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

VEHICLE TECHNOLOGIES OFFICE

# WORKSHOP REPORT:

## Trucks and Heavy-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials

February 2013

## FINAL REPORT

# EXECUTIVE SUMMARY

The Vehicle Technologies Office (VTO) hosted a Lightweight and Propulsion Materials Workshop in March 2011 in Dearborn, Michigan. The Materials area of the Vehicle Technologies Office focuses on developing lightweight materials for structures and propulsion materials for more efficient powertrain systems. This meeting focused on gaining industry's perspective on the out-year material requirements of trucks and heavy duty vehicles (HDVs) as well as current technology gaps that limit adoption of designs utilizing these lighter weight materials. The industry experts who participated in this workshop included original equipment manufacturers (OEMs) tier-one suppliers and materials suppliers to the light truck and HDV value chain. The output from this workshop will serve as the foundation for the VTO Materials Roadmap for trucks and HDVs that also supports the objectives of the U.S. Department of Energy's (DOE's) Twenty-First Century Truck (21CT) Partnership. 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:
  - Designing the next generation of high-efficiency powertrains
  - Minimize efficiency penalties by reducing exhaust emissions
  - Provide aerodynamic solutions with minimal weight penalty
  - Develop lightweighting that improves the fuel economy of light duty trucks and the freight efficiency of HDVs
  - Reduce petroleum dependence by developing propulsion materials that are compatible with advanced fuels
  - Significantly accelerate the adoption of these technologies by expanding the capabilities of modeling and design tools
- 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 trucks and heavy duty vehicle structural and propulsion systems, identifying future performance requirements and the technology gaps that inhibit industry's ability to realize these goals today. This workshop report also identifies technical goals for both truck systems and lightweight and structural materials.

Heavy duty vehicles cover body-on-frame vehicles classified by the Gross Vehicle Weight Ratings (GVWR) system as Class 1 through 8. The body-on-frame architecture is required for these types of vehicles to carry substantial payloads which can be significantly greater than the load carried by a light duty passenger car. This range of vehicles includes the higher volume, Body-on-Frame pickup trucks and vans in Classes 1 through 3, the medium-duty trucks and utility/delivery vehicles in Classes 4 through 6, and the heavy-duty over-the-highway and vocational vehicles in Classes 7 and 8.[1,2,3] Because trucks at the extremes of the classification spectrum (Class 1 & 2 and Class 7 & 8) represent 93% of the fuel used by trucks (see Figure ES1 below), this report will focus primarily on these vehicle classes. However, many of the technology needs and material applications are applicable across the full range of trucks with body-on-frame architectures.

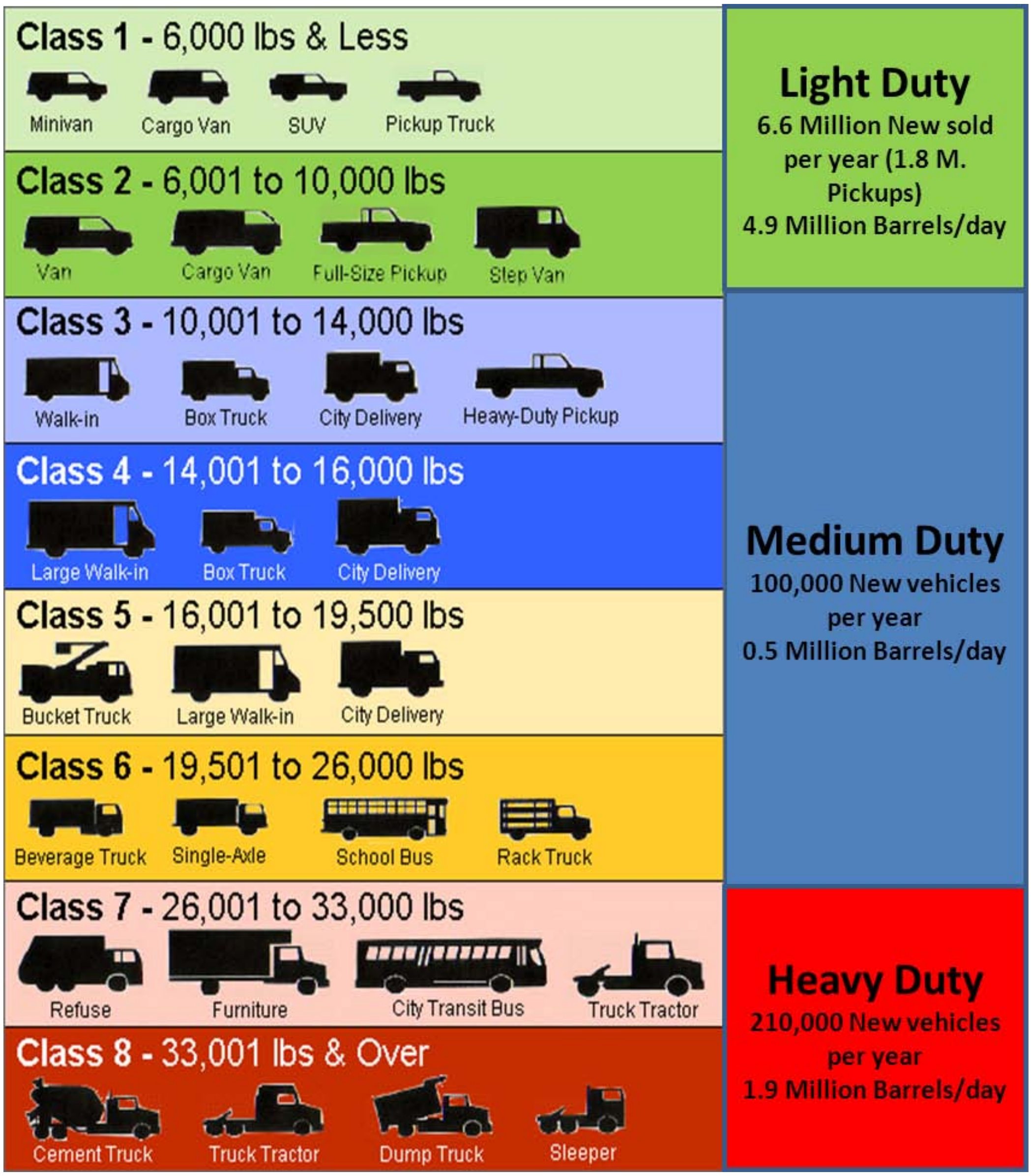


**Figure ES 1: Truck Classification by the U.S. Department of Transportation's GVWR and Vehicle Inventory Use Service (VIUS) Categories**

Material technologies are crosscutting and will enable components and systems to perform at the level required by future light truck and HDVs. The truck manufacturing community needs enabling solutions to realize materials requirements in applications for high-performance engines, structural body and chassis members, and drivetrain components. New and improved materials, processing and manufacturing, and improvements in design are needed to increase the thermal efficiency and fuel economy of both gasoline and diesel engines.

The current effort by the SuperTruck Program, a collaboration between DOE VTO and industry partners in HDVs, takes a holistic approach to increasing freight efficiency through "clean sheet" design of the Class 8 vehicle resulting in improved aerodynamics, engine and powertrain efficiencies, and reduced weight of the tractor and trailer. For example, efficient design coupled with devices that streamline the truck can significantly improve vehicle aerodynamics. These devices can have a significant impact of vehicle energy efficiency, especially at highway speeds. However, while these aerodynamic treatments can improve efficiency, they can also add weight and impact cargo capacity. Innovations in materials and design are needed to maximize flexibility while minimizing or eliminating the need for additional weight.

The powertrain consists of the engine and drivetrain (i.e., transmission, clutch, drive shafts, and drive axles), tire/wheel assemblies, and brakes. In Class 7 and 8 vehicles, the powertrain accounts for about 40% of the total weight. By increasing specific power density, advanced materials could enable engine downsizing and reduced vehicle weight. These materials would require significantly improved mechanical properties while also providing the ability to operate in extreme thermal and tribological conditions. Opportunities for weight reduction in the drivetrain include lighter weight engines, transmissions, braking systems, wheels, and tires.

The body and chassis of modern HDVs are currently made from a wide variety of materials ranging from high-strength steel to glass-reinforced composites. This diversity combined with relatively low production volumes provides an opportunity for additional weight reduction in the body and chassis while also serving as a potential entry point for validating advanced lightweight material designs. In fact, the heavy-duty industry has significant experience lightweighting specific components. However, expanding these techniques to the entire vehicle requires design experience with the available new materials, joining techniques for multi-material approaches, process databases, optimized manufacturing techniques, the availability of advanced materials, established repair technologies, and lower costs materials. These barriers contribute to delays in commercial adoption of designs utilizing lighter weight materials. Significant advances are needed to bridge these gaps while maintaining or improving the performance, durability, utility, and safety of the vehicle.

The industry experts provided stretch goals for weight reductions of different vehicle systems for both the 2025 and 2050 horizons. Table ES.1 contains targets for weight reduction of systems and the total vehicle along with intermediate targets which DOE interpolated between the goals provided at the workshop. This draft report provides an opportunity for industry to review the data documented here and to ensure that it accurately represents the weight reduction potential based on information provided to DOE at the workshop.

### Table ES 1: Targets for Weight Reductions for Systems in Heavy Duty Trucks 2020–2050

| | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Class 8 Tractor Component Group | | | | | |
| Wheels and Tires | 10% | 20% | 20% | 25% | 25% |
| Chassis/Frame | 3% | 10% | 10% | 20% | 20% |
| Drivetrain & Suspension | 3% | 5% | 10% | 15% | 20% |
| Misc. Accessories/Systems | 5% | 15% | 25% | 30% | 35% |
| Truck Body Structure | 15% | 35% | 45% | 55% | 60% |
| Powertrain | 5% | 10% | 15% | 15% | 20% |
| Total Class 8 HDV | 7% | 16% | 22% | 27% | 31% |
| Trailer (53 ft) Component Group | | | | | |
| Wheels and Tires | 10% | 20% | 20% | 25% | 25% |
| Chassis/Frame | 3% | 10% | 10% | 20% | 20% |
| Suspension | 3% | 5% | 10% | 15% | 20% |
| Box/Other | 5% | 10% | 15% | 20% | 25% |
| Total Trailer | 3% | 9% | 13% | 19% | 23% |
| Truck and Trailer Combined Totals | 5.0% | 13.2% | 18.0% | 23.6% | 27.4% |

# ACKNOWLEDGEMENTS

We would like to acknowledge the late Dr. Sidney Diamond whose leadership in materials research resulted in the *2001 Twenty-First Truck Partnership Materials Technical Roadmap* that has been a stellar example of what a roadmap should be.

# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ACE | Advanced combustion engine |
| AHSS | Advanced high-strength steel |
| CF | Carbon Fiber |
| CFCs | Carbon fiber composites |
| CI | Compression ignition |
| CGI | Compacted graphite iron |
| DOE | U.S. Department of Energy |
| DOT | U.S. Department of Transportation |
| EIA | Energy Information Administration |
| GFRP | Glass-fiber reinforced plastic |
| HDV | Heavy-Duty Vehicle |
| MMC | Metal matrix composites |
| NVH | Noise, vibration, and harshness |
| OEM | Original equipment manufacturers |
| R&D | Research and development |
| RPM | Revolutions per minute |
| SI | Spark ignition |
| SMC | Sheet molding compound |
| SUV | Sport utility vehicle |
| VIUS | Vehicle Inventory and Use Survey |
| VTO | Vehicle Technologies Office |

# CONTENTS

## List of Figures

## List of Tables

# 1 INTRODUCTION

The category of vehicles described as trucks includes vehicles with a body-on-frame architecture. This design allows these vehicles to carry or tow heavy loads that may exceed the weight of the truck itself. Unlike passenger cars, which are categorized by the size and weight of the vehicle, trucks are grouped according to their carrying capacity or Gross Vehicle Weight Rating (GVWR), which includes the combined weight of the vehicle and cargo. Trucks are segmented into 8 size classes ranging from 1–8; the Environmental Protection Agency (EPA) segments the Class 2 trucks into Class 2A (6,001–8,500 lbs GVWR) and 2B (8,501–10,000 lbs GVWR). The U.S. Department of Transportation (DOT) Federal Highway Administration's Vehicle Inventory and Use Survey (VIUS) lists Class 1, 2, and 3 trucks and sport utility vehicles (SUVs) as "Light Duty," 4, 5, and 6 trucks as "Medium Duty," and 7–8 trucks as "Heavy Duty."

