Road Transportation Vehicles

Joseph A. Carpenter, Jr. (Department of Energy, USA)
Jerry Gibbs (Department of Energy, USA)
Ahmad A. Pesaran (National Renewable Energy Laboratory, USA)
Laura D. Marlino (Oak Ridge National Laboratory, USA)
Kenneth Kelly (National Renewable Energy Laboratory, USA)

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Abstract

In many industrial countries, road transportation accounts for a significant portion of the country's energy consumption. In developing countries, the use of energy for transportation is on the rise. The recent increase in petroleum prices, expanding world economic prosperity, the probable peaking of conventional petroleum production in the coming decades, and concerns about global climate changes require efforts to increase the efficiency of the use of, and develop alternatives for, petroleum-based fuels used in road transportation. The energy efficiency of a vehicle could be improved in several ways: lightweighting the vehicle structure and powertrain using advanced materials and designs, improving the efficiency of the internal combustion engine, reducing tire rolling resistance, and hybridization. Each of these efforts will require improvements in materials and processes.

Introduction

Like many things in life, there are advantages to motorized road transportation—such as jobs, wealth, and mobility of goods and people—but there are also negatives such as climate pollution; injuries and deaths; and dependence on unstable suppliers for the main energy supply, petroleum. Motorized transportation systems consume about 19% of the world's total energy supplies, with 95% of this amount being petroleum, accounting for about 60% of the total world petroleum production.[1] In the United States (the only country for which detailed data are available), about 80.5% of the motorized transportation energy is consumed by road vehicles.[2] (Statistics show that air transportation accounts for 9% of total energy, water transportation for 5%, transport of materials by pipeline for 3.1%, and rail transportation for 2.4%.[2]) In 2005, about 865 million motorized land transportation vehicles were registered in the world (probably not even including very small vehicles such as motorized bicycles, scooters, motorcycles, and the three-wheel, auto/rickshaw taxis and trucks seen ubiquitously throughout the developing world).[3] Most of those vehicles were registered in the "developed" world consisting of North America; Europe (eastern and western); the Pacific Rim (Japan, South Korea); and some other parts of Asia, the Middle East, and Central and South America, encompassing perhaps two billion of the roughly 6.5 billion persons currently alive, for a vehicle density of around one vehicle for every two persons. In China and India, where perhaps 2.5 billion people live, the vehicle density is on the order of one vehicle per 20 persons, so the growth potential is obvious (see **Figure 1**).

In developing countries, the use of energy for transportation is on the rise. The recent increase in petroleum prices; expanding world economic prosperity, particularly in China and India; the probable peaking of conventional petroleum production in the coming decades; and concerns about global climate changes all necessitate efforts to increase the efficiency of the use of, and development of alternatives for, petroleum-based fuels used in road transportation. Most studies indicate that 70–80% of the energy usage in the lifecycle of a road transportation vehicle is in the use phase. The remainder is energy usage in the production of the vehicles, including the production of the materials, supply of the fuel, and disposing of the vehicles. Thus, advances in many materials and processes will be required in efforts to increase the energy efficiency of motorized vehicles for road transportation.

In today's internal combustion engine vehicles, only about 15% of the fuel consumed is actually used to propel the vehicle and support the accessory loads (such as air conditioning, radio, and lights).[5] The useful work by the fuel's energy is used to overcome the vehicle inertia, tire rolling resistance, and wind drag. The rest of the fuel's energy is lost as heat and friction due to inefficiencies of the engine and drivetrain and idling, for example (**Figure 2**). The energy efficiency of a vehicle can be improved in several ways: lightweighting the vehicle structure and powertrain using advanced materials and designs, improving the energy

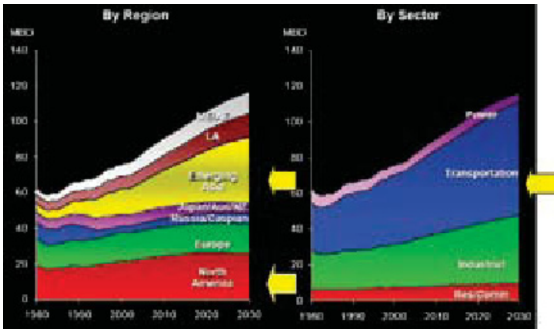

Figure 1. World oil demand. Globally, oil demand is driven by growth in transportation in Asia, Europe, and North America. *Note:* ME/AF is Middle East and Africa, LA is Latin America, Aus is Australia, and NZ is New Zealand. (*Source:* Reference 4.)

