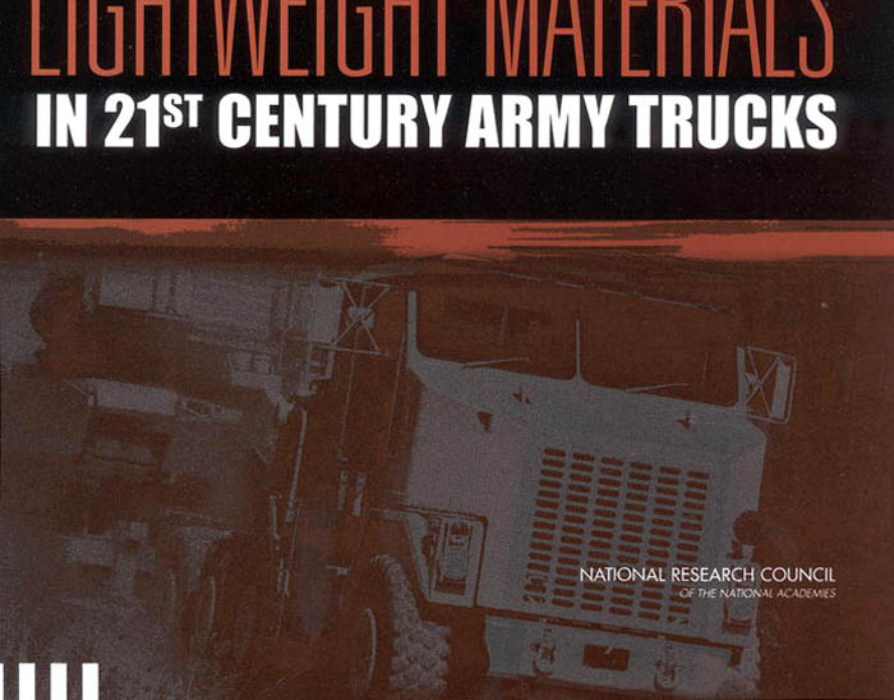
USE OF LIGHTWEIGHT MATERIALS IN 21ST CENTURY ARMY TRUCKS



NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

use of LIGHTWEIGHT MATERIALS in 21st century ARMY TRUCKS

Committee on Lightweight Materials for 21st Century Army Trucks
National Materials Advisory Board
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Preface

With future truck purchases in mind, Paul Skalny of the National Automotive Center (NAC), U.S. Army Tank-Automotive Research, Development, and Engineering Center (TARDEC), asked the National Research Council (NRC) to perform a study under the auspices of the National Materials Advisory Board. Dr. Skalny is program manager of the National Automotive Center, the goals of which include improving the fuel efficiency of several classes of Army tactical wheeled vehicles. One approach to increasing fuel efficiency is to decrease vehicle weight.

The NRC Committee on Lightweight Materials for 21st Century Army Trucks was asked to identify research and technology development opportunities related to the introduction of new lightweight structural materials for light, medium, and heavy Army trucks. To address these objectives, the committee was asked to perform the following tasks:

- Investigate materials, processes, and structural concepts that will be candidates for advanced truck applications for the Army;
- Review the technical state of the art in lightweight structural materials and low-cost processing technology for automotive and truck applications, including advanced steels, wrought and cast aluminum, magnesium, titanium monolithic alloys, polymer matrix composites, and metal matrix composites;
- Identify critical properties, design issues, maintenance issues, potential failure mechanisms, and end-of-life disposal or recycling processes for advanced materials and processes;
- Recommend research and development opportunities and programs to evaluate and develop new advanced materials, processes, and structural concepts for advanced Army truck applications; and
- Recommend methods for TACOM to coordinate its advanced materials research efforts with industry and other federal agencies.

Committee members were chosen for their expertise in mechanical, chemical, and metallurgical processes; inspection and repair; engine systems and fuel efficiency; new materials systems; and the economics involved in the introduction of new materials into automobiles and trucks. The committee held four meetings to gather information and to deliberate. This report is the result of those deliberations.

As a result of its early investigations, the committee came to believe that addressing new materials technologies and the processes for preparing and handling structural materials did not adequately address the charge. It was decided that it was also necessary to consider and discuss the process of introducing new lightweight structural materials, as well as other means of reducing vehicle weight. This belief led the committee to consider, enumerate, and discuss factors peculiar to the Army that interfere with the easy and early introduction of new materials for Army trucks.

An important means of reducing vehicle weight, in addition to using lightweight structural materials and improving fuel economy, is through the use of alternative power sources, such as hybrid electric powertrains. The engine, the heaviest single component in a truck, must have sufficient power to move the fully loaded vehicle under difficult conditions. This power is wasted, however, for the 80 percent of an average Army vehicle's life that is spent partially loaded on paved roads at highway speeds. Because the use of alternative and hybrid power sources has such great potential for reducing engine size and, thereby, vehicle weight, the committee believed that it was appropriate to include a discussion, although not exhaustive, of such power sources in the report.

Vehicle performance depends on a myriad of factors. It was not possible for the committee to predict improvements in fuel efficiency that might result from its recommendations with respect to research and development. Other work referenced in the report—for example, that of the Department of Energy's Heavy Vehicle Technologies Program and the Partnership for a New Generation of Vehicles—addresses potential fuel economy improvements from reduced engine size, the introduction of hybrid designs, and general reductions in vehicle weight.

As chair, I wish to thank the committee members for their enthusiasm, dedication, and service. I also thank the meeting speakers for their hard work, insight, excellent presentations, and stimulating discussions. One individual deserves special mention: Eddie Garcia, director of Government Marketing, served as host to the committee during its visit to Oshkosh Truck Corporation. Mr. Garcia and all of the other Oshkosh employees were completely open with the committee, a most unusual but satisfying occurrence. In addition, Mr. Garcia kept watch over the flow of conversation and, whenever he determined that another engineer with special knowledge was needed, saw to it that that person came quickly to lend his or her expertise.

I believe that our report will serve the Army well for some years to come. Comments and suggestions can be sent via e-mail to NMAB@nas.edu or by fax to 202/334-3718.

Harry A. Lipsitt, *Chair*
Committee on
Lightweight Materials for 21st Century Army Trucks

Acknowledgments

The Committee on Lightweight Materials for 21st Century Army Trucks thanks the following individuals, who prepared and presented so much information: Hal Almand, National Automotive Center (NAC), U.S. Army Tank-Automotive Research, Development, and Engineering Center (TARDEC); Joseph Argento, Industrial Ecology Center, Picatinny Arsenal, U.S. Army; Richard Bazzy, Cost and System Analysis Office, TARDEC; Dale Boulton, AM General; James Brennan, Oshkosh Truck Corporation; Mike Church, Stewart and Stevenson; Paul Decker, Future Combat Systems Program, U.S. Army Tank-automotive and Armaments Command (TACOM); Elio DiVito, Research-Vedtronics Technology Area, TARDEC; James J. Eberhardt, U.S. Department of Energy; Pat Flaherty, U.S. Department of Energy; Eddie Garcia, Oshkosh Truck Corporation; Paul Geck, Ford Motor Company; Nancelee Halle, NAC, TARDEC; I.Carl Handsy, Engineering-MEPS Office, TARDEC; Robert M. Hathaway, Oshkosh Truck Corporation; Chad Johnson, Oshkosh Truck Corporation; Virgil Lambert, Readiness Operations Management Office, TACOM; Mathew Loew, Stewart and Stevenson Tactical Vehicle Systems, LLP; Steve Nimmer, Oshkosh Truck Corporation; Norbert Osborne, Oshkosh Truck Corporation; Donald Ostberg, NAC, TARDEC; George Schnell, Heavy Tactical Vehicles Program, TACOM; Chris Shakes, Oshkosh Truck Corporation; Paul F. Skalny, NAC, TARDEC; Philip S. Sklad, Oak Ridge National Laboratory; Don Szkubiel, NAC, TARDEC; Mark Thomas, Oshkosh Truck Corporation; James A. Wank, Defense Products Marketing, Inc.; Dennis Wend, TACOM; James Zuwucki, Oshkosh Truck Corporation.

The committee also wishes to recognize the outstanding liaison services of Ben DeMarco, Vickie Furman, Don Ostberg, and Paul Skalny, as well as Elio DiVito, Carl Handsy, and George Schnell. The National Materials Advisory Board (NMAB) liaison was T.S. Sudarshan. Dr. Sudarshan and Mr. Handsy were extremely valuable contributors to the committee's understanding of

the processes involved in preparing specifications for and purchasing new trucks for the U.S. Army.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and the draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report: Thomas W. Eagar, Massachusetts Institute of Technology; John A. S. Green, Consultant; Warren H. Hunt, Jr., Aluminum Consultants Group, Inc.; John J. Lewandowski, Case Western Reserve University; Christopher Magee, Massachusetts Institute of Technology; Phillip S. Myers, University of Wisconsin; Philip S. Sklad, Oak Ridge National Laboratory; and Kathleen C. Taylor, General Motors Corporation (retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by R. Stephen Berry of the University of Chicago. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Finally, we thank the staff of the NMAB, especially Julius Chang, later Toni Maréchaux, and finally Bonnie Scarborough, who served as study directors, and Pat Williams, senior project assistant, for their coordination, cooperation, and assistance throughout the entire process, including the editing and publication of this report.

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Executive Summary

INTRODUCTION

The U.S. Army has approximately 250,000 light, medium, and heavy trucks and 110,000 trailers in service at any given time. These trucks and trailers represent the logistical backbone of military operations.[1] The future Army truck fleet must meet the requirements of the Army's envisioned Objective Force, including the requirements related to deployability, transportability, and mobility. These requirements mandate that Army trucks consume less fuel, undergo significant weight reduction, have a reduced logistics footprint, and need less maintenance while maintaining or increasing payload capacity and other performance criteria.

The use of lightweight[2] materials has the potential to help the Army meet its goals by reducing vehicle weight. The reduction of vehicle weight in itself would increase the ability of the Army to transport trucks and could result in reduced fuel consumption. In addition, some lightweight materials offer the potential for improved corrosion resistance, which would decrease the need for maintenance. The increased fuel efficiency that can result from the use of lightweight materials has additional benefits. Reduced fuel consumption would result in a reduced logistics footprint because less equipment and fewer personnel would be required to support a unit in the field. The true cost of fuel, including delivery, for the Army in normal times is approximately $13 per gallon. This increases to between $100 and $400 per gallon for delivery to war zones with no established fuel lines, roads, or infrastructure.[3] The military vehicle multiplier for weight savings is therefore several times that of civilian vehicles.

The Committee on Lightweight Materials for 21st Century Army Trucks was asked to identify research and technology development opportunities

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[1]U.S. Army Tank-automotive and Armaments Command (TACOM). 1998. Tactical Vehicle Fleetbook. Washington, D.C.: Fleet Planning Office, U.S. Army TACOM.
[2]In the context of this report, "lightweight" refers to materials of high specific strength, which is defined as strength divided by density.
[3]Defense Science Board. 2001. Report of the Defense Science Board on More Capable Warfighting Through Reduced Fuel Burden. Washington, D.C.: Office of the Under Secretary of Defense for Acquisition and Technology.

related to the introduction of new lightweight structural materials for light, medium, and heavy Army trucks. To address these objectives, the committee was asked to perform the following tasks: investigate materials, processes, and structural concepts that will be candidates for advanced truck applications for the Army; review the state of the art in lightweight structural materials and low-cost processing technology for automotive and truck applications, including advanced steels, wrought and cast aluminum, magnesium, titanium monolithic alloys, polymer matrix composites, and metal matrix composites; identify critical properties, design issues, maintenance issues, potential failure mechanisms, and end-of-life disposal or recycling processes for advanced materials and processes; recommend research and development opportunities and programs to evaluate and develop new advanced materials, processes, and structural concepts for advanced Army truck applications; and recommend methods for the U.S. Army Tank-automotive and Armaments Command (TACOM) to coordinate its advanced materials research efforts with industry and other federal agencies.

NEW MATERIALS AND PROCESSING OPPORTUNITIES

The structural applications considered in this report are divided into three categories: the frame running the length of the vehicle, to which the engine, drivetrain, suspension, and truck bed are all attached; the secondary structural elements, or vehicle parts that carry passengers and cargo, such as the cab and cargo bed; and the structural drivetrain, including driveshafts, suspension, steering mechanism, and braking components.

Time frames in the report are operationally defined as follows:

- *Short term*: referring to improved materials choices that can be substituted for existing materials in existing truck systems. This category does not include any fundamental redesign of the truck or its subsystems. Care must be exercised in making such changes because any materials substitution can alter the vehicle’s response to terrain changes and its ability to perform certain functions.
- *Medium term*: referring to a new design or significant rebuilding of a proven truck platform that represents an opportunity for more aggressive materials substitutions. Such an instance might involve the use of a modestly

different architecture or different joining methods. For example, the replacement of a truck's steel frame rails with hydroformed tubes would require changes in several other design aspects and would thereby open up opportunities for materials substitutions.

- *Long term*: referring to changes in the present truck paradigm that would permit the use of radically different materials. In the future, truck architecture may become modular, with power plants providing electric power to driven axle or bed modules. This would eliminate the need for driveshafts and fundamentally change frame configurations.

Research and Development

The committee's conclusions regarding opportunities for materials research and development are summarized in Table ES-1. For the short and medium term, advanced galvanized steel alloys combined with selective, justified application of other advanced materials should meet most of the Army's light vehicle needs. A variety of steels in flat and plate forms are likely to remain the material of choice in the heavy truck categories. Additionally, for the short term, a number of commercially available materials and technologies can be used for Army trucks, including high-strength and stainless steels, aluminum and magnesium alloys, and metal matrix composites (MMCs). Manufacturing processes available today include superplastic forming, castings of aluminum and magnesium alloys, and the use of tailor-welded stamping/forging blanks.

For the medium term, materials such as dual-phase and ultrahigh-carbon steels, aluminum 2519, magnesium, MMCs, and polymer matrix composites (PMCs) are candidates. Finally, for long-term applications, Army trucks can benefit from investment in titanium, smart materials, and additive metal process technologies. Investments in advanced materials, including nonferrous alloys, composites, and coatings, that offer superior performance and reduced operations, maintenance, and service costs would serve the longer-term, mission-specific needs of future tactical trucks and combat programs. In such cases, the need for condition-based vehicle health monitoring cannot be overemphasized.

TABLE ES-1 Summary of Opportunities for New Materials, Applications, and Research

Subsystem	Short Term	Medium Term	Long Term
Frames	High-strength steels, stainless steels, galvanic insulation, corrosion-resistant coatings and design	High-strength steels, hydroformed tubes to replace frame rails, truss frame to replace frame rail/ladder construction, and extend benefits to secondary structure	Magnesium castings, PMCs, light modular structures, and embedded sensors.
Secondary structural elements	Stainless steel (truck cabs), aluminum alloys (truck cabs, cargo beds), superplastically formed aluminum (cab structures), magnesium extrusions (passenger seat frames), sheet molding compound (cab components), tailor-welded blanks (door panels), and corrosion design.	Ultrahigh carbon steels (side impact panels), aluminum 2519 (forged and extruded for use in armor plate), magnesium (body and closure components, seats, front and rear backs), PMCs (truck boxes, side panels, cab structures), multifunctional materials for truck cabs (combine armor and structure), electromagnetic joining, adhesive joining, and friction stir welding.	Titanium (armor plate), smart materials, embedded sensors, self-repair, energy storage, and ballistic protection.
Structural drivetrain	Aluminum alloys (driveshafts), magnesium castings (transmission casings and transfer cases), MMCs (brake drums and rotors), PMC springs for light trucks, and corrosion-resistant coatings.	High-strength steels, magnesium alloys (transmission, transmission case and cover, engine block, suspension components), MMCs (powertrain, brake, wheels), PMCs (driveshafts, springs for heavy trucks), high-performance castings, titanium springs, and higher-performance tire cord.	Titanium springs, embedded sensors, additive metal process technologies (parts on demand), and electric/hybrid drivetrains.

RECOMMENDATION. THE ARMY SHOULD PURSUE THE USE OF LIGHTWEIGHT STRUCTURAL MATERIALS IN ITS TRUCK FLEET, AS FOLLOWS:

- **The Army should follow the guidance in the table "Summary of Opportunities for New Materials, Applications, and Research," in this report.**
- **Research programs should be funded to develop the technologies listed in the table as medium- and long-term opportunities, and these programs should include system integration, development testing, and field testing.**
- **The Army should support the development of databases of the properties of these materials as well as the development of models for processing lightweight materials and for predicting the performance of components manufactured using these materials.**

Tracking New Materials for Repair and Disposal

The use of new materials in Army trucks will have consequences for vehicle assembly, repair, and disposal. When assembling new vehicles or recapitalizing older vehicles, it will be necessary to ensure that galvanic isolation exists between parts made from different materials. The inspection, maintenance, and repair procedures for vehicles with such parts will become increasingly complex. End-of-life disposal and recycling processes will also change.

RECOMMENDATION. THE ARMY SHOULD INSTITUTE A MECHANISM FOR ENSURING THAT DIFFERENT TYPES OF MATERIALS ARE TRACKED DURING REPAIR AND DISPOSAL.

One such mechanism might be a color code or a numbering code that provided each alloy with its own identification. A coding system might clearly indicate to those making field repairs where galvanic corrosion may occur and where it is vital to provide galvanic isolation. (As an example, if all steel parts were one color and all parts made of a different metal were another color, it would be obvious which parts needed to be isolated.)

As different materials are increasingly used on Army vehicles, repair and replacement procedures will become more complicated. For example, composites are now used selectively in Army trucks, and repair procedures for these materials are not generally known and are very different from those for metallic materials. Maintenance training will be required for each new generation of vehicles. In addition, as some parts are changed during recapitalization programs, maintenance and repair manuals will need to be continuously updated. Computerization of future depot maintenance manuals would aid in their being kept current for purposes of repair. Vehicle original equipment manufacturers (OEMs) might be required to maintain these manuals, as well as information on common parts failures, on their Web sites.

METHODS OF ENABLING NEW TECHNOLOGY INSERTION

Barriers to the implementation of lightweight materials technologies in Army trucks include organizational risk-aversion, few design cycles per product, and low production volumes. Means of promoting new technologies were identified, however. First, the Army procurement process could be improved with requirements for fuel efficiency and the use of life-cycle assessment and best-value procurement. Second, maintenance systems could be improved through design for reduced maintenance, systematic replacement of older trucks, and the use of alternative ownership strategies. Third, methods to reduce the cost of new technologies could be used—for example, modular design, the use of common systems and components, and standardization with commercial parts. Fourth, the use of alternative power systems could result in new truck paradigms that enable the insertion of radically different materials. Finally, commercial technologies could be leveraged through the Army's participation in existing collaborative programs. The following three recommendations address enabling technology insertion.

Future Tactical Truck Strategy

The Army truck fleet continues to degrade faster than it can be upgraded through new acquisitions, forcing the Army to use recapitalization techniques simply to maintain the fleet size and effectiveness ratio.[1] While recapitalization permits the introduction of improved components such as the engine, improvements in overall vehicle configuration and structural architecture or the introduction of new lightweight materials are not feasible. New brigade requirements have created pressure to accelerate the introduction of lightweight materials into the truck fleet. In addition, the Revolution in Military Logistics (RML) initiative requires a 75 percent reduction in vehicle fuel consumption.[2] This initiative will most certainly require the aggressive application of lightweight materials.

The initial application of lightweight materials may increase the acquisition cost of a new truck, although the use of these materials may reduce life-cycle costs through enhanced corrosion resistance and reduced energy consumption. Although operations and support costs over the life of an Army truck can be as high as or higher than the initial acquisition cost, the acquisition cost continues to create a constraint when limited budgets are applied at the individual platform level. Moreover, for fear of not winning a contract, major suppliers are reluctant to risk using new technologies that raise the initial cost and/or add risk to the development process.

RECOMMENDATION. THE ARMY SHOULD DEVELOP A LONG-RANGE, FLEET-LEVEL PORTFOLIO STRATEGY THAT ESTABLISHES A SCHEDULE FOR TRUCK ACQUISITION, REMANUFACTURE, AND REPLACEMENT.

