21CT-002

21st Century Truck Program

Research and Development Plan For Materials

December 12, 2001

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TWENTY-FIRST CENTURY TRUCK PROGRAM

RESEARCH AND DEVELOPMENT PLAN FOR MATERIALS

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EXECUTIVE SUMMARY

The Twenty-First Century Truck (21CT) Program represents a unique partnership of industry and government to develop the technology for commercially viable, fuel-efficient, clean, and safe trucks. A technology roadmap[1] was completed in December 2000 to guide the development of technical advancements. It identified technical objectives and goals—long-term stretch goals for which technology breakthroughs will be required. The Program objectives are as follows:

- Improve fuel efficiency
- Reduce emissions
- Enhance safety
- Reduce total owning and operating costs
- Maintain or enhance performance

21CT objectives include reducing total owning and operating costs for trucks while meeting the Program's goals and maintaining or enhancing all performance attributes of the truck. To meet these objectives, cost-effective materials, design procedures, and manufacturing processes must be developed.

Materials technologies are crosscutting technologies that enable specific components and systems to perform at a level required for the truck or bus to meet 21CT Program goals. Improved materials are needed for propulsion systems (diesel engines, hybrid electric vehicles, and fuel cells), structural body and chassis members, powertrain components (brakes, wheels and tires, and drivetrain), and functional applications (thermal management and smart materials).

Improved materials are required to meet the existing and proposed emission regulations for diesel engines. Materials, manufacturing, and design improvements are needed to improve the thermal efficiency and fuel economy of the diesel engine while maintaining its cost advantages over competing propulsion systems.

Hybrid electric vehicles (HEVs) feature a power plant in combination with an electric motor(s) and electrical storage systems. HEVs offer potential for significant improvements in fuel efficiency and emissions for short-haul trucks and buses. Enabling research is needed to develop materials for diesel engines; fuel cells; and the electric motors, electrical storage systems, and power electronics needed for HEVs.

Recent technological advances make fuel cells potentially attractive for HEVs and for auxiliary electric power. Fuel cells convert fuel directly to electrical power and produce virtually zero emissions. Specific materials requirements are unique to the competing fuel cell types; however, some generalizations can be made: R&D is needed to reduce the cost of fuel cells. Much of the cost is in the stack, but additional costs are in the fuel storage system, fuel reformers (if necessary), and balance of plant (e.g., power converters, signal processors). These auxiliary systems must be reliable and inexpensive. Materials R&D is also needed to improve the durability and manufacturability of mobile fuel cell systems.

Current 21CT goals of increased fuel efficiency, decreased emissions, and improved performance and safety will require significant weight reduction in body and chassis structures. Although lightweight materials and structural design approaches exist, it is not feasible to implement them currently because of cost and manufacturing issues. A quantum jump is needed in the development of affordable, new, innovative materials; appropriate design databases; design methods; manufacturing processes; joining methods; maintenance and repair technologies; and

recycling. However, work aimed at reducing vehicle mass must also increase the performance, the durability, and, most critically, the safety of the vehicle. To meet the future safety goals, materials R&D should focus on development and application of advanced materials and design approaches to make truck cabs more resistant to crash deformation, especially in rollovers. Truck aggressivity in truck/car collisions must be reduced. It is important to develop energy-absorbing lightweight materials and innovative designs capable of making the front-end structure of trucks more compatible with smaller vehicles and capable of dissipating crash energy and diverting a smaller vehicle on impact.

The powertrain consists of the drivetrain (transmission, clutch, drive shafts and drive axles), tire/wheel assemblies, and brakes. The powertrain accounts for nearly 40% of Class 7–8 vehicle weight. Therefore, application and development of light materials for powertrain components offers a very significant opportunity to reduce vehicle weight. However, these materials should be capable of operating in extreme thermal and tribological conditions. Tires directly impact rolling resistance losses, which account for over 30% of non-engine energy losses on a Class 8 truck. Tires also have a major role in vehicle safety, particularly for heavy-duty trucks where they impact brake performance, vehicle stability, and payload capacity.

The 21CT safety goals will require higher-performance braking systems. Approaches to improve fuel efficiency, such as reducing parasitic losses (primarily drive-train friction and rolling resistance) and aerodynamic drag, will make it even more difficult to stop vehicles. Reductions in vehicle weight and lower operating costs require lightweight, longer-lasting brake materials. The principal materials issues for braking systems are in friction materials and materials for brake rotor and drum materials.

The drivetrain consists of components that transmit engine torque to the drive wheels and tires: the clutch, transmission, driveshaft, and drive axles. These components account for approximately 15% of the overall weight of a heavy-duty tractor; therefore the use of high-strength lightweight materials in drivetrain components has the potential to reduce vehicle weight. Advanced transmission concepts, such as continuously variable transmissions (CVTs), that offer improved engine efficiency and reduced emissions are currently not feasible for heavy trucks because of a lack of high-performance gear materials.

The management of thermal energy will play a critical role in achieving the energy efficiency goals of the 21CT. The engine and transmission, aftertreatment systems, electronic on-board computer systems, braking systems, and tires are heat-generating sources found on on-highway vehicles. Currently, thermal management involves removing undesired heat energy from these sources by transferring it to the environment. The functionality of heat generating systems is maintained by not exceeding specified temperature limits; thus approximately ⅔ of available thermal energy is not used. The overall goal of the 21CT is to find better ways to use and manage thermal energy by developing enabling thermal management materials.

Materials whose properties change with an application of a control signal are called “smart” materials. With the increased sophistication of truck and propulsion engineering, the introduction of smart materials offers levels of flexibility, controllability, and accuracy not achievable with conventional materials. Possible applications are numerous and require a wide range of smart materials, including piezoelectric, magnetostrictive, and thermoelectric materials.

This *Research and Development Plan for Materials* in the 21CT Program includes a detailed plan for materials research and development to support the technologies described. In addition, ongoing government-funded projects were analyzed and gaps in the existing R&D portfolio identified. Finally, an estimate of the funding required to complete the identified research and development is presented. Funding requirements are summarized in the following table.

Materials technology funding requirements by fiscal year
($ in thousands)[a]

Technology	Fiscal year					
	2002	2003	2004	2005	2006	2007
Propulsion materials						
Diesel engine	5,500	13,000	13,000	12,500	11,500	10,000
Hybrid propulsion	100	1,000	2,000	3,000	2,000	2,000
Fuel cells	100	2,000	4,000	5,000	6,000	6,000
Subtotal	5,700	16,000	19,000	20,500	19,500	18,000
Percentage of total	33	40	39	37	38	41
Structural body and chassis						
Crashworthiness	200	1,500	2,000	2,500	2,000	2,000
Materials development	1,400	2,500	3,000	3,000	2,500	2,000
Manufacturing	6,000	6,500	7,000	7,500	7,000	6,500
Design and database	500	2,500	2,500	3,000	2,500	2,000
Joining, maintenance, and repair	600	2,000	2,500	3,500	3,000	2,500
Subtotal	8,700	15,000	17,000	19,500	17,000	15,000
Percentage of total	51	37	35	35	33	34
Power transmission						
Braking	900	2,500	3,000	3,500	3,000	2,000
Tires	200	600	1,200	2,000	2,500	2,000
Drive train	300	2,500	3,000	3,000	3,000	2,000
Subtotal	1,400	5,600	7,200	8,500	8,500	6,000
Percentage of total	8	14	15	15	17	14
Functional materials						
Thermal management	500	1,500	2,000	3,000	3,000	2,500
Smart materials	800	2,000	3,000	4,000	3,000	2,000
Subtotal	1,300	3,500	5,000	7,000	6,000	4,500
Percentage of total	7	9	10	13	12	10
Total	17,100	40,100	48,200	55,500	51,000	43,500

[a]These funding estimates do not include the projects in the DOE Office of Advanced Automotive Technologies or the DOE Fossil Energy Solid State Energy Conversion Alliance, which are shown in the Appendix A, Table A.2. Part of that research is, of course, relevant to heavy-duty applications. The funding estimates shown are the government share of the project cost; it is assumed that industry cost share will match the government contribution.

INTRODUCTION

The 21st Century Truck (21CT) Program, announced in Romulus, Michigan, on April 21, 2000, will support the development and implementation of commercially viable technologies that will drastically cut the fuel use and emissions of trucks and buses while enhancing safety, affordability, and performance.

The 21CT Program will be conducted by a unique industry-government partnership. The manufacturers of trucks and buses, along with their suppliers and trade associations, have formed the Twenty-First Century Truck Partnership (21CTP). Its members include Allison Transmissions; BAE SYSTEMS Controls; Caterpillar, Inc.; Cummins, Inc.; DaimlerChrysler Corporation; Detroit Diesel; Eaton Corporation; Freightliner LLC; General Motors; Honeywell International, Inc.; International Truck and Engine Corporation; Mack Trucks, Inc.; NovaBUS, Inc.; Oshkosh Truck Corporation; PACCAR, Inc.; and Volvo Trucks North America, Inc.

The government sector is represented by a unique teaming of four U.S. government agencies: the U.S. Departments of Energy (DOE), Transportation (DOT), and Defense (DOD) and the Environmental Protection Agency (EPA).

A technology roadmap[1] was completed in December 2000 to guide the development of technical advancements. It identified technical objectives and goals—long-term stretch goals for which technology breakthroughs will be required. The Program objectives are as follows:

- Improve fuel efficiency
- Reduce emissions
- Enhance safety
- Reduce total owning and operating costs
- Maintain or enhance performance

A central goal of this initiative is to develop cost-effective, heavy-duty vehicles for truck operators that are fully competitive in prevailing markets.

A government-industry Partnership Coordinating Committee (PCC) was formed to oversee the program. The PCC reviewed ongoing government-funded programs relevant to 21CT objectives and developed a database of government research and development (R&D) programs. In March 2001, the PCC reviewed ongoing government-funded R&D programs in materials technology. Subsequently, the preparation of a detailed 10-year R&D plan for materials technologies in 21CT was initiated. The present document is the result of that effort.

Materials technologies are not specific goals of the 21CT Program. Rather, they are crosscutting technologies that enable specific components and systems to perform at the level required for a truck or bus to meet 21CT Program goals. Advanced designs for the truck engine, chassis, or body—developed to meet the aggressive 21CT goals—are subject to failure if they do not address materials performance, durability, manufacturability, and cost. This document examines specific goals for research in propulsion materials, structural body and chassis materials, power transmission materials, and functional materials. Table 1 indicates the relevance of each of these technologies to the 21CT goals.

The overall goal of materials R&D in 21CT is to enable successful realization of 21CT Program objectives. Technical barriers to meeting the goals are identified and R&D activities recommended. The recommended R&D activities are compared with the 21CTP database of ongoing government-funded programs, and gaps in research activity are identified. Finally, resource requirements (e.g., program funding and unique research and testing facilities) are estimated.