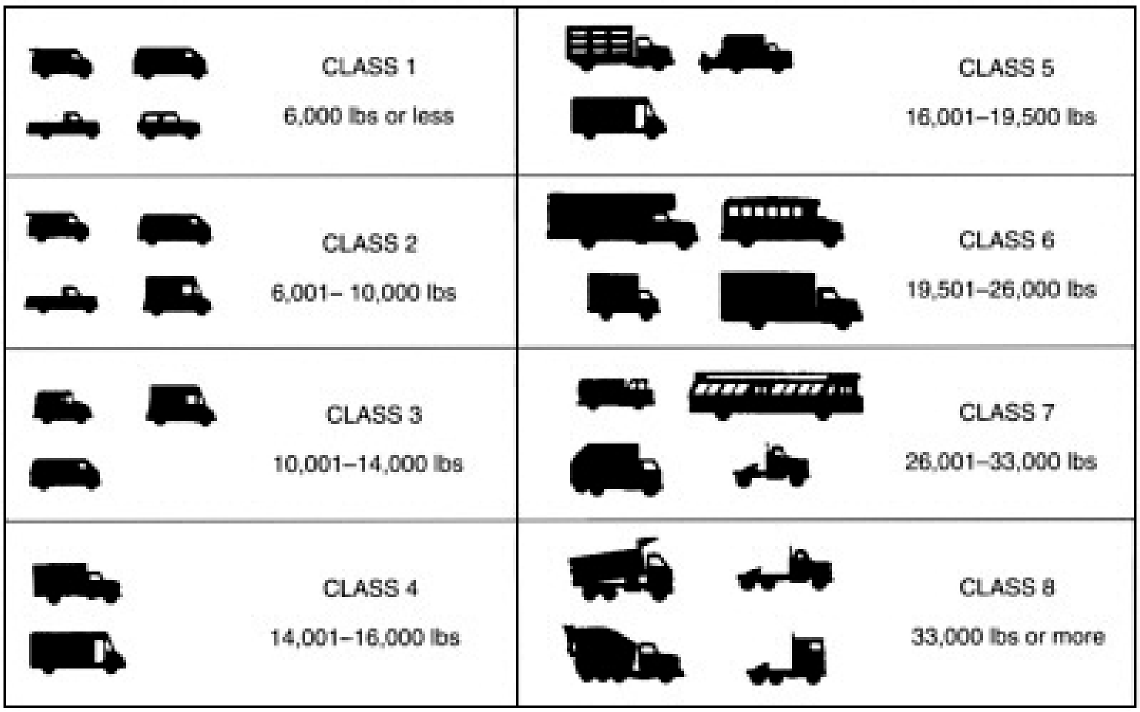


**Figure 1: Truck Classification by Gross Vehicle Weight[4]**

The volumes of trucks sold in the United States vary greatly by class. In 2011, a total of 213,000 heavy duty trucks (Classes 7 and 8), 100,000 medium duty trucks (Classes 4–6), and 6.6 million light duty (Classes 1 and 2) sold, of which 1,783,000 were pickup trucks. Over 300,000 units of each of the most popular light duty trucks were sold (Ford F150 and Chevrolet Silverado) whereas only 52,276 units of the most popular Class 8 trucks were sold (All Freightliner Class 8 Trucks).[5]

The United States imports over half of all petroleum. This petroleum consumption represents a strategic risk and an economic liability. According to the Energy Information Administration, the transportation sector accounts for over two-thirds of all U.S. petroleum consumption. Trucks represent over 50% of the petroleum used in transportation and are the largest growth sector with respect to petroleum consumption. Figure 2 illustrates the utilization of fuel by highway vehicles from 1970 to today.[6] These data show that while the percentage of total consumption of fuel by cars decreased slightly from ~40% in 1970 to ~37%–38% in 2010, the total use of fuel by light duty and heavy duty trucks climbed to over 50% in 2010

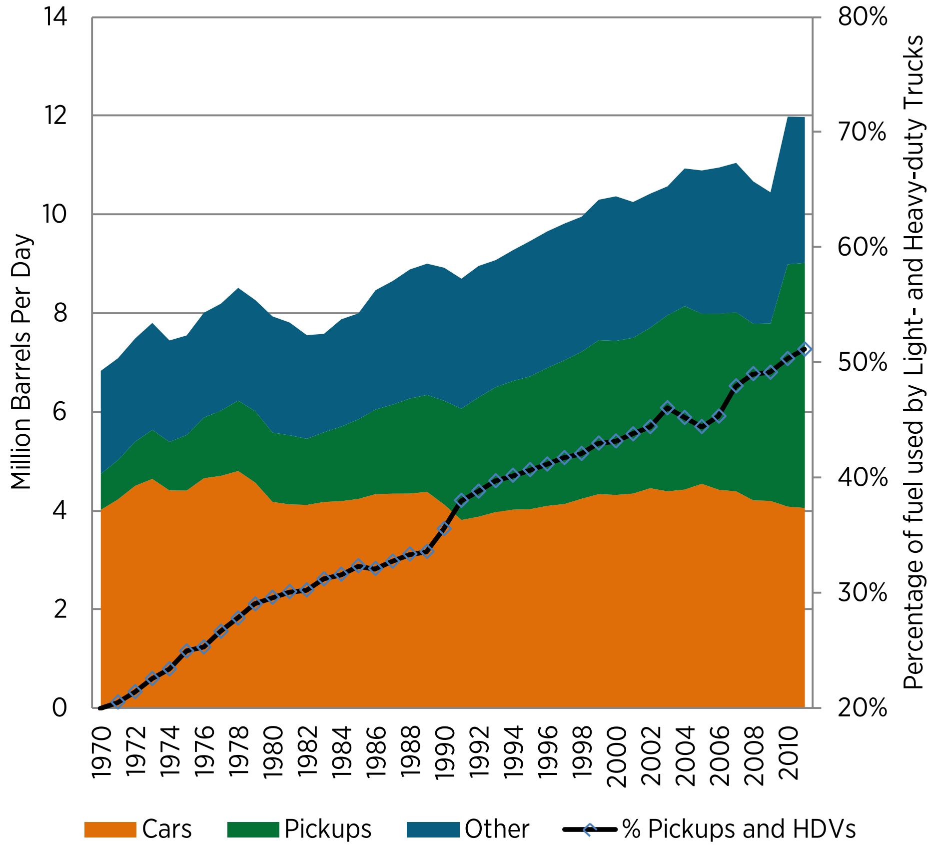


**Figure 2: Utilization of Motor Fuel by Highway Vehicles**

To address the risks associated with petroleum dependence, the U.S. Department of Energy Vehicle Technologies Office (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 Technology Subprogram addresses the materials requirements of existing and future transportation systems as identified by VTO and its partners.

In order to update our current understanding of industry needs, DOE held a materials workshop with industry experts on automotive and heavy-duty vehicle systems representing OEMs, manufacturers, and suppliers in Dearborn Michigan in March 2011. The purpose of the workshop was to:

- Understand industry's needs with respect to out-year requirements and quantitative metrics
- Understand technology gaps in:
  - Lightweighting to improve the fuel economy of light duty trucks and the freight efficiency of HDVs
  - Realizing the next generation high efficiency powertrains
  - Minimizing efficiency penalties of reducing exhaust emissions
  - Reducing petroleum dependence with propulsion materials compatible with advanced fuels
  - Enabling aerodynamic solutions with minimal weight penalty
  - Accelerating adoption of these technologies by expanding capabilities for computational modeling and design tools
- 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- and heavy-duty trucks 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.

The workshop report documents the materials requirements and gaps for each of the three major systems (body and cab, chassis and suspension, and powertrain) that comprise the majority of vehicle weight. Using a combination of data on EPA vehicle classes, composites of teardowns by third parties, and industry interviews, the DOE Materials team established quantitative baselines for each relevant class prior to the workshop so that stretch targets could be established. Greater emphasis is placed on those classes that represent the best opportunity for petroleum displacement, as illustrated in Figure 3.

Passenger cars account for 38% of all petroleum used by on-road transportation. This percentage is the highest amount used by any single class of vehicle. This significant rate of use is followed closely by light trucks (Classes 1 and 2) that use 24% and 17% respectively. The majority of the remaining fuel use (15%) is attributed to Class 8 heavy-duty trucks. Trucks in Classes 3 through 7 account for only 5% of on-road motor fuel use in the United States. This workshop report focuses on opportunities in light-duty trucks (Class 1 and 2) and Class 8 Semi tractor trailer combination heavy-duty vehicles (HDVs).

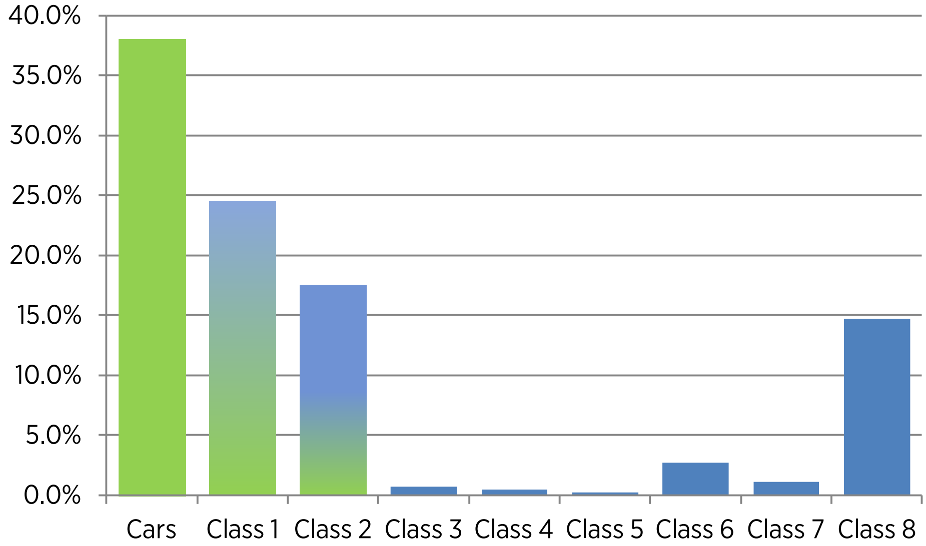


**Figure 3: 2010 On-Road Fuel Consumption by Vehicle Class (Vehicles Covered by this Report Shown in Blue)**[7]

# BASELINES OF TRUCK WEIGHTS AND TRENDS

## 1.1 Weight of Light-Duty Trucks (Classes 1 through 3)

The weight of light-duty trucks has increased steadily from 1980 to 2010, as shown in Figure 4.[8] The average curb weight of all pickup trucks in 2010 was about 4,700 lbs, an increase of over 1,000 pounds since 1980. The average GVWR for these trucks is about 7,000 lbs. Most offerings of pickups in the EPA small pickup category ended in 2006 as the demand for larger trucks continued to dominate the market. The trend for fuel economy of mid-size pickups declined from 22 mpg in 1980 to 17 mpg in 2002 and then rebounded to 20 mpg in 2010.