Although contingent on future funding, the plan would establish priorities for vehicle replacement with specific requirements for performance, including vehicle weight and fuel consumption for each type of vehicle. In order to reduce the technology development cost burden typically placed on an individual vehicle program, the strategy should also establish a broad technology development program plan. The technology development program should be based on a budget process that prioritizes new technology

[1]V. Lambert, Fleet Planning Office, TACOM. Economic and Military Useful Life of Army Trucks. Presentation to the committee, May 9, 2002.
[2]P.F. Skalny, A.J. Smith, and D. Powell. 2001. 21st Century Truck Initiative Support to the Army Transformation Process. SAE Paper No. 2001-01-2772. Warrendale, Pa.: Society of Automotive Engineers.

development. The program should establish concept development activities leading to the fabrication of prototype vehicle demonstrators. In order to leverage resources outside the Army, the technology program should involve vehicle integrators, material and component suppliers, other branches of the Department of Defense, other government agencies, and any other key sources of technology. The accomplishments of existing government programs should be leveraged to the greatest extent possible.

Bid Solicitation and Procurement Processes

The most effective way for the Army to influence the cost and performance of future truck designs is through the procurement process.

RECOMMENDATION. THE ARMY SHOULD MODIFY ITS BID SOLICITATION AND PROCUREMENT PROCESSES TO STIMULATE AND REINFORCE DESIRED REACTIONS, INCLUDING:

- **The Army should clearly define the performance attributes that are important in its use of trucks. For example, if reduction of the logistical footprint is important, this attribute and its method of measure must be defined; if the total cost of ownership or life-cycle costs are important, these attributes should be defined. The bidding process should be structured to reward improvements in these performance attributes.**
- **The Army should provide minimum values or, preferably, scaled values for each performance attribute. For example, the value to the Army of reducing the logistical footprint or increasing fuel economy should be indicated.**
- **In selecting the winner of a competition, the Army should make certain that all performance attributes, including specifically the cost of ownership, are given their appropriate weighting in the decision.**
- **The Army should develop and adopt a consistent life-cycle costing methodology for evaluating alternative technologies. At a minimum, energy costs, maintenance costs, and end-of-life costs should be incorporated into this methodology. It should be emphasized in the request for proposals that life-cycle cost will be heavily weighted in the selection decision.**

- **Life-cycle costs should be extended to implement best-value procurement practices. The value of all performance attributes should be quantified and these metrics used to select the best-value truck to meet the Army's needs.**
- **The Army should review and revise its needs regularly. The description of an ideal truck varies across time, geography, and need for use. The procurement process must be flexible and responsive to these changing demands.**

System for Tracking Vehicle Age and Condition

Army trucks are kept in service far beyond their economically useful life, resulting in increased operations and support costs and decreased performance. The effectiveness ratio of the total Army tactical wheeled vehicle fleet was recently calculated to be about 0.63 (compared with 1.0 for a new fleet).[3] Effectively, eight existing trucks are required to do the work of five new ones. In addition, the annual total operating and maintenance (O&M) costs for the Army truck fleet is about $1.5 billion, or more than $6,000 per truck. These costs are increasing at a rate of about $30 million per year, while the fleet size is being reduced from about 250,000 to about 225,000 trucks.[4] Other data indicate that a large fraction of these costs are for corrosion repair. The economically useful life of a truck has recently been estimated to be about 13 to 16 years, at which point the effectiveness ratio is reduced to 0.5.[5] Retirement and/or replacement should be considered at this age.

RECOMMENDATION. THE ARMY SHOULD ESTABLISH A MECHANISM FOR RETIRING OLDER TRUCKS AND FOR REPLACING TRUCKS IN POOR CONDITION WHEN THE AVERAGE YEARLY MAINTENANCE COST BECOMES PROHIBITIVELY HIGH.

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[3] See note 1 above.
[4] See note 1 above.
[5] See note 1 above.

A centralized tracking system might be used to record the present position of every truck in the fleet and ensure that trucks are retired and/or replaced on a regular basis. (Both Federal Express and United Parcel Service use such tracking systems for their trucks.) Such a system might also be used to select trucks for participation in recapitalization programs. Currently, the age and condition of Army trucks sent to such programs varies widely.[6] Data on repairs and parts failure could be shared with manufacturers in order to facilitate design improvements. A more standardized system for the replacement of damaged trucks would promote the introduction of new materials and technologies into the truck fleet.

COORDINATION OF RESEARCH

The committee was asked to recommend methods for TACOM to coordinate its advanced materials research efforts with industry and other federal agencies. The following recommendation addresses this issue.

Leveraging Commercial Advances

The unique duty cycles and mission profiles of Army trucks constitute a special defense requirement. To respond to this requirement, the Army must take the lead in driving investments in new materials that have the potential to deliver competitive advantage in the logistics arena, supporting warfighters and combat equipment. At the same time, the Army can more actively leverage new materials and manufacturing technologies from the private and academic sectors by investing directly in research and development programs that lead to proof-of-concept demonstrations. The Army's Small Business Innovative Research (SBIR) program is to be complimented for past accomplishments in this area; it should be kept well funded and targeted to the lightweight trucks initiative in order to encourage high-quality material and manufacturing innovations from academia and industry.

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[6]R.M. Hathaway, Oshkosh Truck Corporation. Presentation to the committee, May 9, 2002.

RECOMMENDATION. THE ARMY SHOULD LEVERAGE NEW COMMERCIAL MATERIALS AND MANUFACTURING TECHNOLOGIES TO ACCOMPLISH ITS GOALS OF IMPROVED MOBILITY, DURABILITY, AND FUEL EFFICIENCY IN NEW TACTICAL TRUCKS. TO ACCELERATE TECHNOLOGY TRANSITION, THE ARMY SHOULD PARTICIPATE IN COLLABORATIVE PROGRAMS WITH ADVANCED MATERIALS INDUSTRY CONSORTIA.

Effective leveraging can allow the Army to evaluate the technical feasibility of new materials and technologies. Pilot demonstrations of new materials and technologies in Army applications would also increase the knowledge and capabilities of the supplier base.

Additional leveraging opportunities for the Army exist in the form of industry-government programs sponsored by the Department of Energy and the Department of Commerce that have identified advanced materials for application development. The emphasis of participants from the commercial automotive industry on the affordability of new materials, such as titanium, magnesium, and polymer matrix composites, should greatly facilitate prudent investment decisions by the Army. By working more closely with university centers of excellence, the Army can identify new enabling technologies in lightweight materials and in sensing and vehicle health monitoring, and it can also fund demonstration projects. The early involvement of key stakeholders—including suppliers, maintenance personnel, and end users—in decisions regarding new materials is essential.

Chapter One

Introduction

> Trucks represent the backbone of any military operation, providing fighting forces with the integral support supplies—equipment, food, water, ammunition and fuel—required for success on the battlefield.[1]

USE OF TRUCKS IN THE U.S. ARMY

The U.S. Army has approximately 250,000 trucks and 110,000 trailers in service at any given time.[2] The majority (approximately 80 percent) of trucks fall into the following three classifications: Class 2B (8,500 to 10,000 lb); Class 6 (19,501 to 26,000 lb); and Class 8 (33,001 lb and over). About 100,000 of the Army's trucks are High Mobility Multipurpose Wheeled Vehicles (HMMWVs), known as Humvees. These fall into Class 2B and are the representative military light truck. An additional 100,000 medium-duty trucks, with 2.5- or 5-ton payload capacities are under Class 6. Finally, more than 20,000 heavy-duty vehicles are under Class 8. These include off-road trucks and specialty vehicles, such as the Palletized Loading System (PLS) truck, the Heavy Expanded Mobility Tactical Truck (HEMTT), the 70-ton Heavy Equipment Transporter System (HETS), the Medium Equipment Transporter (MET), the Light Equipment Transporter (LET), and three models of line-haul tractors. The 110,000 trailers include cargo, flatbed, lowbed, ammunition, van, tanker, and special-purpose trailers.

These trucks and trailers represent the logistical backbone of military operations. The light-truck fleet provides transportation for unit commanders, ambulances, and communications and weapons platforms. The medium-truck fleet is the primary mover of unit equipment and personnel. The heavy-truck fleet provides transportation for bulk quantities of fuel, ammunition,

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[1]P.F. Skalny, A.J. Smith, and D. Powell. 2001. 21st Century Truck Initiative Support to the Army Transformation Process. SAE Paper No. 2001-01-2772. Warrendale, Pa.: Society of Automotive Engineers.
[2]U.S. Army Tank-automotive and Armaments Command (TACOM). 1998. Tactical Vehicle Fleetbook. Washington, D.C.: Fleet Planning Office, U.S. Army TACOM.

and other supplies, and for the deployment of combat vehicles and engineering equipment.[3]

Army trucks are subject to environmental conditions that are very different from those typical for commercial trucks. For one thing, being stationed all over the world, they are subject to a wide range of environmental conditions, including hot dry deserts, damp salty marshes, and cold snowy fields. Exposure to these harsh conditions results in extensive truck corrosion. In addition, Army trucks are subject to tactical threats such as mine blasts and shrapnel fragments.

The duty cycle of Army trucks is also significantly different from that of commercial vehicles. First, Army trucks are typically kept in service for decades, and because the Army has no top-down allocation for vehicles at various stations, there may be a different mix of new and old trucks at each station. Second, because the Army has no dedicated truck operators, Army trucks are driven by many different drivers with many different driving styles. Third, most of the time, Army trucks are parked in unsheltered locations between missions. An Army truck typically averages only 2,000 to 3,000 miles per year. Finally, truck use is highly variable, ranging from peacetime driving on public roads (nearly 80 percent of the time) to battlefield scenarios that include harsh environments and terrains.

U.S. Army Tank-automotive and Armaments Command

Within the U.S. Army, the Tank-automotive and Armaments Command (TACOM) has responsibility for trucks. TACOM dates back to 1940, when the U.S. government built an arsenal in Warren, Michigan. This arsenal collaborated with the automotive industry and built more than 25,000 tanks for the Allied nations during World War II. In 1967, the arsenal was renamed the U.S. Army Tank-Automotive Command and was given control over nearly all of the Army's tank-automotive systems. In 1995, the Armament and Chemical Acquisition and Logistics Activity at Rock Island, Illinois, and the Armament Research, Development, and Engineering Center at Picatinny Arsenal, New Jersey, were added to the command, which then changed its name to the U.S. Army Tank-automotive and Armaments Command. In 1998, Red River Army Depot in Texas and Anniston Army Depot in Alabama were added. Today, TACOM's mission is to provide the Army with ground combat

[3]See note 2 above.

equipment (i.e., tanks), automotive equipment (i.e., trucks), marine equipment (i.e., boats), and armaments technologies and systems (e.g., small arms, machine guns, cannons, and large artillery systems). TACOM's activities include research and development, procurement and fielding, sustainment, and retirement.[4]

Trucks in the Legacy Force Fleet

The Army is facing significantly curtailed budgets for the purchase of new tactical wheeled vehicles. TACOM has estimated that funding is at least $300 million a year below the optimum level for the types and quantities of trucks required.[5] At current replacement rates, more than half of the light-truck fleet will be overdue for either replacement or servicing in the extended service program by 2013. At that time, 5,000 trucks from the original Commercial Utility Cargo Vehicle (CUCV) fleet procured from General Motors between 1983 and 1986 will still be awaiting replacement. Significant numbers of medium-duty trucks will be more than 35 years old.

The age of the Army's existing fleet of trucks, known as the Legacy Force fleet, is resulting in problems in mobility for deployment, readiness, and availability to support combat operations. A recent analysis indicates that the effectiveness ratio of the total tactical wheeled vehicle fleet, now at 0.63, is expected to deteriorate to less than 0.4 by 2013.[6,7] Army planners are faced with setting acceptable levels of economic useful life and operational readiness below those that would be achieved by a full and continuous modernization of the entire fleet.

FUTURE ARMY TRUCKS

The U.S. Army's plans for improvement and modernization are known as the Army Transformation. This transformation has as its goal the evolution of

[4]U.S. Army Tank-automotive and Armaments Command (TACOM). 2001. Our History. Available at <http://www.tacom.army.mil/history.htm>. Accessed March 2003.
[5]See note 2 above.
[6]The effectiveness ratio is one way of measuring the condition of the truck fleet. It is a parameter used by the Army to measure fleet capability by comparing a fleet with a mixture of old and new vehicles against a totally modernized fleet. A totally modernized fleet would have an effectiveness ratio of 1, indicating that the requirements are completely filled. A fleet with an effectiveness ratio of 0.9 would theoretically be able to accomplish 90 percent of its mission.
[7]See note 2 above.

the current Army, defined as the Legacy Force, into the desired future Army, known as the Objective Force. The Objective Force must be capable of meeting and defeating any threat to the national security in the 21st century, including threats from small groups of terrorists and threats from enemies equipped with sophisticated weapons and tactics. The state of the Army between these two stages is referred to as the Interim Force.

The requirements for the Objective Force are deployability, sustainability, survivability, lethality, responsiveness, versatility, and agility.[8] The Objective Force must be able to be deployed anywhere in the world on short notice and must be deployable using air, sea, or land transportation. The goals of the Army Transformation include the ability to place a combat-capable brigade anywhere in the world in 96 hours; a division (four brigades) on the ground in 120 hours; and five divisions on the ground in a theater of war in 30 days. The goal is to produce an affordable, technologically superior Objective Force that has the capability to sustain itself with the equipment, food, water, ammunition, and fuel needed to overcome enemy threats.

The truck fleet must support the ability of the Objective Force to fight in any terrain under any weather conditions or visibility conditions. It must also support the ability to self-protect and to mitigate the effects of conflicts. The truck fleet's payload capacity must support the unit of action for 7 days of self-sustainment, must be compatible with the prevailing shelter and storage configurations, and must meet all applicable International Standards Organization (ISO) requirements.

Strategy for Transforming the Army's Truck Fleet

The Army has a three-pronged strategy for transforming its truck fleet from the current Legacy Force fleet to the future Objective Force fleet:

1. The science and technology-based advances that are anticipated in the longer term will be focused on meeting the Objective Force's future needs for superior, highly maneuverable, and mobile combat platforms. These platforms require significantly better automotive performance than existing vehicles can provide. Development of the Future Combat System (FCS) and the Future Tactical Truck System (FTTS) are the main manifestations of this vision.[9,10] A technology roadmap is being developed with the goal of achieving

[8]See note 1 above.
[9]See note 1 above.

the requirements of the Objective Force. This roadmap identifies and prioritizes common technologies across future combat platforms. New technologies will be applied to platform design for the FCS and the FTTS, which together will become the backbone of the Objective Force.

2. The Army intends to field an Interim Force that is capable of providing early deployment and that is more agile and lethal and has greater survivability than the Legacy Force. The Interim Force truck fleet will be composed of existing systems or systems that can meet the initial requirement with only slight modifications. As research for the Objective Force leads to major system development, integration, testing and evaluation, and production, these new technologies will be inserted into the Interim Force fleet, which will thereby evolve into the final state of the Objective Force fleet.

3. Because the current truck fleet continues to degrade faster than it can be upgraded by new product acquisition, the Army is using a recapitalization program to maintain Legacy Force fleet size and capability. The recapitalization program is aimed at improving the reliability, safety, maintainability, and efficiency of the equipment; extending service life; reducing operations and support (O&S) costs; and providing enhanced capability until substantial portions of new systems are fielded. The recapitalization program includes both rebuilding and upgrading. The rebuild process returns aging systems to their original performance specifications. Upgrading under this program can provide additional or replacement components that enhance the war-fighting capability of the system, although it does not permit improvements in major systems or subsystems, such as advances in overall vehicle configuration or structural architecture.

Requirements of the Future Army Truck Fleet

In order to achieve the characteristics required of the Army's Objective Force, the future truck fleet must meet a variety of requirements, including deployability, transportability, and mobility. As discussed below, these goals require that Army trucks consume less fuel, undergo significant weight reduction, have a reduced logistics footprint, and need less maintenance while maintaining or increasing payload capability and other performance criteria.

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[10] N. Halle, TACOM. Future Tactical Truck Systems. Presentation to the committee, May 9, 2002.

Reduced Fuel Consumption

Fuel comprises about 70 percent of the Army tonnage shipped to a battle zone. An armored division consumes approximately 600,000 gallons per day, and an air assault division requires approximately 300,000 gallons per day. It is interesting to note that of the top 10 Army battlefield fuel users, only 2—tanks and combat helicopters—are actual combat platforms; the major contributors to fuel use are Army trucks and supply and support equipment. Although the Army uses the actual cost of fuel, set at around $1.01 per gallon, in all of its cost calculations, the true cost of fuel is much higher. In normal times, the true cost of fuel, including delivery, is closer to $13 per gallon. This increases to between $100 and $400 per gallon for delivery to war zones with no established fuel lines, roads, or infrastructure.[11,12]

The numerous advantages to reduced vehicle fuel consumption include the following:

1. Improved fuel efficiency would enhance platform performance. For example, the range of many weapons systems is currently limited by the capacity of their fuel tanks.
2. Improved fuel efficiency would reduce the size and cost of the fuel logistics system. High fuel consumption currently limits the Army's agility. The Army Research Laboratory has estimated that if the Abrams tank were 50 percent more fuel-efficient, the Desert Storm buildup could have taken 20 percent less time.[13]
3. The fuel burden also places constraints on deployability and transportability. The ability to transport Army trucks using C-130 aircraft is a key performance attribute of the Objective Force.
4. In the future, geopolitical considerations may impose severe constraints on fuel availability.

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[11]Defense Science Board. 2001. Report of the Defense Science Board on More Capable Warfighting Through Reduced Fuel Burden. Washington, D.C.: Office of the Under Secretary of Defense for Acquisition and Technology.
[12]C. Mahan. Sustainment Needs for Army Transformation. Speech at National Center for Manufacturing Sciences (NCMS), Commercial Technologies for Maintenance Activities (CTMA) Working Symposium on Sustainment, Jacksonville, Fla., April 16, 2002.
[13]See note 11 above.

Weight Reduction

A light infantry division of 11,520 troops is deployed with a weight of 18,122 tons—which includes the weight of the soldiers, their personal gear, and all equipment as well as 1 day's ammunition, 5 days' rations, construction materials, and personal items; and clothing, petroleum products, medical supplies, and spare parts for 15 days. This so-called "light" division deploys 3,841 vehicles and 83 aircraft. To move this force requires 816 C-141 sorties or 61 C-17 sorties. A "heavy" armor division, by contrast, weighs 102,052 tons and includes 17,186 troops and 8,125 vehicles.[14] Currently, the Legacy and Interim Forces cannot meet the future requirements of rapid deployment and mobility because the available aircraft cannot transport the necessary weight to every possible outpost within the allowable time limits.

When designing equipment and planning operations involving transport by C-130 aircraft, Army planners need to consider certain major operational limitations.[15] The range of the aircraft can be severely compromised by the aircraft's total weight (which includes aircraft, crew, equipment, fuel, and cargo). For structural reasons, increases in the C-130's payload weight above 36,500 lb require a disproportionate increase in the landing fuel required, with a significant decrease in range. A major payoff would be realizable in the Army Transformation if a fully assembled Army vehicle and its fuel were transportable on the same aircraft. In addition to that consideration, weight reduction in Army trucks is a critical design feature that would enable them to achieve greater survivability, longer cruising range, and extended operation without resupply, all at higher road speeds and maneuverability.[16]

Reduced vehicle weight can lead to increased fuel efficiency and increased payload capacity. For heavy vehicles, it has been estimated that a reduction of 15 to 20 percent in vehicle weight is realistic. Such a weight reduction could reduce the vehicle's rolling resistance by at least 5 percent and could also enhance braking efficiency. The payload capability could be increased by up to 10 percent and, assuming fully loaded travel 30 to 50

[14]National Research Council. 1999. Reducing the Logistics Burden for the Army After Next: Doing More with Less. Washington, D.C.: National Academy Press.
[15]J.F. Cassidy. 2001. C-130 Transportability of Army Vehicles. Report No. MTMCTEA (MTTE-DPE). Newport News, Virginia: Military Traffic Management Command.
[16] See note 1 above.

percent of the time, the overall increase in fuel efficiency would be about 2 to 5 percent.[17]

Reduced Logistics Footprint

The principal logistics burdens for the Army truck fleet are the fuel, ammunition, food, water, and spare parts necessary to sustain a military force during operations. But the logistics burden also includes the logistics personnel and equipment that provide supplies, maintenance, transportation, medical services, and other support for combat units, and the supplies and support required to keep these logistics organizations in operation. Reductions in the consumption of fuel, ammunition, water, food, and spare parts during an operation can therefore lead to an even greater reduction in the logistics burden.[18]

To meet the challenges of reducing the logistics footprint, the Army has developed an initiative entitled Revolution in Military Logistics (RML). The interrelated objectives of the initiative are as follows:

1. Establish a distribution-based logistics system;
2. Reduce O&S costs,
3. Reduce maintenance costs,
4. Reduce fuel consumption by 75 percent,
5. Reduce the logistics infrastructure by 50 percent,
6. Enhance the ability of the Army to deploy in a timely manner,
7. Provide a power source for digitization,
8. Adapt to the increased operation tempo, and
9. Survive in the battlefield.