Table 1. Comparison of the 21st Century Truck Program goals to the elements of the Materials R&D Plan[a]

Materials Technology	21CT Goals					
	Efficiency by truck class			Emissions	Safety	Affordability
	8	2b–6	Buses			
Propulsion materials						
Diesel engine	X	X	X	X		X
Hybrid propulsion	X	X	X	X		X
Fuel cells	*b*	X	X	X		X
Structural body and chassis						
Weight reduction (Manufacturing, design and database, joining, maintenance, and repair)	X	X	X	*c*		X
Crashworthiness					X	X
Power transmission						
Braking					X	X
Tires	X	X	X		X	X
Drivetrain	X	X	X	*c*		X
Functional materials						
Thermal management	X	X	X	X	X	X
Smart materials	X	X	X	X	X	X

[a]Items marked with an "X" are relevant to a specific goal.

[b]Although fuel cells are not likely to be used as the prime mover in Class 8 trucks, the use of fuel cells as essential power units may provide a significant increase in efficiency.

[c]Weight reduction increases efficiency, reduces fuel consumption, and thus decreases emissions.

COST AND MANUFACTURABILITY

The 21CT objectives include reducing the total owning and operating costs for trucks while meeting Program performance goals and maintaining or enhancing all performance attributes of the truck. To meet these objectives, cost-effective materials and manufacturing processes must be developed. The cost and manufacturability issues are specific to truck class.

Cost and manufacturing requirements for light-, medium-, and heavy-duty vehicles vary widely because of significant differences in production volumes, market forces, and life-cycle requirements. For example, typical light-duty (Class 2–3) and many Class 4–5 truck body structures are based on modified pickup trucks manufactured in volumes of 500,000 units or more per year. In these cases, materials and manufacturing methods compete directly with low-cost established automotive manufacturing technology. To be competitive, advanced materials need to be cost-effective, the manufacturing methods must have rapid cycle times to meet volume requirements, and assembly and joining methods must be compatible with high-volume automated manufacturing. In contrast, typical Class 8 heavy trucks are manufactured in volumes ranging from thousands to tens of thousands per manufacturer. Within this volume range, product customization will often require components that can be designed and manufactured cost-effectively in low volumes. R&D programs should be considered that track or manage the migration of technologies from the low-volume heavy truck production into high-volume light truck production.

Further differentiating the cost and manufacturability issues for the different commercial classes are service and life cycle expectations. For Class 2–3 light-duty trucks, initial cost is generally the key driver, and service life is likely to be in the 100,000 to 300,000 mile range. These requirements favor lower-cost automotive manufacturing and light-duty, automotive-based powertrains. For typical Class 8 vehicles, a life expectancy of more than 1 million miles with minimum maintenance is a common requirement. Combined with the emphasis on payload and performance, Class 8 vehicles favor lightweight, durable cabs and highly durable engine and powertrain materials. However, an overwhelming driver for Class 8 truck manufacturers is manufacturing methods that are compatible with lower-volume production. Although advanced materials are desirable for heavy-duty engines and powertrains, they must meet durability, thermal performance, and aggressive cost targets associated with the steel and cast iron components currently used.

The 21CT materials R&D plan that follows emphasizes the critical issues of cost and manufacturability of all of the material solutions associated with the key application areas: propulsion materials, structural body and chassis materials, power train materials and functional materials. An integral part of this road map is the emphasis on manufacturing and life cycle analysis to provide realistic comparisons with existing materials and manufacturing technologies. In addition, the R&D plan will focus on those materials and manufacturing methods that are most appropriate for the given production volumes and existing manufacturing infrastructure associated with the commercial vehicle class.

TECHNICAL PLAN

PROPULSION MATERIALS

Propulsion Materials—Diesel Engine

Introduction
Improvements in materials are required to meet the existing and proposed emission regulations for diesel engines used in the 21CT. Materials, manufacturing, and design improvements are needed to improve the thermal efficiency and fuel economy of the diesel engine while maintaining the diesel's cost advantages over competing propulsion systems.

Goals
The goal for the propulsion materials effort is to develop materials that enable the achievement of the overall 21CT goals of fuel efficiency, emissions reduction, safety, and affordability (see Table 1). Accomplishing those goals will require that specific performance and cost targets are met for individual engine components. New and/or improved materials and cost-effective manufacturing processes must be developed for fuel systems, exhaust aftertreatment, air handling, the valve train, and structural components. Specific requirements are discussed in the following sections.

Barriers
The principal barriers to meeting the propulsion materials goals are in the areas of performance, manufacturability, and cost.

Performance
The technologies currently under consideration for reducing emissions result in significant fuel-efficiency penalties. In addition, many of these technologies may decrease the reliability and durability of the engine by, for example, increasing pressures and temperatures within the engine and introducing corrosive and erosive species into the engine. Materials needed to achieve the program goals in specific engine components may not exist today as durable reliable materials.

Manufacturability and Cost
Key advanced materials required to meet the goals of 21CT are not available today in high volumes, the required precision, reproducible quality, and acceptable cost.

R&D Needed to Overcome Barriers
The following materials research efforts are critical to meeting the program goals.

Fuel Systems
The fuel systems for diesel engines are precision systems that are critically important to achieving the highest diesel engine efficiency while reducing noise, vibration, and harshness (NVH) and meeting stringent emissions targets. Virtually every path to improve the combustion control depends on improvements in the fuel injection system. The fuel system and air-handling system currently represent a significant portion of the cost of a heavy-duty diesel engine. Enabling materials and cost-effective, precision manufacturing processes will be instrumental in developing improved fuel injection systems.

The electronic fuel injectors on heavy-duty diesel engines operate at ~20,000 psi to minimize particulate emissions. The fuel injection pressure is likely to increase to as much as 35,000 psi to meet emerging emissions regulations while maintaining engine performance. The high-pressure

fuel injection results in challenges with wear and scuffing of fuel injector plungers and with erosion, wear, and fatigue of fuel injector nozzles. In addition, low-sulfur fuels required to meet the low emissions targets typically do not lubricate the fuel injector components as well as current diesel fuel. The ultra-low-sulfur fuels expected in the near future may exacerbate the need for wear- and scuff-resistant materials.

Fuel injectors are highly precise systems. The individual components must fit together with clearances of sometimes less than a few microns. Control of the combustion process requires precise control of the size, shape, and surface finish of the injector components. In addition to new and improved materials, improved manufacturing and inspection methods for the injector components are needed.

Exhaust Aftertreatment

The reduction of NO_x and particulate emissions is required to achieve future emissions standards. Significant reductions in exhaust emissions will require improvements in engine design, engine control technologies, exhaust aftertreatment technologies, and improved fuel quality. Advanced engine control technology may require quantitative real-time NO_x sensors, miniature ceramic electrochemical cells, and on-board diagnostic and control devices.

The sulfur in diesel fuel is a major barrier to several promising aftertreatment technologies. Currently available U.S. diesel fuel contains up to 500 ppm of sulfur. The diesel engine community believes the fuel sulfur must be reduced to 30 ppm or less to achieve expected environmental regulations for 2007. EPA is involved in rule making that will likely lead to low-sulfur fuel (30–50 ppm) becoming widely available in the 2004 timeframe. For the purposes of our program plan, it is assumed that the 2004 goals must be met with the current 500-ppm sulfur diesel fuel.

Even when lower-sulfur fuels (estimated to be in the 30-ppm range) become commercially available, catalyst poisoning will continue to be an issue for the durability of exhaust aftertreatment devices. Development of sulfur-tolerant catalysts and sulfur-removal technologies (SO_x absorbers) is considered critically important to meeting future emissions regulations.

Catalysts are by nature high-surface-area materials. The behavior of catalysts is strongly influenced by microstructure, which is in turn determined by processing history and exposure conditions. Material development is needed to produce catalysts with stable microstructures that can operate at high efficiency over a wide range of exhaust conditions, including low temperatures and varying levels of oxygen and unburned fuel.

The characterization of catalyst systems shares methodology common to many materials systems, for example, high-resolution microscopy and microanalysis using primarily electrons and photons. The synthesis and processing of catalyst systems (substrate, washcoat, catalyst particles) are also familiar to the materials research community. R&D projects are expected to include synthesis and processing studies, bench test and engine exposures, and postmortem analysis of the chemistry and microstructure of the catalyst systems.

Durability of exhaust aftertreatment systems in heavy vehicles is a major concern. Lifetimes of at least 500,000 miles are expected, and 1,000,000 miles is desired (compared with 100,000 miles for automobiles). Exposure of the aftertreatment systems to high temperature, vibration, erosion, and chemical attack by species in the oil and fuel will result in a degradation of the catalyst performance. Characterization of the effects of exposure in service on the microstructure and microchemistry of the aftertreatment systems will be needed. The characterization may lead to the development of more durable systems and may point to material development paths that result in an optimized temperature window for aftertreatment operation.

In addition to the emissions regulated by EPA, unregulated emissions—such as N_2O, H_2S, COS, NH_3, and polyaromatic hydrocarbons (PAHs)—are becoming increasingly important. The effect of exhaust aftertreatment systems on unregulated emissions must be determined and quantified and steps taken to minimize the unregulated emissions. The following are among the exhaust aftertreatment technologies that may be relevant:

- lean NOx catalysts
- NO_x absorbers
- selective catalytic reduction (SCR)
- plasma-assisted catalysts
- oxidation catalysts
- PM filters

Some of these technologies require a reductant to promote the chemical reactions that reduce emissions. Where an HC reductant is needed, materials and systems for fuel modification may be required to avoid the need for anti-defeat features when a secondary reductant source system is added.

Additional engine controls may be required that will depend on new sensors developed for reliable, real-time measurement of NOx, O_2, temperature, and possibly some unregulated species over a wide range of temperatures and operating conditions. The sensor materials currently available are limited in range, or they require long lag times to respond to a change and thus are inadequate for measuring transient or rapid changes in operating conditions.

Valve Train

Materials are an enabling technology for durable valve train components in advanced engines. Fuel sulfur and other contaminants corrode diesel engine valves. The exhaust gas recirculation (EGR) required to meet 2004 emissions regulations will increase the average temperature, pressure, and corrosive species in contact with the valve face and seat and thus accelerate valve failure. Valve stem–valve guide seals must be completely leakproof to meet 2008 PM requirements. The lower reciprocating mass in valve train components will reduce stress in higher-RPM light-duty engines. R&D is needed to develop lightweight, wear- and corrosion-resistant valve train materials (valves, valve seats, valve guides, rollers, rocker arms) for use in all classes of heavy-duty diesel engines. New concepts for joining dissimilar materials (e.g., intermetallic valve head to steel shaft) are needed to reduce the cost of new valve materials.

Major Engine Components

The goal of 50% efficiency in an engine, which meets the emission reduction goals, will likely involve higher specific power. Higher specific power will call for higher peak cylinder pressure and brake mean effective pressure (BMEP). The higher pressures require cost-effective materials with higher strength and fatigue resistance for engine blocks and cylinder heads: either higher-quality cast iron or the use of high-strength materials to reinforce highly stressed areas in conventional cast iron components.

Engine weight needs to be reduced to make diesel engines competitive with spark ignition engines. R&D is needed for aluminum alloy engine blocks and cylinder heads with the strength and fatigue resistance necessary for the high-efficiency direct-injection diesel engine.

Higher peak cylinder pressures will also put additional stresses on pistons, liners, connecting rods, and crankshafts. Crankshaft loading may affect gearing that is incorporated into the engine design. Research is needed to evaluate the tribological characteristics of materials in piston-piston ring-liner systems, bearings and bushings, and gear systems.