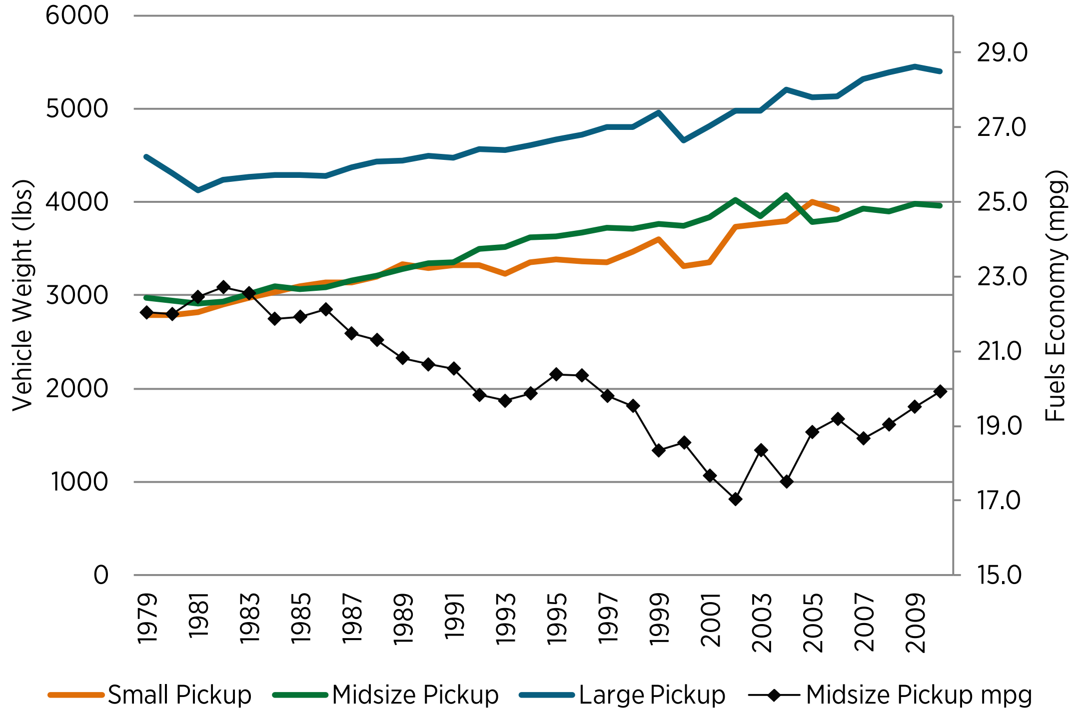


**Figure 4: Weight Trends for Light-Duty Trucks**

Figure 5 shows that the weight distribution is rather even across the three major systems: body and cab, suspension and frame, and powertrain. Therefore, the weight and mechanical requirements of all of these systems must be addressed to achieve maximum improvement in vehicle efficiency.

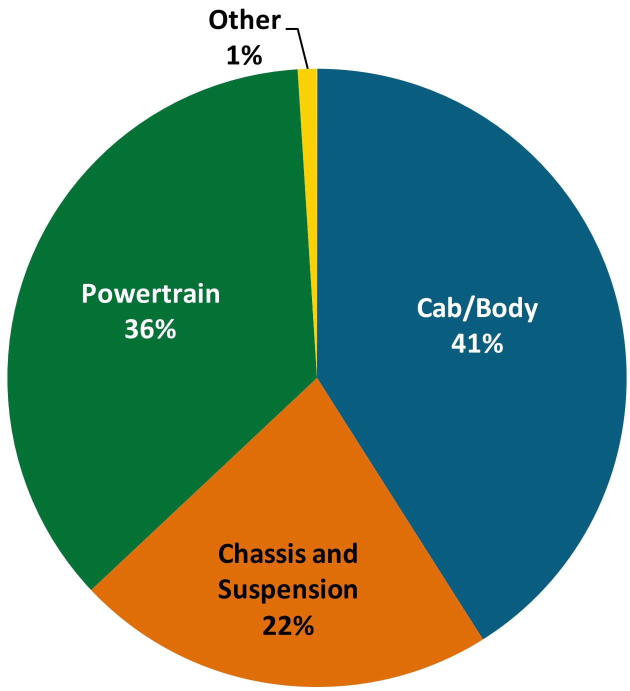


**Figure 5: Weight Distribution of Light Truck Systems (Pickup Trucks)**

## 1.2 Weight of Heavy-Duty Trucks (Classes 7 and 8)

The weight of the typical heavy-duty truck increased from about 16,500 lbs in 1999 to between 17,500 and 19,500 lbs in 2012. Three factors are responsible for much of this weight increase: 1) engine displacement and horsepower increased from about 12 liters and 350 hp in 1999 to 15 liters and 450 hp today, resulting in a weight increase of about 300 lbs.; 2) additional requirements for exhaust after-treatment systems and emissions systems resulting in a weight increase of about 400 lbs.; and the weight of the cooling system increased by almost 200 lbs. Typically, day cabs are about 5,000 lbs lighter than trucks, with sleeper cabs that typically weigh 19,500 lbs. Many trucks now include aerodynamic devices to improve fuel economy; however, a full truck and trailer aerodynamic package can weigh up to 4,000 lbs. In addition, many manufacturers offer Auxiliary Power Units to comply with anti-idling laws; these units can weigh up to 600 lbs. Although these changes may not have a negative impact on fuel economy, the increase in truck weight will negatively impact overall cargo capacity and freight efficiency when calculated on a delivered ton-mile/gallon basis. Figure 6 shows that the majority of Class 8 tractor weight is in the powertrain (48%), followed by the chassis/suspension (31%), and the body/cab (18%).

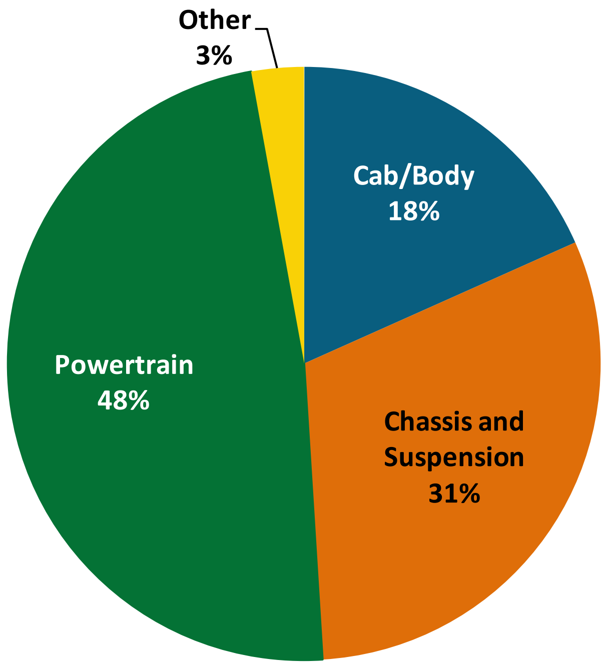


**Figure 6: Weight Distribution of Heavy Duty Vehicle Systems (Class 8 Trucks)**

## 1.3 Class 8 Semi Trailers

The typical 53’ semi-trailer weighs approximately 15,000 lbs and consists of a ladder frame, a suspension, braking system, and a platform or box. The frame and suspension system accounts for about 75% of the trailer weight and will benefit from lightweighting technology improvements developed for heavy-duty trucks. The lifecycle of a semi-trailer is approximately three times longer than that of a heavy-duty tractor with many remaining in service over 30 years. Thus, trailers with advanced technologies will take longer to penetrate the national fleet significantly. Applying lightweight technologies to semi-trailers can have a significant impact on freight efficiency and traffic congestion. Based on an 80,000-lb fully loaded tractor-trailer combination, a 10% weight reduction of the trailer would result in a 3% improvement in total vehicle freight efficiency for load-limited trucks that are measured in delivered ton miles/gallon. Reducing the weight of the trailer would also allow fewer trucks to deliver the same freight tonnage, thus reducing highway traffic.

# 2 VEHICLE SYSTEMS AND MATERIAL REQUIREMENTS

## 2.1 Body and Cab Structures

### 2.1.1 BODY ON FRAME ARCHITECTURE

Truck body and cabs represent 40% of the total weight of a pickup (Classes 2A & B) and 18% of a heavy-duty tractor (Classes 7 and 8). As such, these structures represent a significant opportunity for weight reduction for all trucks. Although pickup trucks rely on body-on-frame architecture, the construction of the body and cab of most pickup trucks is actually very similar to that of automobiles using unibody designs, with each having similar construction of the A-pillar, door enclosures, floor pan, and fenders. These designs are usually based on sheet steel, sheet aluminum, and aluminum castings. Many advances addressing the needs of bodies for automobiles will have an impact on the construction of the body and cab for the pickup truck.

In contrast to the body architecture for pickup trucks, heavy-duty trucks usually employ a construction of a multi-material modular body, consisting of a cab (with or without sleeper), separate hood, fenders, and fairings mounted on a frame. The requirements for carrying payloads greater than the weight of the vehicle dictate this design. These structures use a wide variety of materials in the cab, sleeper, fairings, and hoods. The typical material mix includes steel, aluminum, plastics, sheet molding compound (SMC) and other fiberglass composites. For cabs in heavy-duty trucks, manufacturers use a combination of sheet steel and/or aluminum. In most cases, aerodynamic fairings and hoods are manufactured from aluminum sheet, plastic, or chopped glass fiber composites. The variety of materials and manufacturing techniques that trucks currently employ suggest that, were it not for the existence of technology gaps limiting acceptance, virtually all sheet metals, composites, and lightweight castings would be employed on truck bodies to reduce the weight of the truck and improve efficiency.

### 2.1.2 TARGETS AND KEY METRICS

#### 2.1.2.1 Light-Duty Truck Body

Because light-duty trucks and SUVs employ body designs and manufacturing techniques similar to those used on passenger cars, there are several similarities in material performance requirements for weight reduction. For this reason, the strategies for lightweighting should also be similar to that of the unibody for the passenger car. The near-term targets for weight reduction rely on technologies that are more mature, such as the use of lightweight metals (steels, aluminum, and initial uses of magnesium), whereas the longer term targets require implementation of materials with greater potential for weight reduction. This strategy includes increased use of magnesium and also carbon fiber (CF) composites for future body structures.

### Table 1: Light Truck Body and Cab Goals and Metrics

LIGHT-DUTY TRUCK CAB AND BODY (INCLUDING INTERIOR)
TARGETS (RELATIVE TO 2010 BASELINE)

| | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Weight Reduction of cab and body | 25% | 35% | 45% | 50% | 55% |
| Cost Penalty | 10% | 10% | 10% | 20% | 20% |
| Fuel-Based Cost Tolerance $/lbs saved | $2.25/lbs. Saved* | $2.38/lbs. Saved* | $2.44/lbs. Saved* | $2.63/lbs. Saved* | $2.93/lbs. Saved* |
| Stiffness and noise, vibration, and harshness (NVH) | Match Baseline | Match Baseline | Match Baseline | Match Baseline | Match Baseline |
| Durability | Match Baseline | Match Baseline | Match Baseline | Match Baseline | Match Baseline |
| Production time | Match Baseline | Match Baseline | +10% | +20% | +10% |
| Synergies | Automotive Body (Metal) & Interior | Automotive Body (Metal) & Interior | Automotive Body (Metal) & Interior | Automotive Body (Composites) & Interior | Automotive Body (Composites) & Interior |

*Represents Cost Neutrality for light trucks based on EIA gasoline price projections, 4 year payback and annual VMT of 13,000 miles

#### 2.1.2.2 Heavy-Duty Truck Body and Cab

The heavy duty truck community is an early adopter of new technologies, and many heavy-duty truck cab and body structures already include technologies for lightweighting to some degree. Early use of glass fiber composites serve as the lightweight structures for the hood and fender while also providing design flexibility that contributes to lower aerodynamic forces. The weight targets for body structures in heavy-duty vehicles, provided in Table 2, rely on near-term approaches utilizing lightweight metals (steels, aluminum, and some magnesium) with additional early adoption of glass fiber composites, and the long-term targets transition to using materials with greater weight reduction capability, such as magnesium and CF composites.