The RML would leverage advances in information systems technology and fuse operations concepts with logistics systems. This change would involve a shift from a system of accumulation of supplies to a distribution-based logistics system with real-time situational understanding, new organizational designs, and use of proven commercial business practices.

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[17]Department of Energy. 2000. Technology Roadmap for the 21st Century Truck Program: A Government-Industry Research Partnership. Report No. 21CT-001. Available at <http://www.trucks.doe.gov/pdfs/P/62.pdf>. Accessed March 2003.
[18]See note 14 above.

The goal of the RML is to reduce sustainment requirements and logistics infrastructure.[19]

Reduced Maintenance

The goals of the Army Transformation require that future Army trucks need less maintenance and have lower O&S costs than those of trucks in the Legacy Force fleet. O&S costs include those for maintenance, support equipment, personnel training, supply management, facilities, storage, and spares inventory. Over the life cycle of an Army truck, these costs are at least as high as the initial acquisition and procurement costs. In fact, a study by TACOM concluded that, when personnel costs were included, the total O&S costs for the medium tactical truck ranged from 66 to 72 percent of the total life-cycle cost of the vehicle.[20] As vehicles age, the O&S costs increase.

Corrosion accounts for a high fraction of the O&S costs. Army trucks quickly develop problems with corrosion owing to harsh environmental conditions and duty cycles. The annual cost of corrosion maintenance alone typically ranges from $800 to $1,200 per 5-ton vehicle, or approximately 1 percent of initial vehicle cost. Some Army vehicles become so seriously damaged from corrosion that the structural integrity of the vehicle is compromised.[21] When no longer safe for use, these vehicles must be replaced with new purchases of improved models. However, corrosion and environmental damage remain a serious problem even in newer vehicles, such as the FMTV.[22] This damage needs to be contained by maintenance activities, which in turn increase the cost of ownership.

A report on the cost of corrosion for 5-ton Army trucks indicates that consideration of the cost of downtime due to corrosion treatment and maintenance further exacerbates the O&S cost profile.[23] This study estimated that the total cost of corrosion for 5-ton Army trucks over a 4-year period was more than $31 million.

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[19]See note 18 above.
[20]R.S. Bazzy. TACOM. Cost and Systems Analysis Information. Presentation to the committee, May 9, 2002.
[21]Army Materiel Systems Analysis Activity (AMSAA). 1978. An Evaluation of the Rust Condition of Trucks, 1/4 Ton: M151 Series. Report No. TR-226. Warren, Mich.: AMSAA.
[22]General Accounting Office. 1999. Army Medium Trucks: Information on Delivery Delays and Corrosion Problems. Washington, D.C.: General Accounting Office.
[23]E. Harris. 1987. The Real Cost of Corrosion: Accounting for Downtime, Implications and Methodology. Report No. MTL-TR-87-8. Watertown, Mass.: U.S. Army Materials Technology Laboratory.

Crashworthiness and Road Safety

As the fuel requirements, maintenance, logistics footprint, and weight of Army trucks are reduced, performance criteria such as crashworthiness and road safety must remain the same or be improved. Army trucks spend about 80 percent of their time on highways. The Army must therefore consider not only the safety of the occupants of military vehicles, but also that of the civilian vehicles' occupants.

Civilian truck crashes cause disproportionately more serious injuries and fatalities than crashes of other vehicle types because of the mass of the trucks and the high speeds permitted on the roads. The majority of the injuries and fatalities in civilian truck crashes are to the occupants of the vehicles that collided with the trucks.

A major concern with heavy military trucks is the aggressivity that results from the vehicle-to-vehicle collisions when there are incompatibilities in the fleet mix. Collision partners are considered to be incompatible if collision deformation and structural characteristics imply that loads are unequally distributed between the vehicles. Possible vehicle-to-vehicle incompatibilities include mismatches of mass (heavy versus light), geometry (bumper height versus door sills), and structure (stiff versus compliant). Mass differences probably dominate heavy-truck aggressivity, and there is no clear corrective action except reduction in vehicle weight. Geometric and structural incompatibilities may be mitigated by design changes related to front-end properties. The development of heavy military trucks should follow the lead of heavy commercial trucks, which are becoming less aggressive, in part by adhering to government-imposed regulations.

The most frequent causes of injuries for occupants of large military trucks are rollovers (and concomitant ejection), frontal-impact collisions, and rear-end collisions, with rollovers dominating. Injuries in rollovers are most often due to occupant contact with unpadded interior components such as mounting brackets.[24] Special devices necessary for military activities are often installed in trucks and may contribute to safety problems by increasing the number of potentially dangerous contact surfaces. Currently, padding in Army trucks seems to be included for acoustic and thermal reasons, not for safety. Fears of nuclear and biological contamination have reduced the use

[24]Simula Technologies. 1999. Enhanced Crash Protection for Occupants of Heavy Tactical Vehicles: Inflatable Restraint Systems and Crew Cab Delethalization Techniques. Report No. TR-99042. Phoenix, Ariz.: Simula Technologies.

of padding for reasons of safety. Some protection from rollover injuries is offered by ensuring adequate cab structural integrity and by the installation of seat tie downs and retractors designed for large commercial trucks. Countermeasures to make Army trucks safer for their occupants are basically the same as those being considered for commercial trucks: seat belt restraints, air bags, head restraints, and knee bolsters. Such devices should be made part of the bid specifications for Army trucks.

It is the policy of the U.S. Army to have trucks that adhere reasonably closely to Federal Motor Vehicle Safety Standards (FMVSS) regulations for safety. The Army must also take into account the safety regulations of other countries where U.S. troops are deployed.

ROLE OF NEW MATERIALS IN MEETING FUTURE NEEDS

> Substituting lightweight materials with equivalent or superior functionality in designs for air and ground vehicles is the most promising approach for reducing total system weight . . . [and] vehicle system weight [is] the most important factor in reducing Army After Next fuel demand.[25]

Advantages of Lightweight Materials

The use of lightweight[26] materials has the potential to help the Army meet its goals by reducing vehicle weight and fuel consumption; by reducing fuel consumption, the logistics footprint would also be reduced. In addition, some lightweight materials offer the potential for greater corrosion resistance, which would decrease the need for maintenance and lower O&S costs. A recent review of the U.S. Department of Energy's (DOE's) Heavy Vehicle Technologies Program noted that sufficient emphasis had not been placed on "decreasing unloaded vehicle weight by innovative design incorporating high-strength, weight reduction materials."[27] High-strength steel, stainless steel, aluminum, aluminum metal matrix composites (MMCs), magnesium, titanium, glass-fiber-reinforced plastic, and carbon-fiber-

[25]See note 18 above, p. 8.
[26]In the context of this report, "lightweight" refers to materials of high specific strength, which is defined as strength divided by density.
[27]National Research Council. 2000. Review of the U.S. Department of Energy's Heavy Vehicle Technologies Program. Washington, D.C.: National Academy Press. pp. 35.

reinforced plastic are structural materials that can be substituted for mild steel with considerable weight savings.[28]

Lightweight materials can play a part in improved truck performance either through the substitution of stronger and/or lighter materials for traditional materials or by enabling novel redesign concepts. The traditional material of choice in Army trucks is carbon steel plate, because of its versatility in application and low cost. Previous efforts at direct materials substitution have had limited results because component redesign is usually necessary to achieve the full weight-savings potential. With the increasing availability of high-performance, low-cost material options and manufacturing technologies, it is now possible to more effectively marry performance and durability with clever, robust design in order to optimize materials use. Although lightweight materials may initially result in higher vehicle procurement costs, significant potential exists for savings in terms of reduced fuel consumption, reduced maintenance, and reduced O&S costs. In addition, there are significant opportunities for the Army to adopt and exploit specialty and niche vehicle-manufacturing practices to achieve greater economy and affordability.

Previous Studies on Lightweight Materials for Vehicles

The Army's interest in lightweight materials is not new. In 1982, the Deputy Undersecretary of Defense, Research and Engineering sponsored a study by the National Materials Advisory Board on materials for lightweight military combat vehicles.[29] That NRC report reached a number of conclusions regarding the state of materials technology 20 years ago:

- Advanced materials (composites and new alloys) offered potential for improved performance through significant weight savings;
- The design and manufacturing base for polymer matrix composites was well developed, and it was realistic to assess their potential for use in combat vehicles;

[28]National Research Council. 2001. Review of the Research Program of the Partnership for a New Generation of Vehicles: Seventh Report. Washington, D.C.: National Academy Press.
[29]National Research Council. 1982. Materials for Lightweight Military Combat Vehicles. Washington, D.C.: National Academy Press.

- Extensive effort was required to certify new materials for use in combat vehicles because dynamic structural loads are largely unknown, many composites are anisotropic, the combat environment is unique, and manufacturing must be adapted to vehicle requirements; and
- Maximum benefit from the use of new materials can be realized only if the overall structural design takes advantage of the properties of the new materials—that is, the properties of the advanced material should be incorporated early in the design phase of a new vehicle.

In 1993, the National Science Foundation sponsored a report on lightweight materials for the automotive and aircraft industries.[30] That report concluded that advances in materials could be applied to improve product performance, quality, and reliability and to permit creative product design. The report stated that common materials needs are for cost-effective, easily manufacturable, lightweight, structurally efficient, strong, environmentally benign, recyclable materials. Materials for automotive applications should be viewed as part of a system, in which appropriate trade-offs can be made. This new paradigm should consider the entire life cycle of a product including manufacturing, transportation, treatment of hazardous by-products, operational use, maintenance, and disposal. The report concluded that computer modeling techniques should be developed to assist in the development and evaluation of product performance and reliability, materials synthesis and processing, and materials fabrication into components to facilitate materials design and selection.

In the 1999 NRC report on reducing the Army's logistics burden, including fuel, one roadmap objective was the use of lightweight materials for air and ground vehicles.[31] That study identified the following areas for technology development: distributed modeling and simulation (M&S) environment, materials selection databases, and information resources. Recommended research areas included M&S for materials design, and advanced armor and protection concepts. Therefore, the report concluded, new metrics and strategies are needed for comparing advanced material options and conventional materials for use in new generations of trucks.

[30]National Research Council. 1993. Materials Research Agenda for the Automotive and Aircraft Industries. Washington, D.C.: National Academy Press.
[31] See note 18 above.

ORGANIZATION OF THE REPORT

Following this introductory section, Chapter 2 discusses the new materials and processing opportunities that are candidates for use in the manufacture of Army trucks. Chapter 3 describes a variety of barriers to the implementation of new technologies and discusses methods of enabling the insertion of lightweight structural materials. Chapter 4 presents the conclusions and recommendations of the Committee on LIghtweight Materials for 21st Century Army Trucks.

Chapter Two

New Materials and Processing Opportunities

INTRODUCTION

Any discussion of new materials and processing opportunities can be wide-ranging, so to structure the discussion here, the problem is divided by application and time frame. For the purposes of this report, only structural elements are considered; the power generation and electrical parts of trucks are not considered.

The structural elements of a truck are divided into the following three categories:

- *Frame*: The primary structural element in all current military trucks is a steel frame that runs the length of the vehicle; the engine, drivetrain, suspension, and truck bed are all attached to the frame;
- *Secondary structural elements*: The secondary structural elements are the parts of the truck that carry passengers and cargo—for example, the cab and the cargo bed. Although these elements may account for a significant portion of the vehicle's weight, they do not provide the essential strength or stiffness of the truck; and
- *Structural drivetrain*: This category includes driveshafts, the suspension, the steering mechanism, and braking components. These elements may contribute significantly to vehicle weight and are critical to the vehicle's safe and reliable functioning.

With respect to time frames for the maturation of research and development and the insertion of new technologies, chronological time is not appropriate—there are Army trucks in operation using 30-year-old designs that may very well remain in the field for the next 30 years. At the same time, new systems will most likely be developed that will enable the use of new materials, processes, and designs. Time frames are therefore operationally defined as follows:

- *Short term:* This category refers to improved materials choices that can be substituted for existing materials in existing truck systems. This category does not include any fundamental redesign of the truck or its subsystems. The substitution of higher-strength or coated materials are examples of short-term opportunities. Care must be exercised in making such changes because any materials substitution can alter the vehicle's response to terrain changes and affect its ability to perform certain functions.

- *Medium term:* A new design or significant rebuilding of a proven truck platform represents an opportunity for more aggressive materials substitutions. Such an instance might involve the use of a modestly different architecture or different joining methods. For example, the replacement of a truck's steel frame rails with hydroformed tubes would require changes in several other design aspects and would thereby open up opportunities for materials substitutions.
- *Long term:* The present truck paradigm consists of a power plant burning a single fossil fuel and providing power to the vehicle's wheels through driveshafts. It is unclear how long this paradigm will remain the dominant one. Prototypes of hybrid electric vehicles have been produced.[1] In the future, truck architecture may become modular, with power plants providing electric power to driven axle or bed modules. This would eliminate the need for driveshafts and fundamentally change frame configurations. Such changes in the basic truck paradigm would enable the use of radically different materials.

Selection of New Materials and Processes

Component Shape

In specifying a material for the final design of a vehicle or component, a number of characteristics must be considered. Materials properties play an important role in the performance of a component, affecting: strength, density, fracture toughness, fatigue resistance, cost, availability, available forms, formability, joinability, and corrosion or environmental resistance. The suitability of any mechanical system for meeting a performance objective is only partly governed by materials, however. The configuration, or shape, of the component also has a large effect. For example, an I-beam shape is much stronger and stiffer with respect to cantilever-bending loads than a simple cylindrical shape of the same mass per length. Other characteristics,

[1]Nimmer, S. Oshkosh Truck Corporation. Presentation to the committee, August 2002.

such as section stiffness, force for permanent deformation, energy absorption, and fracture load, can be affected by the shape of the component as well as by the material from which it is made.

A process has been developed for selecting the optimal materials for an application on the basis of objective functions such as physical properties, cost, and the type of loading to which the material will be subjected.[2] This approach is not a finite element analysis package, but rather a materials selection process that includes a database on materials, properties, costs, and advantages, with the data accessible in many ways. The approach has been extended to include the effect of component shape, and many features have been incorporated into commercial software.[3] This type of design tool can be of great service in making short-term design and materials selection decisions.

The design of Army trucks should include a minimum-weight study as the final step in the design process. As is often done with commercial vehicles, a minimum-weight, optimal-shape design study should be performed on a vehicle after the preliminary designs, including the selection of lightweight materials, are complete. The minimum weight-design would lead to structural shapes (e.g, cross-sectional shapes of truck frameworks) that correspond to a significant reduction in vehicle weight. A weight reduction of at least 5 percent should be expected. It is, of course, essential that the performance of the truck not be degraded by the reduction of weight. As part of the minimum-weight process, constraints should include those involving structural integrity, noise, vibrations, armor cladding, on-road requirements, survivability, crashworthiness, stealthiness, load capacity, and load flexibility. Satisfaction of constraints in these areas will require a complex computer program that cycles among various analyses corresponding to the constraints.

Shape selection of the actual minimum-weight structural member is a reasonably efficient process. Typically, a geometric description of the cross section of various members is fed into an optimization routine that requires shape-sensitivity functions. Finite element analyses of member cross sections are introduced. The optimization program shapes the cross section with minimum weight as the objective function.[4]

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[2]M. Ashby. 1992. Materials Selection in Mechanical Design. Oxford, U.K.: Pergamon Press.
[3]For example, <http://www.grantadesign.com>. Accessed March 2003.
[4]W.D. Pilkey. 2002. Analysis and Design of Elastic Beams: Computational Methods. New York, N.Y.: Wiley.

Low-Cost Processing

The issue of materials and component shape selection is further complicated by the realities of available material forms, manufacturing methods, cost, joining methods, and production volumes. In selecting a processing method, engineering judgment is required, and formal design methods are of limited value. The difficulty of shaping a material is directly related to the characteristics of the material. Although machining can always be used to create a shape, it is prohibitively expensive for many applications, such as frames for trucks. Net shape processes such as casting or stamping are low-cost methods of fabricating complex geometries, but these techniques cannot be used with all materials. In general, lower-strength materials are more easily fabricated by casting or sheet forming.

Advanced modeling and simulation tools could be used cost-effectively to evaluate various alternative materials for a given application or to optimize vehicle designs.[5] However, the data needed to design components to meet specific performance requirements, e.g., fatigue life, is often unavailable for the specific material being evaluated. The lack of adequate databases needed for accurate finite element modeling (FEM) exacerbates the design community's existing lack of familiarity with lightweight materials. In addition, appropriate models for processing lightweight materials and for predicting the performance of components manufactured using these materials must be developed. Very good models currently exist for casting, forging, rolling, and extrusion. More such work would greatly help transition new materials into appropriate applications in new designs.

The cost of transforming materials into desired shapes is dependent on a number of things, including production volume. Sand, lost wax, and lost foam castings can be done by hand at low fixed tooling costs. These processes are amenable to the low production volumes commonly associated with military tactical trucks. Higher-quality parts can be formed by means of die casting or squeeze casting, but the costs of dies and tooling are significant and can run into the tens of thousands of dollars. Amortizing these costs over the number of units to be made is difficult. In sheet metal forming, the matched tools used for mass production again typically cost tens of thousands of dollars. However, in aerospace production, much-less-expensive

[5]National Research Council. 2003. Materials Research for 21st Century Defense Needs. Washington D.C.: National Academy Press.

single-sided dies are used in conjunction with processes such as rubber-pad hydroforming. The marginal cost per part is much higher than in mass-production stamping, but this higher cost is offset by lower tooling and setup costs.

Low production volumes can enable the use of more expensive materials provided that tooling and fabrication costs are minimized. For example, for Freightliner trucks and Panoz roadsters, the use of superplastic aluminum alloys is favored over the less expensive (and higher strength) cold-formable alloys, largely because the one-sided tooling used in superplastic forming is relatively inexpensive. When varied designs are being manufactured, many factors must be considered in order to find a solution that approaches the optimal. Because of the low production volumes typical for Army truck manufacturers, it may not be possible to take advantage of all of the low-cost processing experience of automobile manufacturing.

Some technologies that may become viable at low production volumes include the following:

- Superplastic forming, especially for cases in which commercial superplastic alloys, such as 5083, exist;
- Compression molding of thermosetting polymer composites;
- Rubber-pad hydroforming of sheet components;
- Tube hydroforming;
- Electromagnetic forming of tubes and sheets;
- Explosive forming of tubes and sheets;
- Thin-walled castings;
- Other agile shaping methods for thermosetting polymer composites; and
- Interfacing with joining technology.

The increased use of new lightweight materials depends on the development of robust joining processes that produce acceptable joint properties at costs and assembly times comparable to those for resistance spot welding of steel. The joining of these new materials to themselves and to other materials presents technical challenges. Improved joint designs must also be developed in order to take full advantage of the benefits that these materials can provide. Significant work must be done to develop joint designs, methodologies for dealing with galvanic effects, mechanical fastener technologies, nonfusion joining, and hybrid joints.

Repair and Disposal of New Materials

The use of new materials in Army trucks will have consequences with respect to vehicle assembly, repair, and disposal. When assembling new vehicles or recapitalizing older vehicles, it will be necessary to ensure that galvanic isolation exists between parts made from different materials in order to avoid galvanic coupling effects that can lead to corrosion. Galvanic isolation will have to be maintained during inspection, maintenance, and repair. Welding, bonding, brazing, and other repair and replacement procedures will therefore become more complicated.

Composites are a relatively new class of materials now being used selectively on Army vehicles. Composites are very attractive because they can be designed with specific properties. However, a number of factors must be considered before a decision is made to use composite materials in an Army vehicle. Composite repair procedures are very different from those for metallic materials and are generally not known within the Army's repair facilities. The insertion of composite materials into Army vehicles must therefore be accompanied by new repair manuals and the training of Army personnel in these new procedures.

Careful handling and storage of composites is also necessary, because their properties are sensitive to the presence of surface flaws. Other issues with these materials include the decrease in strength that results from absorption of water in places where the surface protective coating is penetrated. Many composite properties are also temperature-sensitive, so the use of composites in extreme climates must be carefully monitored. Careful handling and storage can eliminate many potential problems for this class of materials.