Selected insulation of hot section and exhaust components to reduce heat rejection has been used to increase diesel engine efficiency in the Office of Heavy Vehicle Technology's LE-55 research program. Although efficiencies of up to 55% were demonstrated in a single-cylinder engine, the insulating materials used in the demonstration are not available as durable, cost-effective components. Research is needed to develop durable thick thermal barrier coatings, monolithic or coated cylinder head plates with low thermal conductivity, and insulated exhaust ports.

Air Handling

Turbocharging and associated air-handling equipment are important elements of engine control for heavy-duty diesel engines, and advanced engines will place new demands on the air handling system. The air handling system represents a significant fraction of the cost of a heavy-duty diesel engine. Cost-effective materials and manufacturing methods are needed to meet the performance requirements for air-handling components at an acceptable cost..

EGR will likely be required to meet 2004 emission requirements. EGR introduces corrosion of heat exchanger components for cooling the EGR and makes it necessary to increase the turbocharger boost to maintain the necessary oxygen partial pressure in the combustion chamber. Therefore, corrosion-resistant materials for EGR coolers will be needed. Higher-temperature compressor system alloys also will be necessary because the additional heat of compression will push conventional aluminum compressor materials to temperatures at which creep deformation will be a problem. EGR will need valving and controls, so corrosion-resistant materials for EGR valves will be needed.

Advanced engine control strategies require continuous control of the inlet air pressure, making variable-geometry turbochargers and continuously variable wastegate valves necessary. Better materials are needed for the linkage to control the variable geometry turbocharger inlet and the wastegate valve, which operates at high temperature (up to 600°C) without liquid lubrication. In addition, lower-mass materials are needed for turbocharger rotors because the inertia of the turbocharger limits the ability of the system to respond rapidly.

Manufacturing and Machining of New Materials

R&D in propulsion materials has focused on stronger, higher-temperature, corrosion-resistant materials. Cost-effective manufacturing processes also are necessary for the widespread commercialization of materials such as superalloys, intermetallics, and ceramics. For ceramics, raw material cost is a significant fraction of the overall component cost. Lower-cost alternatives and lower-cost upstream processes (e.g., powder production, powder consolidation and sintering) should be investigated. Composite materials also must be easily machinable for finished components to be cost-effective. Using current machining technologies, high-strength materials such as compacted graphite iron or selectively reinforced cast iron composites may require more machining time. Increasing machining time slows down the manufacturing process, reducing factory output and increasing costs. If advanced materials are to be commercially viable, new machining technologies must be developed for them.

Design and Engineering of New Components

Truck engine manufacturers generally prefer conservative designs to ensure reliable products. This conservatism inhibits the introduction of new, higher-risk materials without a proven track record. Therefore, commercializing new materials will require extensive databases of material properties. New design and testing methodologies will also be required. For example, high-strength materials often are less ductile and thus less forgiving. It will be a challenge to ensure that they are reliable under high-temperature, low-lubrication conditions for up to a million miles. There will be an increasing need to *simulate* component performance and life to avoid expensive engine testing. Simulation tools that integrate finite analysis of component designs, material properties of component materials and interacting fluids, surface properties and topography, and

knowledge of the operating conditions will be necessary. New higher-resolution non-destructive evaluation techniques also will be required to ensure component survival during operation.

Standards
The commercialization of new materials and manufacturing processes depends on having standard testing methods that generate useful data for design and modeling and that are accepted by the industry. Materials testing standards in the U.S. are primarily voluntary consensus standards developed by the American Society for Testing and Materials (ASTM). ASTM standards are coordinated with international standards by the International Standards Organization (ISO).

Propulsion Materials—Hybrid Propulsion

Introduction
Hybrid electric propulsion systems may be needed to meet performance and efficiency goals for both commercial and military vehicles. Hybrid electric vehicles (HEVs) feature a power plant in combination with an electric motor (or motors) and electrical energy storage system. Many series, parallel, and power-split hybrid propulsion system configurations are possible. The optimum propulsion system configuration is dependent on the vehicle performance goals, efficiency goals, duty cycle, and other practical considerations, including manufacturing cost, serviceability, market differentiation, and customer acceptance of the technology.

A "crosscut" R&D effort is needed to develop enabling technologies for hybrid electric propulsion systems. Electric motors, electrical energy storage, power electronics, electrical safety, regenerative braking, and power-plant control optimization have been identified as the most critical technologies requiring further research to enable the development of higher-efficiency hybrid electric propulsion systems. Development of improved electrical energy storage systems and power electronics is especially important due to the high cost and limited availability of new components and subsystems. This section will focus on materials research to improve the electric motor, electrical storage systems, and power electronics of the HEV.

Goals
The goal of R&D for hybrid propulsion materials is to making enabling materials available for high-performance, durable, cost-effective hybrid vehicle components: electric motors and generators, power electronics, batteries, ultracapacitors, and electric flywheels.

Barriers
Electrical components for HEVs are expensive and, in most cases, were not designed for use in HEVs. Electrical components tend to be costly because precision manufacturing tools are needed to produce them and production volumes are low.

The next generation of electric motors must have higher specific power and lower cost. Drive motors (including gear reduction) for HEVs are very expensive ($30,000–$40,000) and heavy (1,000–2,000 lb). Motors, gear reduction systems, and cooling systems must be improved through the use of advanced materials, improved cooling systems, novel packaging, and advanced assembly techniques. They should be designed for minimum cost, weight, and parasitic losses, and they must be extremely reliable and durable.

An understanding of safety issues (rotor stress design margin, rotor integrity, control of rotor failure modes, and containment system design) must be developed for flywheel technology in order to be commercially viable.

R&D Needed to Overcome Barriers

Computer-aided design, systems optimization, and improved manufacturing techniques are needed to improve the performance and efficiency of electrical HEV components.

Highly conductive, lightweight materials and thermal management materials for optimized cooling systems are needed to improve the specific power and reduce the cost of electric motors. Systems analysis is needed to identify the best opportunities for cost and weight reduction.

Battery cost and life cycle costs are critical issues that could influence market acceptance for heavy vehicle applications. There are several different battery types used in HEVs. These include conventional lead acid, nickel-cadmium, nickel metal hydride, lithium ion, and lithium polymer. Currently, many battery materials are too expensive, and the batteries are hard to recycle. Fail-safe design, packaging, and weight are also concerns. There are significant safety issues for lithium ion batteries, which may call for advanced lightweight materials to contain the battery pack. In addition, thermal management materials are needed to control and balance the pack to ensure optimum performance and safe operation.

Ultra-capacitors may accept regenerative braking energy more readily than batteries and therefore could be a key enabling technology for improving energy efficiency. Materials R&D needs include packaging, safety, energy management, and thermal management of ultra-capacitor banks.

A key design issue for flywheels is developing the structural properties of the rotor to permit the high-speed operation necessary for reasonable specific energy and minimize the risks associated with rotor failure. The rotor is normally fabricated with materials with a high strength-to-density ratio, such as a carbon fiber-epoxy composite. Safety and containment are major issues to be addressed by R&D.

Technologies related to device packaging need to be investigated for developing a power switch:

- topside power connection without wire bonds,
- minimization of wire bonds,
- topside probing for dynamic matching,
- heat-sinking on both sides of the die,
- direct bond copper on alumina and aluminum-nitride substrates,
- interconnect solutions for large-scale manufacturing and reliable operation of power modules, and
- other related packaging technologies.

Research on silicon carbide needs to be accelerated to enable its application to high-power switching devices. Capacitors with high-frequency, high-voltage operation, low ESR, and high ripple current capability need to be further developed. Advanced materials are needed for packaging, to operate over a much higher temperature range. Novel means to transfer heat quickly from the devices should be examined, including advanced thermal management materials.

Power electronic components and subsystems need to be further developed to meet the reliability, service life, and cost expectations for commercial and military vehicles. To reduce the total system cost, the materials and manufacturing effort should be focused on the following:

- integration and packaging of the inverter and the motor as one system by using a design that can be tailored to meet specific vehicle requirements;
- low-cost manufacturing methods for the motor and inverter;
- development of low-cost, high-temperature magnets;
- use of efficient cooling systems;
- improvements in connector technology;
- development of capacitor technology, including improved dielectric components;
- lightweight enclosures that are waterproof and are immune to electromagnetic interference; and
- fault-tolerant, fail-safe designs.

Propulsion Materials—Fuel Cells

Introduction

There is increasing concern in the industry as to whether continued improvement in conventional internal combustion engine technology will satisfy the demand for cleaner and more efficient trucks for the 21st century. For example, by 2007 there will be significant reductions in permitted emissions for heavy-duty diesel engines for on-highway truck applications, particularly in NO_x and particulates. Moreover, with increasing fuel costs projected over the next decade, more fuel-efficient power generating systems will be required to minimize cost to the end-user.

Fuel cell technology has received considerable attention over the past 25 years. While they have been around since the early 1800s, only recently have fuel cells emerged as a long-term competitive threat to the internal combustion engine. The reasons for this are relative simple: fuel cells convert the chemical energy of the fuel directly into electrical energy, whereas internal combustion engines go through an additional step involving mechanical energy. This direct conversion process allows some fuel cell technologies to generate electricity more efficiently than even latest-generation diesel engine technology, upward of 50–60% efficiency (compared with mid-40% levels for current diesels).

Another advantage of fuel cells is that they produce virtually zero emissions. Since hydrogen or natural gas is generally the hydrocarbon source for fuel cells, emissions are limited to water vapor and carbon dioxide. Moreover, fuel cells operate at low temperatures at which NO_x formation is insignificant. Depending of the type of fuel cell, operating temperatures are generally either below 200EC, or in the case of solid oxide fuel cells (SOFCs), on the order of 1000EC. Even at this higher temperature, NO_x emissions are negligible.

Of the several fuel cell technologies available, only three stand out as viable candidates for mobile applications: the polymer electrolyte membrane (PEM) cell, also referred to as the proton exchange membrane; the SOFC; and the alkaline fuel cell (AFC). There is general agreement that the PEM technology surpasses the SOFC for mobile applications mainly because of its low-temperature operation (80EC) and therefore simpler and safer design. The same is true for the AFC. However, higher power densities are possible with SOFCs, which operate at 800–1000EC, implying a smaller footprint. SOFCs also exhibit greater fuel flexibility, whereas the PEM and AFC require either pure hydrogen or complex reforming and purification systems to convert fuels such as methanol or natural gas into an appropriate hydrogen source. Considerable research is currently under way with all three of these technologies vying for the top spot for mobile auxiliary power units (APUs).

Goals

The goals of R&D on materials for fuel cells is to enable the development of cost-effective, reliable fuel cell systems for propulsion, presumably as part of a hybrid electric propulsion system, and for auxiliary power. This goal is relevant to the 21CT goals of efficiency increases (see Table 1) and of emission reduction.