### Table 2: Heavy-Duty Vehicle Body and Cab Goals and Metrics

HEAVY-DUTY TRUCK CAB AND BODY (INCLUDING INTERIOR)
TARGETS (RELATIVE TO 2010 BASELINE)

| | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Weight Reduction of body and cab | 15% | 35% | 45% | 55% | 60% |
| Cost Penalty | Match Baseline | <10% | <10% | <20% | <20% |
| Fuel Based Cost Tolerance $/lbs. saved | $3.45/lbs. Saved* | $3.76/lbs. Saved* | $4.00/lbs. Saved* | $4.68/lbs. Saved* | $5.12/lbs. Saved* |
| Stiffness and NVH | Match Baseline | Match Baseline | Match Baseline | Match Baseline | Match Baseline |
| Durability | Match Baseline | Match Baseline | Match Baseline | Match Baseline | Match Baseline |
| Production time | Match Baseline | Match Baseline | +10% | +20% | +10% |
| Synergies | Automotive Body (Metal) & Interior, Marine (Composites) | Automotive Body (Metal) & Interior, Marine (Composites) | Automotive Body (Metal) & Interior, Marine (Composites) | Automotive Body (Composites) & Interior | Automotive Body (Composites) & Interior |

*Represents Cost Neutrality for Class 8 trucks based on EIA diesel fuel price projections, 4 year payback and annual VMT of 100,000 miles

### 2.1.3 TECHNOLOGY GAPS-BODY AND CAB STRUCTURES

The technology gaps hindering the adoption of advanced lightweight truck body and cab structures revolve around several key issues. These gaps include the lack of:

**1) Readily available high-performance lightweight materials**

- Some of the leading candidate materials are produced for low-volume high-cost applications such as aircraft, but there is a lack of domestic, high-volume, low-cost, automotive-grade material production capacity.

**2) Experience with designs utilizing these newer materials**

- Designers are well educated with respect to traditional sheet steel, and there are extensive design tools (CAD, CAE, FEA, and crash models) for these materials. However, there is a lack of education, understanding of properties, and design tools for many candidate advanced materials.

**3) Joining technologies for multiple material junctions**

- There are established techniques for joining most sheet steels and aluminum components currently in use. However, there is a lack of well-validated technologies for joining dissimilar materials, such as aluminum, to advanced high strength steel (AHSS) or combinations of more than two materials.

**4) Established low-cost manufacturing techniques for new materials**

- Low-cost manufacturing techniques require a balance between appropriately fast cycle times and capital investment costs. However, many of the most promising candidate materials for lightweighting lack manufacturing techniques that are competitive with respect to cycle time, component performance, or cost.

**5) Clear strategies for risk mitigation to implement new technologies**

- Vehicle manufacturers have invested decades in existing infrastructure and production technologies based on current materials. The transition to new materials and manufacturing techniques represents a significant new investment with many unknowns. The lack of validated data on new technologies with respect to ramp-up requirements, production volumes, and system acceptance hinders the development of strategies for risk mitigation for OEMs considering new technologies.

**6) Known cost structure for production of advanced truck bodies and cabs**

- The costs associated with manufacturing light- and heavy-duty trucks is well known, with contributions including capital depreciation, raw materials cost, labor cost, plant utility costs, advertising, and profit. There is a lack of validated cost or market price data for many aspects of prime candidate lightweight materials.

## 2.2 Components for Chassis Structures

The chassis and suspension of trucks and heavy-duty vehicles is typically made up of a channel ladder frame with the suspension, fuel system, and other accessories attached along its length. In HDVs, the suspension usually includes a solid front axle and solid rear drive axles. In light-duty trucks, the suspension can use solid axles or it can have a solid rear axle and independent suspension on the front axle. Some SUVs, like the “Hummer” for example, may have fully independent suspension. Chassis structures and associated utility components hung from the frame represents 22% of the total weight of light duty trucks (Classes 1 and 2) and 31% of a heavy-duty tractor (Classes 7 and 8). Because the Chassis structure is such a significant fraction of the weight of the vehicle, it also represents a significant opportunity for weight reduction in trucks and heavy-duty vehicles. Currently, many of the chassis structures used in trucks and heavy-duty vehicles are manufactured from carbon steel because it offers low cost, ease of manufacture and assembly, has established design databases, has well-established repair and maintenance practices, and is compatible with large capital investments in the existing manufacturing infrastructure. Other components, including the axles, suspension, brakes, wheels, and tires, employ a diverse set of materials that also have well-established performance requirements and manufacturing infrastructure. New technologies that could reduce the weight of these components must meet the functional requirements at a competitive cost while being compatible with existing manufacturing infrastructure. Safety is also an important consideration for chassis structures as they serve as the foundational structure for the vehicle and changes in materials or configuration will impact the overall performance of the truck in the event of a collision. A change in material for structurally critical systems such as the chassis must present a low level of risk while meeting all functional requirements.

Over the last few years, the use of lightweight materials (e.g., higher-strength steels, aluminum castings, polymers, and composites) increased somewhat in these chassis applications. Although lightweight materials and structural design approaches have been suggested, cost and manufacturing issues have prevented widespread implementation of these approaches.

## 2.2.1 KEY METRICS AND TARGETS

### 2.2.1.1 Light-Duty Truck and SUV Chassis

Light duty truck and SUV chassis have a number of pathways to reduce chassis weight. Vehicles that do not actually need the ability to carry cargo can reduce their GVWR and/or transition to a unibody architecture. Those vehicles that need to retain maximum GVWR capacity can reduce chassis weight in the near term by utilizing lightweight castings or stampings in place of heavier materials. Over the long term, these vehicles can transition to optimized chassis designs utilizing lightweight space frames, composite frame structures, and/or multi-material approaches.

**Table 3: Light Truck Chassis Metrics and Targets**

| | 2010 (Overall Baseline) | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Key Chassis Metrics and Targets (Relative to 2010 Baseline) | | | | | |
| Overall Weight Reduction | Materials, mostly steel, close to full optimization | 15%--16% lighter weight using advanced materials | 17%–20% weight reduction using advanced materials | 21%–24% lighter weight with advanced materials and some component integration | 25%–27% lighter using new material and integration with other components |
| Fuel-Based Cost Tolerance $/lbs saved | – | $2.38/lbs. Saved* | $2.44/lbs. Saved* | $2.63/lbs. Saved* | $2.93/lbs. Saved* |
| By Chassis Sub-system | | | | | |
| Ladder frames | – | Lighter by 10% | Lighter by 10% | Lighter by 20% | Lighter by 20% |
| Wheels and tires | – | Lighter by 5% | Lighter by 8% | Lighter by 10% | Lighter by 15% |
| Axles | – | Lighter by 5% | Lighter by 10% | Lighter by 10% | Lighter by 10% |
| Brakes | – | Lighter by 5% | Lighter by 10% | Lighter by 10% | Lighter by 15% |
| Springs | – | Lighter by 5% | Lighter by 7% | Lighter by 10% | Lighter by 12% |
| Chassis accessories: fuel system, exhaust, battery systems | – | Lighter by 15% | Lighter by 18% | Lighter by 20% | Lighter by 25% |

*Represents Cost Neutrality for light trucks based on EIA gasoline price projections, 4 year payback and annual VMT of 13,000 miles

### 2.2.1.2 Heavy-Duty Vehicle Chassis

Heavy-duty vehicle chassis will continue to need the maximum GVWR capacity available to meet their functional requirements so pathways to lightweighting these chassis systems will require optimized designs utilizing high-strength alloys, composite frame structures, multi-material approaches, and lightweight space frames. In addition, these vehicles will need to aggressively target weight reduction opportunities in the various sub-systems such as fifth wheels, suspension (replacing springs), and brakes.

### Table 4: Heavy-Duty Vehicle Chassis Metrics and Targets

| | 2010 (Overall Baseline) | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Key Chassis Metrics and Targets (Relative to 2010 Baseline) | | | | | |
| Overall Weight Reduction | Materials mostly steel, close to full optimization | 10% lighter weight using advanced materials | 10% weight reduction using advanced materials | 20% lighter weight with advanced materials and some component integration | 20% lighter using new material and integration with other components |
| Fuel-Based Cost Tolerance $/lbs saved | – | $3.76/lbs. Saved* | $4.00/lbs. Saved* | $4.68/lbs. Saved* | $5.12/lbs. Saved* |
| Ladder frames | – | Lighter by 20% | Lighter by 20% | Lighter by 25% | Lighter by 25% |
| By Chassis Sub-system | | | | | |
| Wheels and tires | – | Lighter by 10% | Lighter by 10% | Lighter by 20% | Lighter by 20% |
| Axles | – | Lighter by 5% | Lighter by 10% | Lighter by 10% | Lighter by 10% |
| Brakes | – | Lighter by 5% | Lighter by 10% | Lighter by 15% | Lighter by 20% |
| Springs | – | Lighter by 10% | Lighter by 10% | Lighter by 10% | Lighter by 10% |
| Chassis accessories: fuel system, exhaust, battery systems | – | Lighter by 15% | Lighter by 25% | Lighter by 30% | Lighter by 35% |

*Represents Cost Neutrality for Class 8 trucks based on EIA diesel fuel price projections, 4 year payback and annual VMT of 100,000 miles

## 2.2.2 TECHNOLOGY GAPS-CHASSIS STRUCTURES AND COMPONENTS

The technology gaps hindering the adoption of advanced lightweight truck chassis structures and components revolve around several key issues. These gaps include the lack of:

1) **Modeling design capabilities**

- There are insufficient computational modeling tools for materials development, manufacturing, processing, and assembly currently in place that are appropriate for body-on-frame chassis systems.
- The collaboration among stakeholders in developing software tools for optimizing truck and HDV chassis up to the component level is inadequate.

2) **New materials development**

- There is a lack of materials development devoted to the unique needs in applications for body-on-frame trucks and HDV chassis. Furthermore, the available infrastructure is insufficient to produce many advanced materials for these chassis systems in a cost-effective manner.

**3) Multi-material joining across various systems**

- The capability for joining the many different materials used in HDV chassis parts is imperfect. Insufficient resources are devoted to advancing existing joining capabilities or to identifying new ones.

**4) Processing**

- The collaboration among stakeholders in developing processes for optimizing vehicle systems up to the component level is inadequate.
- Energy-efficient manufacturing processes for producing body-on-frame type chassis structures utilizing alternative materials are not optimized.

## 2.3 Powertrain: Engines and Transmission

The powertrain of trucks and HDVs represents a diverse portfolio of engine architectures. The engine for the typical light-duty truck is a naturally aspirated, 5 liter, 308 horsepower, V8 running on gasoline. However, the engine displacement of light-duty trucks can range from 2 liter gasoline engines for Class 1s to 7+ liter diesel engines for Class 2B. Smaller gasoline engines may use aluminum blocks and cylinder heads while larger engines may use cast iron, and intermediate displacement engines may use a combination of aluminum and cast iron. The thermal efficiency of these engines can range from a low of about 25% for gasoline engines to 40% for the higher efficiency diesels. The complete powertrain of a light-duty truck represents about 36% of the total vehicle weight, but the wide range of engine displacements and materials used makes this figure highly variable from vehicle to vehicle.

At 42% thermal efficiency, the engine for the heavy-duty Class 8 truck represents one of the most energy-efficient internal combustion engine technologies available. These 3,300 lb, 500 horsepower, turbocharged diesel engines usually have a cast-iron cylinder head and block; steel crankshaft, connecting rods, and camshafts; high performance pistons; and a combination of NOx selective catalyst reduction and diesel particulate filters for exhaust after-treatment. Currently these engines are near their maximum operating capabilities because of limitations in the materials of construction that inhibit performance beyond peak cylinder pressures of 190 bar. When the exhaust system, cooling system, transmission, clutches, and drive axles are included, the powertrain weight represents 48% of a 19,000 lbs Class 8 tractor.

### 2.3.1 ENGINE ADVANCED COMBUSTION

Trucks and heavy-duty vehicles are under increasing pressure to improve fuel economy while maintaining overall vehicle performance. One of the most effective ways to achieve improved fuel economy is by increasing the efficiency of the internal combustion engine. The theoretical limit for efficiency for liquid fueled internal combustion engines is about 60%. These new engine configurations and combustion regimes will 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

200 BAR and 300 BAR) than gasoline or diesel currently require. Therefore, ACE approaches have the potential to improve thermal efficiency by 50% over heavy-duty diesels and 100% over 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. 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 light-duty trucks complicates powertrain requirements. Many light-duty trucks perform functions similar to passenger cars (carrying people and small amounts of cargo) but, by their very design and GVWR classification, they must be capable of carrying or towing significantly larger loads. From the perspective of a passenger vehicle, the powertrain should be as light a possible while providing the necessary power requirements. But due to implications of their GVWR size classification the powertrain must be able to provide the power necessary for safe operations in the vehicles fully loaded state. Therefore, the powertrain of a light duty truck will need to be heavier and more durable than the typical passenger car engine and technologies may not directly translate between these vehicle classes.

