efficiency penalties by reducing exhaust emissions
    - Provide aerodynamic solutions with minimal weight penalty
    - Develop lightweighting that improves the fuel economy of light duty vehicles
    - Reduce petroleum dependence by developing propulsion materials that are compatible with advanced fuels
- To provide a forum for input by industry experts and for developing consensus on targets, gaps, and performance metrics

The purpose of the workshop is to understand what technologies must be developed in order to realize these objectives. The workshop and report serve as a benchmark of the current state-of-the-art for light-duty vehicle structural and propulsion systems, identifying future performance requirements and the technology gaps that inhibit our ability to realize these goals today. This workshop report also identifies technical goals for light-duty systems and lightweight and structural materials. This workshop report, *Light-Duty Vehicles Material Technical Requirements and Gaps for Lightweight and Propulsion Materials*, documents the results of this workshop only. A workshop focusing on materials for heavy-duty vehicles was held at the same time and the output from that meeting is documented in a separate report.[1]

Light Duty vehicles cover those classified by the U.S. Environmental Protection Agency (EPA) class system ranging in size from Class 1 through Class 2B. There is an overlap between the classes of light duty vehicles in this report and the class of high-volume truck and heavy-duty vehicles that utilize a body-on-frame architecture, such as large pickup trucks and sport utility vehicles (SUVs), which are also discussed in the *WORKSHOP REPORT: Trucks and Heavy-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials*.

This report presents the performance metrics, goals, and technology gaps for each of four major vehicle systems that comprise the majority of the weight of light-duty vehicles: body structures; chassis and suspension; closures, fenders, and bumpers; and engine and transmission. This report also provides performance metrics, goals, and technology gaps for each of the classes of lightweight materials: magnesium, carbon fiber and carbon fiber composites, aluminum, glass fiber composites and unreinforced plastics, and steels and advanced high-strength steels (structural), advanced materials, and steel and cast iron (propulsion). In general, the set of materials that are considered for light-duty applications and heavy-duty applications are the same. However, the performance requirements, which are defined by specific duty cycles, require different approaches to design and manufacturing. Where it is appropriate, the discussions centered on materials will describe the similarities and differences between heavy- and light-duty vehicles.

During the workshop, industry experts provided stretch goals for reducing the weight of major vehicle systems by the years 2025 and 2050. Table ES.1 contains weight reduction targets for both vehicle systems and total vehicles with internal combustion engines (ICEs). U.S. Department of Energy (DOE) interpolated intermediate targets from the goals provided at the workshop. Table ES.2 provides preliminary targets for weight reduction goals for systems of a conceptualized battery electric vehicle (I-BEV) in the same time horizon for comparison purposes. These tables assume that the same lightweighting concepts for systems in vehicles using ICE can be applied to systems in BEVs.

Table ES 1: Targets for Weight Reductions for Systems of the Light Duty ICE Vehicles 2020–2050

LDV Component Group	2020	2025	2030	2040	2050
Body	35%	45%	55%	60%	65%
Power train	10%	20%	30%	35%	40%
Chassis/suspension	25%	35%	45%	50%	55%
Interior	5%	15%	25%	30%	35%
Completed Vehicle	**20%**	**30%**	**40%**	**45%**	**50%**

Table ES 2: Targets for Weight Reductions for Systems of a Conceptualized Battery Electric Vehicle 2020–2050

LDV Component Group	2020	2025	2030	2040	2050
Body	35%	45%	55%	60%	65%
Chassis	25%	35%	45%	50%	55%
Interior/closures/misc.	5%	15%	25%	30%	35%
Battery Assembly	30%	64%	70%	75%	80%
Motor/electronics	25%	29%	33%	37%	40%
Completed Vehicle	**26%**	**46%**	**54%**	**59%**	**64%**

ACRONYMS AND ABBREVIATIONS

AHSS	Advanced high-strength steel
ACE	Advanced combustion engine
BEV	Battery electric vehicle
CAD	Computer-aided design
CAFE	Corporate Average Fleet Economy
CF	Carbon fiber
CFCs	Carbon fiber composites
CI	Compression ignition
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FMVSS	Federal Motor Vehicle Safety Standards
FRP	Fiber-reinforced polymer
GFRP	Glass-fiber reinforced plastic
GVWR	Gross vehicle weight rating
ICE	Internal combustion engine
MMC	Metal matrix composites
NVH	Noise, vibration, and harshness
OEM	Original equipment manufacturers
Re	Rhenium
SI	Spark ignition
SUV	Sport utility vehicle
VTO	Vehicles Technologies Office

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1 INTRODUCTION

This workshop report covers vehicles that range in size from Class 1 through Class 2b, as defined by the U.S. Environmental Protection Agency's (EPA) classification system. This report presents the performance metrics and goals and identifies the technology gaps that limit implementation of lightweighting and improved propulsion performance for the following four major systems that comprise the majority of the vehicle's weight: body structures; chassis and suspension; closures, fenders, and bumpers; and engine and transmission. It also provides performance metrics and goals and identifies technology gaps for each of the classes of lightweight materials: magnesium, carbon fiber and carbon fiber composites, aluminum, glass fiber composites and unreinforced plastics, and steels and advanced high-strength steels (structural), advanced materials, and steel and cast iron (propulsion). In general, the set of materials that are considered for light-duty and heavy-duty applications are the same. However, the performance requirements that are defined by specific duty cycles require different approaches to design and manufacturing. When it is appropriate, the discussions centered on materials will identify the similarities and differences between the needs of heavy- and light-duty vehicles.

Over half of all the petroleum consumed in the United States is imported, which presents a strategic risk as well as an economic liability. According to the Energy Information Administration, the transportation sector accounts for over two-thirds of all U.S. petroleum consumption.

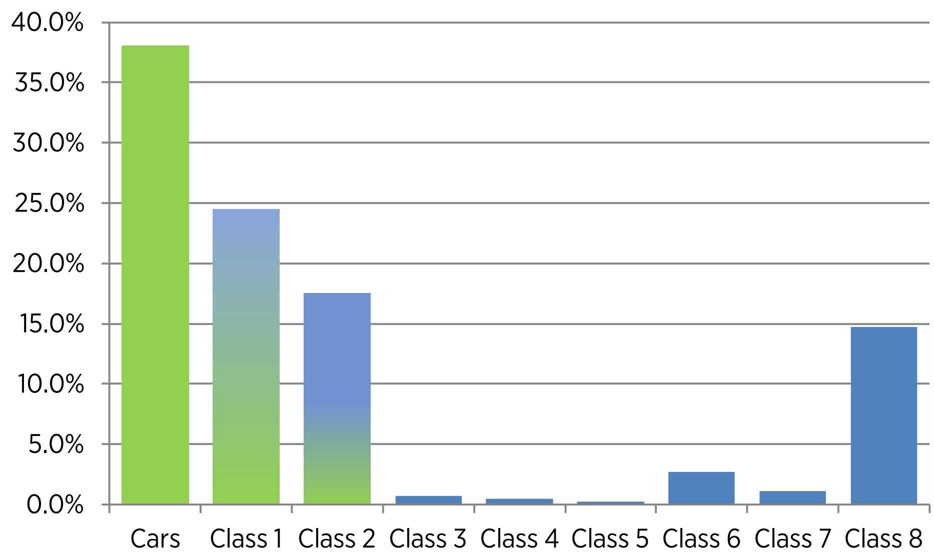

Figure 1: 2010 On-Road Fuel Consumption by Vehicle Class (Vehicles Covered by this Report Shown in Green)[2]

Passenger cars account for 38% of all petroleum used in on-road transportation. This is the highest amount used by any single vehicle size class. This significant percentage of fuel usage is followed closely by those for Classes 1 and 2 light trucks (24%) and sport utility vehicles (SUVs) (17%), respectively.[2] The remaining fuel use (20%) is attributed to medium- and heavy-duty trucks (Classes 3 through 8). This workshop report focuses on opportunities to reduce petroleum use for passenger cars as well as a portion of light-duty trucks and SUVs (Classes 1 and 2) that can transition to car-like architectures without significant loss of utility.

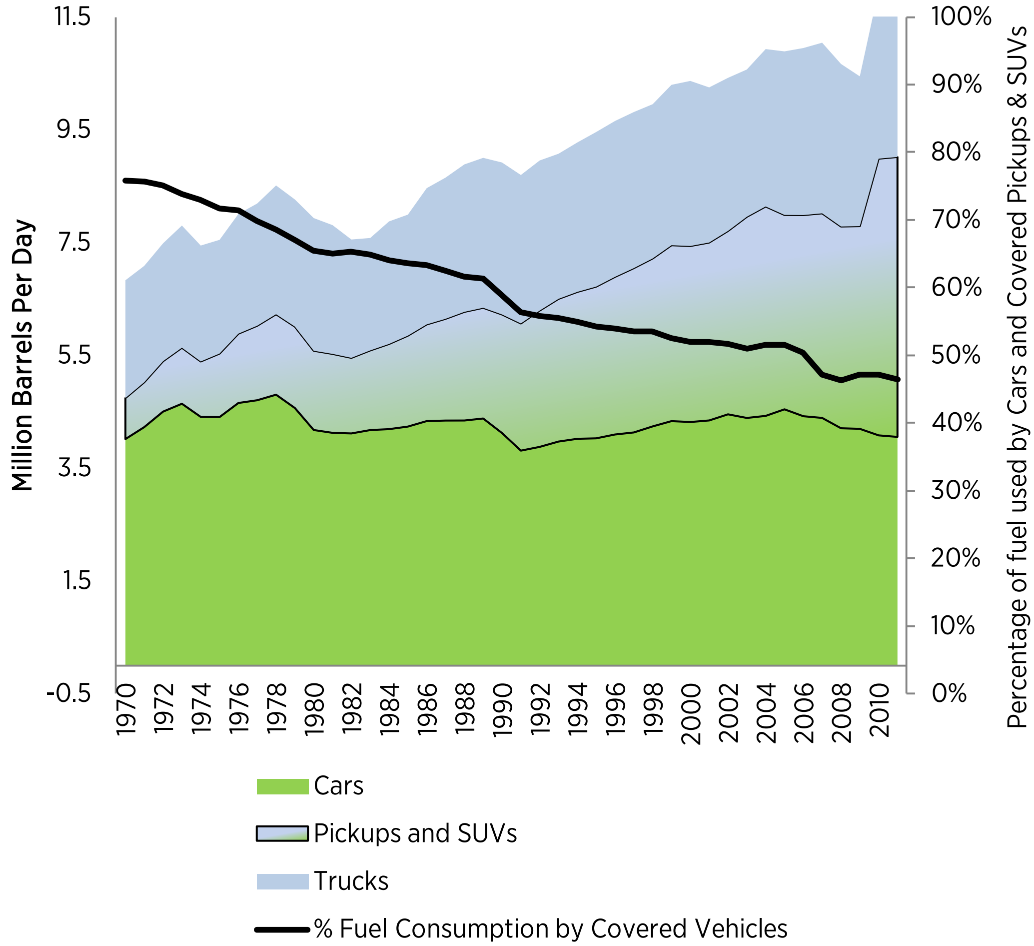

Figure 2: Historical Utilization of Motor Fuel by Highway Vehicles (Vehicles Covered by this Report Shown in Green)

Historically, these vehicles (passenger cars plus 25% of Class 1 and 2 trucks and SUVs) have represented the majority of the transportation fuel used in the United States. Combined, the vehicles covered in this report represent about 48% of the on-road transportation fuel consumed in the United States today. Vehicles outside these parameters are covered in the Vehicles Technologies Office (VTO) workshop report, *Trucks and Heavy-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials*. Combined, the two reports represent a comprehensive review of the opportunities, requirements, and gaps for materials-based efficiency improvements to transportation vehicles.

To address the risks associated with petroleum dependence, the U.S. Department of Energy's (DOE) VTO works with industry, researchers, academia, and stakeholders to reduce petroleum consumption by improving vehicle efficiency, developing alternatives to petroleum, and exploring transportation technologies that are less reliant on petroleum. Within this framework, the Materials area under the VTO addresses the materials requirements of existing and future transportation systems as identified by the program and its partners.

In order to update current understanding of industry needs, DOE held a materials workshop with industry experts on automotive and heavy-duty vehicle systems representing original equipment manufacturers (OEMs), manufacturers, and suppliers in Dearborn, Michigan, in March 2011.