Barriers

Several technical and economic hurdles continue to plague rapid commercialization of fuel cell technologies. One is that energy produced from virtually any fuel cell technology is 5–10 times more expensive than that produced from low-cost diesel engines. Some of this cost is due to a lack of economies of scale—the volume of fuel cells sold is still relatively small. Many of the materials are expensive—platinum catalysts, specialty polymers and ceramic electrolyte membranes, high-temperature superalloy manifolds and seals, and high-purity graphite electrodes, to name but a few. Another significant cost is related to the fuel itself. For example, if pure hydrogen is used, then a safe hydrogen storage system is required. Not all fuel cells can use natural gas directly; for those systems, therefore, an additional reformer is necessary, which adds to the cost. Therefore, fuel cells may not replace internal combustion engines outright within the next 20 years. However, there is great near-term interest in fuel cells as mobile APUs, whereby their high efficiency and clean operation can be used to satisfy ever-increasing electrical demands (e.g., air conditioning and heating, particularly during idle overnight).

Heavy-vehicle-type balance-of-plant components (compressors, humidifiers, heat exchangers, sensors, and controls) have not been developed and integrated into fuel cell systems. Laboratory tests have been conducted with off-the-shelf components that were not designed for vehicular fuel cells. The result was systems that are heavy, inefficient, and costly.

Durability is another barrier for heavy-vehicle fuel cells. Fuel cells must provide comparable hours of operation vis-à-vis internal combustion engines: at least 30,000 hours before a rebuild is required.

R&D Needed to Overcome Barriers

PEM

Lower-cost, lighter bipolar plates and low-cost, high-performance membranes and catalysts are needed to make fuel cells competitive for heavy-vehicle applications. Alternative bipolar plates must be mass-produced, as opposed to today's customized machining. These plates must maintain a high electronic conductivity, ductility, and structural integrity and must be corrosion-resistant and non-porous to hydrogen. Some bipolar plates have been developed from engineered polymers, but the electronic conductivity is low. Metallic plates also under development have shown resistance to corrosion and promise as future bi-polar plates.

Higher-temperature membranes, which can operate above 100°C, are needed to reduce deleterious reactions with carbon monoxide (CO). Catalysts with greater tolerance for CO are required as well; otherwise, pure hydrogen with less than 10 ppm of CO is required as fuel. The fuel cell must be able to produce electrical power from –20°C to above 100°C.

The need for alternative electrode catalysts instead of platinum is critical; else the system becomes unaffordable. R&D on the performance and durability of catalyst materials is needed to identify and develop lower-cost catalyst systems.

Advanced materials are needed for heavy-vehicle-type balance of plant components that meet overall system requirements for cost, packaging, and performance. Thermal management materials are needed to optimize system design. Thermal management processes include waste heat utilization, cooling, and steam generation. Currently available systems are not thermally integrated to achieve the maximum potential efficiency.

Compressed gas hydrogen storage systems are currently too bulky for heavy-vehicle applications, limiting vehicle range. High-pressure storage systems use expensive carbon fibers and composite tank liners. Breakthroughs in the areas of less expensive materials and fabrication processes are needed, as well as more compact storage systems.

SOFC

At the other spectrum, high-temperature SOFCs have their own set of technical challenges. For example, to enhance functionality, power densities must be increased to maximize power output in the smallest-volume package. To achieve the higher power densities, solid electrolyte layers having higher ionic conductivities are necessary. Reduced ohmic losses at the electrode–electrolyte interfaces also will lead to higher power densities. Thinner electrolyte layers would dramatically improve power output per unit surface area (thicknesses currently are typically 20–500 μm). Cell geometry is also important, as power density is a function of surface area—longer cell lengths and innovative cell geometries beyond tubular and planar designs all improve power output.

The high-temperature operation of SOFCs raises questions of long-term durability of the stack. Although investigators have shown that the cell itself is fairly robust during high-temperature steady-state operation, reliability over a large number of thermal cycles is necessary before SOFCs can be accepted as a viable commercial technology. The stability of the ceramic electrolytes and electrodes and the sealing components, and oxidation of the superalloy and high-temperature ferrous alloy interconnections are all issues of concern. R&D is needed to characterize the durability of SOFC materials, predict component lifetimes, and develop improved materials to enhance fuel cell durability. SOFC durability is a safety issue: if a cell breaks during operation, fuel and air can be mixed creating an explosive environment, particularly during startup conditions.

Another area of concern with SOFCs is the lag time associated with heating up the stack. During steady-state operation (i.e., as the primary power source for stationary applications) this is less a concern. However, for an SOFC used as a stationary backup power source, or as an APU for mobile applications, this lag time is critical. Therefore, thermal management of the stack during startup is necessary to minimize this delay without subjecting the ceramic cell components to thermal shock. R&D to identify or develop advanced materials for thermal management is needed.

One way of mitigating many startup and operation problems associated with high-temperature SOFCs is to run them at lower temperatures. Currently, SOFCs operate at 800–1000EC because, in that temperature regime, the current ceramic electrolyte becomes sufficiently conductive. Recent advances in zirconia electrolyte materials suggest that SOFC electrolytes can be developed to work at temperatures as low as 500EC.

Moreover, at 500EC, low-cost ferrous alloys could be used in place of exotic superalloys, provided these materials have sufficient oxidation resistance and thermal expansion match to other cell components. Therefore, it is necessary to develop metallic compositions with the thermal expansion and oxidation resistance necessary for the low-temperature SOFC. With these

advances, long-term durability, sealing technology, and manifolding designs all become greatly simplified.

Finally, a key element in the cost of SOFCs is manufacturing. Some tubular SOFC designs use expensive electrochemical vapor deposition processes for the zirconia electrolyte. Other designs are fabricated from conventional, yet still expensive, ceramic processing methods such as extrusion, tape-casting, and subsequent sintering. Better manufacturing routes that use lower-cost raw materials and novel but lower-cost processes all go to reducing the cost of the fuel cell.

AFC

AFCs are being developed for commercial transportation applications and have spurred considerable interest from both the auto and petroleum industries because of their inherent low cost (<$200/kW). AFCs are potentially the lowest-cost fuel cells because of the materials and manufacturing processes used to make them. They are also restorable (replacing the electrolyte restores output to near that of a new cell) and recyclable. They have been operated for more than 20,000 hours and from –30 to 90°C, and they have 50% full power at room temperature. The reliability of AFCs has been demonstrated convincingly over 30 years of service in space missions by United Technologies.

However, the AFC used for space exploration is too expensive for commercial applications. The new low-cost AFCs being developed by other manufacturers are intended to be equally reliable, but at a fraction of the cost. However, additional development is needed to improve AFC sensitivity to atmospheric CO_2, increase efficiency, and improve power density. Also, lightweight current collectors need to be developed and integrated into the AFC designs to reduce overall weight. While current mono-polar designs have operating efficiencies as high as 57%, new, higher-temperature but cost-competitive plastics that are injection-moldable are needed. Their use would allow higher operating temperatures (beyond the current 70EC), resulting in higher efficiencies. In addition, long-term testing of AFCs from various manufacturers and stack/system testing is needed.

STRUCTURAL BODY AND CHASSIS MATERIALS

Introduction

Current 21CT goals of increased fuel efficiency, decreased emissions, and improved performance and safety will require significant weight reduction in body and chassis structure. At present, most of the body and chassis structures used in all classes of commercial heavy vehicles are still manufactured from plain carbon steels and aluminum because of their lower cost, ease of manufacture and assembly, well-established design databases, well-established repair and maintenance practices, and large capital investments in the existing manufacturing infrastructure. The use of lightweight materials—such as higher-strength steels, aluminum castings, plastics, and composites—has increased somewhat over the last few years. However, lack of R&D resources within the U.S. heavy truck industry and increased cost pressure by truck users has hindered widespread utilization of lightweight materials. Implementation of these materials in Class 2b/3 trucks also has been slow. Although lightweight materials and structural design approaches exist, it is not currently possible to implement them because of cost and manufacturing issues. To achieve these goals, a quantum jump is needed in the development of affordable, new, and innovative materials; appropriate design databases; design procedures; manufacturing processes; joining methods; maintenance and repair technologies; and recycling.

However, work aimed at reducing vehicle mass must also increase vehicle safety. Historically, most efforts to improve truck safety have focused on preventative measures. However, recent voluntary efforts by heavy vehicle manufacturers, carried out under the auspices of the Society of Automotive Engineers, have developed a basis for improving the protection of truck occupants. The future safety goals should focus on the application and development of advanced materials and design approaches that would make truck cabs more resistant to crash deformation, especially in rollovers. Reducing truck aggressivity in truck/car collisions is another area requiring attention. It is important to develop lightweight energy-absorbing materials and designs capable of making the front-end structure of trucks more compatible with smaller vehicles and capable of dissipating crash energy and diverting the smaller vehicle on impact. The safety concerns regarding sport utility vehicles (SUVs), with respect to both occupant protection and interaction with other vehicles, would also benefit from such an approach.

Goals

Weight reduction goals in the 21CT roadmap vary according to the weight class of the vehicle. However, the targets for all classes range between 10 and 33% weight reduction. The weight targets for each vehicle class depend on the performance requirements and duty cycle. The targets reflect the goal for total vehicle weight. It is recognized that, in some cases, the weight reduction in the body and chassis will likely be significantly higher. Weight reduction must not in any way sacrifice the durability, reliability, and performance of the vehicle. Attaining these goals will yield substantial benefits by reducing inertial loading and increasing the available payload of the vehicles.

The 21CT also has a goal to improve vehicle safety. This overall goal is related to improving the crash performance characteristics of each vehicle platform by reducing truck frontal and side structural aggressivity in multi-vehicle collisions (vehicle/vehicle dimensional compatibility and truck structural kinetic energy absorption/deflection performance). This goal must be met without increasing vehicle weight or length. Although the goals of mass reduction and improved safety may appear to be in conflict, there are significant opportunities to develop improved crash energy management designs that take advantage of the inherent properties of lightweight materials.

Barriers

The principal barriers to achieving the weight reduction goals for heavy vehicles (Class 7 and 8) are the inherently higher cost of alternate lightweight materials and the unavailability of fully developed, production-ready, cost-effective manufacturing technologies (e.g., formability, castability, machinability) that are suitable for the lower-volume truck market.

Manufacturing, and assembly technologies developed for lightweight automotive material applications are often not suitable for lower production volumes. Similarly, manufacturing processes developed for aerospace components are not cost-effective for the production volumes necessary for trucks. Excessive lead times, the high cost of tooling, and the capital investment required for factories to manufacture components from lightweight materials are not compatible with production volumes in the heavy-vehicle industry.

A contributing barrier is a lack of design databases and methods that allow new, advanced, lightweight materials and processes to be applied efficiently in heavy truck body and chassis structures. This is particularly true for composite structures and for designs for joints made of alternate materials for heavy vehicles. The performance of candidate lightweight materials subjected to high-mileage, high-fatigue cycles and corrosive environments is not sufficiently understood. In particular, databases for fatigue properties, fracture toughness and impact, NVH-related performance properties such as damping, torsional and bending stiffness, and corrosion are inadequate.

Technologies for joining and fastening dissimilar materials are inadequate. The effect of bolted and bonded joints made of materials with different structural stiffness, durability, fatigue, and fracture toughness is unknown for extended use.

Accurate computer simulation models are lacking in many areas, including process simulation for manufacturability, models to predict performance of materials (e.g., joints, fatigue, corrosion), and crash simulation.