One pathway for lightweighting the powertrain of trucks and heavy-duty vehicles will require 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 for vehicles in the various Classes, such as high-performance lightweight aluminum alloys for Class 1 and 2A gasoline truck engines and high-performance ferrous alloys for Class 8 diesel engines.

In light-duty trucks and heavy-duty vehicles alike, new or improved materials development and cost-effective manufacturing process design for fuel systems, exhaust after treatment, air-handling systems (turbochargers, etc.), valve trains, and structural components such as engine blocks are lacking. Specific requirements and limitations are identified in the following sections.

## 2.3.2 PROPULSION SYSTEM KEY METRICS AND TARGETS

### 2.3.2.1 Light-Duty Truck Propulsion Systems

Powertrains for light duty trucks and SUVs can be expected to cover the full range of combustion strategies available with SI gasoline and CI diesel in the near term and high efficiency ACE having major impacts in the long term. As a result of the wide range of powertrain options expected for these vehicles, there will be a very wide range of material requirements depending on the specific vehicle requirements.

**Table 5: Light Truck Propulsion Metrics and Targets**

| | 2010 (Overall Baseline) | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Key Propulsion Metrics and Targets (Relative to 2010 Baseline) | | | | | |
| Weight Reduction | – | 25% lighter - | 25% lighter - | 28% lighter - | 30% lighter- |
| Power density | • SI-5L 308 HP (61 HP/L)<br>• CI-6.9L 275 HP (40 HP/L) Boosted | • 15% augmented<br>• SI– 3.0L 308 HP (101HP/L) boosted<br>• CI-5.9L 275 HP (47 HP/L) Boosted | • 18% augmented<br>• SI– 2.6L 308 HP (110 HP/L) boosted<br>• CI-5.7L 275 HP (49 HP/L) Boosted | • 24% augmented<br>• SI– 2.0L 308 HP (149 HP/L) boosted<br>• CI-5.2L 275 HP (52 HP/L) Boosted | • 30% augmented<br>• SI– 1.6L 308 HP (192 HP/L) boosted<br>• CI-4.8L 275 HP (57 HP/L) Boosted |
| Thermal Efficiency (Percent) | • 30%-SI<br>• 40%-CI | • 37%-SI<br>• 42%-CI | • 38%-SI<br>• 44%-CI<br>• 40% (LD-ACE) | • 41%-SI<br>• 47%-CI<br>• 45% (LD-ACE) | • 45%-SI<br>• 50+%-CI<br>• 50%(LD-ACE) |
| Vehicles with Waste Heat Recovery | 5% recovery (turbo-machinery) | 20% recovery –Turbo / Thermoelectric (TEs) | 25% recovery - Turbo/TEs/ Rankine Cycle (RC) | 35% recovery - Turbo/TEs/ RC | 50% recovery - Turbo/TEs/ RC |
| Exhaust Temperatures (Exhaust Valve to Turbo Inlet) | • 870°C SI<br>• 700°C CI | • 950°C SI<br>• 800°C CI | • 970°C SI<br>• 830°C CI | • 985°C SI<br>• 870°C CI | • 1,000°C SI<br>• 900°C CI |
| Cylinder Peak Pressures | • 50 bar SI<br>• 150 bar CI | • 75 bar SI<br>• 190 bar CI | • 80 bar SI<br>• 195bar CI/ACE | • 90 bar SI<br>• 200 bar CI/ACE | • 103 bar SI<br>• 206+ bar CI/ACE |

### 2.3.2.2 Heavy-Duty Propulsion Systems

Heavy-duty power trains will continue to serve as pathfinders for high-efficiency technologies. As such, these engines will demand materials with the most cost-effective performance available. It is expected that these engines will continue to use CI diesel or a variant of it, in order to approach the maximum theoretical thermal efficiency. To reach these goals, these engines will need to minimize friction, energy loss to rotating mass, and lost heat to cooling and exhaust systems while maximizing air flow, peak cylinder pressures, and recovery of thermal energy from the cooling and exhaust systems. Each of these objectives will require advancements in materials beyond the current state-of-the-art.

**Table 6: Heavy-Duty Vehicle Propulsion Metrics and Targets**

| | 2010 (Overall Baseline) | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Key Propulsion Metrics and Targets (Relative to 2010 Baseline) | | | | | |
| Weight Reduction | – | 15% lighter | 15% lighter | 18% lighter | 20% lighter |
| Power density Fossil Fuel | 15L 475HP (32 HP/L) | 27% augmented –11L 475HP (43 HP/L) | 30% augmented – 10.5L 475HP (45HP/L) | 33% augmented – 10L 475HP (48 HP/L) | 40% augmented – 9L 475HP (53 HP/L) |
| Thermal Efficiency (Percent) | 42% | 50% | 50% | 55% | 60% |
| Exhaust Temperatures (Exhaust Valve to Turbo Inlet) | 700°C | 800°C | 850°C | 875°C | 900°C |
| Cylinder Peak Pressures | 190 bar | 250 bar | 250 bar | 275 bar | 300 bar |

### 2.3.3 TECHNOLOGY GAPS-POWERTRAIN

The technology gaps hindering the adoption of advanced propulsion system components revolve around several key issues. These gaps include the lack of:

**1) Modeling design capabilities**

- There are insufficient computational modeling tools for materials development, manufacturing, processing, and assembly currently in place that focus on advanced powertrain materials.
- The collaboration among stakeholders in developing software tools for optimizing truck and heavy-duty vehicle powertrain components may be inadequate.

**2) New materials development**

- There is a lack of materials development devoted to the unique needs of cast alloys for either lightweight light-duty truck engines or high-performance heavy-duty engines. Furthermore, there is a growing deficiency in domestic casting capabilities for high-performance materials.

  a. Alloys that can withstand the thermal and mechanical demands of future propulsion systems are needed. There is an inadequate ability to produce cost-effective thin walled castings (thickness ≤2mm ) for engine blocks, heads, and exhaust manifolds (employing materials that have the ability to withstand pressures [ ≥ 300 bar for heavy-duty truck engines and ≥ 200 bar for light-duty truck engines]).
  b. Highly durable low-cost coatings for engine rotating components used in thermal, corrosion, or wear applications are limited.

**3) High-performance joining, fastening, and sealing technologies**

- There is currently very little effort devoted to low-cost, high-performance joining, fasteners, and sealing technologies capable of meeting requirements for very high efficiency engines.

**4) Processing**

- Energy-efficient manufacturing processes have not been established for use in the production and finishing of high-performance light and heavy duty powertrain components utilizing alternative materials.
- The collaboration among stakeholders in developing processes for optimizing vehicle systems up to the component level is inadequate.

This page is intentionally left blank

# 3 THE IMPACT OF MATERIALS ON 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 powertrains. These pathways are not exclusive but can build upon each other leading to lighter vehicles with higher efficiency powertrains. Lightweighting can impact the energy efficiency of vehicles regardless of the powertrain configuration. In conventional internal combustion engine light-duty applications, a 10% weight reduction can result in a 6%–8% improvement in fuel economy. In light-duty electric-powered vehicles, weight reduction can also result in increased vehicle range without increasing the battery size. For load-limited, heavy-duty vehicles, lightweighting can result in increased freight capacity and improvement in delivered ton-miles per gallon. Vehicle lightweighting can thereby reduce the number of trucks required to ship a given tonnage. In volume-limited shipping, weight reduction impacts on heavy-duty vehicles are similar to those for light-duty vehicles.

**Table 7: 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 |

When advanced materials are applied to the engine, there is significant opportunity for energy efficiency improvements. The efficiency of today's light-duty gasoline engines is about 30% and heavy-duty diesel engine efficiency is about 42%; whereas maximum theoretical efficiency is about 62%. Achieving theoretical maximum engine efficiency would represent a 2X improvement in light-duty vehicles and a 50% improvement in heavy-duty vehicles. Unfortunately, the properties of conventional powertrain materials currently limit the combustion temperature and pressure, restricting further improvement in efficiency.

In order for significant improvements in engine efficiencies to the theoretical maximum of 60%, future engines will need to use the most efficient combustion regime available and will need to perform reliably at peak cylinder pressures up to 300 BAR. These new engine configurations and combustion regimes will blur the distinctions between gasoline and diesel engines, creating a continuum of operating characteristics and material requirements. Figure 7 below illustrates how the current materials reach their performance limits at levels far below the desired performance goals of 240 (50% thermal efficiency) and 300 BAR (55+% thermal efficiency) peak cylinder pressures. As illustrated in figure 7, the performance of Mg and Al alloys as well as metal matrix composites falls short of the higher peak cylinder pressures of interest. 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.

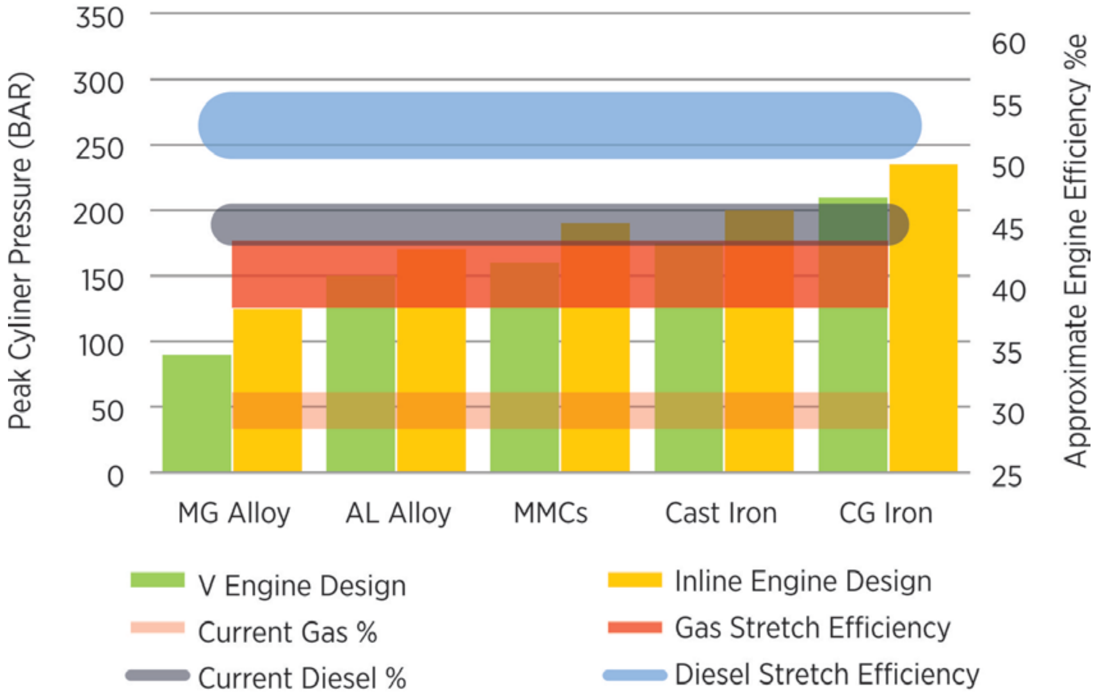


**Figure 7: Materials and Peak Cylinder Pressure Capabilities (Current Material Design Limits)**

## 3.1 Material-Specific Technology Gaps that Prohibit the Realization of Efficiency Improvements Today

During the second day of the workshop, participants worked together in a series of material-specific breakout sessions designed to identify technology gaps, metrics, and targets for material systems and identify performance requirements that would enable improved vehicle efficiency. The industry experts came to consensus on the highest priority technology gaps under each category of material. These gaps are discussed below.