The primary objectives for this workshop are as follows:

- To understand industry's needs with respect to out-year requirements and quantitative metrics
- To understand technology gaps that inhibit development of materials that will help the industry obtain the following objectives (the vehicles community could significantly accelerate the adoption of these technologies by expanding capabilities for modeling and design tools):
    - Develop the next generation high-efficiency power trains
    - Minimize efficiency penalties by reducing exhaust emissions
    - Provide aerodynamic solutions with minimal weight penalty
    - Develop lightweighting that improves the fuel economy of light duty vehicles
    - Reduce petroleum dependence by developing propulsion materials compatible with advanced fuels
- To provide a forum for input by industry experts and for developing consensus on targets, gaps, and performance metrics

The results of the workshop will provide the basis of a materials technology roadmap by identifying, at a systems level, the material requirements necessary for light-duty vehicles to achieve the maximum possible efficiency. This draft report documents the consensus reached on stretch targets, metrics for performance, priorities on technology gaps, and areas of synergy across materials and vehicle classes. At the same time this workshop was held, a similar workshop was also conducted that focused on materials for heavy duty vehicles.[1]

1.1 Vehicle Weight Baselines and Trends

The passenger car fleet Corporate Average Fuel Economy (CAFE) increased rapidly from 18 mpg in 1978 to 28 mpg in 1990, where it remained flat until 2010 (Figure 3a). Since 2010 fuel economy has increased above 30 mpg and is expected to continue to climb in response to new regulations.

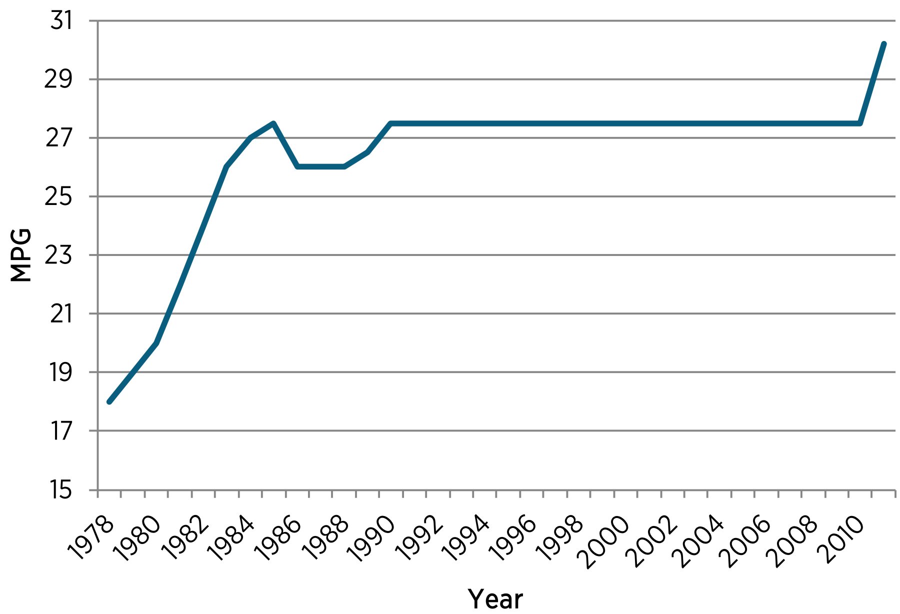

Figure 3a: Passenger Car CAFE Fuel Economy from 1978 to 2011[3]

The average vehicle weight went down from 1975 to 1981 (Figure 3b). Starting in 1982, vehicle weights increased through larger cabin volumes, added requirements for both safety and environmental demands, and through the addition of customer features.[4]

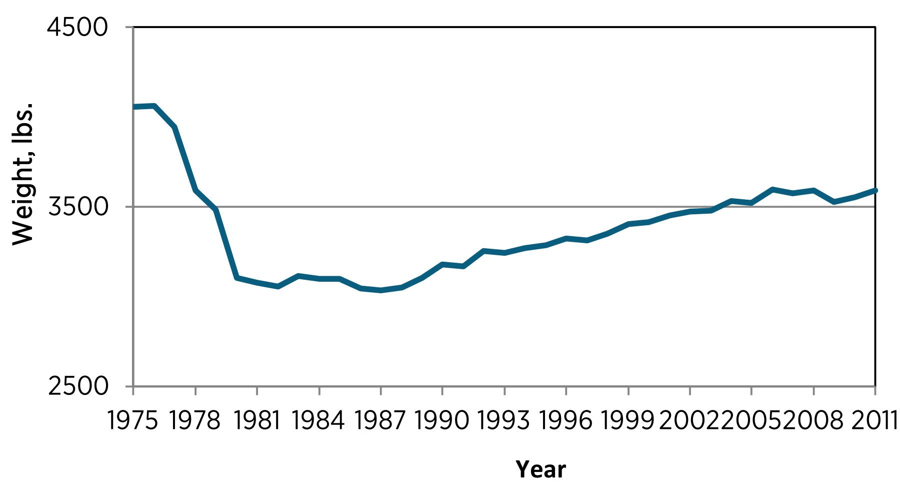

Figure 3b: Weight of the Average Light Duty Vehicle, 1975 to 2011[3]

Over the same period acceleration performance continued to improve as seen in Figure 3c.

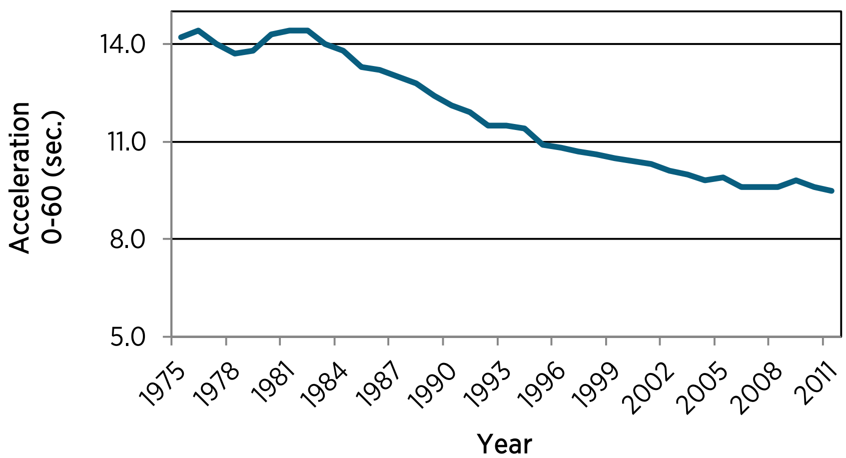

Figure 3c: Trends in Acceleration of the Average Light Duty Vehicle, 1975 to 2011[3]

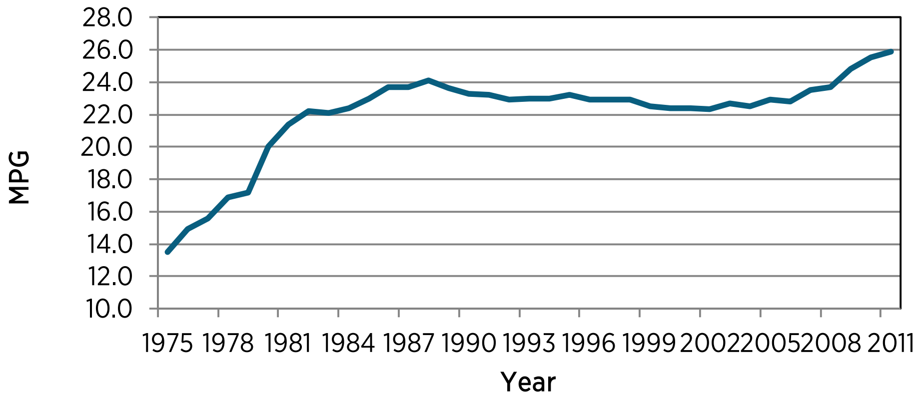

Figure 3d: Trends in Vehicle Miles per Gallon, 1975 to 2011[3]

The trends illustrated in Figure 3d show that, despite the increase in the weight of the average vehicles, the OEMs have improved the fuel efficiency and rate of acceleration. Now, however, the demand to reduce greenhouse gases and use of oil require additional solutions for improving fuel efficiency, including lightweighting and improved propulsion systems.

A recent study by Zoepf illustrates the distribution of types of weight of the vehicle from 1975 to 2010 (Figure 4).[5] His findings show that while the structural weight of the vehicle has remained fairly constant at 1,200 kg from 1980 on, the weight attributed to comfort, safety, and emissions has grown. These data show an increase in weight for nonstructural functions of the vehicle. This trend illustrates the significant challenge that lightweighting faces in order to support improved fuel efficiency in future affordable vehicles. In order for lightweighting to improve the efficiency of the vehicle, cost-effective lightweight designs and materials must enable reduction of the total weight of the vehicle that includes overcoming the added weight due to increased requirements for safety, mitigation of emissions, and comfort.

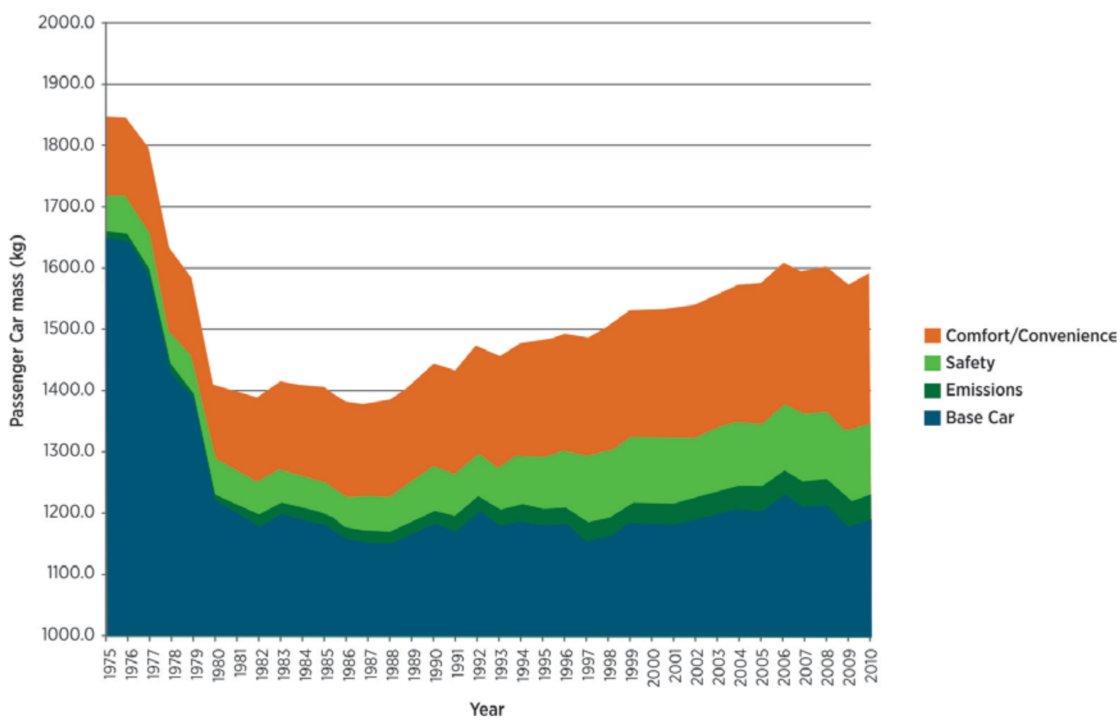

Figure 4: Mass of Passenger Cars 1975-2010 and Weight Attributed to Safety, Emissions and Comfort/Convenience Features (Secondary Mass Included).[5]

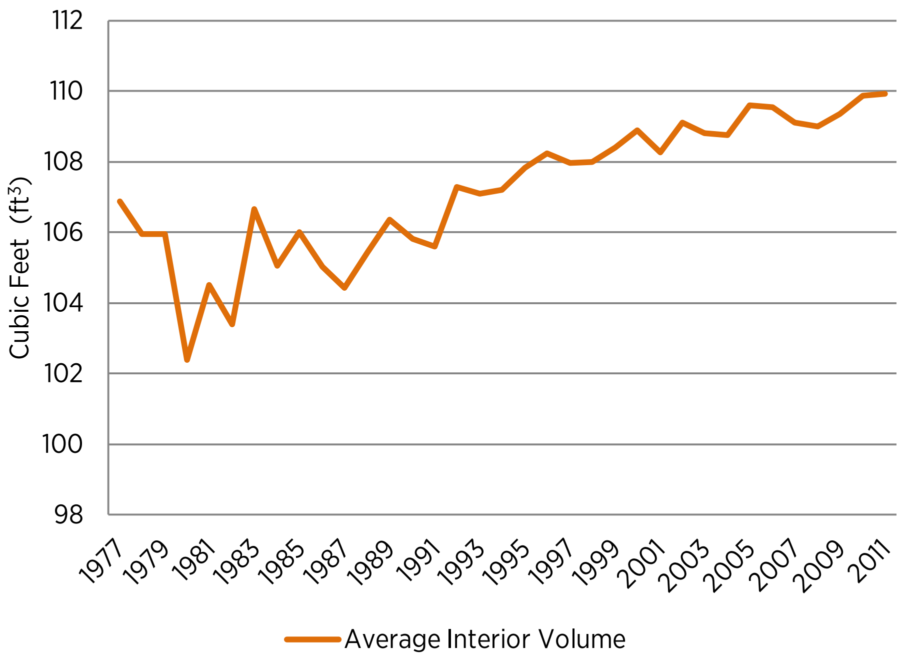

Figure 5: Passenger Car Interior Volume Trends Extrapolated from Appendix E of the EPA's "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2011"

The average interior volume of the passenger vehicle declined to a minimum of 102 cubic feet in 1980. From that point, the passenger volume increased steadily to 110 cubic feet by 2011 (Figure 5).[6] This trend matches the increase in mass in Zoepf's study (Figure 4).