The lack of well-developed maintenance and repair procedures and infrastructure for new lightweight materials results in uncertain repair and maintenance costs.

R&D Needed to Overcome Barriers

Because the use of alternative lightweight materials can significantly improve fuel economy and emissions, the automotive industry has begun to take advantage of lightweight materials to improve the fuel efficiency of its fleets. However, the annual production volumes for heavy vehicles, from 3,000 to 70,000, typically are much lower than in the automobile industry. Further, increased demands from customers and increased competitive pressures have reduced profit margins in the heavy commercial vehicle industry.

To take advantage of the benefits of lightweight materials, it will be necessary to develop materials that are cost-effective, stronger, more durable, and safer, and to develop efficient manufacturing processes to make them available. R&D needs may vary depending on the size of the vehicle, its performance requirements, and its duty cycle. However, materials or technologies developed for a particular vehicle class are not necessarily limited to that class. For example, materials developed for lightweight frames for pickup trucks, vans, or SUVs will eventually be used in Class 3 vehicles, and materials developed to meet the demanding performance requirements for Class 7 and 8 trucks will find application in smaller vehicles.

Materials Development

Materials having high strength-to-weight and high stiffness-to-weight ratios—such as aluminum alloys, high-strength steels, austempered ductile irons, magnesium alloys, glass and carbon-fiber-reinforced polymer composites, and even titanium alloys—have been developed and been the focus of research for several years. However, as yet there has been no widespread use of these materials in ground transportation applications. Continued efforts are required to optimize these materials for performance, cost, manufacturability, and safety. Effort should also be made to identify, develop, and apply new, innovative materials and the means to manufacture them, with the goal of significantly improving performance or reducing vehicle weight. The potential of higher-strength, lightweight, metal matrix composites should be evaluated for heavy vehicles. They have the potential to reduce weight and provide increased stiffness at acceptable cost.

An area of materials technology that is of increased interest to truck manufacturers is carbon fiber–reinforced polymer composites. These materials have the potential to reduce the weight of body and chassis components by more than 60%, and they offer significant opportunities for functional integration and part count reduction. Their associated forming processes typically allow for a much lower capital investment, which should prove especially advantageous at the volumes and cycle times of most heavy vehicle manufacturers. The use of these advanced composites has been limited primarily by their high material costs, limited performance characterization, and immature design methodologies. It is important to pursue the potential of these high-strength, high-stiffness materials to meet the performance and cost targets for structural applications in trucks.

The largest single barrier to implementing advanced lightweight materials in heavy vehicles is cost. Raw-material costs of titanium, magnesium, carbon fiber, resin systems, and aluminum need to be reduced. Advanced manufacturing methods are needed to reduce the cost of fabricating the materials into body and chassis components. Only if both cost barriers are addressed can the final component be manufactured at costs comparable to those of current materials and processes.

Manufacturability

New lightweight materials often are not used because of difficulty in shaping, joining, finishing, and/or assembly. Because they do not benefit from the long history of processing developments for more conventional materials, processing methods for lightweight materials are relatively immature. There is a need to develop processes that enhance formability, castability, machinability, and joinability. Cost-effective and novel hybrid processes, such as squeeze casting, vacuum casting, powdered metal forging, metal injection molding, and semi-solid forming could enable the use of lightweight materials in structural and chassis applications in the truck industry.

For metals, further development of processes such as hot metal gas forming, warm forming, superplastic forming, hydroforming, thixoforging and thixomolding, and electromagnetic forming—if optimized for commercial vehicle volumes—could make the manufacturing process for cab structures more flexible and allow the weight and durability of heavy vehicles to be optimized for service conditions (long haul versus vocational). In addition, many of these processes offer the potential for lower-cost tooling and lower capital investment in production facilities, benefits particularly well suited to low-volume manufacturing.
Manufacturing costs are also tied to the capability to fabricate and assemble a single component from multiple stamped parts. A low-cost, high-volume process for manufacturing large components is necessary to eliminate the need for assembly and reduce the overall weight of components.

Magnesium and titanium alloys are attractive alternatives to steel and aluminum because of their low density. However, lack of experience with these alloys, together with their high costs compared with steel, has limited their use in truck applications. Robust, cost-effective

manufacturing processes need to be developed and optimized for these materials to take advantage of their high specific strength.

The inability to manufacture large structural components cost-effectively in high volumes is one of the barriers to the increased use of carbon fiber–reinforced polymer matrix composites. Class 7 and 8 trucks offer a low-production-volume entry point with appropriate technical barriers and with financial incentives that justify a modest price premium for competent lightweight materials. It will be necessary to develop robust manufacturing processes for thermoplastic and thermoset resin-based carbon fiber composites optimized for stiffness, strength, weight, cost, design flexibility, manufacturing capability, and cycle times. Additionally, further development of net-shape composite processes will reduce the material scrap rate, which helps mitigate material costs.

In reality, vehicles are not constructed of a single material but require the appropriate use of several different materials. The design and manufacture of trucks of all sizes must be based on a total system approach in which the correct material is selected for each application. Substantial benefits are possible from the combined use of two materials, for example, carbon fiber composite and aluminum. It will be necessary to develop a fundamental understanding of the application of composite/metal hybrids to heavy-duty vehicles and of how well these hybrids can be integrated in moderate-volume production.

Finally, because the major truck original equipment manufacturers (OEMs) do limited manufacturing in-house, there is a need to develop, document, and implement advanced materials and manufacturing technologies in such a manner that they can be readily transferred to the OEM truck supplier base.

Design and Database

To make the best use of the properties of lightweight materials in heavy-vehicle structural applications, component design philosophy must change significantly. Additionally, the differences in properties of the materials under consideration make it necessary to develop enabling technologies to predict the response of materials after long-term loading, under exposure to different aggressive environments, and in crash events. Design engineers currently are most familiar with steel and cast iron and manufacturing technologies optimized over several decades. High-strength, lightweight materials must be incorporated at the conceptual design level, not simply substituted into existing designs. An extensive body of knowledge is needed about these alternative materials to give designers the flexibility to design for lightweight systems. Such knowledge, in the form of design databases and guidelines, is a prerequisite for the acceptance and implementation of these materials by the heavy-vehicle industry.

Significant opportunities exist for reducing the weight of SUVs and pickup trucks. However, unfamiliarity with materials performance properties and lack of design guidelines have hindered progress. Design feasibility studies are needed to determine potential cost, weight, and performance implications of advanced lightweight frame designs.

Trucks have much longer design lifetime than automobiles, so applications of lightweight materials must consider not only initial cost but also life-cycle costs. The extended lifetimes and duty cycles of heavy vehicles require that designers account for fatigue, NVH, and potential high levels of corrosion. There is a strong need to develop databases for fatigue properties, properties related to noise and vibration dampening, torsional and bending stiffness, and corrosion properties. Associated with the need for these databases is the need for suitable laboratory test methods that predict the performance of new, advanced lightweight materials and structures.

One of the barriers to the use of polymer composite materials is the lack of understanding of their basic behavior, specifically in the area of joints and joint design. Significant effort must be applied to developing an understanding of this behavior for the new resin systems and establishing guidelines for designers.

To protect the environment and conserve natural resources, there is increased emphasis on the use of recycled materials and materials that can be recycled economically. Currently, data are limited on the recycled content and recyclability of various materials, especially polymeric materials. To design a vehicle that meets environmental goals, there is need to develop the database that helps select materials that cause the least damage to the environment.

The availability of improved simulation/analytical tools affects the ability of designers to consider lightweight materials for components or vehicles. Validated models are essential to evaluate potential materials. Predictive tools are needed in all phases of design for material performance, process modeling, and manufacturing.

It is also important that the manufacturing performance of the materials be consistent and predictable to reduce manufacturing scrap and cycle time. Therefore, there is need for process simulation models that can predict the manufacturability of individual components at the design stage. For example, tools must be developed for springback prediction/compensation for high-strength steel and aluminum, die design for stamping, and distortion prediction. Likewise, prediction of resin flow/mold-filling and fiber perform stability is required for polymer composites. These models can be used to optimize components for performance, weight, and cost. Finally, models must be developed for dimensional management of full assemblies.

Joining, Maintenance, and Repair

Common joining methods used in body and chassis structures include resistance spot welding, resistance seam welding, MIG welding, TIG welding, adhesive bonding, and mechanical fastening. The effects of these different joining methods on stiffness and durability are not fully known. To make efficient use of lightweight materials, models are needed that can predict the effects of these methods on the stiffness of structures and their fatigue life.

New joining methods also are needed that improve fatigue performance and fracture toughness and allow the joining of dissimilar materials of different thicknesses. For innovative joining methods such as laser welding, friction stir welding, and magnetic pulse welding to be viable for the heavy-vehicle industry, significant R&D is needed to reduce the costs of these joining processes and develop their performance databases.

Mechanical fastening requires forming holes in composites, which destroy the continuity of the reinforcing fibers. An understanding of the mechanics of this effect will provide designers with critical data and is essential to increased use of these materials in heavy-vehicle structures. Satisfactory fastening solutions have been developed for many aircraft and spacecraft applications, but they are generally uneconomical for commercial vehicles. Commercially viable fastening solutions must consider the economics of fabrication and assembly in commercial vehicle manufacturing.

The costs of maintenance and maintenance downtime significantly impact the efficiency of freight movement and the profitability of the trucking industry. More-durable materials and components will help to reduce those costs. Materials that resist wear and corrosion and require no lubrication or can extend lubrication intervals are needed to reduce the frequency and cost of maintenance. Joining processes have a significant impact on not only the manufacturability and assembly of heavy vehicles but also on the durability, maintenance, and repair of the vehicle.

Cost and ease of repair depend heavily on the materials and joining methods used in body and chassis structures. Key deterrents to the use of new lightweight materials are a lack of well-developed repair procedures and infrastructure and the high cost of repair. New cost-effective repair procedures must be developed so that the introduction of lightweight materials does not have a negative effect on profitability.

Crashworthiness

Although there are presently no laws mandating rollover protection for heavy vehicles, to increase the safety of vehicle occupants, several voluntary standards are used to improve the crashworthiness of structures. Goals for improved safety will require that crashworthiness be a continued consideration in design. Efforts to design vehicles that are more resistant to crash deformation, especially in rollovers, and less aggressive in truck/car collisions will require a better understanding of the energy absorption capabilities of various lightweight materials. This will require increased knowledge of the fracture toughness and impact properties of those materials. R&D is needed to reduce the cost and improve the manufacturability of innovative sandwich materials, such as metallic and polymer honeycomb sheets and aluminum foams, that are extremely lightweight and energy absorbing.

New designs intended to reduce truck frontal and side structural aggressivity by deflecting smaller vehicles on impact must to be evaluated using computer simulations prior to their implementation on vehicles. More accurate crash simulation models for heavy-vehicle structures interacting with smaller vehicles must be developed and validated.

POWER TRANSMISSION MATERIALS

Introduction

The power transmission system includes the components involved in transferring engine torque to the ground (clutch, transmission, drivelines, drive axles, wheels and tires), along with non-driving axles and brakes. The principal focus of this section is on medium- and heavy-duty trucks, which account for more than 60% of the fuel used in commercial operations. Where applicable, drivetrain materials suitable for light-duty Class 2 and 3 vehicles, transit buses, and hybrid powertrains are included. Taken as a group of components, the powertrain accounts for approximately 40% of the total weight of a typical Class 8 heavy truck.