A coding system might be used to differentiate material types and to facilitate proper assembly, repair, and disposal. In addition, training will be required for the proper maintenance of vehicles that have been manufactured with new materials or that have had parts changed in recapitalization programs. Maintenance and repair manuals should be continuously updated. However, it will be difficult to keep issuing and delivering repair-manual updates to the necessary field and depot repair facilities. One solution would be for vehicle original equipment manufacturers (OEM) to maintain repair and maintenance manuals on a Web site, along with information on the symptoms, possible causes, and remedies for known truck problems. Repeated failure of any one part could be communicated to the OEM by e-mail so that corrective action could be taken.

Finally, end-of-life disposal and recycling issues will become more complex as new and different materials are introduced. Many disposal yards are equipped to separate different classes of materials for recycling. When older Army trucks are sold for disposal, the contracts should specify which materials classes must be separated and how the disposal facility is held accountable for appropriate recycling.

The Vehicle Recycling Partnership, formed between the three large domestic automobile manufacturers, proved that dismantling a vehicle was too labor-intensive and time-consuming to be cost-effective. By comparison, a full vehicle can be shredded in approximately 40 seconds, and the subsequent separation and sorting of metals are both fully automated. The sequence of fluff removal, magnetic separation, heavy/light media flotation and separation, eddy current separation, color separation, and, finally, laser-induced breakdown spectroscopy is now well established. All of the common metal groups can be separated in an industrial process, and in fact a specialty steel company in Detroit is presently operating plants in both the United States and Europe to do this separation.

SHORT-TERM OPPORTUNITIES

The short-term problem as defined in the introduction to this chapter is constrained by the absence of changes in present truck designs and by the use of commercially available materials and forms. Under these constraints, the approach pioneered by Ashby and described above in the subsection "Component Shape" can be used to identify appropriate materials options.[6] The basis of the Ashby materials selection process is the use of quantitative performance indices, or mathematical functions of service requirements, geometric parameters, and materials properties. The higher the performance index, the better suited a material is for a particular job, with the part weight needed to reach a given level of performance typically inversely related to its performance index. Table 2-1 illustrates some relevant performance indices.

[6]M. Ashby. 1992. Materials Selection in Mechanical Design. Oxford, U.K.: Pergamon Press.

TABLE 2-1 (a) Performance indices for Minimum Weight (Cost, Energy) Design: Stiffness and Strength

Component Shape and Loading	Stiffness Design: Maximize	Strength Design: Maximize
Tie (tensile strut) *load, stiffness, length specified, section area free*	E/ρ	σ_f/ρ
Torsion bar or tube *torque, stiffness, length specified, section area free*	$G^{1/2}/\rho$	$\sigma_f^{2/3}/\rho$
Beam *loaded externally or by self-weight in bending; stiffness, length specified, section area free*	$E^{1/2}/\rho$	$\sigma_f^{2/3}/\rho$
Column (compression strut) *failure by elastic buckling or plastic compression; collapse load and length specified, section area free*	$E^{1/2}/\rho$	σ_f/ρ
Plate *loaded externally or by self weight in bending; stiffness, length, width specified, thickness free*	$E^{1/3}/\rho$	$\sigma_f^{1/2}/\rho$
Plate *loaded in-plane; failure by elastic buckling or plastic compression; collapse load, length and width specified, thickness free*	$E^{1/3}/\rho$	σ_f/ρ
Rotating disks, flywheels *energy storage specified*	—	σ_f/ρ
Cylinder with internal pressure *elastic distortion, pressure and radius specified; wall thickness free*	E/ρ	σ_f/ρ
Spherical shell with internal pressure *elastic distortion, pressure and radius specified, wall thickness free*	$E/(1 - v)\rho$	σ_f/ρ

NOTES: To minimize cost, use the above criteria for minimum weight, replacing density ρ by $C\rho$, where C is the cost per kilogram. To minimize energy content, use the above criteria for minimum weight, replacing density ρ by $q\rho$, where q is the energy content per kilogram. KEY: E = Young's modulus; G = shear modulus; σ_f = failure strength; ρ = density. SOURCE: Reprinted from Materials Selection and Design, M. Ashby, Table 5-1, Copyright 1992, Oxford, U.K.: Pergamon Press, with permission from Elsevier Science.

This approach provides a good quantitative basis for making the first step in materials selection decisions. It also provides a basis for selecting short-term candidate materials for use in Army truck applications. Several of these candidate materials are discussed below.

TABLE 2-1 (b) Performance indices for Minimum Weight (Cost, Energy) Design: Crack Length

Component Shape and Loading	Crack Length Fixed: Maximize	Crack Length ≈ Min Section: Maximize
Tie (tensile strut) *load, length specified, section area free*	K_{IC}/ρ	$K_{IC}^{4/3}/\rho$
Torsion bar or tube *torque, length specified, section area free*	$K_{IC}^{2/3}/\rho$	$K_{IC}^{4/5}/\rho$
Beam *loaded externally or by self-weight in bending; stiffness, length specified, section area free*	$K_{IC}^{2/3}/\rho$	$K_{IC}^{4/5}/\rho$
Column (compression strut) *failure by elastic buckling or plastic compression; collapse load and length specified, section area free*	$K_{IC}^{2/3}/\rho$	$K_{IC}^{4/5}/\rho$
Plate *loaded externally or by self weight in bending; stiffness, length, width specified, thickness free*	$K_{IC}^{1/2}/\rho$	$K_{IC}^{2/3}/\rho$
Plate *loaded in-plane in tension; collapse load, length and width specified, thickness free*	K_{IC}/ρ	K_{IC}^{2}/ρ
Rotating disks, flywheels *energy storage specified*	K_{IC}/ρ	K_{IC}/ρ
Cylinder with internal pressure *elastic distortion, pressure and radius specified; wall thickness free*	K_{IC}/ρ	K_{IC}^{2}/ρ
Spherical shell with internal pressure *elastic distortion, pressure and radius specified, wall thickness free*	$K_{IC}/(1-v)\rho$	$K_{IC}^{2}/(1-v)\rho$

NOTES: To minimize cost, use the above criteria for minimum weight, replacing density ρ by $C\rho$, where C is the cost per kilogram. To minimize energy content, use the above criteria for minimum weight, replacing density ρ by $q\rho$, where q is the energy content per kilogram. KEY: K_{IC} = fracture toughness; ρ = density. SOURCE: Reprinted from Materials Selection and

Aluminum and Magnesium Alloys

Aluminum and magnesium alloys are candidates for the replacement of steel in Army truck applications. The commercial aircraft industry is based on aluminum, with the empty weight of a typical commercial airplane being

TABLE 2-1 (c) Elastic Design

Component and Design Goal	Maximize
Springs *specified energy storage, volume to be minimized*	σ_f^2/E
Springs *specified energy storage, mass to be minimized*	$\sigma_f^2/E\rho$
Elastic hinges *radius of bend to be minimized*	σ_f/E
Knife edges, pivots *minimum contact area*	σ_f^3/E^2 and E
Compression seals and gaskets *maximum contact area with specified maximum contact pressure*	σ_f/E and $1/\sigma_f$
Diaphragms *maximum deflection under specified pressure or force*	$\sigma_f^{3/2}/E$
Rotating devices, centrifuges *maximum angular velocity, radius specified, wall thickness free*	σ_f/ρ
Ties, columns *maximum longitudinal vibration frequencies*	E/ρ
Beams *maximum flexural vibration frequencies*	$E^{1/2}/\rho$
Plates *maximum flexural vibration frequencies*	$E^{1/3}/\rho$
Ties, columns, beams, plates *maximum self damping*	η

NOTES: To minimize cost, use the above criteria for minimum weight, replacing density ρ by $C\rho$, where C is the cost per kilogram. To minimize energy content, use the above criteria for minimum weight, replacing density ρ by $q\rho$ where q is the energy content per kilogram. KEY: E = Young's modulus; σ_f = failure strength; ρ = density; η = *loss coefficient*. SOURCE: Reprinted from Materials Selection and Design, M. Ashby, Table 5-1, Copyright 1992, Oxford, U.K.: Pergamon Press, with permission from Elsevier Science.

composed of approximately 70 to 75 percent aluminum. However, the total substitution of aluminum for steel in Army truck applications is unlikely for several reasons, including the higher cost of aluminum and the need for ballistic protection in some trucks.

Table 2-2 compares the properties of several ferrous, aluminum, and magnesium alloys, including typical values for each alloy class. These values

TABLE 2-2 Comparison of Properties of Some Steels, Aluminum Alloys, and Magnesium Alloys

Materials	Density (g/cm^3)	Young's Modulus (GPa)	Strength Range (MPa)
Steels (typical)	7.85	200	200-850
1018 cold finished	7.87	205	370
1040 cold finished	7.84	200	550
302 stainless, 10% cold work	7.86	193	635
410 tempered at 540 °C	7.8	200	1,005
Aluminum alloys (typical)	2.7	70	100-400
6061 T651	2.7	69	310
2024 T6	2.77	72	345
5083-H32	2.66	71	206
7075 T6	2.81	72	503
Magnesium alloys	1.8	45	100-300
Extruded AZ10A-F	1.76	45	155
Extruded AZ1B	1.77	45	165

SOURCE: MatWeb Material Property Data. Available at <http://www.matweb.com>. Accessed March 2003.

indicate that density and modulus vary only modestly over the full alloy family. However, strength, ductility, fracture toughness, and fatigue resistance can vary substantially depending on the alloy and its processing history.

Low-density materials such as aluminum and magnesium have definite design advantages in terms of elastic properties (see Table 2-3), even when the specific strength or stiffness remains the same. These materials have significant performance advantages when loaded in torsion or bending because the greater section thickness at fixed weight gives greater resistance to bending or dents. In pure tensile loading, performance indices scale with E/ρ. In these applications, steel and aluminum and magnesium alloys perform similarly.

Magnesium alloys cannot be immediately considered for truck applications because of their low ductility and limited processibility. In addition, stress corrosion cracking caused by the presence of in-service residual stresses has limited the use of magnesium alloys in commercial vehicle applications. However, potential applications in the near future include castings for transmission casings or transfer cases, and magnesium

TABLE 2-3 Ratios of Performance Indices for Aluminum and Magnesium Relative to Steel

Ratio	E/ρ	$E^{1/2}/\rho$	$E^{1/3}/\rho$
M_{Al} / M_{steel}	1.0	1.7	2.0
M_{Mg} / M_{steel}	1.0	1.8	2.6

NOTES: The ratios are based on the typical properties shown in Table 2-2. E/ρ is the metric for a component in tension, $E^{1/2}/\rho$ is the metric for beams in bending or columns in compression, and $E^{1/3}/\rho$ is the metric for plates loaded in bending or in plane.

extrusions for secondary structural applications such as passenger-seat frames.

Aluminum, on the other hand, is well developed to compete directly with steel as a means of saving weight, especially in bending beam and plate applications such as truck cabs and cargo beds. Because dent resistance is often the limiting property for vehicle outer skins and performance scales with $\sigma_f^{1/2}/\rho$, weight savings on the order of 50 percent have been seen in many automotive body-in-white[7] studies when aluminum is substituted for steel.[8] The Army's Medium Tactical Vehicle Replacement (MTVR) is available with an aluminum cab, and Freightliner offers several aluminum cab options in its Class 8 trucks.

For the MTVR, cab structures are formed conventionally using aluminum extrusions and tubes with a variety of joining techniques to fabricate a frame. This frame then supports sheet metal, formed largely using press-brake work. Superplastic forming is an approach that can produce higher performance structures, although most likely at a higher cost.

Significant advances have been made in the development of superplastic aluminum alloys and superplastic forming of automotive structures in compositions near alloy 5083.[9,10] Superplastic aluminum sheet

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[7]Body-in-white (BIW) refers to all body structural components, the roof panel, and subframes, but not the closure panels.
[8]Princeton Materials Institute. 1995. Basic Research Needs for Vehicles of the Future. Princeton, N.J.: Princeton Materials Institute.
[9]R. Verma, A.K. Ghosh, S. Kim, and C. Kim. 1995. Grain refinement and superplasticity in 5083 aluminum. Materials Science and Engineering A 191(1-2):143-150.

can be gas-pressure-formed into complex shapes, eliminating expensive welding and other joining requirements and allowing large structures to be produced in a single step. Eight-foot-wide cab roofs have been manufactured commercially by Superform Metals.[11] Superplastic forming of aluminum parts is especially competitive if only a limited number of parts—for example, 1,000 to 5,000 components per year— are produced. This is within the range required in the production of military tactical vehicles.

Both aluminum and steel are used to make the cargo beds of dump trucks. In the commercial sector, the increased cost of an aluminum dump truck bed as compared with that of a steel bed can often be justified because of the increase in payload capacity. For both truck cabs and cargo beds, aluminum's resistance to normal atmospheric corrosion can provide significant life-cycle cost savings in terms of corrosion prevention and repair. However, good engineering design must be exercised to avoid galvanic couple effects, which could produce significant corrosion problems.

High-Strength Steels

Steel is inexpensive and is likely to remain the principal structural material for automobiles and trucks for some time to come. Weight savings can be achieved by increasing the strength of the steel and reducing its gauge. This is the direction taken by the automobile industry. Because much of the loading on structural elements is either in bending or torsion, the advantages derived from increasing strength are not as potent as those from decreasing density. However, significant gains can still be made. A recent study showed that between 1976 and 1996, the increase in the amount of high-strength steels in the average automobile was greater than the increase in the amount of aluminum.[12] By 1996, the amount of substituted high-strength steels was 550 lb compared with 350 lb for substituted aluminum.

[10]E.M. Taleff, P.J. Nevland, and P.E. Krajewski. 1999. Solute-drag creep and tensile ductility in aluminum alloys. Pp. 349-358. Creep Behavior of Advanced Materials for the 21st Century. R.S. Mishra, A.K. Mukherjee, and K.L. Murty, eds. Warrendale, Pa.: The Minerals, Metals, and Materials Society.
[11]A.J. Barnes. 2001. Industrial applications of superplastic forming: Trends and prospects. Vol. 357, pp. 3-16. International Conference on Superplasticity in Advanced Materials (ICSAM-2000). N. Chandra, ed. Switzerland: Trans Tech Publications.
[12]U.S. Department of Energy. 2002. Steel Industry of the Future. Available at <http://www.oit.doe.gov/steel/>. Accessed March 2003.

The trend is likely to continue. Higher-strength steels could be used to reduce the weight of Army trucks, perhaps by as much as 20 percent.

A number of new steels have been developed in recent years for automotive applications. Ultra Light Steel Auto Body (ULSAB) efforts have resulted in yield strengths of 350 to 420 megapascals (Mpa), compared with 140 MPa for mild steel.[13] These higher-strength steels were combined with improved design methods (finite element modeling) and innovative manufacturing processes (such as tailor welded blanks and hydroformed tube structures and roof panels) to reduce the average thickness of steel sheet used for a typical automobile body. At the end of the study, the ULSAB automobile body exhibited a 24 percent reduction in weight.[14] Because steel plate in Army trucks also plays a role in resistance to projectile penetration, it may not be possible to reduce the thickness of some steel plate structures in Army trucks.

Other groups have also undertaken research on alternative steels. In the United States, rephosphorized and solution-strengthened interstitial-free steels have been studied, as have dual-phase steels and transformation-induced plasticity (TRIP) steels. In Japan, steelmakers are aggressively seeking higher-strength steels for automotive applications. The Japanese company NKK has developed a sheet steel for automotive applications that has high strength (tensile strengths of 780 to 980 MPa) and high formability.[15] The strength of this new steel, called Nano Hiten, is based on the creation of nano-obstacles to dislocation motion and on precipitates that are 10 times finer than those in traditional high-strength steels. In addition, Nakayama Steel Works Ltd. has produced an ultrafine-grain steel with ferrite grain size ranging from 2 to 5 micrometers (μm), compared with conventional grain sizes of 10 to 20 μm. The tensile strengths of this steel are in the range of 500 to 600 MPa.[16]

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[13]Steel Today and Tomorrow (Japan). Jul-Sep. 1998. ULSAB Project. 143:9-10.
[14]National Research Council. 2000. Review of the Research Program of the Partnership for a New Generation of Vehicles: Sixth Report. Washington, D.C.: National Academy Press.
[15]T. Furukawa. 2001. NKK's nanotechnology sheet. New Steel. Available at <http://www.newsteel.com/articles/2001/July/nsx0107f4nkk.htm>. Accessed March 2003.
[16]M. Hanmyo. 2002. Production and technology of iron and steel in Japan during 2001. Iron and Steel Institute of Japan International 42(6): 567-580.

Improved Corrosion Resistance

A number of methods are currently used by the Army to protect the traditional carbon steel plate used in Army trucks from corrosion. The steel body and chassis components that are welded or fastened together in assembly are usually protected from corrosion by the application of chemical-agent-resistant coatings (CARCs). A number of other commercially available treatments are also used, including e-coat protection, galvanized steel, the electrical insulation of dissimilar materials to avoid galvanic couples, and good design to avoid crevices and pockets where dirt and moisture can collect.

Some lightweight materials, although initially more expensive, can provide improved corrosion resistance and thereby reduce O&S costs. A materials substitution approach to improving corrosion resistance would be the use of stainless steel cabs. The high work-hardening rates of austenitic stainless steels make them highly formable and relatively easy to use. Such an option should be considered with the aid of holistic life-cycle cost models. Lightweight materials will not solve the problem of corrosion, however. As noted above, the use of aluminum in truck cabs and cargo beds can provide significantly improved corrosion resistance, but galvanic couple effects must be avoided. Corrosion resistance must therefore be considered in any materials selection process for Army trucks.

Other Commercially Available Technologies

Metal Matrix Composite Brake Rotors and Drums

Brake rotors and drums are generally made from cast iron, but recent research has focused on the use of lighter-weight, aluminum-based metal matrix composites and ceramics for braking surfaces. Currently, the Lotus Elise uses aluminum-silicon carbide brake rotors, and Porsche offers ceramic brakes as an option. In addition, there is some interest in using metal matrix composite brake drums in specialty commercial vehicles, such as cement mixers, to save weight and increase payload.

Hydroformed Tubes

Hydroformed steel tubes have been used successfully to reduce mass and increase stiffness in several commercial vehicle frames, including the Corvette and General Motors pickup trucks. This is a candidate technology for primary frames as well as structural supports for the engine and other systems in Army trucks. The challenge in using this technology is in justifying the price of the tooling for the Army's relatively low production volumes. This and other solutions would be more practical if leveraged by commercial use, or if production volumes were increased by producing a NATO-standard truck.

Tailor Welded Sheets

Tailor welded blanks have become important in the automotive industry. They are used, for example, for door inner panels where thicker steel is needed to support the high forces on the hinge face. A welded dual-thickness blank is used, with the thick steel on only a few inches of the inner panel near the hinge. The blank is formed as a monolithic sheet. This technology is a useful way to save mass on closure panels, and it may have applications in military vehicles, although there is very little matched tool metal forming in military trucks.

Driveshafts

Because Army tactical trucks are powered in all wheels, they carry a large mass in driveshafts. Currently, these driveshafts are made of steel, although aluminum and aluminum MMC driveshafts are available for light-duty passenger cars. It might be possible to use higher-strength aluminum alloys to manufacture larger-diameter aluminum driveshafts for use in military trucks. Such aluminum driveshafts could result in a net weight savings.

Composite Springs

Fiberglass-epoxy leaf springs have been developed and are used in some automotive applications. Typically, these composite springs are used in small automobiles, such MGBs, where a 20-lb steel leaf spring can be replaced with a 5-lb composite spring. This technology could also work for military truck applications, with the potential for eliminating 40 to 50 percent of the spring weight. The cost, however, is approximately two-and-a-half times that of steel springs owing to high raw material costs and a long manufacturing process involving time at temperature and pressure.

MEDIUM-TERM OPPORTUNITIES

Medium-term opportunities were defined at the beginning of the chapter as those resulting from a new design or a significant rebuilding of a proven platform. Such changes would provide opportunities for more aggressive materials substitution than the types of substitution listed for the short term. The Army's specification of a 22-year corrosion-free requirement could present medium-term opportunities, as could the HEMTT RECAP program. This Extended Service Program involves the rebuilding of frame rails with technology insertion and corrosion protection. Selective use of advanced, commercially viable materials such as aluminum, magnesium, MMCs, and polymer matrix composites (PMCs) could be advantageous in the medium term.