Hofer, et al., recently presented a study of lightweighting battery electric vehicles that showed that weight reduction of the glider by 450 kg can minimize total vehicle cost.[7] (The term "glider" is often used to include all of the vehicle parts except for the powertrain.) According to their assumptions, the potential downsizing of the battery saved enough cost to balance the expense of lightweighting while still resulting in a total cost reduction of 5%. A separate study by General Motors demonstrated a similar trend for an initial range of weight reduction.[8] These examples illustrate that the benefits of lightweighting must be analyzed in the context of the total vehicle system for which it is intended.

Figure 6a presents the current distribution of weight by system in a traditional internal combustion engine (ICE) passenger vehicle[9,10,11]; figure 6b is the weight distribution for a conceptualized battery electric vehicle for passengers. Clearly any focus on lightweighting a vehicle (ICE or BEV) must include options utilizing alternative materials for the body, chassis and suspension, closures, and engine and transmission. Each of these systems has unique demands that candidate materials must meet.

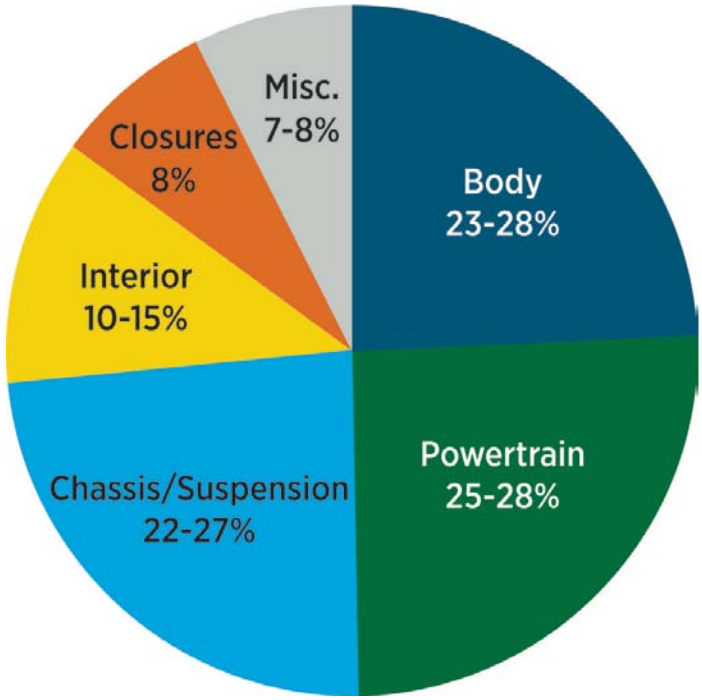

Figure 6a: Distribution of Vehicle Weight by System–ICE
(Actual Definitions of the Systems and System Component Inclusion Can Vary, and Percentage Breakdown Can Vary Substantially from Vehicle to Vehicle.)

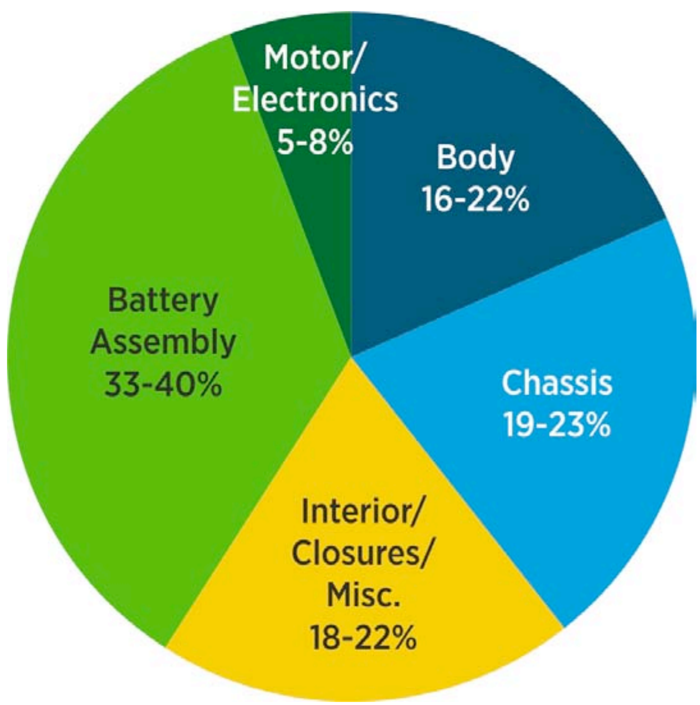

Figure 6b: Distribution of Vehicle Weight by System–Conceptual Battery Electric Vehicle Midsize Car with 300-Mile Range

2 LIGHT-DUTY VEHICLE SYSTEMS

2.1 Body Structures

The body structure makes up 23%–28% of the vehicle weight and represents a significant opportunity to reduce the weight of the vehicle. The construction of the body contains the A-pillar, door enclosures, floor pan, and fenders. The function of the body is to contain the passenger compartment, thus protecting the passengers by providing structure and energy absorption in the event of a crash. Currently, high-strength, high-modulus sheet materials comprise the frame around the passenger compartment, and a mixture of materials provide strength and energy absorption in crush zones. In general, the timeline for utilizing lightweight metals compared to carbon fiber composite (CFCs) for the body structures are different because of the maturity and cost of these two types of structural materials. While CFCs offer a significant weight savings in the longer term, lightweight metals offer shorter term and moderate-to-substantial weight savings with more mature technology. In general, the technologies for lightweight metals are more mature in terms of understanding, availability of databases for properties, design, manufacturability, and repairability. Technology gaps also exist for metallic systems, which are summarized in the following sections. This report covers the specific requirements for each type of material in greater detail in later sections.

2.1.1 BODY STRUCTURES-POLYMER COMPOSITES

2.1.1.1 Goals and Metrics for Composite Body Structures

The goals for composite body structures are summarized in Table 1 below.

Table 1: Goals and Metrics for Composite Body Structures

Metric	Today	2025	2050
Weight	Mainstream Vehicle = 100% (100k vehicles/yr)	50% lower	75% lower
Cost	Mainstream Vehicle = 100% (100k vehicles/yr)	Parity	Parity
Manufacturability (Cycle Time)	2–30 minutes/part	1–3 minutes/part	1 minute/part
Predictability	Simulation based (not prediction based)	Prediction based	Prediction based
Repairability (Quality, Time, Cost, Performance)	Mostly replacement	50-50 ratio of repair to replacement	Mostly repair
Design and Performance	Steel based	Composite based	Composite based
Recyclability (Reclaim Reuse)	Reclaim < 40%	Reclaim 85%	Reclaim 99%
Weight savings cost	Base	< $2.16 per pound saved	< $2.33 per pound saved

2.1.1.2 Technology Gaps-Composite Body Structures

The technology gaps hindering the adoption of lightweight composite body structures for light-duty vehicles are listed below in order of priority.

1) Lack of ductility of fiber-reinforced polymer (FRP) with respect to stable failure, fracture modes, and energy absorption

- The body structure is central to the vehicle. It provides the framework onto which the rest of the vehicle is assembled. More importantly, it provides the protective package responsible for the safety of the passenger in crash scenarios. While polymer composites offer design flexibility and the opportunity for part reduction with the accompanying cost savings, the basic lack of ductility presents major challenges for design engineers seeking to optimize the structure for weight, stiffness, and crashworthiness.
- Lack of basic understanding of fracture modes during impact failure can lead to overdesign to maintain necessary safety performance.

2) Lack of Carbon Fiber Composites CFCs with equal or better performance characteristics to steel and equivalent cost (on a volume basis) to current materials

- There is a potential to reduce weight by 75% by 2050 if a composite composed of low-cost carbon fiber (<$5/lb) is combined with a tailored low-cost resin system (<$1/lb) and a fast manufacturing cycle time that can be produced with a low-cost and effective mechanism to translate loads from fiber to resin. (The section on CFCs provides a more detailed description of these targets and materials technology gaps.)

3) Lack of tools for predictive engineering and analysis

- Vehicle performance directly relates to the basic attributes of the body structure (stiffness; durability; crashworthiness; noise, vibration, and harshness (NVH), etc.). The tools for predictive engineering are necessary to create a structure that integrates all of these requirements; however, these tools are currently insufficient to allow for dependable designs that can be optimized. The lack of maturity of these tools is due mainly to inadequate understanding of material behavior and lack of reliable and consistent databases.
- The following are currently not available: experimental testing standards for all architectures of composites (fibers, braids, etc.), models capable of predicting in-situ properties to 90% accuracy and methods to identify damage initiation and progression.

4) Lack of cost-effective systems and designs, including tooling and high-volume processing

- In order for composite body structures to compete with conventional structures manufactured from steel, it will be necessary produce components or structures at a volume of ~100,000 parts per year or more at a comparable cost. Because of the ability to mold complex shapes, polymer composites provide opportunities for consolidation of parts with attendant cost savings. However, cycle times that are dependent on resin flow for filling the mold and curing cycles to achieve appropriate curing of thermosets, for example, are significantly slower than cycle times for thermoplastic composites or heating and cooling cycles for conventional metallic materials.
- Constructing assemblies of multiple parts requires joining technologies, such as adhesives, that can also add significantly to the manufacturing time and cost.

- Existing processes for manufacturing polymer composite components, especially those based on continuous fibers or cloth, are not fully automated and often exhibit large rates of scrap.
- Design for manufacturability must be integrated into the entire process.

5) **Lack of dependable joining technology for the integration of composite components into the body structure**
   - In order to take full advantage of the potential for weight reduction from composites and to integrate them into a multimaterial solution for lightweighting, the community needs methods for fast, reliable, durable, and predictive joining of composites to metals and composites to composites.
   - Joining technologies must be capable of producing cost-effective joints with sufficient durability and crashworthiness under thermal extremes and in corrosive environments.

2.1.2 BODY STRUCTURES- LIGHTWEIGHT METALS (INCLUDES ADVANCED HIGH-STRENGTH STEELS, ALUMINUM, AND MAGNESIUM)

2.1.2.1 Goals and Metrics for Lightweight Metal Body Structures

Following are the goals established for lightweight metal body structures:

- 35% body weight reduction while meeting requirements for safety, Federal Motor Vehicle Safety Standards (FMVSS), durability, NVH, vehicle size, efficient occupant packaging, and customer content requirements by 2025.
- 60% body weight reduction requirements for safety, FMVSS, durability, NVH, vehicle size, efficient occupant packaging, and customer content requirements by 2050.

Metrics are present in the table below.

Table 2: Goals and Metrics for Body Structures-Lightweight Metals

Metric	Today	2025	2050
Stiffness and NVH	Must meet 2010 benchmark	Must meet 2010 benchmark	Must meet 2010 benchmark
Durability	Must meet 2010 benchmark	Must meet 2010 benchmark	Must meet 2010 benchmark
Crash	Must meet 2010 benchmark	Must meet 2010 benchmark	Must meet 2010 benchmark
Cost	Base	Base + 10%	Base + 20%
Weight savings cost	Base	< $2.16 per pound saved	< $2.33 per pound saved

2.1.2.2 Technology Gaps-Lightweight Metal Body Structures

The technology gaps hindering the adoption of lightweight metal body structures for light-duty vehicles are listed below in order of priority.

1) Lack of proven technology for joining dissimilar metals (Steel-Al, Steel-Mg, Mg-Al, etc.)

- In order to achieve required crashworthiness, durability, and NVH performance, while at the same time significantly reducing weight, techniques must be developed to produce joints between dissimilar metals with strength, fatigue strength, and cost comparable to steel-steel spot welds and corrosion performance similar to Al-steel joints.
- Because the mechanism for improved strength in many advanced metals involves complex phases and microstructures, traditional fusion (melting) welding techniques, including spot welding, cannot be used because it would disrupt the microstructure and diminish strength. The process of joining must also be fast, reliable, and inexpensive.