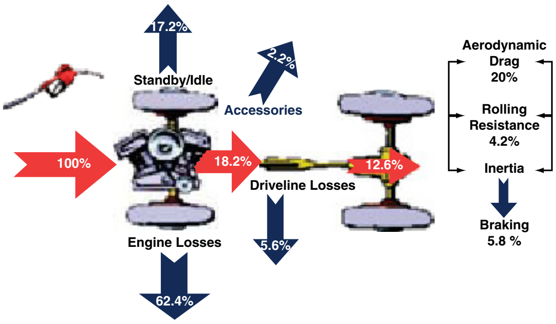

Figure 2. In a typical conventional gasoline vehicle, only about 12–13% of the fuel's energy is transferred to the wheels, the rest is lost in the engine as heat, in idling, and in powering accessories. (*Source:* Reference 5.)

Table I: Lightweighting Potentials and Relative Component Costs for Various Automotive Lightweighting Materials Options.

Lightweighting Material	Material Replaced	Mass Reduction (%)	Relative Cost (per Part)[a]
High-strength steel	Mild steel	10	1
Aluminum	Steel, cast iron	40–60	1.3–2
Magnesium	Steel, cast iron	60–75	1.5–2.5
Magnesium	Aluminum	25–35	1–1.5
Glass FRP composites	Steel	25–35	1–1.5
Graphite FRP composites	Steel	50–60	2–10+
Aluminum matrix composites	Steel, cast iron	50–65	1.5–3+
Titanium	Alloy steel	40–55	1.5–10+
Stainless steel	Carbon steel	20–45	1.2–1.7

Source: Reference 7.

[a] Includes both materials and manufacturing.

efficiency of the internal combustion engine, reducing tire rolling resistance, reducing aerodynamic drag, and hybridization (recapturing kinetic and frictional losses, reducing stop/idle losses, and reducing engine size while providing launch and acceleration assist with a more efficient electric drive system). Plug-in hybrid electric vehicles, battery electric vehicles, and fuel cell electric vehicles use an electric drive system that is much more efficient than conventional internal combustion engines. It is envisioned that fuel cell powertrains might, at some time, replace the internal combustion engine powertrains. (The materials challenges associated with fuel cells are discussed in the article by Crabtree et al. in this issue).

Lightweighting

The term lightweighting means reducing the overall weight of a vehicle and its components. This term is used instead of "lightweight" so as not to imply just the use of lower-density materials. Steel, for instance, is not a low-density material, but by increasing its strength, less can be used, for a net weight reduction. Increased fuel economy is the most obvious effect of lightweighting. It has been estimated[6] that, with every 10% drop in weight, the fuel economy increases by 6–8% (with all other factors held constant). This estimate includes mass compounding, which means that, in addition to the fuel economy increase due to the direct loss of weight by the given component or structure, further gains can be obtained because other mass can be shed elsewhere in other vehicle components or structures such as the powertrain, suspension, and braking system.

In addition, lightweighting offsets the increased weight of vehicle upsizing, features (e.g., audio, video, and navigation systems), and performance factors (e.g., acceleration, safety, exhaust-gas pollution abatement) demanded by customers or mandated by regulations. Such compensation to avoid increased weight has been the primary goal of lightweighting in the automobile industry in the recent past. In the next 5–15 years, lightweighting will also be needed to offset the added weight and cost per unit of power of hybrid and fuel cell powertrains.