The use of advanced materials in replacement or new component applications on Army trucks should be evaluated collaboratively by Army procurers with the participation of commercial suppliers, designers, and maintenance and O&S personnel to arrive at a balance of functionality and price in sourcing decisions. Most of these advanced material alternatives are likely to be ready and affordable for use on commercial niche vehicle programs (manufacturing volumes up to 50,000 per year or less) within the next 5 to 7 years. Several significant advanced materials applications (such as magnesium, aluminum MMC, and PMCs of fiberglass and carbon) have already been demonstrated in both commercial passenger automotive and military truck programs. These collaborative advanced technology demonstrator programs include those sponsored by the Department of Defense (Army, Navy, Air Force, and Marine Corps), the Department of Energy's Office of Energy Efficiency and Renewable Energy (including the Partnership for a New Generation of Vehicles (PNGV) and FreedomCAR Partnerships with the United States Consortium for Automotive Research (USCAR)), and projects of the Department of Commerce's National Institute of Standards and Technology Advanced Technology Program (NIST-ATP).

Ferrous Materials

Steel is likely to remain the structural material of choice for applications such as frame rails and other body and chassis components. The ladder-frame construction of most tactical trucks represents a good compromise of using frame rails with good section strength and modulus. Because the shapes are available, no additional shaping cost is incurred. Lower mass could be obtained if optimized shapes were formed for the requirements.

High-Strength Steel Alloys

Steel remains the lowest-cost structural material for trucks, and important advances have been made in grain refinement, corrosion resistance, processing, and innovative designs for crashworthiness. These advances are the result of industry collaborations over the past decade. In the commercial automotive and truck industries, there has been a proliferation of a wide variety of high-strength martensitic steel alloys and fabrication methods that are strong candidates for application in future Army trucks.

Through the use of dual-phase steel alloys (such as DP600 for frame rails, cross members, suspension components, and wheels) and advanced fabrication methods (such as hydroforming, tailor welded blanks, and laser welding) the Improved Materials and Powertrain Architectures for Trucks (IMPACT) program has demonstrated a mass savings of about 1,310 lb (a 25 percent weight reduction) and an improvement in fuel economy of 8 miles per gallon in a Ford F150 light truck.[17] These results are highly applicable to Army light trucks replacing the C/K class. Certain unresolved issues remain with the use of high-strength steel alloys (i.e., TRIP, martensitic, and dual-phase), such as design optimization, material scrap, tooling investment, and overall formability and springback (i.e., the tendency of a sheet to relax when the forming loads are removed). These factors must be addressed jointly by industry.

Ultrahigh-carbon Steels

Ultrahigh-carbon steels (UHCSs) contain between 1.0 and 2.1 percent carbon and are hypereutectoid steels. These steels have been processed to become superplastic at high temperatures, and strong and ductile at room temperature. The higher the amount of carbon, the higher the strength of the steel. Although these steels have been in development since the mid-1970s through collaborations between industry and research institutions, they are not yet off-the-shelf items. This is principally due to the fact that steel companies will not proceed with production until a large order is guaranteed.[18]

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[17]ULSAB (UltraLight Steel Auto Body). Presentation on Advanced Vehicle Concepts to the U.S. Army Tank-automotive and Armaments Command, April 30, 2002.
[18]J. Sandelin. 2000. Patenting and licensing university research results: The challenges of disruptive technologies. R&D Enterprise-Asia Pacific 3(1-2):24-32.

UHCSs have the potential to reduce weight in trucks' structural components to meet future Army requirements. Potential applications of these steels include their use in fabricating vehicle components that require high strength—such as side impact beams, bumpers, and wires in tires. The desired UHCS structure is the pearlitic state. Pearlite, which consists of alternating layers of iron carbide (cementite) and iron (ferrite), is an in situ, self-laminated, nanoscale composite. This structure can be created directly from primary mechanical processing operations without any additional heat treatment. A typical tensile strength of an as-extruded UHCS bar is 1,000 Mpa, with an elongation of 10 percent. A pearlitic UHCS can lead to higher wire strengths than those of conventional eutectoid composition steels.[19]

Aluminum Alloys

Aluminum offers the greatest potential for weight reduction in truck bodies, but it also requires the use of different construction techniques. Aluminum space frames have been the subject of much research and development in the past decade, owing to the need to improve strain rate sensitivity (i.e., crash performance) and to enhance the metal's capability to support major vehicle body and fatigue loads. Strain rate sensitivity also affects formability. The space frame sections can be joined by welding or adhesive bonding. All-aluminum truck cabs and wheels are already in use in several classes of commercial and Army trucks. For example, the MTVR truck cabs have stamped aluminum components that are adhesively bonded. These applications of aluminum have resulted in significant maintenance cost savings.

Aluminum alloy 2519 (Al-Cu-Mg) is a high-performance alloy that can be used to meet the strength, weight, and mobility requirements of future Army trucks using armor plate, forgings, and extrusions (Fisher et al., 2002). Aluminum alloy 2519 was developed by Alcoa and the Army as a weldable material with ballistic penetration resistance superior to that of Al-Mg (5xxx) alloys and without the susceptibility to stress-corrosion cracking. This material is also being considered by the Marine Corps for fabrication of the Advanced Amphibious Assault Vehicle (AAAV). However, the lack of design data for extrusions and forgings from aluminum alloy 2519 has resulted in

[19]E.M. Taleff, J.J. Lewandowski, and B. Pourladian. 2002. Microstructure-property relationships in pearlitic eutectoid and hypereutectoid carbon steels. Journal of the Minerals, Metals, and Materials Society 57 (7): 25-30.

the alloy's not being more widely used. Research in hot workability testing and manufacturing technology developments is currently under way at the National Center for Excellence in Metalworking Technology. Corrosion for such aluminum alloys is largely in the form of pitting, and it may increase the O&S costs of the vehicle system, whereas stress-corrosion cracking can lead to catastrophic failure. These alloys can, however, be clad with pure aluminum for added corrosion resistance. Specific improvements in aluminum fabrication technology and cost reduction that would accelerate the medium-term use of aluminum alloys in future Army trucks include the following:

- Reduction in sheet raw material prices (e.g., by way of continuous casting);
- Design optimization for crew cabs (such as that done for the steel unibody) and optimization of space frames; and
- Improved sheet formability, castability (such as ultralarge castings), and joining technologies (such as friction stir welding) for higher-strength aluminum alloys such as the 5000 and 6000 series to enable the fabrication of larger, more integral structures.

Friction stir welding produces joints that are much less susceptible to galvanic corrosion. Because the metal is not melted, the galvanic corrosion precursor precipitates in the grains, and boundaries are not formed. Alloys that have traditionally been difficult to weld can now be joined using this technology.

Magnesium Alloys

The relative value of lightweight materials such as magnesium is just now being demonstrated for passenger vehicles. Therefore, magnesium is a good candidate for consideration in the medium term for newer, lighter Army vehicles. Although magnesium is not currently used in Army trucks, it has significant potential as a replacement for steel because it is one of the lightest structural metals and because of its high specific strength, damping capacity, and dent resistance. Because magnesium also has potential for replacing steel in automobiles, it is likely that applications developed by the automotive industry (such as closures and instrument panels) can be leveraged for Army Class 2B and 6 trucks. In order to provide adequate corrosion protection, magnesium components must be coated.

The challenges to implementing magnesium structures in Army trucks include these: technical performance modeling, supplier die-casting and sheet-forming infrastructure, material feedstocks and price stability, vehicle design and development experience, reliability, safety, serviceability, and closed-loop recyclability. Considerable potential exists for collaboration between the Army, DOE laboratories, and the automotive industry for jointly addressing these challenges. Provided that significant improvements can be achieved in feedstock quality, die-casting processing and handling, cost reduction, and structural quality, die-cast and wrought magnesium alloys (e.g., ZK60 and AZ31) have a number of potential component applications in military trucks, including the following:

- Body and closure components for door and hood inner panels, support modules, A and B pillars, and roof-opening panels;
- Powertrain components for transmission, transfer case and cover, and engine block (brackets, mountings, housings, oil pan, covers);
- Road wheels and spare wheels; and
- Interior components for instrument panel cross-vehicle beam, seats, front and rear backs, and steering components (pump housings, brackets, steering wheel).

Metal Matrix Composites

Metal matrix composites have been of military, as well as commercial, interest for nearly three decades, and the market for aluminum MMCs is projected to grow at a 14 percent overall rate to $173 million by 2004. Currently, aluminum MMCs are used primarily in low-volume, specialized applications in the aerospace, automotive, defense, and electronics packaging industries (ALMMCC, 2002). Although these industries have prototyped a number of component applications, only a few have reached production. The majority of these have been limited, niche, applications. Two of the few high-volume, commercialized applications are MMC brake drums and rotors, dominated by Duralcan and Alcan, and MMC pistons for gasoline engines, commercialized by Toyota and Mitsubishi for use in selected small-model vehicle engines. European piston suppliers have developed the squeeze-casting process for making MMC pistons.

The Army has investigated the development of MMCs for application to tank tread shoes, using selective silicon carbide (SiC) whisker reinforcements in high-wear locations.[20] USCAR and DOE—as well as several European and Japanese OEMs—are investigating applications of aluminum MMCs using the powder metallurgy route for low-cost transmission gears and connecting rods. Early commercial successes include the castable-aluminum MMCs, marketed under the trade name of Duralcan, using SiC particulate reinforcement, and wrought products that use alumina (Al_2O_3) particulate reinforcement. Both intermediate raw materials are available in billet form and are increasingly used in fabricating brake drums and rotors. These materials replace the current gray cast iron, with its weight-related problems and performance shortcomings.

The A359 aluminum MMC with SiC particulate (20 percent volume fraction or higher) is a good, general-purpose MMC for structural applications because of its superior heat conduction and reduced storage capacity. For cast-iron brakes, temperature spikes to 700 °C are common. Brake components of this new material would have a lower operating temperature, which would result in a friendlier environment for the lining, rotor, or drum materials.[21] This improvement would also allow for greater use of embedded sensors that could improve structural health monitoring and maintenance applications.[22]

The potential of MMC technology remains largely untapped, however, for a number of reasons. First, there are technical issues that need to be resolved, including fabrication costs, materials handling, and machinability. In the case of cast and powder metal aluminum MMC products, nondestructive evaluation (NDE) technologies must be integrated into manufacturing processes to ensure that consistent component density and minimum variation and discontinuity in properties are achieved. Second, the supplier base is small and fragmented. There is a wide range of potential composite systems, and the cost of materials development and testing has been prohibitively high for individual suppliers. High-volume end uses have

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[20]D. Ostberg. TACOM. U.S. Army Materials Research and Development Activities. Presentation to the committee, April 2001.
[21]M.J. Denholm. 2001. Application and manufacture of Al MMC components in light vehicles. Composites in Manufacturing Quarterly. 17(2):1-5.
[22]R.M. Hathaway, Oshkosh Truck Corporation. Presentation to the committee, May 9, 2002.

therefore not been pursued. Finally, the Army depots have limited experience in remanufacturing processes.

The Army, as a major stakeholder and potential beneficiary, should partner with defense contractors and commercial aluminum MMC suppliers to develop and demonstrate new applications of aluminum MMCs in lightweighting (e.g., powertrain, brake, and suspension components). Research topics outlined in the aluminum MMC technology roadmap include these:[23]

- Development of new aluminum MMC materials, critical processes, and design databases;
- Modeling of engineered materials and product performance, processing, and costs;
- Rapid prototyping and short-run production for cost-effective applications; and
- Improved machinability and joinability (e.g., maintaining clamp loads).

The establishment of a joint commercial-military MMC user resource center might be a valuable way of disseminating knowledge and guidance to military users and component manufacturers. Currently, there is no trade or industry organization that serves the MMC field specifically with respect to technology transfer. A resource center could direct users to sources of information on materials properties, uses, and characteristics—for example, to military handbook data and the educational modules being put together by The Minerals, Metals, and Materials Society (TMS). In addition, it could serve as the focal point for information exchange between end users, suppliers, the government, and the scientific community. Processing and machinability data, for example, could be made available to everyone.

Polymer Matrix Composites

Polymer matrix composites with fiberglass or carbon filaments have already been demonstrated and applied in limited production volumes on Army trucks. Thus far, the application of PMCs has had mixed results. For

[23]Aluminum Metal Matrix Composites Consortium (ALMMCC). 2002. Aluminum Metal Matrix Composites Technology Roadmap. Ann Arbor, Mi: ALMMCC. Available at <http://www.almmc.com>. Accessed January 2003.

example, the use of sheet molding compound (SMC) chopped-fiberglass-reinforced polyester hoods for the Humvee reportedly delivered increased payload, reduced weight, and improved corrosion resistance. However, this application developed maintenance problems due to material delamination, cracking, and susceptibility to impact damage. These problems resulted in high failure rates and increased maintenance and replacement costs. On the other hand, the use of PMC truck hoods for the MTVR is considered a success in lightweighting and production.[24] Mixed results such as these often occur when a new technology is introduced. The successful application of composites in MTVR hoods indicates that the problems with the Humvee hoods should be investigated to determine a solution.

The Composite Armored Vehicle (CAV) requires lightweight hull and turret structures of composite and ceramic armor able to withstand ballistics for production capability at cost-competitive rates. Vacuum-assisted resin transfer molding (VARTM) has emerged in recent years as a commercially viable method for the low-cost production of high-performance composite structures. The use of a single-sided, polyester molding tool at low pressure and a glass- or carbon-fiber preform in the VARTM process has been demonstrated in the boating industry as well as on Dodge Viper body panels. Applications of thermoset polyurethane and epoxy resin systems have already achieved commercial success. Newer, more recyclable engineering and structural thermoplastic resins, such as cyclic thermoplastic polyesters, are strong candidates for component applications in the medium to long term.

The Army should leverage the experience of the commercial automotive industry and other military services in the development, application, and demonstration of PMC and lightweight armor materials. A collaboration in the mid-1990s between USCAR's Automotive Composites Consortium, DOE, and NIST-ATP, combined with the U.S. Air Force Materials Laboratory, resulted in new, full-scale process capability demonstrations of the programmable powder preforming process (P4) technology from Europe. The P4 technology has led to several successful commercial applications of fiberglass and low-cost carbon fiber for automobile components, such as composite pickup-truck boxes, body side panels, and other structural, crash-resistant closure components on current niche passenger vehicles. Some of the relevant

[24]S. Nimmer, Oshkosh Truck Corporation. Presentation to the committee, August 2002.

strategies and areas needing research investments include those of optimizing molding and preforming cycle times, reducing reinforcement prices (especially for carbon fiber), and developing new vehicle architectures and design for manufacturability.

Improved Casting Technologies

The automotive sector is the largest user of nonferrous (i.e., aluminum, zinc, and magnesium) castings, accounting for nearly 60 percent of total shipments. Several competing, economically viable processing routes, such as lost foam casting, die casting, semisolid casting, and rapid prototyping, have been demonstrated and implemented in the automotive industry.

Ferrous and nonferrous alloy castings are already extensively used in the construction of Army vehicle bodies, as well as for most naval ship and submarine hull structures, machinery, suspension, and powertrain components. Care must be taken in processing, because high-strength steel castings are sensitive to hydrogen embrittlement, stress-relief embrittlement, and stress-corrosion cracking. Other cast stainless steels (including austenitic, dual-phase, and precipitation hardening types) have high potential for use where corrosion resistance is required and corrosion protection by coatings cannot be provided. Nickel-based, titanium, and aluminum castings, as well as advanced PMCs, also have strong growth potential in Army trucks in a limited number of structural lightweighting applications, as the technologies and fabrication processes are closer to achieving robustness and economies of scale. Research and development (R&D) efforts are under way at suppliers such as Oshkosh Truck Corporation and Stewart and Stevenson and at other Army research facilities.

LONG-TERM OPPORTUNITIES

Long-term opportunities are defined at the beginning of this chapter as those that would result from changes in the basic truck paradigm and would thereby enable the use of radically different materials.

Titanium Alloys

The use of titanium in production automobiles and trucks is essentially unknown, although it is being studied for future use when costs can be controlled. The use of titanium in components for military vehicles appears poised for significant growth in the long term, when different vehicle configurations become more common. Titanium alloys are of interest to designers of Army ground vehicles because of their unique combination of ballistic-survivable, corrosion-resistant, and mechanical properties. These alloys have high specific-yield strength, fracture toughness, and fatigue resistance. When reinforced or blended with suitable particulate materials, such as SiC, the strength and performance of titanium are dramatically enhanced.

The use of titanium alloys has been limited by their high cost relative to that of steels and aluminum alloys, the high rate of waste in production, and difficulty in machining and welding. Recent developments in processing technologies, such as single-melt cold hearth electron beam melting and plasma-arc melting, however, have reduced the cost of titanium feedstock significantly. Combining the use of single-melt Ti-6Al-4V with near-net-shape processing and compositing technologies such as casting, forging, and powder metallurgy can reduce fabrication costs even further. An ambitious, collaborative R&D program is presently under way between the U.S. Army Tank-Automotive Research, Development, and Engineering Center (TARDEC) and titanium suppliers to develop a single-melt, plasma-arc, cold hearth melting process for casting Ti-6Al-4V slabs that can be directly rolled into armor plate. The development of such a process would reduce the cost of producing titanium plate. The reduction of weight resulting from the use of titanium would help enhance vehicle and armament deployment and performance.

Programs are also under way at USCAR and various DOD and DOE agencies. These programs are examining the issues of purity and processibility of titanium powder from competing low-cost feedstock processes that have recently been demonstrated for extracting titanium from ore and solution. When low-cost processing of titanium is realized and combined with its demonstrated property and performance attributes, there is a strong likelihood that titanium could replace aluminum as well as steel in a variety of armor applications. In addition, titanium springs could be developed as both medium- and long-term applications.

Net Shape Manufacturing

Additive metal-processing technologies, such as laser-engineered net shaping, are being pioneered by companies such as Optomec, Laserfare, and the POM Group. These technologies, which have the advantage of producing a net shape in situ, are being demonstrated and evaluated for use in repair and remanufacturing operations for structural components, as well as for die repairs and modifications. These processes hold great promise for helping the Army meet future needs for products and spare parts on demand, whether in short-run production or as replacement spares in the field.

Self-Repair, Self-Maintenance

Condition-based maintenance and self-monitoring structure technologies are essential for the success of FCS and FTTS. The anticipated future growth of MMC components and less harsh operating environments are expected to result in the greater use of sensors integrated in vehicle components to serve this function. Combined with these advances, there is a need to bring Army depots abreast of new maintenance technologies (NDE, repair, and manufacturing) and to further leverage product and process developments being conducted in private industry, government, and nongovernmental organizations, including the DOE national laboratories, the U.S. Air Force, the U.S. Navy, and the National Center for Manufacturing Sciences.

Chapter Three

Enabling New Technology Insertion

The goals of the Army with respect to its fleet of trucks are to reduce the logistics footprint, maintenance costs, and fuel burden while maintaining other performance parameters. The lightweight structural materials and new processing technologies described in Chapter 2 can help achieve these goals. Barriers to the insertion of new technologies are described briefly below, followed by a discussion of ways to promote the introduction of lightweight materials.

BARRIERS

There is a variety of general barriers to the implementation of new technologies and materials in Army trucks. Large organizations, especially bureaucracies, can become highly risk-averse and resistant to change. Management research has recently focused on this topic because so many commercial companies failed during the past decade as a result of their inability to change quickly enough to remain competitive. Even if upper management supports a new direction, middle management and line personnel can resist the necessary changes. The Army is no exception, and the reluctance of some personnel to make necessary chances is a serious barrier to improving the mobility and fuel efficiency of the truck fleet.

Infrastructure costs inhibit change. Changes in materials systems in Army trucks will require many other adjustments downstream—for example, changes in maintenance practices including service and repair. To keep abreast of such changes, the Army must develop training programs for service personnel and must modify or rewrite service manuals. These downstream changes add costs and may create resistance to system changes. In addition, as the materials mix in Army trucks becomes more varied, recycling issues add additional complexity.

The budget for the Department of Defense (DOD), including its R&D funding, has decreased significantly over the past several decades. In 1960, DOD accounted for over 50 percent of the total R&D spending in the United

States. Today, it accounts for less than 20 percent.[1] Decreased R&D funding, combined with reduced direct funding for Army trucks, will make it difficult for the future Army truck fleet to achieve world-class capability. At current funding levels, the truck fleet will continue to degrade at a significant rate. According to one estimate, 28 percent of the Army truck fleet was judged to be over age in 1997, and this statistic is expected to increase to 40 percent by 2013.[2] Although recent events have created a more positive political attitude toward military spending, the Army will most likely have to continue to do more with less.