2) Lack of advanced high-strength steels (AHSS) with sufficient toughness for body structure applications

- In response to the needs of the automotive community for higher strength materials, steel manufacturers have made substantial progress in developing AHSS to replace standard carbon sheet steel used in the past. However, the increased strength has been achieved with an attendant loss in ductility, primarily due to the microstructures that are responsible for the increased strength. The reduced ductility makes forming complex shapes more difficult due to edge cracking and other complications.
- The need to maintain the microstructure makes the use of conventional joining techniques nearly impossible.
- Lack of ductility has a negative impact on crash behavior. Attempts to develop even higher strength steels (third-generation high-strength steels) for future applications in lightweight body structures must address the need for increased ductility and toughness.

3) High-strength, formable aluminum alloys with low-processing costs are not available

- The strength of current aluminum alloys is insufficient to take advantage of the potential for 40%–60% weight reduction compared to steel in some components in the body-in-white. The community needs new 5xxx and 6xxx alloys with strength > 300MPa.
- Lower cost formable 7xxx alloys need to be developed.

4) Forming and joining of thin sheet of AHSS is unreliable and fracture behavior is not understood

- The higher strength of AHSS offers the potential for a 10%–25% weight savings in structural panels, rails, and cross-members, primarily through down gaging of sheet. However, as the sheet becomes thinner, forming becomes more difficult, particularly in terms of edge formability and shear fracture.
- Joining thin sheets or sheets with different thickness is difficult. In order to take full advantage of these materials, new joining and forming technologies for thin sheet materials will need to be developed. It is necessary to understand forming limit diagrams and to gain an understanding of the fracture behavior of sheet and of welds.

5) **Forming and fracture behavior of Magnesium alloys is not well understood.**

- Magnesium alloys can deliver up to 60% mass reduction for some body structure applications, such as shock towers, instrument panels, cross car beams, and interior components. However, to be useful in crash critical front-end structures, alloys should exhibit 15% ductility at room temperature. The best-performing alloys currently rely on an addition of rare earth elements to develop necessary properties. These rare earth elements are costly and in limited domestic supply, and should therefore be avoided.
- Due to its hexagonal close packed crystal structure, wrought magnesium exhibits substantial anisotropy in properties, making crash behavior problematic. Development of quasi-isotropic alloys with minimal or no addition of rare earth elements is needed for all product forms (castings, sheet, and extrusions).
- A better understanding of structure-process-property relationships will enable optimized components for body structure and can also lead to predictive crash modeling for body structure applications.

6) **Design techniques that provide the capability of performing multi-disciplinary optimization for product development for steel, aluminum, and magnesium are immature and limited in their capabilities**

- While software is available to optimize for stiffness or crash safety individually, additional software tools are needed to model crash, durability, and NVH simultaneously. These types of tools can enable the design of the most optimal load path, geometry, gage, and grade of the most appropriate material. While these tools are in various degrees of maturity and use, they need improvement/maturation in order to become industry-wide standards.
- There is a need for the ability to select the best material for each component based on constraints of cost or manufacturing, thereby enabling optimized weight reduction.

2.2 Chassis and Suspension

2.2.1 GOALS AND METRICS FOR CHASSIS AND SUSPENSION

The chassis and suspension system represents 22%–27% of the weight of the light-duty vehicle and includes the suspension, steering, and brakes as well as tires and wheels. This system provides the load-bearing interface between the vehicle and the road and has substantial strength requirements. The current materials strategy for this system is to apply high-strength sheet materials at corner suspensions; light weight, high-strength cast materials at brakes; and a mixture of cast and wrought materials to provide strength and energy absorption at engine and rear cradles.

The goals and metrics established for the chassis and suspension are presented in the table on the following page.

Table 3: Goals and Metrics for Chassis and Suspension

Metric	Today	2025	2050
Weight of Front/Rear Cradles	Material, design, and process limited	35% lower	50% lower (electric vehicles [EVs], front cradle major downsize)
Weight of Steering Knuckles	Iron castings, replace with Mg, etc.	25%–35% lower	50% lower
Weight of Brakes	Iron castings, replace with metal matrix aluminum composites, ceramics	50% lower	100% lower (regenerative brakes)
Weight of Wheels and Tires	Style, design, and material limited (forged aluminum, etc.)	20% lower	50% lower
Weight of Stabilizers	Replace conventional materials with hollow titanium	50% lower	75% lower (composites)
Weight of Ladder Frames	Replace conventional materials with AHSS while maintaining towing capacity	25% lower	35% lower (carbon fiber, carbon fiber/steel hybrid)
Weight of Springs	Replace conventional steel with composites	50% lower	50% lower
Weight of Fuel Systems/Exhaust	Remove mufflers/resonators (Use noise cancellation)	40% lower (30% + 10% for EV penetration)	100% (all electric vehicles)

2.2.2 TECHNOLOGY GAPS-CHASSIS AND SUSPENSION

The technology gaps hindering the adoption of lightweight materials for chassis and suspensions for light-duty vehicles are listed below in order of priority.

1) **The corrosion resistance of magnesium alloys is insufficient for underbody applications**

   - Corrosion can lead to material loss and/or loss of integrity of chassis and suspension components. Current solutions for galvanic effects rely on costly isolation strategies for mitigation.
   - There is no universal coating technology that is compatible with steel, aluminum, and magnesium due to the sensitive chemistries of pre-treating processes.

2) **Structural castings of aluminum and magnesium for chassis and suspension applications are limited by low ductility and strength as well as insufficient industrial capacity**

   - Large Al/Mg castings can offer significant weight savings due to parts consolidation, but generally contain defects in the microstructures that limit their ductility and affect the capability to absorb energy during a crash.

     North American capacity for large, high-integrity, quality-controlled castings is needed.
   - The following is also needed: improved alloys, reliable models, more efficient processes, and improved die life.

3) Joining processes for fastening various grades and gauges of steel and other metals are inadequate

- Optimized designs for chassis and suspension rely on the combination of components made of many grades and gauges of steel, chosen to meet specific requirements for strength or stiffness. Fast and reliable joining processes that do not degrade the properties in the welded areas are needed to join these components into the larger assembly.
- Accurate models are needed to predict weld behavior in end-use applications.

4) Low-cost titanium alloys are not available

- Titanium alloys have excellent properties for some specific applications requiring high strength, low density, and corrosion resistance (exhaust systems, structural members, and springs). However, high cost prevents implementation. A low-cost, low greenhouse-gas-emitting production method for producing titanium from ore is needed.
- Improved manufacturing processes for producing sheet, rod, etc., are also required.

2.3 Powertrain: Engines and Transmission

The power train of the vehicle includes the engine, transmission, turbocharger, differential, drive shafts, fuel system, and exhaust system and comprises 24%–28% of the vehicle's weight. Many of these components require high strength, high fatigue endurance, and tolerance to high temperatures. Materials in general use include mild steel, cast iron, and cast aluminum.

The typical power train of today's passenger car is a 2.7 liter 196 horsepower naturally aspirated aluminum V-6 cylinder engine coupled to a 4 speed automatic transmission with front wheel drive and weighs about 900 lbs (including cooling system, transmission, differentials, fuel system, and exhaust system).

The typical light-duty pickup or SUV power train consists of a 5 liter, 300 horsepower, naturally aspirated V-8 cylinder engine (split between aluminum and cast iron) coupled to a 4 speed automatic transmission with either rear or all-wheel drive and can weigh up to 1,500 lbs (including cooling system, transmission, differentials, fuel system, and exhaust system).

Today, the majority of light-duty vehicles use gasoline with a small percentage operating on diesel fuel. About 3% of the cars sold are hybrids, which use batteries, power electronics, and electric drive motors to improve the urban drive cycle fuel economy of these vehicles between 10% and 50%. The weight of additional hybrid power train components can increase the weight of the vehicle by up to 500 lbs.

The thermal efficiency of these engines can range from a low of about 25% for gasoline engines to 40% for the higher efficiency diesels, but at substantial weight penalty. One of the most effective ways to achieve improved fuel economy is by increasing the efficiency of the ICE. The theoretical limit for efficiency of liquid fueled ICEs is about 60%. There are promising new engine configurations and combustion regimes that blur the distinctions between spark ignition (SI) gasoline and compression ignition (CI) diesel engines, creating a continuum of operating characteristics and material requirements. These advanced combustion engine (ACE) approaches will need to be tailored for their specific application and will use the most efficient combustion regime meeting the operational requirements of the vehicle. High-efficiency ACE platforms are expected to operate at significantly higher peak cylinder pressures (between 3,000 psi and 4,000 psi) than gasoline or diesel currently require. Therefore, ACE approaches have the potential to double the efficiency of conventional light-duty gasoline engines. However, without augmenting current materials, manufacturing, and design capabilities, improvements in thermal efficiency and the resulting increase in fuel economy will be extremely difficult to achieve (Figure 7). Improvements in material properties are necessary for propulsion systems to reach increased efficiency goals while conforming to existing and proposed emission regulations. Accomplishing those goals will require that individual engine components attain specific performance and cost targets that are currently out of reach.

The dual role of pickups and SUVs complicates power train requirements. Many light-duty trucks perform functions similar to passenger cars (carrying people and small amounts of cargo) but, by their very design and gross vehicle weight rating (GVWR) classification, they must be capable of carrying or towing significantly larger loads. From the perspective of a passenger vehicle, the power train should be as light a possible while providing the necessary power requirements. But due to implications of their GVWR size classification, light truck and SUV power trains must be able to provide the power necessary for safe operations in the vehicles fully loaded state. Therefore, the power train of light-duty vehicles may vary greatly with application.

One pathway for lightweighting the power train requires materials with higher specific strength to enable engine downsizing (reducing the displacement while maintaining horsepower) through boosting (using either turbochargers or mechanically driven compressors). These demands may require a suite of materials solutions to address specific requirements of advanced engines, such as high performance lightweight aluminum alloys for gasoline engines and high-performance ferrous alloys for diesel and ACE engine designs. Figure 7 illustrates the limitations of the various materials used for engines compared to requirements needed for higher peak cylinder pressures. Alloys of Mg and Al as well as metal matrix composites fall short of the projected engine requirements for maximum, long-term, advanced, high-efficiency engine targets. Even cast iron and cast graphite iron are reaching performance limitations short of the maximum goals for enhanced engine efficiency. New alloys must be developed to meet the performance requirements of next- generation high-efficiency engines.

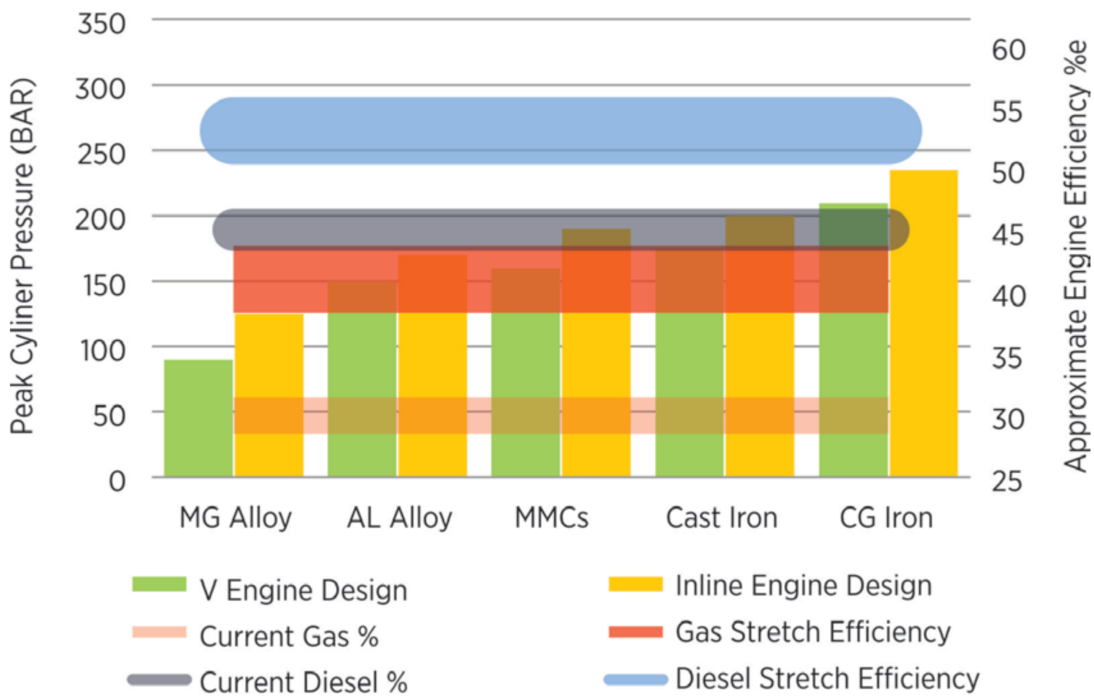

Figure 7: Materials and Peak Cylinder Pressure Capabilities (Current Material Design Limits)

2.3.1 GOALS AND METRICS FOR ENGINES AND TRANSMISSIONS

Table 4 on the following page provides the goals and metrics for light-duty engines and transmissions.