Drivetrain, wheels, tires, and brake materials are a diverse group of materials with varied cost, performance, and manufacturing issues. Powertrain materials may have a measurable impact on vehicle parasitic losses, safety, and vehicle weight. Tires directly impact the rolling resistance losses of the vehicle, which account for over 30% of non-engine energy losses on a Class 8 truck.[2] They also play a major role in vehicle safety, particularly for heavy-duty trucks, where they impact brake performance, vehicle stability, and payload capacity. The powertrain of a typical Class 8 tractor accounts for nearly 40% of its overall weight. In addition to lighter-weight, higher-strength materials to reduce the weight of powertrain components, materials are needed that can operate in extreme wear, thermal, and tribological conditions.

Drivetrain Materials

Introduction

Drivetrain materials are used in the components of the vehicle that transmit engine torque to the drive wheels and tires: the clutch, transmission, driveline, and drive axles. Materials R&D needs for drive components can often be applied to non-driven steer and lift axles as well. Since

drivetrain components account for approximately 15% of the overall weight of a heavy-duty tractor, making them from high-strength lightweight materials could contribute significantly to reducing vehicle weight. Drivetrain efficiencies could be significantly improved by the development and application of advanced coatings and lubricants to reduce friction and wear. Advanced transmission concepts, such as the continuously variable transmission (CVT), are currently not feasible for heavy trucks because suitable materials are lacking. However, if the material barriers were overcome, CVTs could help reduce engine emissions by allowing diesel engines to run at optimum performance and emission points. As aerodynamic drag and rolling resistance are reduced, greater demands are put on the vehicle retarder system, which, in turn, present a number of material development needs.

Goals

The goal of R&D on drivetrain materials is to reduce parasitic energy loses, improve vehicle efficiency, and reduce weight in components by means of advanced materials and component design, materials substitutions, and surface modifications.

Barriers

Lightweight materials do not have the required strength, durability, and surface properties to cost-effectively replace existing iron and steel components in transmissions, clutches, and drivelines. Steels resistant to contact fatigue (pitting) and lubricants needed for applications inside heavy-vehicle CVTs and advanced conventional transmissions are not fully developed. Cost-effective, highly durable, low-friction surface treatments needed for all parts of the drivetrain to reduce wear and frictional losses and improve the durability of lighter-weight components require significant development.

R&D Needed to Overcome Barriers

Driveline Materials

Parasitic losses in drivelines are small, but advanced materials could significantly reduce driveline weight. Lightweight advanced composite drivelines would also reduce driveline vibrations and reduce the need for multiple drivelines and center bearings on long-wheelbase trucks. Research projects aimed at reducing the cost of metal matrix and carbon fiber composites and of other advanced lightweight materials will help accelerate the adoption of these materials in drivelines.

Axle Materials

The energy losses from drive axles in heavy-duty trucks are small compared with aerodynamic and rolling resistance losses. Still, it is estimated that the use of advanced designs, gear coatings/treatments, and lubricants could improve fuel economy by up to 3%. Additionally, truck axles, which contribute substantially to vehicle weight, could be made lighter through the use of advanced lightweight materials and cost-effective manufacturing techniques.

Transmission Materials

Advanced transmissions on the 21st-century truck will need to meet performance criteria that significantly exceed today's capabilities. The development of CVTs and other advanced lightweight transmissions for heavy vehicles requires high-performance gear steels and lubricants. Gear steels of greater toughness, fatigue strength, and resistance to pitting (contact fatigue) than current steels are needed to meet the performance challenges. Development of cost-effective synthetic lubricants that can withstand higher temperatures and stresses is also needed for high-performance transmissions.

Wheel and Tire Materials

Wheels and tires, which make up 14% of the weight of a Class 8 tractor, affect rolling resistance losses and provide the link between vehicle and ground that controls braking and tractive power transmission. The most significant rolling resistance and weight improvements will come from newer wheel and tire configurations. To make advanced wheel and tire designs possible, improved materials and the analytical tools to predict and optimize their performance are needed.

Goals

The goal of materials R&D for wheels and tires is to reduce the weight and rolling resistance of wheels and tires while enhancing vehicle safety by reducing stopping distances and increasing vehicle stability. Specific goals include reducing rolling resistance by at least 15%, reducing tire/wheel weight by 300 kg for a typical 6 × 4 Class 8 tractor, and reducing wet stopping distance by 30%for a Class 8 tractor/trailer. Research to make recapped tires more fuel-efficient and safe will result in significant life-cycle energy savings.

Barriers

The higher cost of alternative lighter metal and composite materials and the lack of durability and reliability data for wheels, which are safety-critical components, are barriers. Analytical, simulation, or evaluation methods are needed for tires and materials for tire rolling resistance, traction, and durability, specifically in the area of tire-to-road contact. An effective pressure monitoring method is needed to reduce average tire rolling resistance. The rolling resistance of recapped tires is often higher than for new tires. Additionally, the durability of recapped tires needs improvement, especially in the area of interfacial bonding of the casing and tread band. The use of new-generation wide-base tires to reduce weight and lower rolling resistance will require pressure monitoring, thorough pavement damage studies, inch-width laws, and run-flat technology for certain truck applications

R&D Needed to Overcome Barriers

Wheel Materials

Steel wheels and conventional ductile iron hubs are standard components offered by heavy-vehicle manufacturers. Forged aluminum wheels and forged or cast aluminum hubs are offered as higher-cost options. Because of the significant cost penalty associated with aluminum hubs and wheels, use of these materials is not widespread. Durability and reliability concerns regarding lower-cost cast aluminum wheels, commonly used in the automotive industry, have prevented their use in heavy vehicles. Short-term research needs include the development of lower-cost, high-strength, high-toughness austempered ductile irons, squeeze-cast aluminum, and semi-solid formed aluminum for heavy-vehicle hubs and wheels. Longer-term research needs include the development and application of magnesium alloys and advanced metal matrix composites (MMCs) for reduced wheel weight, the development of innovative wheel designs that incorporate such features as localized reinforcements, the use of metal foams, and new manufacturing methods for making lighter wheels. This materials research should focus on facilitating the development of cost-effective wide-base single-wheel and -tire systems.

Tire Materials

Tires represent an opportunity to reduce both parasitic losses and weight in trucks while contributing to reductions in stopping distance. The bulk of the weight and rolling resistance savings will come from new configurations (e.g., wide-based singles replacing dual tires), tread and casing design, and improved control of inflation pressure. Reductions in stopping distance will come from new tire tread compounds and new tread pattern designs. Additional improvements in elastomeric materials and the modeling of tire characteristics, tire performance,

and elastomeric materials will yield significant benefits in fuel economy, safety, and tire life. Research needs include the development of new analytical modeling tools and improved test methods to validate model predictions.

Tire traction on wet surfaces can be improved through better simulation, design, and test methods related to tire materials and tire tread pattern design. Current modeling capabilities do not adequately predict road-to-tire surface contact forces or surface temperatures, both essential elements in defining better material design. Specific research is needed in mapping of tire contact surface temperature and its application to tire material research.

Total tire rolling resistance can be reduced through the new tire configurations. Additional reductions are possible through better simulation and design of tire materials. Current test methods and simulation tools used to predict tire rolling resistance and design materials are based on smooth road wheel measurements. Real road surfaces produce significantly higher rolling resistance values. Research is needed in the areas of measurement and simulation tools used to study and design tire materials for actual road surfaces.

A currently available Class 8 type truck tire contains around 28 lb of steel reinforcement, or about 504 lb per tractor-trailer. Specific research is needed in the development of ultra-high-strength reinforcement materials that could reduce this weight by 30%.

Tire rolling resistance increases when the inflation pressure is lower than the prescribed level. Under-inflation also increases the risk of early tire failure. Effective, reliable tire pressure monitoring could reduce rolling resistance losses and improve tire durability. Different sensor and communication technologies are being developed. However, research in sensor and integration materials is needed in order to guarantee robustness in the hostile inflated tire environment.

Tire retreading provides for efficient reuse of tire casings. Retread tire life is often limited by problems with the adhesion of the tire casing to the retread band. Analytical interfacial studies and new bonding materials are needed to improve the overall integrity and robustness of the interface between the tread band and the tire casing.

Braking Materials

To support the DOT goal of a 50% reduction in heavy-vehicle-related fatalities and overall 21CT safety goals, shorter stopping distances and improved vehicle stability during braking and maneuvering are required. Additional 21CT goals include reduction of aerodynamic, rolling, and drive train losses, all of which increase demands on truck brakes. Ideally, trucks would be able to stop in the same distance as passenger vehicles. However, with current brake technology, this is not possible.

Brake system materials consist of mainly iron, steel, and brake shoe/pad friction materials. They have an extremely important impact on vehicle safety and operating cost and contribute significantly to vehicle weight. For example, a Class 8 tractor air drum brake system (drum, hub, brake assembly) is estimated to weigh 600 to 700 kg (1300 to 1500 lb). Safety goals outlined in the 21CT Technology Roadmap[1] include supporting the DOT goal of a 50% reduction in heavy-vehicle-related fatal accidents. Improved brake systems represent the most important technical element in meeting this goal. Additional 21CT goals include reduction of aerodynamic, rolling, and drive train losses, all of which put increased demands on the trucks service brakes. Although brake stopping performance and safety are an overriding requirement, brake material durability and wear characteristics also have a major impact on vehicle maintenance and operating costs and must be effectively addressed in order to obtain market acceptance. Finally, successful

development of improved lightweight brake component materials requires a systems approach that focuses on the overall performance of the friction pair (rotor/drum and brake pad/shoe materials).

Goals

The goal of research on materials for brakes is to facilitate meeting the 21CT safety goal (Table 1): enhancing the stopping distance of trucks by 30% or more and reducing vehicle rollovers by enhancing the stability of the truck during braking.

Barriers

Heavy-duty air disc brake systems that offer some improvement in stopping distances do not have market acceptance because of cost and durability issues. Currently available drum and rotor cast iron materials are approaching their operating limits for wear and fatigue, and research efforts to develop alloy cast irons with improved wear and thermal resistance have been limited. Brake shoe/pad friction materials compatible with lightweight MMC brake drums and rotors for heavy-duty truck applications are not developed. Changes in brake component materials require extensive durability and reliability testing because of potential safety and product liability concerns. Improved laboratory test methods are needed to enhance brake system development. Fundamental analytical and modeling tools do not exist for optimizing friction pair performance. The wear characteristics of brake pad/shoe compositions need to be improved while their friction behavior is maintained. Cost-effective lighter-weight materials need to be developed for auxiliary brake components such as brake calipers, slack adjusters, air brake chambers, and air tanks. Innovative thermal management and thermal capacity concepts are needed. Low-friction, low-wear materials and coatings are needed for brake actuation systems.