Few Design Cycles

The commercial automotive industry is able to continuously improve its production systems and products because of the large number of design cycles per product. Technical risk is mitigated because new technology can be introduced in smaller steps or piloted on lower-volume products until proven ready for large-scale introduction. This sequence of events also helps bring down costs prior to large-scale deployment. Constant practice keeps the design, engineering, and manufacturing teams at top efficiency and capability. Automotive manufacturers, however, still rely heavily on computer-aided design and prototype development, especially when new technologies or materials are being introduced.

Fewer design cycles and limited capability for prototype development increase risk. The Army will need to decrease its use of heavy conventional materials such as mild steel and begin using lighter materials for primary and secondary truck structures. Although the lightweight materials most likely to be used (high-strength steel, aluminum, and composites) have already been used in ground vehicles and aircraft, they will now require different design, development, fabrication, joining, use, and maintenance practices. To reduce risk, the Army should employ the same practices used in commercial product development: computer simulation supported by prototype development and testing. In addition, the Army should leverage appropriate technologies developed for commercial vehicles over the course of multiple design cycles.

[1]National Research Council. 2002. Equipping Tomorrow's Military Force: Integration of Commercial and Military Manufacturing in 2010 and Beyond. Washington, D.C.: National Academies Press.

[2]U.S. Army Tank-automotive and Armaments Command (TACOM). 1998. Tactical Vehicle Fleetbook. Washington, D.C.: Fleet Planning Office, U.S. Army TACOM.

While advanced materials research has been funded, relatively little funding is available for materials system integration and development testing, and none has been allocated for field-testing and evaluation of new materials systems.[3]

Low Production Volumes

Insertion of lightweight materials technologies in Army trucks is inhibited by the fact that development costs must be distributed over the comparatively low production volumes typical for military vehicles.[4] Obvious fixed costs associated with truck manufacture include buildings, equipment, and tooling. Additional costs that are largely fixed are those associated with development, such as vehicle design, engineering, testing, certification, and documentation. These costs can contribute significantly to the overall unit cost of a low-volume truck. Variable costs per unit also tend to decrease as production volume increases, owing to the greater purchasing power of a high-volume buyer and the greater flexibility regarding whether to make or buy components that a high-volume manufacturer has.

Most contracts for new Army trucks call for low production volumes compared with those for commercial products. Because of the difficulty in recovering the costs of low-volume production without setting high prices, many high-volume vehicle manufacturers have withdrawn from bidding on military contracts, resulting in a reduction in the competitive field. The Army must find other ways to minimize unit costs. Several steps are already being taken, including the use of common parts across truck lines, where possible, and the use of modular design permitting commercial off-the-shelf (COTS) components. A strong case has been made for accelerating the use of

[3]J. Eberhardt, U.S. Department of Energy. 21st Century Truck Program: Research and Development Funding Allocation and Project Reviews. Presentation to the committee,.April 23, 2001.

[4]The cost of manufacturing a product is generally dependent on the production volume. The elements that contribute to the cost of a product are categorized as either fixed or variable. *Fixed costs* are those that do not vary with production volume, such as capital equipment costs. *Variable costs* are those that do vary with production volume, such as raw materials costs. When the number of units being produced is small, the per-unit allocation of fixed costs becomes large, and the product becomes more expensive.

commercial technology and components.[5] Additional strategies to control and minimize the costs associated with low-volume manufacturing include minimizing fixed costs and buying flexible fixed assets.

One method of increasing the Army's purchasing power is to partner with other NATO nations in contracting for basic truck structural architectures and standard commercial components. More sensitive systems, such as electronics unique to the U.S. Army, could be added later as "black box" components. Although this approach seems feasible from a business perspective, it may be difficult politically. Changes proposed for DOD business practices, however, may make such an approach possible in the future.[6]

IMPROVED ARMY PROCUREMENT PROCESS

The structure of the current procurement system encourages the acquisition of trucks that have a low purchase cost at the expense of higher operating, maintenance, and disposal costs. The latter costs are not included in the competitive bid process and are therefore not taken sufficiently into consideration during the design and manufacturing process.

Fuel-Efficiency Requirements

Lack of aggressive fuel-efficiency requirements in the acquisition process precludes the introduction of lightweight materials into the Army truck fleet. An important step toward enabling the introduction of those materials is to set more aggressive fuel requirements, with goals for individual vehicle types being determined from an overall fleet strategy. Improved engine efficiency alone is not likely to enable the truck fleet to meet the logistic footprint goals set by the Revolution in Military Logistics initiative. Meeting this goal will require a combination of vehicle improvements, including optimal structural design and the aggressive application of lightweight materials. To provide the incentives for the truck-system integrators who are competing for a new vehicle to include lightweight materials in their proposals, procurement specifications will have to include

[5]National Research Council. 2002. Equipping Tomorrow's Military Force: Integration of Commercial and Military Manufacturing in 2010 and Beyond. Washington, D.C.: National Academies Press.
[6]The Economist. July 20, 2002. A more commercial future. 364(8282):15-16.

aggressive fuel-consumption requirements rather than simply requirements with respect to vehicle range.

Life-Cycle Assessment

As noted earlier, procurement and operating budgets, and therefore decision making regarding these two issues, are currently decoupled within the military. The incorporation of life-cycle assessment as a required element of the procurement process would promote the consideration of operating, maintenance, and disposal costs during initial acquisition. Life-cycle assessment would promote the use of new materials and the replacement of older trucks in the fleet.

Military vehicles have long service lives, often on the order of 20 years. As a result, actual total life-cycle costs include substantial operations and support (O&S) costs that may approach or exceed the initial acquisition cost. When personnel costs are included in O&S costs, TACOM found the total O&S costs for the medium tactical truck to be 66 percent of the total life-cycle cost.[7] The O&S costs for a recapitalized truck could be as high as 72.5 percent. The total life-cycle cost of a tactical truck with an initial cost of $150,000 could be $441,000, and that of a recapitalized truck as high as $546,000.

In some cases, the O&S costs are increased owing to corrosion problems. One study estimated that corrosion damage to cargo trucks cost the Army between $850 and $1,000 per truck per year, not to mention the cost of the downtime of the trucks.[8] Other data indicate that the cost may be as high as $1,200 per year per truck when the cost of labor is included. Corrosion also impairs the readiness of trucks for duty. It was recently reported that 17 percent of the cargo trucks in Hawaii were so corroded their mission capability is seriously impaired.[9]

The use of lightweight, corrosion-resistant structural materials in truck designs would be promoted if real fuel costs and O&S costs were given more prominence in acquisition requirements. Life-cycle costing should be

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[7]R.S. Bazzy. TACOM. Cost and Systems Analysis Information. Presentation to the committee, May 9, 2002.
[8]Army Materiel Command. 1998. Army Corrosion Prevention and Control. Program, Army Regulation 750–59. Available at <http://www.army.mil/usapa/epubs/pdf/r750_59.pdf>. Accessed March 2003.
[9]J.M. Argento. U.S. Army. Industrial Ecology Center Initiatives. Presentation to the committee, May 9, 2002.

institutionalized in future truck procurements in order to evaluate the impact of new vehicle designs, material changes, and technology alternatives by quantifying the cost of ownership of current vehicles and using these data to project fuel efficiency, up front production costs, O&S costs, maintenance and repair costs, and obsolescence and refurbishment costs. The Army should develop a standard life-cycle model that could be used in the acquisition process by both proposers and evaluators. Before a truck is purchased by the Army, the contractor should have in place a government-approved system of cost accounting to justify the selling price of these future systems. This change would require the implementation of new procurement practices, and on Source Selection Boards for Army vehicles there would need to be trained personnel who were capable of taking a holistic approach.

Best-Value Procurement

The "value" of a product is a function of procurement price and operational costs and performance, measured over useful life. An inexpensive product that has high maintenance and operating costs, or that is unreliable, is not a "best value". With Army trucks, it is difficult to harness competitive market forces because of the small market and consequent narrow supplier base. Traditionally, the suppliers of light trucks have been domestic automakers, such as Ford and Dodge. The suppliers for medium and heavy trucks have been specialty vehicle manufacturers and defense contractors with dedicated manufacturing and assembly lines. Stewart and Stevenson is the primary source of the Family of Medium Tactical Vehicles (FMTV), and Oshkosh Truck Corporation is the primary source of heavy tactical vehicles. The remanufacturing program for 2.5- and 5-ton trucks is undertaken by AM General and Oshkosh Truck Corporation. High unit costs and small production runs of items built to military specifications are typical of the defense-unique industrial base for trucks.

An alternative type of procurement process could provide suppliers with incentives to produce products that maximize the Army's value. The Army could develop an understanding of the utility function[10] governing the use of trucks, and then compete its supply contracts in such a way as to reward suppliers whose product maximizes the Army's utility function. For example, it would be useful to understand how much of a reduction in price offsets a 10

[10]The utility of a truck is a complex function of characteristics such as its price, durability, logistical footprint, and reliability.

percent reduction in reliability, or how much more should be paid for a truck with extremely high reliability. At least one study has addressed the principles of measuring utility.[11] The Army would benefit from an investigation of utility analysis and its applicability to the truck procurement process. A utility function could provide the Army with a single, quantitative equation that could be shared with suppliers and used to award procurement contracts. Utility analysis, or a similar method that places a quantitative measure on the value of performance, can be the basis for achieving best-value procurement. The Army's existing procurement system could be adapted to this approach.

IMPROVED MAINTENANCE SYSTEM

Traditionally, trucks are owned and maintained by the Army, with the supplier's role ending shortly after procurement. A network of Army depots provides most or all of the maintenance support. Spare parts may be purchased from commercial suppliers, but these transactions are generally separate from the original procurement. Furthermore, warranties covering material defects rarely extend beyond the first year, and, given the harsh conditions that Army trucks are subjected to, warranties are limited by design. A by-product of this arrangement is that there is no channel for quick feedback of information to the supplier regarding design defects or opportunities for performance improvement.

The Army has done only selected detailed studies of O&S costs to date. The downtime costs associated with repair, maintenance, and overhaul are challenging to quantify and are usually not taken into consideration. These costs, however, have a major impact on operational readiness. The Army does not have enough information to adequately characterize these costs in life-cycle assessments. Because the Army generally does not track vehicles by vehicle identification numbers, it is unable to perform extensive and statistically meaningful studies of maintenance activities for either the fleet as a whole or particular vehicle types. A system of vehicle tracking and better data collection would enable the Army to maintain its fleet more efficiently.

[11]F.R. Field. 1985. Application of Multi-Attribute Utility Analysis to Problems in Materials Selection. Ph.D. dissertation. Cambridge, Mass.: Massachusetts Institute of Technology.

Design for Reduced Maintenance

Products and systems can be designed for reduced maintenance. Using special materials selection, designs that prevent water damage on parts, and corrosion protection, the commercial sector has successfully produced vehicles with superior performance and low maintenance costs. In addition, monitoring the condition of vehicles through inspection procedures could be used to schedule preventive maintenance activities that preserve performance and avoid costlier repairs down the line.[12]

Systematic Replacement of Older Trucks

Based on the average annual cost of ownership, the economic useful life[13] of a truck has been calculated to be approximately 16 years.[14] At that point, the effectiveness factor of the vehicle is reduced to about 0.5 and, in effect, two older trucks are required in order to accomplish the work of one new truck. The useful life of a military truck may be as low as 13 years. Until that point, the average annual cost of ownership has been decreasing. Beyond 13 years, these costs begin to rise. These analyses suggest retiring trucks at some point between 13 and 16 years of service. A centralized tracking system could record the present age of every truck in the fleet and help ensure that trucks were retired and replaced on a regular basis. Federal Express and United Parcel Service both use such tracking systems.

Tracking the age of trucks in the fleet could also enable the selection of appropriate trucks for recapitalization programs. Currently, the age and condition of trucks selected for these programs vary widely. Some are only a few years old, are in good general condition, and have been driven as few as 4,000 miles (Hathaway, 2001). Trucks should be selected for recapitalization on the basis of age or general condition. For example, trucks not built to the 22-year corrosion specification could be recapitalized after 8 to 10 years, since the HEMTT program includes more corrosion protection than was

[12] National Research Council. 2002. Equipping Tomorrow's Military Force: Integration of Commercial and Military Manufacturing in 2010 and Beyond. Washington, D.C.: National Academies Press.

[13] The economic useful life (EUL) is the average age at which replacing an old vehicle with the same type of new vehicle minimizes the life-cycle cumulative cost of ownership for a fleet of similar vehicles.

[14] V. Lambert, Fleet Planning Office, TACOM. Economic and Military Useful Life of Army Trucks. Presentation to the committee, May 9, 2002.

originally available for these vehicles. Data on repairs and parts failure could be shared with manufacturers, thus helping lead to improvements.

An optimum mixture of old and new vehicles would result in a more modern fleet that was cheaper to maintain on a life-cycle cost basis. This mixture could be achieved without increasing the total cost of fleet ownership over the next 20 years. By aggressively retiring vehicles with marginal reliability and performance, significant O&S cost savings could be realized and used to finance additional modernization and rebuilding or remanufacturing programs.

Alternative Ownership Strategies

The remanufacturing program in place with Oshkosh Truck Corporation is an innovative effort to extract better value from the used truck fleet by remanufacturing these trucks to as-new condition. It is also a positive step toward closing the feedback loop between the supplier and the customer, effectively allowing the supplier to take partial ownership of the product as it is used in the market. Alternative ownership strategies could go farther, however. The commercial airline industry has discovered that leasing, rather than buying, is economically efficient. Airlines lease not only aircraft, but also subsystems within aircraft, such as engines and brakes, and effectively pay for these items on a per-use basis. Aircraft engine and brake systems suppliers are responsible for maintenance, repair, and, when necessary, replacement of the subsystems. In this business model, the supplier is highly motivated to develop and implement the best-available technologies—those that improve performance, extend life, increase reliability, and reduce life-cycle costs.

Leasing arrangements have been widely adopted in the commercial sector, especially for complex, long-lived systems requiring extensive maintenance. The Army should investigate alternatives such as the purchase of trucks with extended service warranties, the leasing of trucks by the year or by the mile, and contracts structured so that suppliers are rewarded on the basis of ton-miles transported. In addition, the Army should investigate contracts for life-cycle support. Such arrangements have been shown, in the commercial sector, to be particularly beneficial for products with high operating and maintenance costs. The Marine Corps currently has a contract with Oshkosh Truck Corporation under which the company performs service and repair procedures on some Marine Corps trucks.[15]

REDUCING THE COST OF NEW TECHNOLOGY

In addition to those discussed above, another barrier to the insertion of lightweight structural materials and technologies in Army trucks is the initial higher costs of these materials and the cost of changing to new production processes. Methods of reducing these costs include the use of modular design and of common components and subsystems for several different vehicles.

Modular Design

Designing trucks for modularity can enable the insertion of lightweight materials and reduce costs. As they become available, components using new lightweight materials can be inserted into existing products. In addition, modularity facilitates the sharing of components and subsystems across platforms. Costs can be reduced when the use of a common component or system over several platforms results in increased production volume for that component and subsequently leads to reduced unit cost.

Modularization would enable the improvement of military vehicle performance during design cycles. This strategy has been used extensively by automobile and truck manufacturers to allow for the ongoing improvement of product and a gradual buildup of the processing infrastructure. Life cycles are relatively short in automotive applications because of the dynamics of exhaust emission regulations, which require a new power plant every several years. Despite these short life cycles, manufacturers introduce enhancements, upgrades, and modifications to increase performance and effectiveness. Military vehicles have a longer life cycle and can therefore reap more benefits from performance and efficiency upgrades. Upgrading and retrofitting are enabled if a vehicle is designed with flexibility, allowing major vehicle components and subsystems to be replaced with improved ones. Analytical tools pertaining to system modeling can be used to assess and tailor the desired improvement.

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[15]N. Osborne, Oshkosh Truck Corporation. Presentation to the committee, August 21, 2002.

Modularization works well for stand-alone components, such as engines, suspension springs, wheels, and tires. The electronics and computer industries have used this approach to bring down the unit costs of commercial products. However, modularization cannot be used as extensively for the complex structural systems typical of automotive vehicles.[16] It is more difficult to design modular features into the vehicle architecture, because all the elements of the architecture are part of a system and cannot be retrofitted without affecting the whole system behavior. For example, vibration behavior is affected by mass and stiffness distributions as well as by joint stiffness characteristics. Replacing a critical structural component with one made of a different material could degrade the overall vibration behavior of the vehicle and negatively impact critical performance criteria such as crashworthiness.

Despite these limitations, there are significant opportunities for the Army to use modularity in its truck designs. The Army has already used this approach for electronic systems and information technology and could extend it to stand-alone vehicle components. System analysis tools could provide guidance on what is achievable regarding more complex structural elements.

Common Systems/Components and Standardization

Increased use of common components and subsystems across truck platforms could facilitate the use of new lightweight materials by reducing the cost of these components. Economies of scale could be leveraged for truck procurements, component purchasing, and lean manufacturing and assembly cost reductions, as well as downstream O&S costs on fielded trucks. Lean practices, pioneered by Toyota, combined with flexible building concepts and common locating and fixture systems, are already being implemented in commercial passenger vehicle and truck manufacturing. Some commercial vehicle manufacturers are currently able to switch model builds on the same production line without stopping the line for retooling. The Army has already used component standardization in some truck models—for example, with the use of Steyr Symatec truck cabs from Austria. There are significant opportunities for transferring this strategy to other truck programs,

[16]D.E. Whitney. 1996. Why mechanical design cannot be like VLSI design. Research in Engineering Design: Theory, Applications, and Concurrent Engineering 8(3):125-138.

through the use of common powertrain, drivetrain, and chassis components, as well as telematics and military electronics modules.

Future modified Army trucks bearing common modules and systems could be produced at commercial truck OEM facilities and then turned over to a contractor or specialty truck manufacturer for final assembly, which would include add-on armor or sophisticated military electronics not needed for the civilian market. This is particularly likely for Class 2B vehicles, as was recently demonstrated by the Commercially-Based Tactical Trucks (COMBATT) program of the National Automotive Center (NAC). This program focused on improving the mobility and intelligence-gathering capabilities of commercially manufactured light trucks to meet the Army's tactical support truck needs. Previously, trucks had been purchased directly from the commercial fleet, and in some cases such as that of the Commercial Utility Cargo Vehicle (CUCV), they fell short of meeting the Army's performance requirements.

The insertion of new lightweight materials could be enhanced by the standardization of military vehicle components with commercial components and assembly practices. The Army would thus be able to take advantage of technological advances resulting from the multiple design cycles of commercial vehicle manufacturers. Truck development times and testing times could be reduced if suitable commercial component designs were mature and had a track record of reliability, cost, performance, and maintenance routines. In addition, the unit procurement cost to the Army could be reduced by the purchase of COTS products.

RADICAL REDESIGN ENABLED BY NEW TECHNOLOGIES

The present truck paradigm consists of a power plant burning a single fossil fuel and providing power to the vehicle's wheels through driveshafts. As noted in Chapter 2, future truck architectures may become modular, with power plants providing electric power to driven axle or bed modules. Such fundamental changes in frame configurations would enable the use of radically different lightweight structural materials. The long-term opportunities described in this report refer to the types of materials that might become viable as a result of changes in the basic truck paradigm. New technologies that would require complete vehicle redesign and thereby open up opportunities for the use of lightweight structural materials include hybrid and alternative power sources. A hybrid design could result in the use of a much smaller engine, with significant additional weight savings.

Hybrid Electric Powertrains

The hybrid electric powertrain offers perhaps the greatest potential for tactical vehicle redesign in the near future.[17,18] This system consists of an internal combustion engine coupled with electric motors and an energy storage system or battery. Operating energy is provided by the engine, by the electric motor, or by both. The battery is charged when the engine provides excess power, for example when the vehicle decelerates. When the vehicle requires additional power, such as for climbing hills, the battery adds power by channeling electrical energy to the motors.

Use of the hybrid electric powertrain reduces two important sources of inefficiency in engine-based transportation: the need to use an engine that is oversized for the average duty cycle of the application, and the transient operation of the internal combustion engine caused by the drive-wheel speed and the traction effort required. In addition, hybrid electric powertrains allow auxiliary systems and accessories to be decoupled from the engine, permitting their use on demand and increasing overall efficiency. Finally, because the electric traction motor is designed to function as a generator during deceleration, a portion of the kinetic energy of the vehicle is converted back into electrical energy.