Table 4: Goals and Metrics for Engines and Transmissions

Metric	Today	2025	2050
Weight of Powertrain	Power train - 33% of vehicle weight = 100%, ~1,100 including engine, trans, electronics, exhaust, & fuel systems	25% weight reduction	50% weight reduction
Exhaust Valve Temp.	870°C	950°C	1,000°C
Peak Cylinder Pressure	• Gasoline – 5.1 MPa (750 psi) • Diesel – 17.2 MPa (2,500 psi)	• Gasoline – 7.6 MPa (1,100 psi) • AC-ICE – 11.0 MPa (1,600 psi) • LD Diesel – 19.3 MPa (2,800 psi)	• Gasoline> 10.3 MPa (1,500 psi) • AC-ICE > 20 MPa (2,900 psi) • LD Diesel > 20.7 MPa (3,000 psi)
Part Count	–	10% Reduction	20% reduction
Combustion Engine Portion of Total Vehicle Power (electrification = remainder)	99% ICE	75% ICE 25% – mix of HEV/PHEV/EV	60% ICE 40% – mix of HEV/PHEV/EV
Specific Power	73.4 hp/liter displacement (gasoline)	100 hp/liter (gasoline)*	150 hp/liter (gasoline)*
High Temp. Capability of Al Castings	200°C	250°C	300°C
Turbocharged or Waste Heat Recovery	5%	20%	50%
Power Train Cost	$8/lb at vehicle level	< 20% increase	< 50% increase
Mfg. Energy	X	25% reduction	35% reduction
Modeling Capability	Al, Mg modeling less than iron	Al, Mg modeling = grey iron and steel	CFC modeling = grey iron and steel
Traction Drives	• 1.08 kW/kg • 90%efficiency	2,022 EV Everywhere target • 1.44 kW/kg, • 94% efficiency	•1.65 kW/kg •50% greater power density
Power Density and Durability of Batteries	120 wh/kg	2022 EV target 20% greater 225wh/kg	50% greater
Weight of Wiring	X	15% lower	20% lower
Rare Earth Content in Motors and Batteries	X	25% lower	0% rare earth content

*In 2009, a naturally aspirated gasoline Caparo T1 race car produced 159.3 hp/liter and the turbocharged 2.0 L Mitsubishi Lancer Evolution produced 168 hp/liter; the goals were adjusted to reflect the ever-changing baseline.

2.3.2 TECHNOLOGY GAPS-ENGINES AND TRANSMISSIONS

The technology gaps hindering the adoption of lightweight materials for engines and transmissions for light-duty vehicles are listed below in order of priority.

1) **Lack of cost-effective lightweight materials for rotating components in the engine**
    - The demands placed on rotating components in modern and future engines require a combination of strength at elevated temperatures, low thermal expansion, high fatigue strength, and corrosion resistance as well as manufacturability in high volumes. Ceramics (pistons), Al/Ti alloys (connecting rods), and high-strength steels (solid/hollow crankshafts) are not cost competitive.
2) **Properties of cast aluminum are inadequate to meet the needs of high specific output and high efficiency downsized engines**
    - Improved aluminum alloys and/or aluminum-based composites with mechanical, fatigue, thermal, and chemical properties that can survive in engine operating environments up to 300°C and 10.3 MPa (1,500 psi) are needed.
    - Cost-effective casting processes and alloys to produce engine blocks with uniform microstructures and consistent properties are needed.
3) **Materials property data which is of sufficient depth and quality to be used in modeling and design is lacking or inadequate**
    - The lack of adequate property data for new materials impedes acceptance by designers to consider new materials in power-train-based applications.
    - A validated, process-specific, power-train-specific database for advanced materials is needed.
4) **Lightweight, high-capacity electrical energy storage devices with better performance than Li-ion batteries are nonexistent**
    - Extended driving range, better control of engine transients, opportunities for downsizing, and the ability to run the engine longer at steady state all require higher capacity, more reliable, and lighter weight energy storage devices. Low-cost materials that offer the opportunity for increased power density and improved charge/discharge behavior is needed.
5) **Affordable alternatives to cast iron for blocks and heads are not available.**
    - Alloys that enable higher peak cylinder pressure are needed to improve fuel efficiency.
6) **New casting technologies are needed**
    - Casting capabilities do not exist that support the production of bi-metallic components composed of dissimilar materials (Mg: iron, Mg: steel, Mg: Ti, Al: iron, Al: steel, Al: Ti).
7) **Surface treatment/coatings are needed**
    - Surface treatments and/or coatings to promote metallurgical bonding will enable weight reduction and potential downsizing of engines.

2.4 Closures, Fenders and Bumpers

Closures, fenders, and bumpers make up about 8%–10% of the vehicle mass. Included in this category are front and rear doors, hood, lift gate, bumpers with associated brackets, and fenders. With the exception of bumpers and the associated crash beams, which are part of the front-end structure of the body and the side intrusion beams internal to doors, closures are considered semi-structural. They are commonly made of sheet steel or, in some cases, polymer composite materials. Aluminum sheet is growing in importance for applications in hoods, deck lids, and closer panels. Bumpers are generally steel overlaid with plastic and foam, although aluminum bumpers are experiencing growing acceptance in all vehicle segments.

2.4.1 GOALS AND METRICS FOR CLOSURES, FENDERS, AND BUMPERS

Goals and metrics are present in the table below.

Table 5: Goals and Metrics for Closures, Fenders, and Bumpers

Metric	Today	2025	2050
Weight and Functionality (safety, appearance, impact performance, NVH, etc.)	10% lower weight than 2002 in metal components, net gain in weight because of added content in doors since 2002	Maintain functionality with 50% weight reduction	Maintain functionality with 75% weight reduction
Achieve Weight Savings at a Cost of <$1/lb	Current premium of ~$1/lb in bumpers, >$1/lb in other components	<$1/lb for >50% weight reduction	<%1/lb. for >75% weight reduction
Weight savings cost	Base	< $2.16 per pound saved	< $2.33 per pound saved

2.4.2 TECHNOLOGY GAPS-CLOSURES, FENDERS, AND BUMPERS

The technology gaps hindering the adoption of lightweight materials for closures, fenders, and bumpers for light-duty vehicles are listed below in order of priority.

1) Fast and reliable processes for producing high-quality joints between lightweight materials for closures, fenders, and bumpers are not adequate

- Strategic use of multi-materials in the manufacture of doors, decklids, and hoods can result in a reduction in the weight of those subsystems by 25%–50%. However, optimized designs will require the use of a combination of materials to take advantage of their inherent properties and weight reduction potential. Current manufacturing techniques rely on spot welding of steel components. However, those processes may not be applicable to multi-material assemblies in the future.

2) Relevant knowledge and databases for design and simulation of lightweight materials are inadequate

- Over the past 100 years, the automotive industry has focused on producing vehicles composed mostly of steel and iron. Designs have changed drastically, manufacturing processes have been optimized, and performance has greatly improved over that period; however, the average vehicle in 2004 was still approximately 50-60% iron and steel. Databases, models for simulation and prediction, and manufacturing processes have also been optimized to support the industry. The databases, models, and manufacturing processes for most alternative lightweight materials are relatively immature and insufficient to provide design engineers the level of confidence needed.

3) Lightweight materials are not available in sufficient quantities at costs that are necessary for high-volume applications

- Two basic issues limit the use of lightweight materials: the availability of sufficient quantities at affordable cost and the availability of low-cost manufacturing processes to produce components in high volume. The cost of materials such as carbon fiber, magnesium, and to a lesser extent, aluminum and high-strength steels, is too high.
- The manufacturing processes (e.g., forming of magnesium sheet, direct compounding of composites, cycle times for composites, etc.) to produce components using these materials are not competitive with those for currently used materials.

3 THE IMPACT OF MATERIALS ON LIGHT-DUTY VEHICLE EFFICIENCY

The materials used in a motor vehicle can have a significant impact on vehicle efficiency in two ways: 1) materials can be used to reduce the weight of the vehicle and 2) materials can enable higher efficiency engines and power trains. These pathways are not mutually exclusive but can build upon each other leading to lighter vehicles with higher efficiency power trains.

Lightweighting can impact the energy efficiency of vehicles regardless of the power train configuration. In conventional ICE light-duty applications, a 10% weight reduction can result in a 6%–8% improvement in fuel economy.[12,13,14,15] Light-duty, electric-powered vehicles weight reductions result in increased vehicle range without increasing the battery size. Load-limited, heavy-duty vehicles lightweighting can result in increased freight capacity resulting in an efficiency improvement from a delivered ton-mile per gallon perspective. This also reduces the number of trucks required to ship a given tonnage. In volume-limited, heavy-duty vehicles, the efficiency improvements are similar to those for light-duty vehicles.

When advanced materials are applied to the propulsion system, there is significant opportunity for improvement in energy efficiency. The thermal efficiency of today's light-duty gasoline engines is about 30% and heavy-duty diesel engine efficiency is about 42%. However, if these engines could operate at their maximum theoretical potential, their efficiency would be about 62%. Reaching the 62% theoretical efficiency would represent a 2X improvement in light-duty fuel economy and a 50% improvement in the fuel economy of heavy-duty vehicles. The efficiency of ICEs is currently limited by the constraints imposed by the materials used in their manufacture.

In general, the set of materials that are considered for light-duty applications (passenger cars, crossover vehicles, and light trucks) or heavy-duty applications (vocational trucks and long haul tractor-trailer combinations) are the same. However, the performance requirements, which are defined by the specific duty cycles, require different approaches to design as well as manufacturing. These distinct requirements in performance can lead to different choices of materials for a given component. For example, body, chassis, and suspension or closure subsystems light-duty designs are usually stiffness driven, while heavy-duty designs are driven by considerations of strength and durability, including corrosion and fatigue. For propulsion systems, the material properties are often temperature, strength, or fatigue driven for both light and heavy duty vehicles.

In addition, light-duty production volumes are in millions per year whereas annual production volumes for heavy-duty vehicles are approximately 300,000. The lower volumes of heavy-duty vehicles may allow consideration of manufacturing and assembly techniques that are slower and, perhaps, consideration of materials and processes that are more costly.

Table 6 lays out candidate materials for their weight reduction potential in automobiles with respect to existing steel and/or iron parts and structures. For structural components, the weight reduction potential varies from 10%–28% for AHSS to as much as 60% for Mg and CFCs in specific applications. The discussions that follow will address the results of the workshop in order of decreasing potential to reduce weight. As advanced materials and steel and cast iron are intended for use primarily in engine and power train applications, they are listed after the structural materials.