R&D Needed to Overcome Barriers

Overcoming these barriers will require new non-toxic brake materials that will survive the 900–1000°C temperatures that can be reached on mountain descents while providing desirable friction and wear characteristics under less severe operating conditions where most braking occurs. Furthermore, a high coefficient of friction is desirable so that brake torque can be modulated over a wide range needed for balancing braking action between different wheels to ensure vehicle stability during braking. To achieve these goals, the friction and rotor/drum materials cannot be developed in isolation from each other but must be considered together as a tribosystem.

Friction Materials

Currently available friction materials start to wear rapidly and fade at temperatures above about 450°C. Hence, friction material is the material needing the most improvement to avoid loss of friction and hence stopping power at elevated temperatures. With thermal conductivities typically less than 10% those of gray cast iron, friction materials function much like thermal insulators, forcing the drum or rotor alone to store and dissipate heat generated at the friction interface. Research is needed to develop friction materials with higher thermal conductivity that allow extraction of heat into the caliper, providing the added thermal mass and surface area needed to control the maximum brake temperature.

Friction materials with a longer wear life, in addition to reducing truck operating costs, will reduce undesirable environmental impact and energy consumption. More than 1×10^{8} lb of friction materials that require more than 1×10^{12} Btu of energy to produce are used in North America annually, mostly as a direct consequence of truck operation. Most of this material is turned into wear debris and expelled into the air and water.

Rotor/Drum Materials
Although most heavy trucks in the United States use drum-type brakes, their European counterparts have almost universally converted to disc brake systems. Testing by brake and vehicle makers has shown that disc brake systems outperform drum brakes in terms of stopping distance and fade resistance. However, disc brakes (both rotor and pad materials) often have higher wear rates and rotor failure rates than drum brakes.

Meeting these challenges requires materials with high wear resistance, high thermal conductivity, high heat capacity, and resistance to thermal fatigue and thermal shock, in addition to mechanical strength and toughness. Light weight is beneficial because it will reduce the unsprung mass and tare weight of the vehicle and contribute to ride comfort and payload capacity. Aluminum MMC brake rotors and drums have recently been developed and are available on some passenger cars. Preliminary trials of these materials in heavy-vehicle applications have identified a need for shoe/pad friction materials compatible with aluminum MMCs for the heavy truck duty cycle. Carbon/carbon (C/C) and carbon-fiber-reinforced silicon carbide (CSiC) meet most of these requirements and are used for brakes on some race cars and high-performance sports cars, but current materials are far too expensive for truck brakes. A breakthrough that reduces the cost of raw materials and processing of those materials would enable their use in truck brakes. Lightweight cermets consisting of a unique morphology of ceramic and metal phases offer similar potential, but at a fraction of the cost of the C/C and CSiC materials.

FUNCTIONAL MATERIALS

Thermal Management Materials

Introduction
The management of thermal energies will play a critical role in achieving the 21CT energy-efficiency goals. The engine and transmission, aftertreatment systems, electronic on-board computer systems, braking systems, and tires are some of the heat generating sources found on today's on-highway vehicles. Currently, thermal management comprises removing the undesired heat energy from these sources by transferring it to the environment. The functionality of heat generating systems is maintained by staying within specified temperature limits; thus approximately 2/3 of available thermal energy is not used. The overall 21CT goal would be to find better ways to use and manage thermal energies by developing enabling materials.

Thermal management materials for 21CT can be divided into three functional categories that need to be identified and further developed:

1. *Retention* of heat energy (e.g., using exhaust gases to increase the performance of turbochargers)
2. *Removal* of heat energy (e.g., using an engine/transmission coolant system to avoid overheating)
3. *Maintaining* a specified temperature range for optimal performance (e.g., using a NO_x aftertreatment system)

Meeting federal emission regulations will drive the thermal efficiency of the on-highway truck diesel engine. Higher engine operating temperatures give higher thermal efficiencies (better fuel economy) but produce greater amounts of NO_x; lower engine operating temperatures produce less NO_x but significantly reduce thermal efficiency. Determining the highest operating temperature under which NO_x aftertreatment systems can adequately meet emission regulations will establish the new set point for thermal efficiency of the on-highway truck engine.

Goals

The R&D goals for thermal management materials are to develop materials and systems that use a larger fraction of the heat energy generated by the vehicle, instead of rejecting the heat to the environment, and to transfer heat within the vehicle more efficiently. Specific mid-term (5-year) and long-term (10-year) goals are 10% and 20% increases, respectively, in thermal energy utilization from heat sources in the truck.

These goals are relevant to 21CT goals of efficiency, emissions, and safety. Vehicle aerodynamics, and thus fuel efficiency, are significantly influenced by the size of the radiator and other heat exchangers on the front of the vehicle. More efficient heat transfer will permit down-sizing of the radiator and, possibly, placement of the radiator in a more favorable location for good aerodynamic performance. Exhaust aftertreatment strategies and devices will likely drive the thermal efficiency of highway truck engines; improved thermal management will facilitate emissions reduction. Thermal management is relevant to vehicle safety in that management of heat in braking systems can significantly improve braking performance by reducing or eliminating fading. Finally, thermal management may help lower the cost of ownership by reducing the temperature of electronic computer systems, thus increasing the reliability of the devices and reducing vehicle breakdowns.

Barriers

Barriers to meeting thermal management goals exist in performance, manufacturability, cost, and design and database.

Performance

Materials are needed with higher heat transfer capabilities, better reliability and durability, and improved physical properties, such as thermal expansion match with other materials or components.

Manufacturability

New thermal materials must be available, affordable, and capable of being implemented into production without undue added costs to the customer.

Cost

The trucking industry is becoming more like the automotive market in that adding thermal management materials and systems must be value-added to the industry and driven by customer demand.

Design and Database

Developed thermal management materials must be accepted by truck designers as being viable, reliable, and durable through the development of material property databases and design methodologies that are understood and accepted.

R&D Needed to Overcome Barriers

Diesel Engines

New materials need to be developed to better manage heat rejection from diesel engines. Fuel efficiency could be increased if the aerodynamic drag forces of the truck could be reduced. Materials that remove heat faster from the engine and other generating sources could reduce the cooling requirements on trucks and thus reduce aerodynamic drag forces**.** There is need to develop more efficient heat transfer materials/processes for components such radiators, charge air coolers and A/C condensers which facilitate heat transfer from the diesel engines. In addition, developing uses for the excess thermal energy need to be designed and tested before rejecting it to the environment. Thermal management materials would be at the forefront of this R&D effort.

Aftertreatment Systems
The effort to meet federal regulations on NO_x and particulate aftertreatment systems for diesel engine would benefit greatly from an active closed-loop thermal management system. Aftertreatment systems to reduce NO_x are known to operate most effectively within a narrow temperature window. Active thermal management materials and systems need to be developed that will integrate with yet-to-be-developed NO_x sensors. The future emission controls will generally result in higher operating temperatures for exhaust system components such as exhaust pipes, mufflers, and associated hardware. There is need for more cost-effective, heat-resistant materials for these components**.**

Particulate traps will probably require thermal energy to regenerate their filtering function, and thermal management systems could be used to redirect excess thermal energy from the engine or transmission to the particulate trap. Thermal management materials and systems need to be developed to meet these yet-to-be-defined requirements.

Braking Systems
Brakes generate heat as a result of frictional contact between materials to stop trucks; they present a safety issue if they become overheated. Drum-type brake systems "fade," or lose their stopping ability, because of overheating. Disc-type brake systems are less prone to fading, but they are not installed as standard equipment on most large on-highway vehicles. Hauling heavy loads exacerbates problems with the braking systems for trucks. If thermal management materials and systems were developed to stop trucks without brake fading, trucks would gain additional factors of safety.

Electronics
Too much thermal energy will destroy the functionality of electronic components. Trucks and other highway vehicles are increasingly dependent on electronics and computer systems for standard operation. Thermal cycling of electronic components is the major failure mode, and more heat-resistant materials are needed. Thermal management materials and systems need to be developed to provide greater reliability and durability to address thermal cycle fatigue failures.

Smart Materials

Introduction
Materials whose properties change with an application of a control signal are generally called "smart" materials. Given the increased sophistication of truck and propulsion engineering, the introduction of smart materials offers levels of flexibility, controllability, and accuracy not achievable with conventional materials. Possible application areas are numerous and require a wide range of smart materials types, including piezoelectric, magnetostrictive, and thermoelectric materials.

Goals
R&D goals for smart materials include developing the enabling technologies to commercialize at least one smart material application in trucks within 5 years and applications in propulsion, structural body and chassis, and power transmission systems within 10 years. Longer range goals are to establish the competency of U.S. materials suppliers in developing and manufacturing smart materials and applying them to the design of trucks and truck components, and to develop a comprehensive material properties database and smart material system analysis tools.

Barriers

Performance

Although many performance-related barriers are specific for each type of smart material, several common issues limit the extent of their current use. The performance of a smart material is usually based on a unique physical phenomenon, sometimes discovered in a particular chemical composition. It often takes a long time to discover or develop other compositions with similar behaviors. For example, the piezoelectric properties of quartz and Rochelle salt have for decades been the benchmark of piezoelectric material performance. The discovery of lead zirconate–lead titanate ceramics, with their greatly improved properties, broadened the applicability of piezoelectric materials, taking them from the realm of physical curiosity to engineering designs. New compositions not yet discovered may offer a further increase in piezoelectric properties, allowing design miniaturization and reducing applied voltage requirements.

Manufacturability

Although smart materials generally require expensive precision fabrication, established manufacturing approaches could be used in many cases. When smart materials are included as part of the engineering structure or as a panel, manufacturing techniques developed for composites (e.g., layering, weaving) can be used. Manufacturing of stacks for actuators could be based on established techniques for fabrication of capacitors. Smart materials could be applied as coatings based on various vapor-deposition approaches. Manufacturing-related barriers typically involve the application of established techniques to new materials, rather than the invention of new techniques. Controllability and repeatability of the manufacturing process is extremely important, as smart material properties depend greatly on keeping material density and chemical composition within a narrow range.

Cost

A significant share of smart material costs is contained in the cost of raw materials.

Design and Database

Because smart materials need to respond to a change in the environment or the operating conditions, a systems integration approach to designing smart materials systems is extremely important. Dedicated electronics often are required to leverage the potential for a smart material system, as performance of the smart material needs to be precisely controlled or accurately assessed by an engine or vehicle controller.

Effective application of smart materials is sometimes hindered by a lack of analysis tools that could consider complex chemical, electromagnetic, and mechanical interactions within the framework of a single software package. Material properties databases are often incomplete, and data provided by commercial suppliers are often difficult to compare because they were obtained using different testing methods.

R&D Needed to Overcome Barriers

Sensors

R&D is needed in detection of incipient structural failure, fast-acting temperature measurement devices, measurement of relative humidity for detection of EGR condensation, and detection of the start of combustion.

Actuators

R&D is needed in actuation of diesel fuel injection, active and semi-active vehicle suspension and engine mounts, attenuation of structure-borne noise, and positioning of aerodynamic drag reduction panels.

Structural Panels
Capabilities need to be developed in sensing and reacting to mold fill, resin cure, and fiber damage and in sensing other types of stimuli.