## 3.2 Carbon Fiber Material and Carbon Fiber Composites

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

### 3.2.1 KEY METRICS AND TARGETS-CARBON FIBER AND CARBON FIBER COMPOSITES

Industry experts indicated the following targets for future performance of CFCs. The general consensus is that CF and CFCs need both low-cost fibers and low-cost manufacturing processes with fast cycle times. In addition, predictive tools for materials development through performance development would enable the product development cycle time by speeding it up and targeting efforts toward accurate solutions. Finally, ease and cost of joining needs to be enabled as does recycling and repair. Following are the goals identified for CF and CFCs:

- 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.

Table 8 illustrates the quantitative metrics to achieve these goals.

### 3.2.2 TECHNOLOGY GAPS-CARBON FIBER

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 use of composites for automotive is in its infancy and several elements of this value chain are evolving. There are a number of technology gaps that have hampered the utilization of CF in composite designs for heavy truck applications. Some of the most critical challenges are identified below in the following areas:

**1) Lack of understanding of structure–property relationships**

- There is a need to better understand the structure–property relationships during the precursor-to-CF conversion process. With greater understanding, a low-cost precursor may be engineered to optimize a strong carbon fiber that converts with low energy needs and provides a high yield.
- 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, for example.
- There is a need to understand and optimize interfacial bonding chemistry (i.e., fiber to matrix) which heavily influences the final properties of composite system. Existing coupling chemistries require optimization with most thermoplastic resins.

## Table 8: Carbon Fiber and Carbon Fiber Composites Metrics and Targets

| | 2020 (Baseline) | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| **Carbon Fiber** | | | | | |
| Cost | $9/lbs | $3/lbs | – | – | $3/lbs |
| Precursors | Polyacrylonitrile precursors | 100% petroleum based | Lignin-based feedstocks | – | 100% recyclable materials |
| | < 2/1 yield | >2/1 yield | – | – | – |
| | Low throughput | High rate conversion | – | – | – |
| | High emissions | Low emissions | – | – | 80% reduced compared to baseline |
| Processing temperatures | – | Stable conversion at temperatures 800-1500°C | – | – | – |
| **Carbon Fiber Composites** | | | | | |
| Utilization | Limited-to-No use in HDV | 5% of vehicle mass | – | – | 15-25% of vehicle mass |
| Cost | $12-15/lb | <$5/lb | < $4/lb | < $3/lb | <$2.5/lb |
| Modeling | Limited | Design with 50% Theoretical CF Limits | Predictive with CAE & FEM | Predictive with CAE & FEM | Design with 75% Theoretical CF Limits |
| Design | – | 50% of theoretical limits | Class "A" Surface | – | Design with 75% theoretical CF limits |
| Raw materials | – | Non-petroleum based materials (precursors, fibers, resins) | – | – | – |
| Manufacturing Cycle Times | > 5 minute | < 3 Minute | < 2 Minute | < 1.5 Minute | <1 Minute |
| Joining | – | Joining technology for CF-CF and CF-metal at cost & time ~steel design | – | – | – |
| Recycling | – | • 100% recycled<br>• 25% renewable precursor<br>• 25% reduced carbon footprint | • 100% recycled<br>• 35% renewable precursor<br>• 45% reduced carbon footprint | • 100% recycled<br>• 40% renewable precursor<br>• 60% reduced carbon footprint | • 100% recycled<br>• 50% renewable precursor<br>• 75% reduced carbon footprint |
| Repair | • 0% detection<br>• 0% repair | • 100% detection<br>• 25% repair | • 100% detection<br>• 35% repair | • 100% detection<br>• 45% repair | • 100% detection<br>• 50% repair |

**2) Lack of design tools and a trained workforce**

- An accurate database on properties of CFC is needed to produce relevant CFC designs.
- There is need for engineers trained in CF and CFC design and manufacturing processes.

**3) Lack of processing and manufacturing knowledge**

- Current efficiencies for converting CF precursors to usable CF needs improvement in order to lower the cost of this promising family of materials.
- There is a need to identify alternative precursors that could enable a more economical CF.

**4) Lack of knowledge of behavior of CFCs under conditions of use**

- There is a need to better understand how CF materials behave under a variety of conditions of service to enable accurate predictions of service life.

### 3.2.3 TECHNOLOGY GAPS-CARBON FIBER COMPOSITES

The previously highlighted fundamental hurdles to availability and use of low-cost CF translate to technology challenges in CFCs. Even with a larger supply of CF, the following are the technology gaps with CFCs:

**1) Lack of ability to joining CFCs to other materials**

- Multi-material joining CFCs with other material systems—other composites and magnesium, steel, aluminum, CF, plastic, or fiberglass components—has not advanced far enough to be used extensively in high volumes.
- Durability of joints—with CFCs and other materials—is not robust enough for service in HDVs. Industry needs reliable and low-cost methods that produce joints that will keep their integrity during the long and demanding lifetime of the heavy truck.

**2) Lack of Modeling tools**

- There is a lack of tools for predictive modeling for designing, processing, and evaluating CFCs and the associated methods for joining between similar or dissimilar materials.
- There is a lack of validated databases on properties of materials that are needed to feed into models. In addition, industry lacks standards for testing CFCs in application for HDV applications.

**3) Lack of optimized compatibility of CF with all matrices of interest for making CFCs**

- There are a limited number of available matrix materials that reveal good compatibility and adhesion to CF. Industry needs tools to maximize the composite properties for a wide range of both thermoplastic and thermoset resins.
- The surface of CF heavily influences bonding to the resin and the final properties of the composite system. Current matrix materials are inadequate to take full advantage of the inherent properties of carbon fiber.
- Carbon fiber must be compatible with a variety of resin matrix systems. Existing surface treatments such as coupling chemistries are not optimized for most thermoplastic resin systems that are used to incorporate CFs.

**4) Lack of low-cost and high-volume manufacturing of CFCs**

- Few fiber/resin systems are inexpensive enough and possess rapid curing or cooling through their glass transition temperature to be able to meet fast production cycle times and volume demands compatible with the needs of HDVs.
- More knowledge on CF manufacturing with high-cycle formability and joining of composites is necessary to produce inexpensive, complex-shape composites.

**5) Inability to easily detect damage in CFC and also be compatible with ease of recycling**

- The industry lacks technology to rapidly detect damage to CFCs after impact—hidden or otherwise. 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 perform the following functions:
  - 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
- Tools for modeling damage require validation with composites reinforced with chopped fiber, noncrimp fabrics, woven fabrics, among others.
- There is a need for more CFC recycling and reuse both in other applications and energy reclamation.

## 3.3 Magnesium

Magnesium is the lightest structural metal available for vehicle applications. Magnesium has a density of 1.74 g/cc and can reduce the weight of vehicle components by up to 60% (relative to baseline steels) as a cast, extruded, or sheet product. The combination of low density, reasonable strength, and application flexibility make magnesium a very attractive material for vehicle applications, but there are significant technology gaps that hinder industry-wide acceptance.

### 3.3.1 KEY METRICS AND TARGETS-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 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—assuming the predominant use of the carbonate production method and including thermal energy used to drive off reaction products.

The metrics for magnesium are presented in Table 9.

**Table 9: Magnesium Metrics and Targets**

| | 2010 (Overall Baseline) | 2025 | 2030 | 2050 |
|---|---|---|---|---|
| Mechanical Properties | • Yield Strength 110–120 MPa<br>• 8% Elongation<br>• Fatigue Strength 85 MPa | • Yield Strength 250 MPa<br>• 15% Elongation<br>• Fatigue Strength 125–150 MPa | – | • Yield Strength 350 MPa (Room T), 300 MPa (200°C)<br>• 25% Elongation<br>• Fatigue Strength 200 MPa (Room T), 150 MPa (200°C) |
| Domestic Primary Production | • Majority Imported<br>• ~25kg $CO_2$/kg primary Mg | >10% Domestic | • >25% Domestic<br>• $CO_2$ emissions comparable to Al | • 100% domestic with exportable product<br>• 2-3kg $CO_2$/kg primary Mg |
| Corrosion Prevention and Joining | Baseline | Eliminate galvanic corrosion (low-cost electrical barriers) | – | Universal -tep pretreatment compatible with Al and Steel, "stainless" Mg alloys |
| Sheet | Baseline | – | Uniform Isotropic properties with Room Temperature Forming | Class "A" Surface |

### 3.3.2 TECHNOLOGY GAPS-MAGNESIUM

The technology gaps hindering the wide-scale adoption of magnesium in truck applications revolve around several key issues:

**1) Lack of a domestic source of low-cost magnesium that utilizes a clean production process**

- Currently there is one domestic primary magnesium production facility. Worldwide, the processes used for primary production are energy intensive and carry environmental penalties. In order to take advantage of the weight reduction potential offered by magnesium, there is a need for low-energy, low-cost primary magnesium production capacity in North America.

**2) Lack of effective corrosion evaluation and mitigation strategies**.

- A fundamental understanding of the impacts of surface structure, trace impurities, anisotropy, and texture on corrosion behavior of magnesium alloys is needed. Models capable of predicting corrosion for magnesium alloys are not currently available.
- The cost and complexity of magnesium isolation technologies (e.g., films, spacers) to avoid galvanic corrosion is a major hindrance to significant market penetration.
- Impurities (e.g., Cu, Fe, Re) can enhance corrosion of magnesium alloys. Alloys that mitigate the effects of impurity-driven corrosion are immature or unavailable.
- 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) Lack of joining technologies with adequate performance and manufacturing compatibility**

- Joining techniques must provide a consistent, durable bond between magnesium and steel, aluminum, CF, plastic, or fiberglass components. Multimaterial joining needs to consistently join dissimilar materials to Mg while avoiding corrosion. At the same time, these joining techniques must be compatible with fast cycle times in the factory environment.

**4) 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.

**5) Cast magnesium products exhibit insufficient ductility and wrought products lack isotropic 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.
- Wrought alloys often exhibit significant structural anisotropy which can complicate design and limit performance. A fundamental and complete understanding of magnesium deformation does not exist.

## 3.4 Aluminum

Aluminum alloys in both cast and wrought forms represent a cost-effective material for reducing the weight of many vehicles and their powertrains. With a density of approximately 1/3 that of steel and cast iron, aluminum has the potential of reducing weight by at least 40% (versus baseline steel) in properly designed structures and components. Barriers to the use of aluminum include high material cost, limited room temperature formability, limited strength at elevated operating temperatures, and joining and corrosion issues.

Following are the goals established for aluminum:

- By 2025, produce cast and wrought aluminum with improved mechanical properties, requiring fewer mechanical fasteners for assembly, reduced cost and design time, and increased recyclability.
- By 2050, produce aluminum components with vastly improved mechanical properties, requiring no fasteners for assembly, using modeling and simulation to avoid prototyping, with 100% of high-performance alloys recycled.

### 3.4.1 KEY METRICS AND TARGETS-ALUMINUM

Table 10 provides performance requirements associated with the goals.

**Table 10: Aluminum Metrics and Targets**

| | 2010 (Baseline) | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Mechanical and materials properties | • 180 MPa yield/5% el (cast),<br>• 275 MPa yield/12% el (wrought) | 40% improvement | 100% improvement | 150% improvement | 200% improvement |
| Aluminum joining with dissimilar materials | • Slow, expensive<br>• Can't be modeled | • 50% fewer fasteners<br>• Easier to model | 70% less fasteners | 80% less fasteners | Near zero use of fasteners |
| Parts Cost | Not cost competitive | 25% lower | 30% lower | 35% lower | 40% lower |
| Design Techniques | • Incomplete understanding of system properties<br>• Significant prototyping | 50% reduction in design time | - | - | Zero prototyping |
| Recyclability | •90% overall<br>•0% high performance (HP) alloys | •90% overall<br>•50% of HP alloys reused for HP alloys | •90% overall<br>•70% of HP alloys reused for HP alloys | •90% overall<br>•90% of HP alloys reused for HP alloys | •90% overall<br>•100% of HP alloys reused for HP alloys |

### 3.4.2 TECHNOLOGY GAPS-ALUMINUM

Aluminum requires further development in a number of areas in order for it to be considered for applications in HDVs beyond the current use. The consensus view on the technology gaps that inhibit broader use of Al today includes the following:

**1) Lack of techniques for multi-material joining**

- Wider adoption of aluminum structures requires techniques for optimized, high-integrity joining of aluminum parts to various metals, plastics, and composites. Additionally, adhesives and other methods of attachment used with aluminum require optimization to lower cost and increase processing speeds.
- The capability to accurately model the performance and durability of aluminum-multi-material joints and assemblies is inadequate. As a result, these joints are typically overdesigned to ensure integrity for long-term performance.
- Many multi-material joining processes are incompatible with the heavy vehicle factory environment.