Table 6: Materials' Weight Reduction Potential

Lightweight Material	Material Replaced	Mass Reduction (%)
Carbon Fiber Composites	Steel	50 –70
Magnesium	Steel, Cast Iron	30 –70
Aluminum	Steel, Cast Iron	30 –60
Glass Fiber Composites	Steel	25 - 35
Advanced Materials	Steel	10 –30
Advanced High Strength Steel	Mild Steel, Carbon Steel	10 –30
High Strength Steel	Mild Steel	0 –15

Over the period from 1977 to 2004, the distribution of materials used in the average light duty vehicle shifted to a greater use of lightweight materials.[16] Figure 8 illustrates this shift. These changes in the distribution of materials show an increase in the use of aluminum and high-strength steels at the expense of conventional steel. These materials offer potential weight savings of 10%–30% with moderate obstacles still remaining for their widespread implementation and are thus ready for broader introduction in the nearer term. Magnesium alloys and carbon fiber composites offer greater potential weight savings (over 50%) but have more substantial obstacles to widespread implementation and have a longer timeframe before they are production ready. Compacted graphite steels, titanium alloys, metal matrix composites, and ceramics are materials under development for implementation in propulsion and exhaust systems. This section focuses on the performance requirements needed and technology gaps inhibiting faster adoption of lightweight and enabling propulsion materials

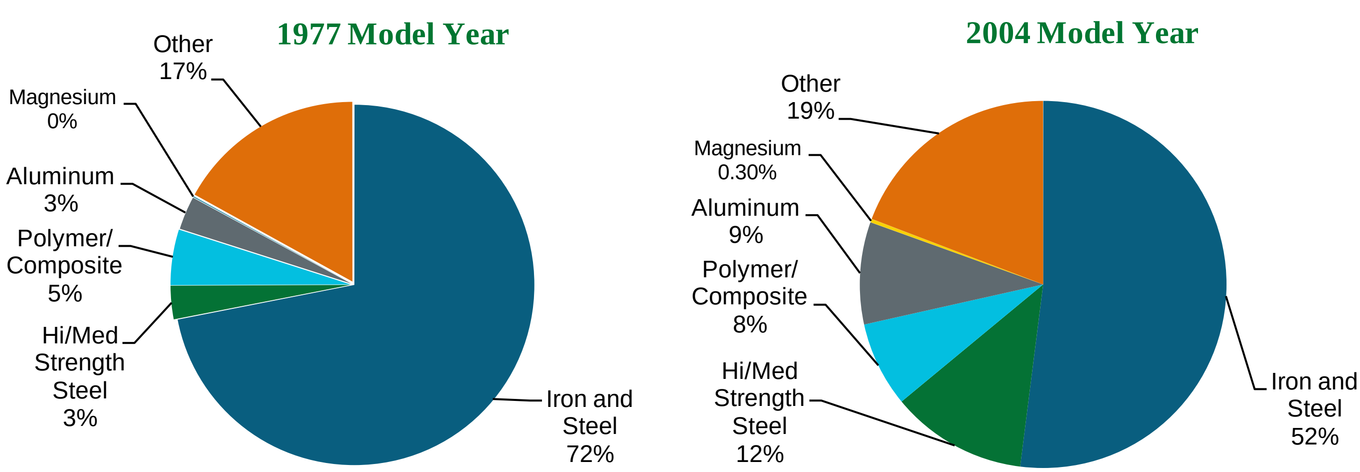

Figure 8: Distribution of Weight of Materials in Typical Family Vehicle[16]

3.1 Carbon Fiber and Carbon Fiber Composites

Carbon fiber (CF) possesses directional properties that exceed those of many other engineering materials. When combined with suitable thermoset polymer matrix materials, such as epoxies or polyesters, or thermoplastics, such as nylon or polypropylene, carbon fiber composites (CFCs) are created. These materials with high strength-to-weight ratios can be used in the design of components to realize weight savings up to 60% compared to steel while delivering the highest specific strength and stiffness of all materials. Primary issues hindering broad use of CF include the cost of the fiber, the cost and source of fiber precursor materials, and the energy requirements for converting precursors to finished fiber. CFCs have found a limited role in various automotive applications due the cost and inadequate CFC design and manufacturing knowledge base.

3.1.1 GOALS AND METRICS FOR CARBON FIBER AND CARBON FIBER COMPOSITES

The goals and metrics for CF and CFCs are shown below.

- By 2025, carbon fiber will be used intensively in high-volume vehicle production.
- By 2050, the materials suppliers to the automotive sector will have materials, tools, and knowledge in place to enable performance/function-driven design and manufacturing.

Metrics for CF and CFCs are shown in the following table.

Table 7: Goals and Metrics for Carbon Fiber and Composites

Metric	Baseline	2025	2050
Utilization	Limited-to-no use	5% of vehicle mass	15%-25% of vehicle mass
Cost	• Fiber: $7/lb • CFCs: $12–$15/lb	• Fiber: $3/lb (stretch goal) • CFCs: <$5/lb	• Fiber: $3/lb (stretch goal) • CFCs: <$2.5/lb
Fuel-Based Cost Tolerance $/lb. saved	Base	$3.42/lbs. saved*	$4.32/lbs. saved*
Modeling	Limited	Design with 50% theoretical CF limits	Design with 75% theoretical CF limits
Design	–	50% of theoretical limits	Design with 75% theoretical CF limits
Raw Materials	• Fibers: polyacrylonitrile • Precursor yield <2/1 • Low throughput • High emissions	• Non-petroleum based materials (precursors, fibers, resins) • Precursor yield > 2/1 • High throughput • Low emissions	100% recyclable materials
Manufacturing Cycle Times for CFCs	> 5 minute	< 3 minute	<1 minute
Joining	–	Joining technology for CF-CF and CF-metal at cost and time ~steel design	–
Recycling	–	• 100% recycled • 25% renewable precursor • 25% reduced carbon footprint	• 100% recycled • 50% renewable precursor • 75% reduced carbon footprint
Repair	• 0% detection • 0% repair	• 100% detection • 25% repair	• 100% detection • 50% repair

3.1.2 TECHNOLOGY GAPS-CARBON FIBER AND CARBON FIBER COMPOSITES

There are a number of technology gaps that hamper the utilization of CF in composite designs. Some of the most critical challenges are identified below in the following areas:

1) **Technologies for producing carbon fiber from precursor materials are not optimized for automotive-grade materials. Thus far, carbon fiber is optimized for aerospace applications with the value chain and infrastructure fairly well established. The field of composites for automotive is still in its infancy and several elements of this value chain are evolving**

    - Current processes for converting available CF precursors to usable fiber are too energy intensive and slow to produce carbon fiber at a cost and in volumes necessary to support significant use for light-duty vehicles.

- In order to improve the cost effectiveness of converting precursor to fiber, the community needs a better understanding of the structure-property relationships between precursor and product and the evolution to final product during the precursor-to-CF conversion process. Better fundamental understanding would enable accurate molecular modeling and optimization of chemical engineering processes and precursor rheology resulting in improved reaction kinetics and yield for both stabilization and conversion.
- A processing route employing non-petroleum-based precursors, which would remove dependence on oil, is not yet available.
- A robust infrastructure supporting this evolving industry also needs engineering education in CF and CF-composite design and manufacturing processes (process/equipment, design processes, material specific processes, manufacturing process development).

2) **With certain resins, the ability to bond the fiber to the resin (interfacial bonding chemistry, for example) is inadequate to take full advantage of the inherent properties of the fiber**

- The surface of carbon fiber heavily influences bonding to the resin and the final properties of composite system. Carbon fiber must be compatible with a variety of resin matrix systems. The ability to tailor surface properties during conversion is needed.
- Existing surface treatments or coupling chemistries are not optimized for most thermoplastic resin systems that are used to incorporate CFs.
- Current sizings are not optimized for wetting characteristics and for the ability to transfer load to enable carbon fiber to be used with polyester resins, for example.

3) **Joining technologies for carbon fiber composites to each other or within a multimaterial system are inadequate**

- Joining technologies to incorporate CFCs in suspension and body applications are either not developed or are not compatible with the fast processes necessary in a production environment.
- Joining composites to other materials such as magnesium, steel, aluminum, plastic, or glass fiber composites to produce multimaterial components has not advanced far enough to be used extensively in high volumes.
- The effects of thermal cycling and environmental effects on durability of joints, the creep and fatigue properties of CFC joints, and compatibility with E-coat are currently poorly understood. As a result, expensive qualification is needed for each application.

4) **Capabilities for accurate predictive models supporting design, processing, and crash energy management are either inadequate or insufficiently validated to avoid "over design" that incorporates additional safety factors.**

- Models are needed to understand the relationship between material physical properties, mechanical properties, processing, and ultimately to predict behavior. However, cost-effective analysis tools and databases to support them are not available.
- There is a lack of validated databases on properties of materials to populate models. In addition, industry lacks standards for testing CFCs.
- Tools that can predict CF performance need improvement in order to be used with confidence and to minimize the need for overdesign in crash-critical components.

5) Few fiber/resin systems are inexpensive enough and provide rapid cycle time to be compatible with high-volume demands and performance needs

- Short cycle time in component manufacturing and joining processes are required for the production of inexpensive, complex-shaped CFC components.
- The following are not sufficiently understood, nor have they been optimized for large-scale implementation in the automotive market: mold design, surface interactions between mold surfaces and resin and between fiber and resin, rheology of heterogeneous material flows, fast cycle manufacturing processes, tribology of machining, and material compatibility for joining.
- The ability to design efficient manufacturing processes for component manufacture and the effect of the process on dimensional control are not currently well understood.
- Understanding of fiber flow/placement control and management are limited.

6) Understanding of CF behavior under service conditions is insufficient

- There is a need to better understand how CF materials behave under a variety of service conditions.
- Comprehensive testing /measurement of CFC components will enable the development of predictive tools for short/discontinuous/chopped fiber in matrix, for example.

7) The technology to detect damage in CFCs as well as the technology to repair components is immature

- The community needs the development of tools for rapidly detecting damage after impact based on non-destructive evaluation such as ultrasonic, thermography, or computer aided tomography. The ability to detect damage and repair needs to be as easy and reliable with composites as it is now with metal structures.
- There is a need for mathematical models that can:
  - Predict the size of damage for a given composite and a given impact scenario.
  - Predict the growth of damage zone with fatigue and environmental exposure along with experimental validation.
  - Relate the size of the damage zone to compromise in structural integrity of a given composite component along with experimental validation.
- Damage modeling approaches require validation with composites reinforced with chopped fiber, noncrimp fabrics, woven fabrics, among others.

3.2 Magnesium

Magnesium is the lightest structural metal available for vehicle applications. With a density of 1.74 g/cc, magnesium can reduce the weight of vehicle components by up to 70% relative to baseline steels and has the potential to be utilized as either a cast or a wrought alloy. The combination of lightweight, good strength, and design flexibility make magnesium a very attractive material for vehicle applications, but there are technology gaps that hinder industry wide acceptance.

3.2.1 GOALS AND METRICS FOR MAGNESIUM

Following are the goals established for magnesium:

- By 2025, produce higher performance magnesium alloys with properties similar to aluminum today. Establish a reliable, affordable domestic supply with low-carbon emission production processes.
- By 2050, develop the technology to enable high-volume production of magnesium at a carbon dioxide equivalent cost of two-to-three (2-3) kilograms of carbon dioxide per kilogram of magnesium.

The metrics for magnesium are presented in the Table 7 below.

Table 8: Goals and Metrics for Magnesium

Metric	2010	2025	2050
Yield Strength and Ductility	• Yield Strength 110–120 MPa • 8% Elongation • Fatigue Strength 85 MPa	• 250 MPa • 15% Elongation	• 350 MPA • 25% Elongation
Production	• Majority Imported • ~25kg CO_2/kg primary Mg	>10% Domestic	• 100% domestic • 2–3 kg CO_2/kg primary Mg
Corrosion and Joining	Baseline	Eliminate galvanic corrosion (low-cost electrical barriers)	Universal one-step pretreatment compatible with aluminum, steel, and “stainless” Mg alloy
Alloy Development	Significant shortfall of automotive Mg alloys (wrought and cast)	Increase number of available automotive Mg alloys by 2X	Increase number of available automotive Mg alloys by 4X
Sheet	Baseline	Uniform properties with Room Temperature Forming	Class “A” Surface
Recycling	Baseline	Design for disassembly (joining technologies)	Meet EU recycling targets

3.2.2 TECHNOLOGY GAPS-MAGNESIUM

The technology gaps hindering the wide-scale adoption of magnesium revolve around several key issues.

1) **A production-scale, environmentally clean process for producing magnesium does not exist in North America**
    - Currently there are few domestic primary magnesium production facilities and the processes used are often energy intensive and carry environmental penalties. In order to effectively take

advantage of the weight reduction potential offered by magnesium, there is a need for environmentally clean, low-cost production capacity in North America.

2) Corrosion behavior of magnesium is inconsistent, unpredictable, and poorly understood

- A fundamental understanding of the impacts of surface structure, trace impurities, anisotropy, and texture on corrosion rates as measured on coupons excised from full-size components is needed.
- Constitutive models capable of predicting corrosion for magnesium alloys are not currently available.
- The cost and complexity of magnesium isolation technologies (films, spacers, etc.) to avoid galvanic corrosion is a major hindrance to significant market penetration.
- Impurities (e.g., Cu, Fe, Re) can facilitate in-situ corrosion of alloys. The lack of alloys that are less likely to corrode or mitigate this behavior is a barrier to greater implementation.
- There is a need for accelerated and validated test protocols for the evaluation of corrosion of magnesium components under a variety of operating conditions.

3) The existing modeling tools for magnesium are inadequate

- There is a need for a comprehensive suite of predictive modeling tools similar to those currently available for steel and aluminum.
- There is a need for engineering and design modeling tools for magnesium components and assemblies.
- There is a need for linked atomic/meso/macro-scale models for magnesium, capable of predicting material behavior based on alloy composition, processing, and fabrication techniques.
- There is a need for capability in modeling corrosion of magnesium alloys and assemblies to support more rapid development of isolation strategies and stainless Mg alloys.