Coatings
Thermo-refractive coatings need to be developed for laser protection/thermal management and self-control of thermal conduction. Thermal reflecting coatings are needed for infrared covering/passive climate control in vehicles. Electrochrome and electro-reflecting systems are needed to control the physical magnitudes of radiation on visible, infrared, and radar spectrum. Light- and mar-resistant glassing for cabins, cockpits, and windows needs to be developed.

RESOURCE REQUIREMENTS

GAP ANALYSIS

Table 2 summarizes the level of activity for each of the materials R&D topics. A more detailed listing of individual projects versus R&D needs from the 21CT Technology Roadmap is given in Table A.1; other relevant projects, funded by DOE OAAT and the DOE Fossil Energy Solid State Energy Conversion Alliance, are listed in Table A.2 (see Appendix A). Although the projects in Table A.2 are not intended to support heavy vehicle applications, a fraction of the materials research is relevant to heavy vehicles.

Table 2 may be used to determine at a glance which of the R&D topics described in this plan are obviously underfunded at present. This information may be useful for establishing priorities for new projects and may help the 21CT Program develop a more balanced portfolio of projects. Unfortunately, the table cannot be used to ascertain which projects are adequately funded. To that end, a summary of estimated resource requirements for meeting the goals contained within this plan is given in Table 3.

The following conclusions may be reached by examining Table 2:

- The current effort in propulsion materials to meet 21CT emissions goals is modest and likely insufficient.
- There is no current effort in materials for heavy vehicle hybrid propulsion. This technology represents a significant opportunity for initiating new government-funded R&D.
- Materials development for fuel cells is an obvious opportunity for developing new projects; there are currently no such projects in the 21CT portfolio. However, there are numerous projects in the DOE automotive and fossil energy SOFC programs (Table A.2)
- Although 21CT has several projects in crashworthiness, none of them is focused on materials. The development of structural body and chassis projects to support the crashworthiness goals is indicated.
- The ongoing effort in braking materials to support safety goals should be encouraged and enhanced to address affordability.
- Materials for tires present an obvious opportunity because 21CT has no projects in materials for tires.
- Although functional materials cut across all the 21CT goals, the ongoing efforts are mostly limited to meeting the fuel efficiency goals. New projects in thermal management and smart materials to support emissions, safety, and affordability should be considered.

Table 2. Relative level of effort for research and development in materials technologies to support the goals of the 21st Century Truck Program

Materials Technology	21CT goals[a]					
	Efficiency by truck class			Emissions	Safety	Affordability
	8	2b–6	Buses			
Propulsion materials						
Diesel engine					NA	
Hybrid propulsion					NA	
Fuel cells					NA	
Structural body and chassis						
Weight reduction (Manufacturing, design and database, joining, maintenance, and repair)				NA	NA	
Crashworthiness	NA	NA	NA	NA		NA
Power transmission						
Braking	NA	NA	NA	NA		
Tires				NA		
Drive train				NA	NA	
Functional materials						
Thermal management						
Smart materials						

[a]In some cases a single, significant project was counted against more than one goal. For example, a technology that improves efficiency might apply to all classes of trucks.

KEY:

A significant level of effort, at least four projects and/or funding of at least $500K per year.

A modest level of effort, two or fewer projects and funding of more than $100K per year but less than $500K per year.

Little ongoing effort.

NA — The technology does not strongly support the specific goal and projects would not be expected.

Table 3. Materials technology funding requirements by fiscal year ($ in thousands)[a]

Technology	Fiscal year					
	2002	2003	2004	2005	2006	2007
Propulsion materials						
Diesel engine	5,500	13,000	13,000	12,500	11,500	10,000
Hybrid propulsion	100	1,000	2,000	3,000	2,000	2,000
Fuel cells	100	2,000	4,000	5,000	6,000	6,000
Subtotal	5,700	16,000	19,000	20,500	19,500	18,000
Percentage of total	33	40	39	37	38	41
Structural body and chassis						
Crashworthiness	200	1,500	2,000	2,500	2,000	2,000
Materials development	1,400	2,500	3,000	3,000	2,500	2,000
Manufacturing	6,000	6,500	7,000	7,500	7,000	6,500
Design and database	500	2,500	2,500	3,000	2,500	2,000
Joining, maintenance, and repair	600	2,000	2,500	3,500	3,000	2,500
Subtotal	8,700	15,000	17,000	19,500	17,000	15,000
Percentage of total	51	37	35	35	33	34
Power transmission						
Braking	900	2,500	3,000	3,500	3,000	2,000
Tires	200	600	1,200	2,000	2,500	2,000
Drive train	300	2,500	3,000	3,000	3,000	2,000
Subtotal	1,400	5,600	7,200	8,500	8,500	6,000
Percentage of total	8	14	15	15	17	14
Functional materials						
Thermal management	500	1,500	2,000	3,000	3,000	2,500
Smart materials	800	2,000	3,000	4,000	3,000	2,000
Subtotal	1,300	3,500	5,000	7,000	6,000	4,500
Percentage of total	7	9	10	13	12	10
Total	17,100	40,100	48,200	55,500	51,000	43,500

[a]These funding estimates do not include the projects in the DOE Office of Advanced Automotive Technologies or the DOE Fossil Energy Solid State Energy Conversion Alliance, which are shown in the Appendix A, Table A.2. Part of that research is, of course, relevant to heavy-duty applications. The funding estimates shown are the government share of the project cost; it is assumed that industry cost share will match the government contribution.

REFERENCES

1. *Technology Roadmap for the 21st Century Truck Program, A Government-Industry Research Partnership*, 21CT-001, December 2000.

2. *Workshop on Opportunities for Heavy Vehicle Energy Efficiency Gains Through Running Resistance and Braking Systems R&D*, September 10, 1999.

APPENDIX A

Table A.1. R&D Needs from the *Technology Roadmap for the 21st Century Truck Program*, 21CT-001 (December 2000)

Table A.2. Table A.2. Expected funding for FY 2002 for relevant projects funded by the DOE Office of Advanced Automotive Technologies and by the Solid State Energy Conversion Alliance

Table A.1. R&D Needs from the *Technology Roadmap for the 21st Century Truck Program*, 21CT-001 (December 2000)	State of R&D				Federal Projects that meet this R&D need			
	Advanced Research	Component and technology Development	System Integration and Development Testing	Field Test and Evaluation	DOE	DOD	DOT	EPA
Propulsion Materials - Diesel Engines								
Develop cost-effective piezoelectric or magnetostrictive fuel injector materials & manufacturing processes to facilitate injection rate-shaping & multiple injections					277, 285			
Develop wear and scuffing-resistant fuel injector materials and coatings for high-pressure use.					279, 286, 287, 289, 276			
Develop precision manufacturing processes for fuel injector system components (precision holes in nozzles and plungers, sharp edges, …)					293, 294			
Develop materials for NOx and PM sensors					284			
Develop materials for NOx & PM reduction technologies with high conversion efficiency and durability					273, 290			
Develop corrosion, creep, wear-resistant and lightweight materials for air-handling systems.					274, 275			
Develop high strength, creep-resistant materials for high BMEP engines						78		
Develop stable, corrosion-resistant materials for natural gas engine components, such as glow plugs and valve train components					291, 272			
Develop materials for on-board gas storage to enable natural gas and hydrogen fuels					308			
Develop physical and mechanical property data needed to design engine components from advanced materials					282, 292, 281, 283			
Propulsion Materials - Hybrid Propulsion								
Develop materials for energy storage: batteries, ultracapacitors, flywheels, hydraulic-pneumatic systems								
Develop improved materials for power electronics: electric motors, capacitors, inductors, power modules, and packaging (seals, clamping, electrical connections)								
Propulsion Materials - Fuel Cells								
PEM: develop effective, low-cost catalysts, lower-cost, higher-temperature membranes, durable, affordable bipolar plates, and improved packaging								
SOFC: develop improved, high-efficiency, lower-temperature electrodes, materials for SOFC packaging and assembly, insulating seals, high-temperature bus bar, gas connections, and metallic housings								
Reformers: develop materials for fuel reformers appropriate to each fuel cell type								
Lightweight Materials								
Develop low-cost processes for manufacturing large components in order to reduce part count and assembly steps					296, 298, 302, 303, 322			
Develop appropriate cost-effective manufacturing technologies for lightweight materials to reduce the weight of structural members of class 7-8 tractors, trailers, and frames in class 2b-6					299, 300, 304, 320, 321	58		
Develop reliable joining methods and maintenance and repair technology for lightweight materials					315			
Develop manufacturing processes to take advantage of the high specific strength of magnesium and titanium alloys								
Develop predictive analytical computer models for dimensional management of full assemblies					318			
Develop design methodology and materials usage to achieve weight reduction					301, 305	48		
Assess the potential of lightweight, high-strength polymer-matrix composites to meet performance and cost goals for structural applications					319, 323		32	
Develop technology in support of advanced lightweight materials, joining, maintenance, and repair					297, 315			
Power Transmission Materials								
Develop improved friction materials and materials for improved braking systems to facilitate 30% reduction in truck stopping distance					248, 314, 363			
Develop materials for improved tires with lower rolling resistance and higher reliability								
Develop improved materials and surface treatments to reducer parasitic losses in drive train components					238, 239, 316			
Functional Materials								
Develop materials with improved heat transfer properties to facilitate thermal management and reduction of heat exchanger sizes					288, 313, 364			
Develop smart materials for sensors and actuators					277, 280, 285			

Table A.2. Expected funding for FY 2002 for relevant projects funded by the DOE Office of Advanced Automotive Technologies and by the Solid State Energy Conversion Alliance ($ in thousands)

Technology	Title	Expected funding
Fuel cells[a]	Carbon Composite Bipolar Plates for PEM Fuel Cells	200
Fuel cells[a]	Inorganic PEM Electrode/Support Development	300
Fuel cells[a]	Microstructural Characterization of PEM Fuel Cells	200
Fuel cells[a]	Cost-Effective Metallic Bipolar Plates Through Innovative Control of Surface Chemistry	200
Fuel cells[a]	Metallized Bacterial Cellulose Membranes	100
Fuel cells[a]	Carbon Foam for Humidification System	100
Fuel cells[b]	5KW SOFC Development(only a fraction is materials)	25,000
Thermal management[a]	Carbon Foam/Nanofluid Radiator Technologies	150
Thermal management[a]	Carbon Foam Thermal Management Materials for Electronics Packaging	700
Hybrid propulsion[a]	DC Buss Capacitors	400
Hybrid propulsion[a]	Low-Cost, High-Energy Permanent Magnets	300
Crashworthiness[c]	5 projects	1,650
Materials development[c]	6 projects	3,000
Manufacturing[c]	10 projects	4,000
Design and database[c]	6 projects	2,750
Joining, maintenance, and repair[c]	8 projects	2,500

Sources: Project descriptions may be found in the following reports. The annual progress reports for 2001 will be available in late 2001.

[a]*2000 Annual Progress Report, Automotive Propulsion Materials,* U.S. Department of Energy, Energy Efficiency and Renewable Energy, Office of Transportation Technologies, October 2000.

[b]Solid State Energy Conversion Alliance (SECA), www.netl.doe.gov.

[c]*2000 Annual Progress Report, Automotive Lightweighting Materials Program,* U.S. Department of Energy, Energy Efficiency and Renewable Energy, Office of Transportation Technologies, October 2000.