Hybrid electric powertrains would be most beneficial in light and medium trucks, the duty cycles of which include variable driving schedules, high operating speeds, and widely varied vehicle loading. Light-duty passenger cars with hybrid electric powertrains have already been commercialized (e.g., the Toyota Prius and the Honda Insight). Prototypes of hybrid electric trucks have also been produced.[19] For this technology, areas that require research include electric motors and generators, electrical energy storage systems, power electronic products, electrical safety, regenerative braking, and engines built for specific purposes (see Appendix B for additional information).

[17]National Research Council. 2001. Review of the Research Program of the Partnership for a New Generation of Vehicles: Seventh Report. Washington, D.C.: National Academy Press.
[18]U.S. Department of Energy. 2000. Technology Roadmap for the 21st Century Truck Program: A Government-Industry Research Partnership. Report No. 21CT-001. Available at <http://www.trucks.doe.gov/pdfs/P/62.pdf>. Accessed March 2003.
[19]S. Nimmer. Oshkosh Truck Corporation. Presentation to the committee, August 21, 2002.

Fuel Cells

The use of fuel cells as auxiliary power sources or, in the very long term, as primary power sources, would provide opportunities for new truck design and the insertion of radical new materials. Fuel cells are electrochemical devices that convert energy from the chemical reaction of hydrogen and oxygen into electricity. By 2005, fuel-cell vehicles using pressurized hydrogen may be produced as passenger cars and sport utility vehicles (SUVs). There are significant barriers to be overcome, however, including overall performance limits, cost, fuel availability and onboard storage, and lack of infrastructure.[20] For military applications, fuel cells will not be a viable primary power alternative for many years to come. As fuel-cell stacks of high efficiency are developed, however, they could be used as auxiliary power units in tractor-trailer, vocational, or medium-duty trucks that have much accessory equipment (see Appendix B for additional information).

LEVERAGING COMMERCIAL TECHNOLOGIES

Despite the potential advantages, there are numerous barriers to the integration of military and commercial business practices. A recent NRC study discusses barriers to the introduction of new commercial technologies, such as lightweight materials, into military products.[21] The barriers are as follows:

- Government practices regarding intellectual property that are inconsistent with commercial practice and limit R&D partnering opportunities;
- Government acquisition provisions that many commercial suppliers are unwilling to accept, thereby limiting the supplier community;
- The lack of longer-term contracts that would motivate suppliers to make investments that would yield savings over the product life cycle; such contracts are particularly important to investments in new manufacturing processes needed to produce structural systems made of lighter-weight materials; and
- A burdensome oversight process, dedicated to preventing abuse, that creates an almost adversarial relationship between the Army and potential R&D partners, truck manufacturers, or suppliers.

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[20]See note 3 above.
[21]National Research Council. 2002. Equipping Tomorrow's Military Force: Integration of Commercial and Military Manufacturing in 2010 and Beyond. Washington, D.C.: National Academies Press.

As the commercial automobile and truck industries make progress in the design, application, and qualification of new lightweight structural materials and related technologies, the Army would benefit from the ability to leverage these advances and incorporate them into new generations of military trucks. Cross-platform dual use (i.e., commercial to military and vice versa) of advanced materials and manufacturing technologies is the key to the Army's benefiting from economies of scale and best manufacturing practices. Partnerships with commercial and passenger vehicle manufacturers are needed to access new technologies and implement them in new truck platforms. Early involvement of maintenance personnel is essential when incorporating advanced lightweight materials into future trucks.

The Army should pay close attention to the global vehicle codes and standards established by commercial industry, regulatory bodies, and trade organizations. These codes and standards would help prevent duplication of R&D, as well as avoiding the dilution of limited supplier resources and capabilities by focusing them on aspects important to achieve battlefield dominance and mobility. Knowledge spillovers from joint government-and-industry-supported R&D programs are critical in accelerating the transfer of emerging advanced materials technologies to the Army truck fleet.[22] Ongoing programs through which the Army can leverage new technologies into truck platforms include the R&D in progress in other military services, commercial automotive partnerships, industry-university consortia, and cross-industry collaborative programs. Some of these programs are described below.

Government Programs

The National Automotive Center is an existing Army program that was established in 1992 as part of the U.S. Army Tank-automotive Research, Development, and Engineering Center under TACOM. The NAC is the focal point for DOD collaboration on ground vehicle research and development with the commercial automotive and truck industries. The NAC aims to develop technology that improves fuel efficiency and reduces emissions without degrading performance in light, medium, and heavy trucks. The NAC funds collaborative automotive technology contracts, Small Business Innovative

[22]C.B. Fitszsimmons. 2001. Knowledge Spillovers from Joint Government-Industry Supported Research: Case Study from the Automotive Industry. Ph.D. dissertation. George Mason University, Fairfax, Virginia.

Research (SBIR) contracts, and Cooperative Research and Development Agreements; sponsors an academic center of excellence for automotive research; and participates in national initiatives such as the Partnership for a New Generation of Vehicles and the Intelligent Transportation System. The goal of these collaborations is to evaluate the technology developed by the automotive industry and to leverage commercial advances in military systems.

The Department of Energy’s Office of Advanced Automotive Technologies (OAAT) has partnered with the domestic "big three" automakers for the development of new technologies, including lightweight materials, alternative fuels, energy storage, combustion and emission control, and power electronics. DOE created the Office of Heavy Vehicle Technologies (OHVT) in 1996 to address the energy-efficiency challenges facing manufacturers, suppliers, and users of heavy transport vehicles. The office works with industry partners and their suppliers to research and develop technologies that make heavy vehicles more energy-efficient and able to use alternative fuels while reducing vehicle emissions. Currently, OHVT programs are focused on high-efficiency, clean diesel and natural gas technologies. OHVT takes an integrated systems approach that encompasses a wide range of technologies. The high-strength, lightweight materials program aims to reduce vehicle weight by 35 to 40 percent for Class 1 and 2 vehicles, 25 percent for Class 3 to 6 vehicles, and by 5,000 lb for Class 7 and 8 vehicles (up to 65 tons). The propulsion materials program aims to develop new materials for fuel systems, exhaust gas after-treatment systems, valve trains, and air-handling systems.[23]

Commercial Automotive Partnerships

The United States Council for Automotive Research is the umbrella organization of DaimlerChrysler, Ford, and General Motors. USCAR was formed in 1992 to further strengthen the technology base of the domestic auto industry through cooperative precompetitive research. The Auto Aluminum Alliance (AAA) was created in 1999 as a cooperative effort between the major aluminum suppliers and the big three auto companies. AAA promotes collaboration on research to accelerate the use of new aluminum technologies in cars and light trucks. This alliance conducts joint

[23]U.S. Department of Energy. 2001. Office of Heavy Vehicles Technologies. Available at <http://www.trucks.doe.gov>. Accessed March 2003.

R&D projects and, with the assistance of a specialty steel company, has had some recent breakthroughs in the recycling area. UltraLight Steel Auto Body is an international design consortium of 35 steelmakers from 18 countries that joined forces in 1994. ULSAB is making great progress in component design. The ULSAB designs for a body-in-white used high-strength steels, finite element modeling, and innovations such as laser-welded blanks, hydroformed tube structures, and roof panels.[24]

Joint Government-Industry Collaborations

The 21st Century Truck Initiative was established in 1997 by the National Automotive Center to address challenges facing the trucking industry. This initiative, a collaboration between government agencies and industry, seeks to improve fuel efficiency, reduce emissions, increase safety, and reduce the cost of ownership for commercial and military trucks. The program seeks to increase triple fuel efficiency for Class 2B and 6 trucks and Class 8 buses and to double fuel efficiency for Class 8 line-haul vehicles.

The 21st Century Truck Partnership was established in 2000 and includes the Army, DOD, DOE, the Department of Transportation, the Environmental Protection Agency, trucking industry affiliates, and academic institutions. This partnership seeks to develop advanced, commercially viable truck technologies through partnerships between government and industry. The goals of the partnership are to improve fuel efficiency, enhance safety, reduce operating and ownership costs, lower emissions, and maintain or enhance performance. The partnership has a thrust area for advanced materials and plans for an integrated approach to R&D on hybrid electric powertrains for commercial and military applications. Use of high-strength steel, increased use of aluminum, and incorporation of carbon fiber composites are several examples of technical approaches under consideration by the 21st Century Truck Partnership.[25]

Commercial Technologies for Maintenance Activities is a cooperative agreement between DOD and the National Center for Manufacturing Sciences established in 1998 to leverage commercial practices in repair, remanufacturing, and maintenance technologies. This program is aimed at

[24]National Research Council. 2000. Review of the Research Program of the Partnership for a New Generation of Vehicles: Sixth Report. Washington, D.C.: National Academies Press.
[25]See note 18 above.

the development of commercially proven methods and tools for reducing the O&S costs incurred by Army depots supporting the remanufacturing and rebuilding of weapon and support platforms. Thus far, this partnership has resulted in several new-fielded technologies in rapid prototyping, nondestructive evaluation, and corrosion sensing and repair.

IMPACT is a joint program between NAC, the Ford Motor Company, the University of Louisville, and the American Iron and Steel Institute. The program supports the development of lightweight, fuel-efficient, corrosion-resistant, low-cost technologies for commercial and military vehicles. It focuses on the use of high-strength steels, laser-welded blanks, and improved bonding to significantly reduce the weight of the Ford F-series for potential military applications. Ford's P2000 lightweight vehicle platform uses aluminum extensively for major components such as the body and frame, as well as carbon fiber, magnesium, and titanium for a variety of parts. IMPACT is also studying the potential for using primarily steel, a more affordable material, to achieve near-P2000 weight reductions.

The Partnership for a New Generation of Vehicles is a nonprofit organization established in 1992 as a joint effort between government and automobile manufacturers for R&D into vehicle technologies that are safer, stronger, lighter, and more fuel-efficient. The PNGV program seeks to reduce body-in-white weight by 50 percent and conducts studies of weight reduction in the chassis and powertrain of automobiles.

Chapter Four

Conclusions and Recommendations

The Committee on Lightweight Materials for 21st Century Army Trucks was asked to recommend research and development opportunities and programs aimed at evaluating and developing advanced materials, processes, and structural concepts for U.S. Army truck applications (see Chapter 2). In the process of identifying these opportunities, it became clear that a number of nontechnical issues had to be addressed in order to enable the insertion of lightweight structural materials and new processing technologies in Army truck applications (see Chapter 3).

The committee was also asked to recommend methods the U.S. Army Tank-automotive and Armaments Command (TACOM) can use to coordinate its advanced materials research efforts with industry and other federal agencies. This chapter presents the committee's final conclusions and recommendations.

OPPORTUNITIES FOR RESEARCH AND DEVELOPMENT

The committee's conclusions regarding opportunities for materials research and development are summarized in Table 4-1. For the short and medium term, advanced galvanized steel alloys combined with selective, justified application of other advanced materials should meet most of the Army's light-vehicle needs. A variety of steels in flat and plate forms are likely to remain the material of choice in the heavy-truck categories. Additionally, for the short term, a number of commercially available materials and technologies can be used for Army trucks, including high-strength and stainless steels, aluminum and magnesium alloys, and MMCs.

Manufacturing processes available today include superplastic forming, castings of aluminum and magnesium alloys, and the use of tailor welded stamping/forging blanks. For the medium term, materials such as dual-phase and ultrahigh carbon steels, aluminum 2519, magnesium, MMCs, and PMCs are candidates.

TABLE 4-1 Summary of Opportunities for New Materials, Applications, and Research

Subsystem	Short Term	Medium Term	Long Term
Frames	High-strength steels, stainless steels, galvanic insulation, corrosion-resistant coatings and design	High-strength steels, hydroformed tubes to replace frame rails, truss frame to replace frame rail/ladder construction, and extend benefits to secondary structure	Magnesium castings, PMCs, light modular structures, and embedded sensors.
Secondary structural elements	Stainless steel (truck cabs), aluminum alloys (truck cabs, cargo beds), superplastically formed aluminum (cab structures), magnesium extrusions (passenger seat frames), sheet molding compound (cab components), tailor-welded blanks (door panels), and corrosion design.	Ultrahigh carbon steels (side impact panels), aluminum 2519 (forged and extruded for use in armor plate), magnesium (body and closure components, seats, front and rear backs), PMCs (truck boxes, side panels, cab structures), multifunctional materials for truck cabs (combine armor and structure), electromagnetic joining, adhesive joining, and friction stir welding.	Titanium (armor plate), smart materials, embedded sensors, self-repair, energy storage, and ballistic protection.
Structural drivetrain	Aluminum alloys (driveshafts), magnesium castings (transmission casings and transfer cases), MMCs (brake drums and rotors), PMC springs for light trucks, and corrosion-resistant coatings.	High-strength steels, magnesium alloys (transmission, transmission case and cover, engine block, suspension components), MMCs (powertrain, brake, wheels), PMCs (driveshafts, springs for heavy trucks), high-performance castings, titanium springs, and higher-performance tire cord.	Titanium springs, embedded sensors, additive metal process technologies (parts on demand), and electric/hybrid drivetrains.

Finally, for long-term applications, Army trucks can benefit from investment in titanium, smart materials, and additive metal process technologies. Investments in advanced materials, including nonferrous alloys, composites, and coatings, that offer superior performance and reduced operations, maintenance, and service costs would serve the longer-term, mission-specific needs of future tactical trucks and combat programs. In such cases, the need for condition-based vehicle health monitoring cannot be overemphasized.

RECOMMENDATION. THE ARMY SHOULD PURSUE THE USE OF LIGHTWEIGHT STRUCTURAL MATERIALS IN ITS TRUCK FLEET, AS FOLLOWS:

- **The Army should follow the guidance in the table "Summary of Opportunities for New Materials, Applications, and Research," in this report.**
- **Research programs should be funded to develop the technologies listed in the table as medium- and long-term opportunities, and these programs should include system integration, development testing, and field testing.**
- **The Army should support the development of databases of the properties of these materials as well as the development of models for processing lightweight materials and for predicting the performance of components manufactured using these materials.**

FUTURE TACTICAL TRUCK STRATEGY

The Army truck fleet continues to degrade faster than it can be upgraded through new acquisitions, forcing the Army to use recapitalization techniques simply to maintain the fleet size and effectiveness ratio.[1] While this approach permits the possible introduction of improved components such as the engine, it renders almost impossible advances in overall vehicle configuration and structural architecture or the introduction of new lightweight materials.

New brigade requirements such as enhanced mobility have created pressure to accelerate the introduction of lightweight materials into the truck fleet. In addition, an objective of the Revolution in Military Logistics (RML)

[1]V. Lambert, Fleet Planning Office, TACOM. Economic and Military Useful Life of Army Trucks. Presentation to the committee, May 9, 2002.

initiative is to reduce vehicle fuel consumption by 75 percent.[2] This initiative will most certainly require the aggressive application of lightweight materials.

Unfortunately, the application of lightweight materials may increase the acquisition cost of a new truck, even though the use of these materials may reduce life-cycle costs through enhanced corrosion resistance as well as reduced energy consumption. Although operations and support (O&S) costs over the life of the truck can be as high as or higher than the initial acquisition cost, the acquisition cost continues to create a constraint when limited budgets are applied at the individual platform level. Moreover, for fear of not winning a contract, major suppliers are reluctant to risk using new technologies that raise the initial cost and/or add risk to the development process.

RECOMMENDATION. THE ARMY SHOULD DEVELOP A LONG-RANGE, FLEET-LEVEL PORTFOLIO STRATEGY THAT ESTABLISHES A SCHEDULE FOR TRUCK ACQUISITION, REMANUFACTURE, AND REPLACEMENT.

Although contingent on future funding, the plan should establish priorities for vehicle replacement with specific requirements for performance, including vehicle weight and fuel consumption for each type of vehicle. In order to reduce the technology development cost burden typically placed on an individual vehicle program, the strategy should also establish a broad technology development program plan. A technology development program should be based on a budget process that prioritizes new technology development. The program should establish concept development activities leading to the fabrication of prototype vehicle demonstrators. In order to leverage resources outside the Army, the technology program should involve vehicle integrators, material and component suppliers, other branches of the Department of Defense, other government agencies, and any other key sources of technology. The accomplishments of existing government programs should be leveraged to the greatest extent possible.

[2]P.F. Skalny, A.J. Smith, and D. Powell. 2001. 21st Century Truck Initiative Support to the Army Transformation Process. SAE Paper No. 2001-01-2772. Warrendale, Pa.: Society of Automotive Engineers.

BID SOLICITATION AND PROCUREMENT PROCESSES

Suppliers respond to solicitations with whatever legitimate means are at their disposal in an attempt to win contracts. This behavior is entirely appropriate in a competitive market. Therefore, the most effective way for the Army to influence the cost and performance of future truck designs is through the procurement process.

RECOMMENDATION. THE ARMY SHOULD MODIFY ITS BID SOLICITATION AND PROCUREMENT PROCESSES TO STIMULATE AND REINFORCE DESIRED REACTIONS, INCLUDING:

- **The Army should clearly define the performance attributes that are important in its use of trucks. For example, if reduction of the logistical footprint is important, this attribute and its method of measure must be defined; if the total cost of ownership or life-cycle costs are important, these attributes should be defined. The bidding process should be structured to reward improvements in these performance attributes.**
- **The Army should provide minimum values or, preferably, scaled values for each performance attribute. For example, the value to the Army of reducing the logistical footprint or increasing fuel economy should be indicated.**
- **In selecting the winner of a competition, the Army should make certain that all performance attributes, including specifically the cost of ownership, are given their appropriate weighting in the decision.**
- **The Army should develop and adopt a consistent life-cycle costing methodology for evaluating alternative technologies. At a minimum, energy costs, maintenance costs, and end-of-life costs should be incorporated into this methodology. It should be emphasized in the request for proposals that life-cycle cost will be heavily weighted in the selection decision.**
- **Life-cycle costs should be extended to implement best-value procurement practices. The value of all performance attributes should be quantified and these metrics used to select the best-value truck to meet the Army's needs.**
- **The Army should review and revise its needs regularly. The description of an ideal truck varies across time, geography, and need for use. The procurement process must be flexible and responsive to these changing demands.**

LEVERAGING COMMERCIAL ADVANCES

The unique duty cycles and mission profiles of Army trucks constitute a special defense requirement. To respond to this requirement, the Army must take the lead in driving investments in new materials that have the potential to deliver competitive advantage in the logistics arena, supporting warfighters and combat equipment. At the same time, the Army can more actively leverage new materials and manufacturing technologies from the private and academic sectors by investing directly in research and development programs that lead to proof-of-concept demonstrations. The Army's Small Business Innovative Research (SBIR) program is to be complimented; it should be kept well funded and targeted to the lightweight trucks initiative in order to encourage high-quality material and manufacturing innovations from academia and industry.

RECOMMENDATION. THE ARMY SHOULD LEVERAGE NEW COMMERCIAL MATERIALS AND MANUFACTURING TECHNOLOGIES TO ACCOMPLISH ITS GOALS OF IMPROVED MOBILITY, DURABILITY, AND FUEL EFFICIENCY IN NEW TACTICAL TRUCKS. TO ACCELERATE TECHNOLOGY TRANSITION, THE ARMY SHOULD PARTICIPATE IN COLLABORATIVE PROGRAMS WITH ADVANCED MATERIALS INDUSTRY CONSORTIA.

By leveraging commercial advances, the Army can evaluate the technical feasibility of new materials and technologies. Pilot demonstrations of new materials and technologies in Army applications could then be used to increase the knowledge and capabilities of the supplier base.

Additional leveraging opportunities for the Army exist in the form of industry-government programs sponsored by the Department of Energy and the Department of Commerce that have identified advanced materials for application development. The emphasis of participants from the commercial automotive industry on the affordability of new materials, such as titanium, magnesium, and polymer matrix composites, should greatly facilitate prudent investment decisions by the Army. By working more closely with university centers of excellence, the Army can identify new enabling technologies in lightweight materials and in sensing and health monitoring, and it can also fund demonstration projects.

The early involvement of key stakeholders—including suppliers, maintenance personnel, and end users—in decisions regarding new materials is essential. The Army should assign a larger role to its material and component suppliers, and perhaps provide incentives for using new materials and technologies. The cradle-to-grave research and development for processing, assembly, service, remanufacturing, and operator training, which is currently done primarily within the Army, should be shifted to establish a more collaborative approach with these material and component suppliers.