4) Cast magnesium products exhibit insufficient ductility and wrought products lack uniform properties

- Cast alloys with strength and ductility necessary to meet the increased demands for specific safety-related components envisioned for future applications are not available.
- A fundamental atomic-level understanding of the deformation properties of wrought magnesium (non-basal slip, twinning, etc.) does not exist.

5) Effective repair and recycling protocols and infrastructure do not exist for magnesium

- Strategies for cost-effective repair of magnesium components do not exist.
- There is a need for end-of-life separation technologies for magnesium.
- Post-recycling purification technologies are needed for magnesium scrap.

3.3 Aluminum

Aluminum alloys in both cast and wrought forms represent a cost-effective material for reducing the weight of vehicles and their power trains. With a density of approximately one-third that of steel and cast iron, aluminum has the potential of reducing weight by at least 40% in properly designed structures and components. Barriers to the use of aluminum include higher material cost, lack of formability, limited strength at elevated operating temperatures, and joining and corrosion issues.

3.3.1 GOALS AND METRICS FOR ALUMINUM

The goals and metrics for aluminum are presented in the table below.

Table 9: Goals and Metrics for Aluminum Alloys

Metric	2010 (Baseline)	2025	2050
Mechanical and materials Properties	• 180 MPa yield/5% el (cast), • 275 MPa yield/12% el (wrought)	40% improvement	200% improvement
Aluminum Joining with Dissimilar materials	• Slow, expensive • Can't be modeled	• 50% less fasteners • Easier to model	Near zero use of fasteners
Parts Cost	Not cost competitive	25% lower	40% lower
Design Techniques	• Incomplete understanding of system properties • Significant prototyping	50% reduction in design time	Design to manufacturing with no prototyping required
Recyclability	• 90% overall • 0% high-performance alloys	• 90% overall • 50% of high-performance alloys (HP) reused for HP alloys	• 90% overall • 100% of high performance alloys reused for HP alloys

3.3.2 TECHNOLOGY GAPS-ALUMINUM

Aluminum requires further development in a number of areas in order for it to be considered for more applications. A few of these technical gaps are listed below.

1) Techniques for joining aluminum to other metals are inadequate. As a result, these joints are typically overdesigned to ensure integrity for long-term performance

- Accurate predictive modeling of the performance and durability of aluminum-multi-material joints and assemblies (integrity, stiffness, fatigue, etc.) is required if these materials are to be implemented on a large scale.
- Current joining processes require cleaning or pretreatment to ensure bond integrity. Such treatments impact both cost and high-volume manufacturing.
- The rivets, adhesives, etc., used to join aluminum to other materials require optimization to lower cost, reduce cycle time, and improve reliability.

2) Modeling, simulation, design-processes, and optimization techniques are not adequate

- Improved tools for design and computer-aided-engineering to optimize aluminum part manufacturing and in-service performance are needed.

- Failure analysis and fracture mechanics models for aluminum parts are inadequate to allow designers to take full advantage of the weight reduction opportunity for aluminum components.
- Current databases and property prediction tools for casting and forming do not accurately approximate mechanical properties and in-service performance of components.

3) Processing techniques for high performance castings are not reliable or repeatable

- Existing casting methods for aluminum components are not well understood. Consequently castings are often limited by porosity and other defects and cannot be utilized in high-performance intricate-shape applications. The relationship between process variables and casting quality is poorly correlated.

4) Material properties are inadequate for many specific applications

- The ability to use aluminum alloys in the following specialty applications is currently limited by inadequate properties: high-temperature fatigue for applications in turbo-machinery and cylinder heads, tensile strength, fatigue strength, ductility for body, and chassis, etc.

3.4 Glass Fiber Composites

The majority of glass fiber composites are used in semi-structural applications such as outer door panels, hoods, etc. Although the weight reduction potential of GFRP composites is much lower than CF composites, the combination of low-cost and flexible manufacturing make them competitive in many applications.

3.4.1 GOALS AND METRICS FOR GLASS FIBER COMPOSITES

Following are the goals established for glass fiber composites:

- By 2025, increase industry penetration of glass fiber composites to 30% of vehicle weight by OEM acceptance of validated, production-ready technology.
- By 2050, increase industry penetration of glass fiber composites to 50% of vehicles weight by OEM acceptance of validated, production-ready technology.

The metrics for glass fiber composites are presented in the table below.

Table 10: Goals and Metrics for Glass Fiber Composites

Metric	2010 (Baseline)	2025	2050
Material Property Database and Modeling	Baseline not comprehensive for all material properties	A comprehensive database	Predictive modeling and correlation with field data
Stiffness	Variables ranges are large	30% improvement in material stiffness	Same stiffness as aluminum
Appearance	• Class "A" appearance possible • Low fill levels, stiffness ~steel	• Parity with steel (painted)	Same as 2025
Recycling, Chemical and Energy Recovery	• Typically no recycling • Potential exists	Achieve 50% recyclability and recovery	Eliminate light-duty and heavy-duty vehicle-related landfill load composites/plastics
Design Techniques	• Incomplete understanding of system properties • Significant prototyping	50% reduction in design time	Design to manufacturing with no prototyping required
Recyclability	• 90% overall • 0% high-performance alloys	• 90% overall • 50% of high-performance alloys (HP) reused for HP alloys	• 90% overall • 100% of high performance alloys reused for HP alloys
Fiber Characteristics	Processes tend to break fibers	Improved predictive fiber characteristics	• Aluminum-like thermoplastic • Low coefficient of linear thermal expansion and isentropic properties
Joining of Composites	Many methods, few standards	• More methods and available data • Standards for multi-material joining	Continued technology, methods, and standards advancement
System Cost Parity	Sheet molding compound (SMC) $1–$2 /lb	Parity with steel	Same as 2025
Reduced Part Weight via Design Optimization or Reduced Density	–	30% part weight reduction relative to composite components	50% part weight reduction relative to composite components
Regulatory Standards –VOC emissions	Baseline today's standards	50% from baseline	95% from baseline
Process	Shrink/warp due to fiber orientation	Eliminate warp	Continued advancement
Liquid Thermoset Resin/Continuous Fiber	10 min	<5 min	<2 min

3.4.2 TECHNOLOGY GAPS-GLASS FIBER COMPOSITES

In order to utilize more glass fiber composites in components and structures, the following technical gaps need to be addressed:

1) Reinforcement chemistry and technology for the use of novel reinforcements is insufficient to develop necessary properties

- There are limited available reinforcement technologies to improve mechanical properties and durability of glass fiber composites.
- Demonstration of improved properties and performance with traditional or hybrid systems (glass and CF or natural fiber) has been limited.
- Technology for the use of nano-reinforcements to improve mechanical properties and reduce density is needed.

2) The material property database and design knowledge for glass fiber composites is incomplete

- Materials attributes such as glass transition temperature, stiffness, shear strength, etc., are not currently available in a comprehensive database for use by designers and modelers.

3) Modeling and simulation software of glass fiber composites and unreinforced plastics is relatively immature

- Existing software cannot reliably model processing and then predict resulting reinforcement orientation and composite properties for short glass, long glass, and continuous glass composites.

4) Process cycle times are not competitive with competing materials (metals)

- Process cycle times are lengthy for higher volume glass fiber composite applications resulting in reduced production volumes.

3.5 Advanced Materials (e.g., Titanium, Ni-Based Alloys, MMCs)

Advanced materials (e.g., titanium alloys, metal matrix composites, nickel-based alloys, etc.) have unique sets of properties that cannot be achieved by more common materials such as aluminum, steels, magnesium, and composites. In engine and transmission applications, these materials have the ability to retain strength and other properties at significantly higher operating temperatures, or, in the case of titanium, exhibit properties comparable with high-strength steels, but with a lower material density. These properties make these materials attractive alternatives for higher efficiency internal combustion engines or small diesel engines.

3.5.1 GOALS AND METRICS FOR ADVANCED MATERIALS

Following are the goals established for advanced materials:

- By 2025, reduce the cost of advanced materials and improve manufacturability as a function of cost vs. performance by 50%.
- By 2050, reduce advanced materials cost vs. performance to 2011 levels for conventional materials.

The metrics for advanced materials are presented in the table below.

Table 11: Goals and Metrics for Advanced Materials

Metric	Baseline Metric	2025	2050
Titanium	• Cost > \$6.00/lb • Current operating temperature = 400°C	Cost versus performance - 50% reduction from baseline	Decrease cost versus performance to parity with aluminum
Nickel Alloys	• Cost = 4 X stainless steel • Operating temperature = 950°C	• Decrease cost by 50% • Operating temperature ≥ 1,050°C	Decrease cost by additional 50%
Metal Matrix Composites	• Cost - \$3.00/lb • Limited production base	• Decrease cost by 25% • Develop manufacturing capability	Decrease cost by additional 25%

3.5.2 TECHNOLOGY GAPS - ADVANCED MATERIALS

The technology gaps hindering the adoption of advanced materials for light-duty vehicles are listed below in order of priority.

1) **There is limited commercial capability for mass production of components made of advanced materials (titanium and metal matrix composites [MMCs]) from powders**
    - In order to take advantage of the properties of these advanced materials, process improvements are required to allow near net shape production from powders for high-volume component manufacturing.
2) **Existing materials (superalloys and MMCs) exhibit inadequate thermal performance**
    - Advanced gasoline and diesel engines, turbochargers, and systems for after-treatment with higher operating temperatures will require development of nickel-based alloys that can maintain properties up to 1050°C and improved MMCs for both high- and low-temperature applications.
3) **Production capacity for Ti raw materials is limited**
    - Current annual Ti powder production capacity is insufficient to meet expected demand in 2025 (5 X current levels) and 2050 (10 X current levels). Improvements in separation and purification as well as increased size of production facilities is required to take advantage of potential 40% mass reduction versus steel for engine components.
4) **Databases for design and processing for advanced materials is immature**

3.6 High-Strength Steels and Advanced High-Strength Steels (Structural)

Various classes of steels are used in body structures, chassis and suspension components, and closures, fenders, and bumpers. The combination of low material cost, high strength and stiffness (modulus), outstanding formability, and an extensive modeling and design database make high-strength steel a highly competitive material in vehicle applications. Challenges to steel's dominance in structural applications include the increasing cost, reduced formability of the advanced high-strength steels alloys, joinability, and the continuing development and optimization of competitive materials such as aluminum and fiber-reinforced composites.

3.6.1 GOALS AND METRICS FOR HIGH-STRENGTH STEELS (HSS) AND ADVANCED HIGH-STRENGTH STEELS (AHSS)

Following are the goals established for structural steels:

- By 2025, develop new steels with enhanced mechanical properties that are manufacturable, less energy intensive, reliably joinable, and corrosion resistant. In parallel, develop cost-effective laminated steels, nanoparticle reinforced steels, improved processing techniques to produce thinner gauges and wider sheets, multi-scale models populated with appropriate data, and a more environmentally friendly steel-making process.
- By 2050, develop new steels with enhanced mechanical properties that are manufacturable, less energy intensive, reliably joinable, and corrosion resistant. In parallel, develop cost-effective laminated steels, nanoparticle reinforced steels, improved processing techniques to produce thinner gauges and wider sheets, multi-scale models populated with appropriate data, and a more environmentally friendly steel-making process. Develop the ability to seamlessly produce 3-D constructions of mixed materials with high strength and no joints.

The metrics for high strength steels and AHSS are presented in the table below.