**2) Lack of modeling, simulation, and design tools**

- Tools for design and computer-aided-engineering to optimize manufacturing and performance of aluminum parts are incomplete.
- Models of failure analysis and fracture mechanics for aluminum parts are lacking. Comprehensive databases and tools for prediction of properties of castings and wrought materials need improvement to better approximate mechanical properties and in-service performance.

**3) High-performance castings lack reliable and repeatable performance**

- The castability of high-performance alloys is poor, which often results in poor integrity or low consistency between castings.
- Ductility and high-temperature fatigue of high-performance Al castings is often insufficient for heavy-duty truck applications.

**4) Limited alloys and material properties specifically suited for vehicle applications**

- A wide range of Al alloys exists; however, there is a general lack of alloy/process combinations developed specifically for vehicle applications with specific requirements on temperature range, strength, fatigue performance, and cost.

## 3.5 Glass-Fiber Reinforced Polymer Composites

Glass-fiber reinforced polymer (GFRP) composites are currently used almost extensively in semi-structural applications for HDV cab and body structures. Although the majority of glass composites are used in semi-structural applications (e.g., truck hoods, cab fairings, and chassis fairings), a number of truck designs have used GFRP composites for major portions of the cab structure and closures (e.g., doors, hatches). 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 near-term applications.

### 3.5.1 KEY METRICS AND TARGETS- GLASS-FIBER REINFORCED POLYMER COMPOSITES

The following table lists metrics for out-year targets for GFRP composites. Targets include tools for better modeling and prediction of properties, improved mechanical properties, recyclability, multimaterial joining, and cost, including fast cycle time in manufacturing.

- 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.

## 3.5.2 TECHNOLOGY GAPS – GLASS-FIBER REINFORCED POLYMER COMPOSITES

In order to utilize more glass fiber (GF) composites in HDV component and structures, the following hurdles need to be addressed:

- **Lack of material performance**
    - GF composites have limited options to improve fiber/resin bonding to improve mechanical properties and durability. Demonstration of improved properties and performance with traditional or hybrid systems (GF and CF or natural fiber) has been limited.
- **Lack of tools for modeling and simulation**
    - Existing immature software cannot reliably model GF composite processing and then predict orientation of the fibers and resulting composite properties.
- **The material property database & design knowledge for GF composites is incomplete**
    - The material property database & 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.
- **Lack of low-cost processing**
    - Process cycle times are lengthy for higher volume GF composite applications reducing production volumes.

## Table 11: Glass-Fiber Reinforced Plastic Metrics and Targets

| | 2020 (Baseline) | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Material Property Database & Modeling | Baseline not comprehensive for all material properties | A comprehensive database | – | – | Predictive modeling & correlation with field data |
| Stiffness | Variables ranges are large | 30% improvement in material stiffness | – | – | Same stiffness as Aluminum |
| Appearance | • Class "A" appearance possible<br>• Low fill levels, stiffness ~steel | Parity with steel (painted) | – | – | Same as 2025 |
| Recycling, Chemical & Energy Recovery | • Typically no recycling<br>• Potential exists | Achieve 50% recyclability & recovery | – | – | Eliminate related landfill load composites/plastics |
| Fiber Characteristics | Processes tend to break fibers | Improved predictive fiber characteristics | – | – | • Aluminum-like thermoplastic<br>• Low CLTE & isentropic properties |
| Joining of Composites | Many methods, few standards | • More methods /available data<br>• Standards for multi-material | – | – | Continued technology - methods & standards- advancement |
| System Cost Parity | 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 | 40% part weight reduction relative to composite components (extrapolated) | 45% part weight reduction relative to composite components (extrapolated) | 50% part weight reduction relative to composite components |
| Regulatory Standards - VOC emissions | Baseline today's standards | 50% from baseline | 70% from baseline (extrapolated) | 80% from baseline (extrapolated) | 95% from baseline |
| Process | Shrink/Warp due to fiber orientation | Eliminate warp | – | – | Continued advancement |
| Cycle Times | | | | | |
| Liquid Thermoset Resin/Continuous Fiber | 10 min | <5 min | <4 mins (extrapolated) | < 3mins (extrapolated) | <2min |
| SMC Thermosets | 1.5 min | <1 min | 45 sec (extrapolated) | 30sec (extrapolated) | 30 sec |
| Thermoplastics | ~1 min | 30 sec | 25 sec (extrapolated) | 20sec (extrapolated) | <10 sec |

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

Advanced materials exhibit unique properties that cannot be achieved by more common materials such as aluminum, steels, magnesium, and composites. The advanced materials of interest for HDVs and their powertrains can retain strength and other properties at significantly higher operating temperatures, and, in the case of titanium, exhibit properties comparable with high-strength steels, but with a lower material density. At the extreme temperatures achieved during combustion in highly efficient diesel engines, only metals, particularly nickel-based alloys, can provide the required strength, creep resistance, and oxidation resistance. Some barriers to using advanced materials in HDVs and powertrains are high material costs and difficult processing, forming, and machining.

Following are the goals 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.

### 3.6.1 KEY METRICS AND TARGETS-ADVANCED MATERIALS

The following table shows the metrics required for the out year targets. The requirements focus on lowering the cost of raw materials,

**Table 12: Advanced Materials Metrics and Targets**

| | 2010 (Baseline) | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Titanium | • Cost > $6.00/lb<br>• 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<br>• Operating temperature = 950°C | • Reduce cost by 50%<br>• Operating temperature ≥ 1,050°C | – | – | Decrease cost by additional 50% |
| Metal Matrix Composites | • Cost - $3.00/lb<br>• Limited production base | • Reduce cost by 25%<br>• Develop manufacturing capability | – | – | Decrease cost by additional 25% |

### 3.6.2 TECHNOLOGY GAPS -ADVANCED MATERIALS

Following are the technology gaps hindering the widespread availability of advanced materials for HDV use:

**1) Lack of available techniques, infrastructure, and expertise in high-volume manufacturing**

- There is a need to advance near-net-shape manufacturing capabilities for titanium to a level comparable to that of material systems like aluminum and steels.
- High-volume production of metal-matrix composites (MMCs) is inadequate.
- Processing, forming, finishing capabilities to produce intricate shape MMC components are extremely limited.

**2) Insufficient high-temperature performance for highly efficient diesel combustion**

- Existing advanced materials, superalloys, and MMCs cannot survive at the temperature extremes found during efficient diesel combustion.
- Existing MMCs' possess limited low and room temperature ductility.

**3) Lack of raw materials**

- There is an insufficient supply of low-cost titanium base powders, limiting the production of bulk titanium.

**4) Lack of databases on properties**

- The design and processing database for advanced materials is very immature.

## 3.7 High-Strength Steels and Advanced High-Strength Steels (Structural)

Various classes of steels are used in cab and body structures, for chassis structures, and for other components. The combination of low material cost, high strength and stiffness (modulus), and an extensive modeling and design database make various grades of high-strength steels highly competitive materials for HDV applications. Challenges to wider adoptions of advanced steels in structural applications include the higher cost and reduced formability of the AHSS alloys and the continuing development and optimization of competitive materials such as aluminum and fiber-reinforced composites.

Following are the goals established for structural steels:

- By 2025, develop new steels with enhanced mechanical properties that are easily manufactured, have low energy intensity, and are 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, and multi-scale models populated with appropriate data.
- By 2050, develop new steels with *enhanced* mechanical properties that are easily manufactured, have low energy intensity and are 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 produce seamless 3-D constructions of mixed materials with high strength and no joints.

### 3.7.1 KEY METRICS AND TARGETS-ADVANCED HIGH-STRENGTH STEELS (AHSS) AND HIGH-STRENGTH STEELS (HSS)

The following table lists key requirements to meet out-year goals. These include enhanced mechanical performance, process-ability, improved techniques for multimaterial joining, and improved tools for modeling and simulation.

**Table 13: Advanced High Strength Steels (AHSS) and High Strength Steels (HSS) Metrics and Targets**

| | 2010 (Baseline) | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Tensile strength and elongation | • 590 MPa<br>• 20% elongation | • 1,500-2,000 MPa UTS<br>• 20% elongation | • 1,750-2,250 MPa UTS<br>• 20% elongation | • 2,250-2,750 MPa UTS<br>• 20% elongation | • 2,500-3,000 MPa UTS<br>• 20% elongation |
| Density | 7.87 g/cm$^3$ | 5% density reduction | 7% density reduction | 9% density reduction | 10% density reduction |
| Modulus | 211 GPa | 10% increase | 13% increase | 17% increase | 20% increase |
| Gauge and width | 0.65 mm thickness, 1,500 mm width | • Reduce gauge to 0.5mm<br>• Increase width to 1,800mm | – | – | • Reduce gauge to 0.4mm<br>• Increase width to 1,800mm |
| Reliable joining processes for mixed materials | – | 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 80% confidence in correlation | Models achieve 85% confidence in correlation | Models achieve 90% confidence in correlation |

### 3.7.2 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 truck applications. The most critical are identified below:

**1) Lack of structure-property relationships**

- The next-generation -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.

- There is an incomplete understanding on the impact precipitates, such as nanoparticles and whiskers, have on macroscopic properties of the next-generation steels.

**2) Limitations in post-processing**

- Rolling and forming methods for AHSS require development to be fully exploited for a variety of applications for HDVs.
- Joining and corrosion technologies need advancement in order to reliably use these steels in service.
- Processing routes needed to produce the ultra-thin (0.4 mm) wide (1800mm) sheet from ultra-high strength steels are currently not available. Post-processing (piercing, forming, cutting, machining, lubrication, etc.) manufacturing steps necessary to handle very thin steels with strengths ~ 2,000 MPa do not exist.

**3) Lack of tools in modeling and simulation**

- Models capable of predicting AHSS and HSS microstructures as a function of composition and processing are inadequate. Current modeling and simulation tools are too immature to predict:
  - Properties utilizing physics-based models
  - Microstructures and resulting morphology & properties as well links to failure mode
  - Manufacturability & performance

## 3.8 Steel and Cast Iron (Propulsion)

Steel and cast iron are widely used in the design and manufacture of heavy-duty diesel engines and associated drivetrain components. Offering a combination of low material cost, high strength, and good processing and manufacturing characteristics, steel and cast iron remain the dominant materials 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.

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

- 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.

### 3.8.1 KEY METRICS AND TARGETS-STEEL AND CAST IRON

The following table lists specific metrics for out-year goals. These metrics include improvements in mechanical properties, especially at higher temperature, and low-cost effective processability.

### Table 14: Steel and Cast Iron Metrics and Targets

| | 2010 (Baseline) | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Specific Strength | Baseline Adv. Steel Alloys | 10% Increase | 15% Increase | 17% Increase | 20% Increase |
| Coefficient of Variation of Strength | Baseline Strength Variation | Decrease by 50% | Decrease by 60% | Decrease by 70% | 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 20% | Increase 25% | Increase 30% |
| Contact Fatigue | Baseline 220 ksi | Increase 10% | Increase 15% | Increase 17% | Increase 20% |
| Thermal Oxidation Resistance | Baseline | Increase 100°C | Increase 150°C | Increase 175°C | Increase 200°C |

## 3.8.2 TECHNOLOGY GAPS – STEEL AND CAST IRON

Even though there are significant resources focused on the realization of next-generation steels, the emphasis is generally on sheet. There should be some focus on near-term needs of steel and cast iron. Following are some of the critical technology gaps:

**1) Lack of technologies for processing**

- Processes for cost-effective forging of steels are lacking.
- Variability in iron casting results in heterogeneous material properties (especially in large castings).
- Economically viable machining processes for highly alloyed steel, cast iron, and compacted graphite iron (CGI) are inadequate.