SYSTEM FOR TRACKING VEHICLE AGE AND CONDITION

Army trucks are kept in service far beyond their economically useful life, resulting in increased operations and support costs and decreased performance. The effectiveness ratio of the total Army tactical wheeled vehicle fleet was recently calculated to be about 0.63 (compared with 1.0 for a new fleet). Effectively, eight existing trucks are required to do the work of five new ones. In addition, the annual total operating and maintenance cost for the Army truck fleet is about $1.5 billion, or more than $6,000 per truck. These costs are increasing at a rate of about $30 million per year, while the fleet size is being reduced from about 250,000 to about 225,000 trucks.[3] Other data indicate that a large fraction of these costs are for corrosion repair. The economically useful life of a truck has recently been estimated to be about 13 to 16 years, at which point the effectiveness ratio is reduced to 0.5.[4] Retirement and/or replacement should be considered at this age.

RECOMMENDATION. THE ARMY SHOULD ESTABLISH A MECHANISM FOR RETIRING OLDER TRUCKS AND FOR REPLACING TRUCKS IN POOR CONDITION WHEN THE AVERAGE YEARLY MAINTENANCE COST BECOMES PROHIBITIVELY HIGH.

A centralized tracking system could be used to record the present position of every truck in the fleet and to ensure that trucks were retired and/or replaced on a regular basis. (Both Federal Express and United Parcel Service use such tracking systems for their trucks.) Such a system could also

[3]U.S. Army Tank-automotive and Armaments Command (TACOM). 1998. Tactical Vehicle Fleetbook. Washington, D.C.: Fleet Planning Office, U.S. Army TACOM.
[4]V. Lambert, Fleet Planning Office, TACOM. Economic and Military Useful Life of Army Trucks. Presentation to the committee, May 9, 2002.

be used to select trucks for participation in recapitalization programs. Currently, the age and condition of Army trucks sent to such programs varies widely (Hathaway, 2001). Data on repairs and parts failure could be shared with manufacturers in order to facilitate design improvements. A more standardized system for the replacement of damaged trucks would promote the introduction of new materials and technologies into the truck fleet.

TRACKING NEW MATERIALS FOR REPAIR AND DISPOSAL

The majority of material used in Army trucks today is plain carbon steel. The corrosive galvanic current between two plain carbon steel parts placed in contact will be small and may not cause serious corrosion. However, as more new materials are introduced into Army trucks, galvanic isolation between parts made from widely differing materials will become increasingly necessary. The inspection, maintenance, and repair procedures for vehicles with such parts will become increasingly complex.

RECOMMENDATION. THE ARMY SHOULD INSTITUTE A MECHANISM FOR ENSURING THAT DIFFERENT TYPES OF MATERIALS ARE TRACKED DURING REPAIR AND DISPOSAL.

A color code or a numbering code that provides each alloy with its own identification is one such mechanism. A coding system could clearly indicate to those making field repairs where galvanic corrosion would occur and where it would be vital to provide galvanic isolation. (As an example, if all steel parts were coded with one color and all parts made of cast aluminum were coded with another color, it would be obvious which parts needed to be isolated.)

As different materials are increasingly used on Army vehicles, repair and replacement procedures will become more complicated. For example, composites are a class of materials now being selectively used in Army trucks— repair procedures for these materials are not generally known and are very different from those for metallic materials. Maintenance training will be required for each new generation of vehicles. In addition, as some parts are changed during recapitalization programs, maintenance and repair manuals will need to be continuously updated. Computerization of future depot maintenance manuals would aid in their being kept current for purposes of repair. Vehicle OEMs (original equipment manufacturers) could be required to maintain these manuals, as well as information on common parts failures, on their Web sites.

Appendixes

Appendix A

Biographical Sketches of Committee Members

Harry A. Lipsitt, *Chair*, is professor emeritus in the Department of Mechanical and Materials Engineering at Wright State University. He spent 30 years at the Air Force Wright Laboratories working on the development and optimization of metallic and intermetallic materials for use in high-temperature applications. His earlier research included fracture toughness in ceramics; deformation mechanisms in two-phase alloys, and deformation mechanisms in ordered intermetallics. Dr. Lipsitt has published more than 100 technical articles in refereed journals and has served on the editorial review boards of *International Metallurgical Reviews* and *Metallurgical Transactions*. Dr. Lipsitt has chaired and served on numerous National Research Council committees and on the National Materials Advisory Board.

Rodica A. Baranescu (NAE) is chief engineer of engine performance analysis at the Technical Center, Engine and Foundry Division, International Truck and Engine Corporation. She is responsible for leadership and coordination of research and development activities in low-emission diesel engines for truck applications; simulation and modeling of combustion, emissions, processes, and systems in diesel engines; and the evaluation and development of alternative fuels for heavy-duty engines. Previously, she worked for International Navistar. Dr. Baranescu has authored numerous technical papers on topics such as the performance and emission optimization of diesel engines, assessment of alternative fuels potential for automotive applications, simulation analysis of engine processes, and statistical optimization of engine design. She has been active in SAE (Society of Automotive Engineers) International for the past 20 years, holding positions including president, member of the board of directors, chair of the International Services Committee, and chair of the Chicago section. Dr. Baranescu was made a fellow of SAE in 1999 and in 2001 was elected to the National Academy of Engineering.

John V. Busch is general manager of Van Custom Millwork, a manufacturer of high-end architectural wood products. His area of expertise is materials economics, specifically the cost modeling of new technologies. Previously, he served as director of business development for Composite Products, which supplies long-fiber-reinforced molded composite components to automotive and office furniture manufacturers. For 13 years, Dr. Busch was president and founder of IBIS Associates, which conducts international management consulting studies for technology-based organizations. At IBIS, he specialized in business development, cost modeling, and technology assessment. Prior to that, he worked as a materials engineer at United Technologies. Dr. Busch has served on the board of directors of Brunswick Technologies, an innovative composites reinforcement supplier, and as a special partner in Ampersand Special Materials Ventures, a venture capital fund for investing in emerging specialty materials and chemicals businesses. He has also served on numerous National Research Council committees and has been a member of the National Materials Advisory Board.

Glenn S. Daehn is professor in the Department of Materials Science and Engineering at Ohio State University. His research interests include metal forming processes, mechanical behavior, plasticity, and the design and manufacture of affordable lightweight structures. Dr. Daehn's recent work includes research into improving materials formability via high-velocity sheet metal forming and electromagnetic forming as a means of flexibly producing very high velocity deformation. Dr. Daehn and his research group are working with automotive, aluminum, and aerospace companies and the National Science Foundation to develop this process. He has also worked in the development of new processes for the fabrication of metal matrix composites by novel reactive and powder processing routes.

Larry J. Howell retired as executive director for science at the General Motors (GM) Research and Development Center. In this position, he served as chief scientist for GM, overseeing six science laboratories working on thermal and energy systems, electrical and controls integration, materials and processes, enterprise systems, chemical and environmental sciences, and vehicle analysis and dynamics. In addition, Dr. Howell had global responsibility for joint research with universities, government agencies, and industrial partners; he also served as secretary to GM's Corporate Science Advisory Committee, which reports on technology issues to GM's board of directors. Previously, Dr. Howell served as executive director of body and vehicle integration at GM Research Laboratories. His areas of responsibility included research and development in body engineering and manufacturing, chassis and electrical systems, vehicle integration, and vehicle safety. In this capacity, he was also responsible for the Research and Development Center's advanced vehicle programs, including the Partnership for a New Generation of Vehicles and the Intelligent Transportation Systems program.

Manish Mehta is director of collaboration programs at the National Center for Manufacturing Sciences (NCMS). His responsibilities include assessing technology needs and developing collaborative research and development projects with NCMS's defense and industrial members for the use of lightweight materials and production processes. In addition, Dr. Mehta is executive director of the Aluminum Metal Matrix Composites Consortium, a supplier group organized and managed by NCMS, and convener of the Steel Joint Industry Alliance of steel-making, forging, heat treating, and end-user industries and trade organizations. Dr. Mehta has developed and managed complex technology demonstrators for collaborative projects sponsored by the Department of Defense, the National Institute of Standards and Technology (NIST), and the Department of Energy. He has been involved in numerous technology assessments of advanced materials and their associated manufacturing technologies, and has worked on strategic planning and commercialization roadmapping for several technologies emerging from projects of NIST's Advanced Technology Program. Dr. Mehta is active in the Engineering Society of Detroit and has been an organizer of the annual Advanced Composites Conference for several years. He is a member of the Manufacturing Working Group of the United States Council for Automotive Research, and a member of the National Research Council's Board on Manufacturing and Engineering Design.

Walter D. Pilkey is Frederick Tracy Morse Professor of Mechanical Engineering at the University of Virginia, where he has worked for 33 years. In addition, he has been the director of the university's Impact Biomechanics

Program and a professor in neurosurgery. Dr. Pilkey's research interests include computational structural mechanics, optimization, and injury biomechanics. His specific research has included developing the methodology to uncouple longitudinal structural analyses from cross-sectional analyses, and investigating technology for determining the limiting performance of mechanical systems subject to impact loading. Previously, Dr. Pilkey assisted in setting up a School of Engineering at Kabul University in Afghanistan and worked at the Illinois Institute of Technology Research Institute (IITRI) in Chicago.

Oleg D. Sherby (NAE) is professor emeritus in the Department of Materials Science and Engineering at Stanford University. His research interests include the properties of ultrahigh carbon steels, the history of ancient blacksmiths and Damascus steels, and mechanisms of creep of fine-grained and composite materials at high temperatures. He is the coholder of 8 U.S. patents; the author or coauthor of 340 publications on mechanical behavior, materials processing, and diffusion in materials and metal-laminated composites; the coauthor of a text on superplasticity in metals and ceramics; and the technical editor of two books. He has been granted numerous awards and distinctions during his career, including the following: fellow of ASM International (1970), fellow of the American Institute of Mining and Metallurgical Engineers (1985), honorary member of the Japan Institute of Metals (1996), honorary member of the Iron and Steel Institute of Japan (1999), ASM Gold Medal (1985), Yukawa Silver Medal (1988 and 1999), Albert White Distinguished Teaching Award (1988), Campbell Memorial Lecture Award (1998), Albert Sauveur Achievement Award (2000), Lifetime Achievement Award in Superplasticity (2000) at the International Conference on Superplasticity of Advanced Materials, and the Thermec 2000 Distinguished Award for pioneering work on ultrahigh carbon steels. Dr. Sherby was elected a member of the National Academy of Engineering in 1979.

Appendix B

Alternative Power Sources

The main drivers for making improvements in vehicle propulsion systems are these: reducing the weight of vehicle bodies, increasing power density, improving fuel economy, complying with stringent emissions regulations, reducing noise and signature, and increasing driver comfort and safety. Material- and process-improvement programs that target increased horsepower of diesel engines and alternative energy powertrains, as well as the evaluation of hybrid electric and fuel-cell power systems, are key to the realization of the needs of future Army tactical trucks. The use of these alternative energy sources also opens opportunities for inserting lightweight structural materials and new processing technologies into new truck designs.

Hybrid Electric Powertrains

The hybrid electric powertrain offers perhaps the greatest potential for tactical vehicle redesign in the near future.[1,2] This technology would be most beneficial in light and medium trucks with variable driving schedules, high speeds, and vehicle loading that varies widely between fully loaded and empty. The hybrid electric powertrain consists of an internal combustion engine coupled with electric motors and an energy storage system or battery. Operating energy is provided by the engine, by the electric motor, or by both. The battery is charged when the engine provides excess power, when the vehicle decelerates, or when the brakes are applied. When the vehicle requires additional power for passing, for grades during acceleration, or for

[1]National Research Council. 2001. Review of the Research Program of the Partnership for a New Generation of Vehicles: Seventh Report. Washington, D.C.: National Academy Press.
[2]U.S. Department of Energy. 2000. Technology Roadmap for the 21st Century Truck Program: A Government-Industry Research Partnership. Report No. 21CT-001. Available at <http://www.trucks.doe.gov/pdfs/P/62.pdf>. Accessed March 2003.

climbing hills, the battery adds power by channeling electrical energy to the motors.

The hybrid electric powertrain provides solutions for two of the most important sources of inefficiency in engine-based transportation. The first source of inefficiency is the need to use an oversized engine for the average duty cycle of the application. Currently, the size and power of an engine are both determined by the most extreme operating conditions, such as maximum torque and highest driving speed. However, because light or medium trucks make frequent stops and are often driven unloaded, they use only part of their engine power. The mechanical or friction losses from having an oversized engine can be quite large, of the same order of magnitude as the driving power. The second source of inefficiency is the transient operation of the internal combustion engine caused by the drive-wheel speed and the traction effort required. As a result of driving schedule, terrain configuration, vehicle load, driver technique, and other factors, the engine coupled with the driveline operates in a transient mode with a variable efficiency far below maximum.

By using a hybrid electric powertrain, the engine can be made the right size for the needs of the average application. It will operate at or close to a specific speed and load point at which the fuel efficiency is highest. A 3- to 4-liter diesel engine in a hybrid system will probably be able to replace a 7- to 9-liter diesel engine in a standard system. In addition, advanced turbocharging can be used to boost the engine torque and power, further reducing engine size and weight. In a smaller engine, the mechanical or friction losses are lower.

Two additional advantages make hybrid electric powertrains desirable. First, auxiliary systems and accessories can be decoupled from the engine, permitting their use on demand, reducing accessory losses, and increasing overall efficiency. Because the position of these accessories is no longer tied to the engine shaft, more compact packaging of the engine under the hood is possible, as are opportunities for improved cabin and hood design. Such designs could improve road visibility and stealth features, among other things. Second, because the electric traction motor is designed to function as a generator during deceleration, a portion of the kinetic energy of the vehicle is converted back into electrical energy. The vehicle is slowed down by this process, so the friction brakes can be downsized.

The optimum configuration of a hybrid electric powertrain depends on the specific application, the efficiency and performance requirements, manufacturing cost, serviceability, market differentiation, and customer acceptance of the new technology. Light-duty passenger cars with hybrid electric powertrains have already been commercialized (e.g., the Toyota Prius and the Honda Insight), albeit in small numbers. Although heavy-duty vehicles with hybrid electric powertrain systems are not yet in production, there have been several demonstrations of the system in urban transit buses. These demonstrations have highlighted several shortcomings. Most of the demonstrations to date have used commercially available components, rather than components designed and optimized for use in hybrid electric powertrains. In low volume, the precision manufacturing of these mostly electrical components cannot be achieved at reasonable cost. Moreover, systems engineering and integrated manufacturing technologies cannot be applied unless commercial capabilities and economies of scale are leveraged.

Several critical technologies require additional research to support innovative systems: electric motors and generators, electrical energy storage systems, power electronic products, electrical safety, regenerative braking, and purpose-built engines. Electric motors and generators are typical for series or parallel hybrid systems and their corresponding couplings and gear sets. Issues that need to be addressed with regard to these components include those of improving specific power, reducing weight and cost, and leveraging modern manufacturing and automated production.

Electrical-energy storage systems in hybrid electric powertrains capture energy from the generator, store energy during braking events, and return energy when required by the driver. Systems under consideration include electrochemical batteries, ultracapacitors, and electric flywheels. Because of the potential for commercializing them in the short term for light-duty vehicles, batteries have received more attention in the past through the Partnership for a New Generation of Vehicles. For heavy-duty hybrid electric systems, batteries must be developed that have high specific energy, improved life, and good cold-temperature performance. Ultracapacitors are capable of providing even higher energy density than batteries and could be used to provide primary energy during acceleration and hill climbing, as well as to recover braking energy. In addition, ultracapacitors can be used as a secondary energy provider for load leveling power to chemical batteries. Research is needed to develop suitable materials for ultracapacitors that can be used in automotive applications. Electric flywheels have high power-handling capability and moderate energy density. They are efficient, durable, and have robust performance in various ambient temperatures. Although their initial cost is high, they are attractive on a life-cycle cost basis.

In the area of power electronic products for military and commercial applications, more research is needed in high-power transistors, which are not currently produced by any domestic manufacturer. Obstacles with respect to high-power transistors that need to be overcome by the developers of motors and inverters include high cost, excessive complexity, insufficient reliability; and the demands of harsh operating environments.

Electrical safety is an area in which hybrid electric powertrain technology needs R&D. The presence of higher voltage components and cabling requires the development of standard practices and protocols in categories ranging from functional to personnel. The identification, management, and mitigation of hazards will also be required.

Regenerative braking is an essential capability of the hybrid electric powertrain concept. Significant development is required, however, in order to maximize energy recovery, provide adequate storage, and minimize the dependence on the conventional braking system.

In order to obtain the full efficiency benefits of hybrid electric powertrain systems, engines must be built specifically for these systems. Only then can the engine be operated in such a way as to avoid inefficient points (i.e., low load and high speed) and remain close to peak efficiency most of the time. Alternative power sources such as gas turbines have been used in demonstration hybrid vehicles. Although these power sources have some merits due to the synergism between the turbine and the electrical generators, they represent a major departure from vehicular engines and cannot therefore leverage the advantages of high-volume production.

Fuel Cells

Fuel cells are electrochemical devices that convert energy from the chemical reaction of hydrogen and oxygen into electricity. Fuel cells are seen as the ultimate power source in the hydrogen-based energy scenario of the future. This type of energy conversion has the greatest potential for combining high energy with low emissions. There are significant barriers to be overcome, however, before the technology can be used in consumer vehicles. These barriers include overall performance limits; cost; fuel availability, including onboard storage; and lack of infrastructure.[3]

By 2005, fuel-cell vehicles using pressurized hydrogen may be produced for cars and sport utility vehicles (SUVs). They will probably be limited to special fleet applications for which hydrogen can be made available. The production of hydrogen from natural gas involves considerable loss of energy and the generation of emissions. These factors must be included in the energy balance of a fuel cell if a systems approach is used. The use of methanol or conventional petroleum fuels can circumvent the difficulties of implementing a hydrogen fuel delivery infrastructure. However, the onboard fuel processor required in such a case reduces energy efficiency so much that the fuel cell is not superior to an internal combustion engine.

For military applications, fuel cells may not be a viable primary power alternative for many years to come. But as fuel-cell stacks of high efficiency are developed, they can be used as auxiliary power units (APUs) in tractor-trailer, vocational, or medium-duty trucks that have a lot of accessory equipment and long idle times. For such applications, the main engine running at idle is very inefficient, fuel consumption is high, and emissions are high. Auxiliary power units based on small internal combustion engines are heavy, bulky, and costly.[4] An interesting alternative is the use of a proton exchange membrane power cell as an APU for a Class 8 truck. The Department of Transportation has a demonstrator unit that uses methanol and an onboard reformer to generate the means for powering a truck's accessories and refrigeration unit overnight. It is claimed that with such an APU, 1 gallon of methanol could replace 11 gallons of diesel fuel. The reason for these outstanding savings is that the idle operation of a diesel engine is very inefficient, while a small fuel cell operates at high efficiency.

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[3]National Research Council. 2001. Review of the Research Program of the Partnership for a New Generation of Vehicles: Seventh Report. Washington, D.C.: National Academy Press.

[4]U.S. Department of Energy. 2000. Technology Roadmap for the 21st Century Truck Program: A Government-Industry Research Partnership. Report No. 21CT-001. Available at <http://www.trucks.doe.gov/pdfs/P/62.pdf>. Accessed March 2003.

Appendix C

Acronyms and Abbreviations

AAA	Auto Aluminum Alliance
APU	auxiliary power unit
BIW	body-in-white
COTS	commercial off-the-shelf
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
FCS	Future Combat System
FMTV	Family of Medium Tactical Vehicles
FTTS	Future Tactical Truck System
HEMTT	Heavy Expanded Mobility Tactical Truck
HMMWV	High Mobility Multipurpose Wheeled Vehicle (Humvee)
IMPACT	Improved Materials and Powertrain Architectures for Trucks
M&S	modeling and simulation
MMC	metal matrix composite
MTVR	Medium Tactical Vehicle Replacement
NAC	National Automotive Center
NATO	North Atlantic Treaty Organization
NDE	nondestructive evaluation
NIST-ATP	National Institute of Standards and Technology's Advanced Technology Program
NMAB	National Materials Advisory Board
NRC	National Research Council
O&M	operating and maintenance
O&S	operations and support
OEM	original equipment manufacturer
OHVT	Office of Heavy Vehicle Technology (DOE)
P4	programmable powder preforming process
PMC	polymer matrix composite
PNGV	Partnership for a New Generation of Vehicles
R&D	research and development

RML	Revolution in Military Logistics
SiC	silicon carbide
TACOM	Tank-automotive and Armaments Command (Army)
TARDEC	Tank-Automotive Research, Development, and Engineering Center (Army)
TRIP	transformation-induced plasticity
UHCS	ultrahigh carbon steel
ULSAB	UltraLight Steel Auto Body
USCAR	United States Council for Automotive Research
VARTM	vacuum-assisted resin transfer molding