Table 12: Goals and Metrics for High-Strength Steels and Advanced High-Strength Steels

Metric	2010 (Baseline)	2025	2050
Tensile strength and elongation	• 590 MPa • 20% elongation	• 1,500–2,000 MPa ultimate tensile strength (UTS) • 20% elongation	• 2,500–3,000 MPa UTS • 20% elongation
Density	7.87 g/cm^3	5% density reduction	10% density reduction
Modulus	211 GPa	10% increase	20% increase
Gauge and Width	• 0.65 mm thickness, • 1,500 mm width	• Reduce gauge to 0.5 mm • Increase width to 1,800 mm	• Reduce gauge to 0.4 mm • Increase width to 1,800 mm
Fuel Based Cost Tolerance $/lb. Saved	Base	• $3.42/lbs. saved*	• $4.32/lbs. saved*
Reliable Joining Processes for Mixed Materials	Spot welding	Mechanical properties equivalent to steel-to-steel spot welding	Seamless 3-D construction of multi-material structures
Increase Modeling Capabilities Across the Board (cost, crash, fatigue, formability, corrosion, etc.)	–	Models achieve 75% confidence in correlation	Models achieve 90% confidence in correlation

3.6.2 TECHNOLOGY GAPS - HIGH STRENGTH STEELS AND ADVANCED HIGH STRENGTH STEELS

Next-generation steels face a number of technology development challenges before they can be readily considered for use in vehicle applications. The most critical are identified below:

1) **Structure-property relationships for new grades of steels are poorly understood**
    - The next generation high-strength steels will be required to exhibit tensile strengths of 1,500–2,000 MPa, 20% ductility, corrosion resistance, and the ability to be joined without loss of joint strength. Current understanding of structure property relationships is insufficiently well developed to guide such developments.
2) **Joining processes for high-strength steels are inadequate**
    - The ability to use advanced high strength steels in fabricated structures requires reliable joining techniques that are cost efficient and rapid. Current spot welding approaches often result in degradation of properties in the weld zone and may also lead to increased corrosion.
    - Higher strength materials will lead to thinner gauges. New joining techniques are needed for these thinner materials.
3) **Modeling and simulation software for multi-scale modeling of AHSS are too immature to predict properties utilizing physics-based models, microstructures and resulting morphology and properties, as well links to failure modes and manufacturability and performance**
    - Models capable of predicting microstructure as a function of composition and processing are inadequate.
    - The variation of properties from phase to phase and at interfaces and the effect of microstructure on resulting mechanical behavior during processes such as forming, joining, and ultimately structural performance and failure in vehicle applications are not well understood.
4) **Rolling and forming processes for producing ultra-thin, high-strength steels are not currently available**
    - Processing routes needed to produce the ultra-thin (0.4 mm), wide (1,800 mm) sheet from ultra-high strength steels are currently not available.
    - Post -processing (piercing, forming, cutting, machining, lubrication, etc.) manufacturing steps necessary to handle steels with strengths ~ 2,000 MPa do not exist.

3.7 Steel and Cast Iron (Propulsion)

Offering a combination of low material cost, high strength, and good processing and manufacturing characteristics, steel and cast iron remain the dominant material in engine and drivetrain applications. As engine designs move toward higher cylinder pressures, increased operating temperatures, and higher power densities, steel and cast iron must be improved and optimized to meet application requirements.

3.7.1 GOALS AND METRICS FOR STEEL AND CAST IRON

Following are the goals established for steel and cast iron for propulsion applications:

- By 2025, develop the ability to use higher property materials for increased operating conditions to improve efficiency and performance and reduce weight and lifecycle cost, thus enabling 25% improvement in specific power.
- By 2050, develop the ability to use higher property materials for increased operating conditions to improve efficiency and performance and reduce weight and lifecycle cost, thus enabling a 50% improvement in specific power.

The metrics for steel and cast iron for propulsion applications are presented in the table below.

Table 13: Goals and Metrics for Cast Iron

Metric	2010 (Baseline)	2025	2050
Specific Strength	Baseline adv. steel alloys	10% Increase	20% Increase
Coefficient of Variation of Strength	Baseline strength variation	Decrease by 50%	Decrease by 75%
Castability	Baseline wall thickness 5 mm +/- 2.5 mm	Wall thickness 3 mm +/- 1.0 mm	Wall thickness 2.5 mm +/- 0.75 mm
Thermal Fatigue Strength	Baseline	Increase 15%	Increase 30%
Contact Fatigue	Baseline 220 ksi	Increase 10%	Increase 20%
Thermal Oxidation Resistance	Baseline	Increase 100°C	Increase 200°C

3.7.2 TECHNOLOGY GAPS FOR STEEL AND CAST IRON

Critical technology gaps that inhibit the application of steel and cast iron are listed below by priority.

1) Cost-effective methods for forging high-strength steels are inadequate

- Alloys with improved thermal fatigue behavior and processing equipment to manufacture them are needed.

2) Material property variations result in excessive design margins leading to higher cost and weight

- Improved alloys and processes together with improved models to predict properties are needed for both cast and wrought products. These improvements could enable a significant decrease in the variability of properties and lead to a 50% decrease in cast wall thickness for large complex castings.

3) The iron casting process has wide variability which results in heterogeneous material properties, especially in large castings

- More accurate methodologies for control of melt composition, cooling rate to generate desired microstructures (and properties), and technologies to detect and control casting solidification rate are needed to produce more homogeneous castings.

4) Current alloys have inadequate properties to meet the demands of future engine technologies.

- Materials with the castability and machinability of gray iron and the strength and modulus of steel do not presently exist.

5) Economically viable machining processes for highly alloyed steel, cast iron, and compacted graphite iron are inadequate

- Process controls including real-time closed-loop feedback during machining as well as improved tool materials are needed to manufacture future high-performance engines.

4 SUMMARY

4.1 Systems

An analysis of the technical gaps identified in the preceding sections demonstrates that the most significant technical barriers limiting implementation of lightweighting technologies for the main systems of light-duty vehicles (body, chassis and suspension, closures, and engines and transmissions) are common to more than one subsystem. Table 14 illustrates the three highest priority gaps identified during the workshop for each of the systems.

Table 14: Key Technical Gaps for Systems for Light-Duty Vehicles

System	Three Most Significant Technical Gaps Impeding Widespread Implementation		
Body Structures (Composites)	Lack of understanding of properties with respect to fracture and energy absorption	Lack of predictive engineering and modeling tools	Lack of high-volume manufacturing capability
Body Structures (Metals)	Lack of technology for joining dissimilar materials	Properties of alternative lightweighting materials are inadequate for forming and energy absorption	Modeling, simulation, and design tools are inadequate for optimization
Chassis and Suspension	Inadequate properties (strength, ductility, corrosion resistance, etc.)	Manufacturing capacity to produce high- integrity components is inadequate	Robust joining processes, especially to other materials, are lacking
Closures, Fenders, and Bumpers	Fast and reliable processes for joining dissimilar materials are not available	Design knowledge and databases are inadequate	Cost/availability of most lightweight materials and current manufacturing processes are not competitive
Engines and Transmissions	Materials needed for advanced technology propulsion systems are not cost competitive	Properties of current materials are not adequate	Databases for modeling and design are inadequate

The lack of adequate properties, the inability to manufacture high-quality components with necessary cycle times to produce sufficient volumes for automotive applications, the inadequacy or lack of modeling and design tools, and inadequate joining technologies appear repeatedly and illustrate the problem facing design engineers seeking to reduce vehicle weight without compromising safety and performance. The severity of the problem is further increased by the fact that each of these deficiencies also serves to increase the cost associated with using new materials. From a systems perspective, these major technical gaps are discussed below.

Lack of adequate properties was identified as a high-priority gap for body structures (metal and composite), chassis and suspension, and engines and transmissions. Without exception, all of the materials of interest for lightweighting were developed for other applications. The particular properties required for light-duty vehicles are specific to each application within a system (e.g., energy absorption, corrosion resistance, formability, castability, thermal stability, etc.), and it is clear that significant effort will be required to develop the set of "automotive grade" lightweight materials with enhanced properties that will meet these diverse needs.

Over the past 100 years, vehicle manufacturers and suppliers have invested heavily in infrastructure and production technologies based on current materials. With the exception of aluminum castings for engine and suspension applications, the focus has been on plain carbon steel and cast iron. Many of the leading candidate lightweight materials lack manufacturing techniques that are cost competitive. Manufacturing issues were identified as high-priority technical gaps for four of the five systems: body structure-composite (long cycle times for glass fiber polymer composites and CFCs), body structure-metal (formability in stamping at room temperature for Mg and Al), chassis and suspension (technology and capacity for high-integrity castings of Al and Mg), and closures (cost competitive forming processes for sheet aluminum and high-strength steels). Although some effort has been initiated in a few of these areas, much more is needed to meet the goals established.

Although significant progress has been made to move from trial-and-error techniques to computer-based design and engineering (CAD, CAE, FEA, crash modeling), most of the development is focused on sheet steel, and design tools and modeling techniques still rely on simulations to estimate component behavior. Groups focused on body structure, closures, and engines and transmissions all highlighted inadequate databases, design tools, and modeling techniques for the new materials as significant barriers to lightweighting.

In order to reach the aggressive goals set for reducing the weight of light-duty vehicles in 2025 and 2050, the materials must be strategically applied to optimally match their special properties to key application needs. This approach will allow reduced weight at minimal or no cost penalty while still addressing the optimization of strength and stiffness; improvement of vehicle dynamics, handling, and safety; and improvement of durability, maintenance, repair, and recycle. Such optimization will require improved joining technologies to enable part consolidation and reduced assembly costs. Significant technical gaps identified in body structures, chassis and suspension, and closures were focused on the need for fast, reliable techniques for joining dissimilar materials and dissimilar product forms (wrought to cast).

4.2 Materials

A similar analysis of the technical gaps identified in the discussion of materials demonstrates that the most significant barriers to progress in implementing lightweighting materials in light-duty vehicles are also common to several materials. Table 15 illustrates the three highest priority gaps identified during the workshop for each of the materials.

Table 15: Key Technical Gaps for Materials for Light-Duty Vehicles

Structural Materials	Wt. Reduction Potential	Three Most Significant Technical Gaps Impeding Widespread Implementation		
Carbon Fiber Composites	50%–70%	Lack of low-cost precursors and energy-efficient conversion processes for carbon fiber	Design methods and predictive modeling capabilities are inadequate	Lack of high-volume manufacturing methods amenable to non-epoxy resin systems
Magnesium	30%–70%	Cost-effective, environmentally friendly process for magnesium production does not exist.	Current alloys exhibit poor corrosion properties and insufficient ductility for crash protection and manufacturability	Models for predicting properties and behavior of components are not available
Aluminum	30%–60%	Processes for joining Al alloys to dissimilar materials and welding of 7,000 series Al are inadequate.	Modeling, simulation, and design tools are inadequate for optimization	Processing techniques for high-performance castings are unreliable.
Glass Fiber Composites	25%–35%	Lack of technologies to improve properties	Incomplete property databases and design knowledge	Immature modeling and simulation software
Advanced Materials	10%–30%	Lack of commercial manufacturing methods	Inadequate thermal performance	Cost/availability of raw materials
Advanced High Strength Steels	10–30%	Understanding of structure/property relationships is insufficient to guide development of improved properties	Joining processes are inadequate	Modeling and simulation software are immature
Steel and Cast Iron (Propulsion)	0%–15%	Manufacturing processes (forging, casting, etc.) are not cost effective or are inadequate	Inadequate properties to meet demands for future engine technologies	Lack of economical machining processes

Once again, the lack of adequate properties, the inability to manufacture high-quality components with necessary cycle times to produce sufficient volumes for automotive applications, the insufficiency or lack of modeling and design tools are common to several materials. Cost/availability of materials and joining also are of concern.

The major technical gaps for materials can be grouped as shown below.

When examined from the perspective of the potential lightweight(ing) materials addressed at the workshop, the high-priority technical gaps reinforce the results seen in the analysis of the systems, but provide more specific detail. The lack of adequate properties was specified for five of the seven materials: inadequate thermal performance in advanced engine applications for advanced materials, lack of clear pathways to achieve necessary properties for glass fiber polymer composites, poor corrosion resistance and insufficient ductility for crash applications for magnesium, insufficient understanding of the structure/property relationship to control properties of AHSS, and inadequate thermal properties to meet the requirements of advanced engines for steel and cast iron. Significant research focused on each of these materials is required to develop the properties required to meet future goals.

Discussion of manufacturing issues related to materials focused on both material production and downstream processing. High-priority technical gaps for advanced materials, CFCs, and magnesium illustrate the need for cost-effective, environmentally friendly processes for producing materials. The need for cost-effective processes for manufacturing of components was identified for aluminum (large-scale, high-performance castings), CFCs (high-volume processing), and steel and cast iron (cost-competitive processing). Significant investment in technology development is necessary to make these materials available in sufficient quantities at costs comparable to those for incumbent materials.

Five of seven breakout sessions identified inadequate databases and modeling and design tools as significant barriers for further development of new materials. For most of these materials, a lack of understanding of the basic behavior of the material (microstructural development, microstructure/property relationships, fracture and failure mechanisms, durability, temperature dependent behavior, etc.) hinders progress in developing design tools and predictive models. Development of high-quality, consistent, and available databases is needed to support this development.

The current availability/cost of raw materials (compared to plain carbon steels and cast iron) and the higher costs of downstream processing (rolling, forging, machining, molding of composites, etc.) were identified as major barriers to implementation for advanced materials, CFCs, magnesium, and steel and cast iron. Significant effort is required to increase domestic production of these materials to make them competitive. Lack of infrastructure and unfamiliarity with processing routes for these materials also impedes acceptance by the design and manufacturing community.

Significant technical gaps identified in sessions on aluminum, AHSS, and other materials were focused on the need for fast, reliable techniques for joining dissimilar materials and developing new joining methods to avoid degradation of properties. Processes for joining dissimilar product forms (e.g., wrought to cast) are also needed.

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