**2) Improvement in properties**

- Large variations in material properties lead to excessive design margins, driving higher weight and cost.
- There are inadequate methods to produce cost-effective higher strength iron and steel materials.

**3) 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.

**4) Economically viable machining processes for highly alloyed steel, cast iron, and CGI 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.

This page is intentionally left blank

# 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 alternative material technologies for the main systems of trucks and HDVs (body, chassis and suspension, body and cab, and powertrain) are common to more than one subsystem. Table 15 illustrates the three highest priority gaps identified during the workshop for each of the systems.

**Table 15: Key Technical Gaps for Systems for Trucks and HDVs**

| System | Three Most Significant Technical Gaps Impeding Widespread Implementation | | |
|---|---|---|---|
| Body and Cab | Fast and reliable processes for joining dissimilar materials are not available | Lack of predictive engineering and modeling tools: Design knowledge and databases are inadequate | Cost/availability of most lightweight materials and current manufacturing processes are not competitive |
| 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 |
| Powertrain | 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 these vehicle 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 and improve engine efficiency. 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 alternative materials with adequate properties was identified as a high-priority gap for body and cab structures, chassis and suspension, and powertrains. Without exception, all of the materials of interest for lightweighting were developed for other applications. The particular properties required for trucks and HDVs 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 every system: body and cab-composite (long cycle times for glass fiber polymer composites and CFC), body and cab-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 powertrains (casting and machining of high-performance materials). 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 and cabs and powertrains each highlighted inadequate databases, design tools and modeling techniques for the new materials as significant barriers to lightweighting and implementation of high-efficiency engine designs.

In order to reach the aggressive goals set for reducing the weight of trucks and HDVs 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 a 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 and cab and chassis and suspension are 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 trucks and HDVs are also common to several materials. Table 16 illustrates the three highest priority gaps identified during the workshop for each of the materials.

### Table 16: Key Technical Gaps for Materials for Trucks and HDVs

| 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 7000 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 | High-cost/ low 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 truck and HDV applications, and 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 scarce availability/high 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 implementing 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.

# APPENDIX 1. LIST OF MEETING PARTICIPANTS

**Saad Abouzahr**
Chrysler LLC

**Bill Altergott**
Triton Systems, Inc.

**Mary Apostolico**
SRA International

**Robb Augustine**
Honda R&D Americas, Inc.

**Eric Boettcher**
Honda R&D Americas, Inc.

**Richard Bogacz**
New West Technologies

**Scott Boyce**
Dow Chemical Company

**Alan Brooks**
Novelis

**Wolfram Buschhaus**
Ford Motor Company

**Steve Calandro**
SRA International

**Blair Carlson**
General Motors

**Bill Charron**
Ford Motor Company

**Bulent Chavdar**
Eaton Corporation

**Yong-Ching Chen**
Cummins, Inc.

**Suzanne M. Cole**
Cole & Associates, Inc.

**Terry Cullum**
Auto/Steel Partnership

**Michael Davenport**
Chrysler LLC

**Bruce Davis**
Magnesium Elektron North America, Inc.

**Xavier Demonet**
Volvo

**Steve Derezinski**
MOxST

**Ajit Desai**
Chrysler LLC

**Jim deVries**
Ford Motor Company

**Paul Dolan**
Engineering Technology Associates, Inc. (ETA)

**Steven Doyle**
ArvinMeritor

**Bill Dykstra**
Temper, Inc.

**Akbar Farahani**
ETA

**John Fehring**
Navistar

**Carmen Franko**
Global Composite Solutions

**Lisa Franks**
U.S. Army TARDEC

**Abi Gaines**
SRA International

**Umesh N. Gandhi**
Toyota Motor Engineering & Manufacturing North America, Inc.

**Bill Gaw**
U.S. Army TARDEC

**Richard Gerth**
U.S. Army TARDEC

**Jerry L. Gibbs**
U.S. Department of Energy

**Ron Graves**
Oak Ridge National Laboratory

**Kipp Grumm, P.E**
BASF Corporation

**Xiaomin Gu**
Michelman, Inc.

**Eric Haiss**
Toho Tenax America, Inc.

**Nabil Hakim**
NabMag Technologies

**Vince Hammond**
Army Research Laboratory

**Hugh Harris**
United States - Environmental Protection Agency

**Darrell Herling**
Pacific Northwest National Laboratory

**Peter Heywood**
New West Technologies

**Clifton Higdon**
Eaton Corporation

**Jon Hurwitch**
SRA International

**George E. Husman**
Zoltek Corporation

**Jennifer Jackman**
Natural Resources Canada - Canada CANMET

**Stephen James**
Faurecia

**Corey Jarocki**
Ford Motor Company

**D. Ray Johnson**
Oak Ridge National Laboratory

**Stephen Jones**
Faurecia

**Will Joost**
U.S. Department of Energy

**Dean Kanelos**
Nucor

**Wojciech Kasprzak**
Natural Resources Canada - Canada CANMET

**Lazlo Kecskes**
Army Research Laboratory

**James Kolb**
American Chemistry Council

**Aleksy Konieczny**
US Steel

**Mark Kozdras**
Natural Resources Canada - Canada CANMET

**Gregory Koztrzewsky**
Cummins, Inc.

**Mark Kralevich**
Honda R&D Americas

**Ron P. Krupitzer**
American Iron and Steel Institute

**Kenyon Larsen**
SRA International

**Nona Larson**
PACCAR Tech Center

**Michael Laughlin**
New West Technologies

**Jeremy Lee**
Faurecia

**Renato Liardo**
Volvo

**Stephen Logan**
Chrysler LLC

**Dana Lowell**
Faurecia

**Mo Mahmood**
Global Composite Solutions

**P.K. Mallick**
University of Michigan-Dearborn

**Peter McCallum**
New West Technologies

**Daniel McKay**
New West Technologies

**Paul McKune**
ThyssenKrupp Steel USA

**Jake Mello**
New West Technologies

**Alexander Monroe**
North American Die Casting Association (NADCA)

**Marianne Morgan**
BASF Corporation

**George Muntean**
Pacific Northwest National Laboratory

**Mark Negley**
Boeing Commercial

**Matthew Oesterling**
New West Technologies

**Michael Olechiw**
U.S. Environmental Protection Agency

**Richard Osborne**
General Motors

**Edwin Owens**
U.S. Department of Energy

**Russell Owens**
New West Technologies

**Bryan Pai**
SRA International

**Kalathur Pattabiraman**
Honeywell

**Randall Patterson**
TPI Composites

**Dean Paxton**
Pacific Northwest National Laboratory

**Doug Peterson**
Chrysler LLC

**Robert Powell**
General Motors

**Thomas E. Prucha**
American Foundry Society (AFS)

**James Quinn**
General Motors

**Anand Raghunathan**
Energetics Incorporated

**Nippani R. Rao**
Global Composite Solutions

**Anand V. Rau**
Toray Carbon Fibers America, Inc.

**Jackie Rehkopf**
PLASAN Carbon Composites

**D.A. Richman**
Kaiser Aluminum Fabricated Products

**Richard Ridgway**
Navistar

**Philip Rizzi**
SRA International

**Jeffrey Robbins**
Magna

**Jules Routbort**
Argonne National Laboratory

**Bryan Roy**
New West Technologies

**Thomas Russell**
Allied Composite Technologies LLC

**Anil Sachdev**
General Motors

**Kumar Sadayappan**
Natural Resources Canada - Canada CANMET

**Rich Scheer**
Scheer Ventures

**Rick Schroden**
Dow Chemical Company

**Carol Schutte**
U.S. Department of Energy

**Khaled Shahwan**
Chrysler LLC

**Bob Shureb**
Detroit Diesel

**Philip Sklad**
Oak Ridge National Laboratory

**Tim Skszek**
Cosma Engineering

**Mark T. Smith**
Pacific Northwest National Laboratory

**Tory Snetsinger**
Navistar

**Raj Sohmshetty**
Ford Motor Company

**Thomas Steinhäusler**
AOC Composites

**Jim Stike**
Materials Innovation Technologies, LLC

**Lee-Ann Tracy**
SRA International

**Demetrios Tzelepis**
U.S. Army TARDEC

**Kathi Vaughan**
Oak Ridge National Laboratory

**Kevin Veloso**
TPI Composites

**Justin Verba**
Navistar

**David Wagner**
Ford Motor Company

**Eric Walker**
Honda R&D Americas, Inc.

**Paul Wang**
Mississippi State University

**C. David Warren**
Oak Ridge National Laboratory

**Michael J. Warwick**
Eaton Corporation

**Kenneth Weaver**
New West Technologies

**Bruce Wilkinson**
ThyssenKrupp Steel USA

**Benda Yan**
ArcelorMittal

**Justin Yee**
Daimler Trucks North America LLC

**Tom Yonushonis**
Cummins, Inc

**Matt Zaluzec**
Ford Motor Company

**Dick Ziegler**
SRA International

**Jake Zindel**
Ford Motor Company

**Conrad Zumhagen**
PlastiComp LLC

# APPENDIX 2. REFERENCES

[1] Classes of Trucks, their Gross Vehicle Weight Ratings, annual Manufacturing volume, daily fuel consumption, and % of total US fuel consumption. Sources: DOE fact of the week Fact #707: December 26, 2011

[2] Illustration of truck classes from http://www1.eere.energy.gov/vehiclesandfuels/facts/2011_fotw707.html data from *Transportation Energy Book*, Volume 30, Tables 1.12 and 2.7. and Energy Information Administration, *Annual Energy Outlook 2011*, April 2011; and *2002 Economic Census, Vehicle Inventory and Use Survey*, U.S. Department of Commerce. 2011.

[3] Truck sales data from http://fleetowner.com/equipment/news/truck-sales-surged-0119 (downloaded 6/15/2012).

[4] In FIGURE 1-1 Truck classification by gross vehicle weight (GVW), note that Class 2 is composed of Class 2A (6,001–8,500 lbs) and Class 2B (8,501–10,000 lbs) and tractor trailers in Class 7 or Class 8 can be single trailers, double trailers, and, in some cases, triple trailers. Source: U.S. Department of Commerce, 1995; Davis, 1999; Eberhardt, 2000a, Review of the U.S. Department of Energy's Heavy Vehicle Technologies Office Committee on Review of DOE's Office of Heavy Vehicle Technologies, Board on Energy and Environmental Systems, Commission on Engineering and Technical Systems, National Research Council, NATIONAL ACADEMY PRESS, Washington, D.C., and *Transportation Energy Book*, Volume 31, 2012.

[5] Source: http://fleetowner.com/equipment/news/truck-sales-surged-0119.

[6] Source: *Transportation Energy Book*, Volume 30, Tables 1.12 and 2.7. and Energy Information Administration.

[7] Source: *Transportation Energy Book*, Volume 30, Tables 1.12 and 2.7. and Energy Information Administration, *Annual Energy Outlook 2011*, April 2011; *2002 Economic Census, Vehicle Inventory and Use Survey*, U.S. Department of Commerce.

[8] Source: U.S. Environmental Protection Agency, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2010."

## For additional information, contact

**Jerry Gibbs**
Materials Engineer
Propulsion Materials
Vehicle Technologies Office
1000 Independence Ave. SW
Washington, DC 20585
e-mail: Jerry.Gibbs@ee.doe.gov
Tel: (202) 586-1182

**Will Joost**
Lightweight Materials
Vehicle Technologies Office
United States Department of Energy
1000 Independence Ave. SW
Washington, DC 20585
e-mail: william.joost@ee.doe.gov
Tel: (202) 287-6020

**Carol Schutte, PhD**
Team Lead for Materials Technology
Vehicle Technologies Office
United States Department of Energy
1000 Independence Ave. SW
Washington DC 20585
email: carol.schutte@ee.doe.gov
Tel: (202) 287-5371

vehicles.energy.gov

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

DOE/EE-0867 • February 2013

Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 10% post consumer waste.