After many years of research and development, education, and price reductions, many auto companies and their lower tier suppliers have started using lightweighting materials and components in the structures and powertrains of vehicles. The relative weight-saving potentials and costs of the main lightweighting materials are listed in **Table I**. High-strength steels, aluminum, magnesium, and glass- and carbon-fiber-reinforced polymer–matrix composites (FRPMCs) are the main contenders. This evolution and the technologies behind them have been well described elsewhere.[8–11] Of these, high-strength steels, aluminum, and glass-FRPMCs are the most mature. Aluminum matrix composites, titanium, and stainless steels are niche materials because of their relatively high costs. The main challenge to the further use of these materials in the coming years will be lowering the manufactured costs of components and structures made from them. In addition to cost, nontechnical challenges include manufacturers' lack of comfort and familiarity with the manufacturing and safety of the vehicles made from these new materials; capital already invested in steel-forming technologies; and recycling, especially of FRPMCs.

Powertrain Materials

The internal combustion engine and driveline are the result of 100 years of constant innovation. Today's engines demonstrate a high power density and extreme cost competitiveness. In the future, the combination of regulatory and economic pressures will drive manufacturers to develop engines that redefine energy efficiency and fuel economy. The next generation of heavy- and light-duty engines will push the thermomechanical limits of existing materials and will encourage the exploration of new cost-effective materials to meet the needs of new combustion regimes, energy recovery systems, and lightweight high-efficiency drivelines.

Improvements for heavy-duty truck diesel engines are expected to include high-efficiency, clean-combustion techniques that result in higher peak cylinder pressures and temperatures and increased rise rates for temperatures and pressures.[12–17] The most common clean-combustion techniques under consideration are homogeneous charge compression ignition (HCCI) and low-temperature combustion (LTC); both involve modifications to the air–fuel mixture, ignition timing, air charge boost pressures, and percentage of exhaust gas recirculation (EGR) in the charge air. The goal of each of these technologies is to improve the engine thermal efficiency while minimizing unwanted exhaust compounds such as NO_x and particulate matter (PM/soot).

These advanced combustion techniques will push the limit of existing cast iron engine-block and cast-iron or cast-aluminum cylinder-head materials. Initial data indicate that engines operating in these new combustion regimes might experience peak cylinder pressures in excess of 180 bar. **Figure 3** suggests that cast materials for these applications might require compacted graphite iron or some new high-strength lightweight cast alloy. (Compacted graphite iron is cast iron with graphite incorporated into its basic structure as blunt flakes that are interconnected within each cell. This results in a cast iron with properties that are intermediate between those of gray and ductile iron.) In addition, these pressures might push the limits of traditional joining and sealing techniques used to connect the cylinder head to the engine block.

These new engines might require advanced fuel injection systems capable of providing multiple fuel injection events at injection pressures above 2,000 bar. In turn, these fuel injection systems might require new materials with properties of strength, durability, and toughness equal to or greater than those of steel while allowing for the fabrication of injector orifices measuring less than 50 microns (μm). New processing techniques for injector tips and piezoelectric actuator mechanisms will also be needed.

Higher exhaust temperatures, turbocompounding, solid-state waste-heat recovery, and emissions controls will push the limits of materials currently used in exhaust manifolds, valves, and turbocharger components, such as stainless steel, SiMO cast iron, high-Ni superalloys, aircraft-grade titanium alloys, and other high-performance aluminum-based alloys. It is expected that manufacturers will explore the use of materials such as stainless steels, titanium alloys, low-Ni superalloys, high-temperature aluminum alloys, and ceramics to address the needs of these components.

In addition to materials needs resulting from changing combustion regimes, the heavy-duty engine sector is expected to continue expanding its use of exhaust aftertreatment devices such as catalysts and diesel particulate filters. The long lifecycle requirements of these devices will require detailed knowledge of the fatigue behavior of filters, ceramic substrates, and catalyst coatings. Further, lifecycle costs will push the industry to find replacements for precious-metal-based catalysts.

Light-duty automobile engines are expected to transition to direct-injection, turbocharged, high-compression, spark-ignition combustion, which might exceed the properties of the lightweight aluminum- or magnesium-based alloys currently used in engine blocks. The combination of increased operating thermomechanical stresses and the drive for lightweight vehicle systems will push engine manufacturers to explore new materials options for future engine designs.

Engine blocks and cylinder heads are expected to continue using lightweight alloys, but design changes might be needed to add strengthening elements. Strengthening can be provided by designs with increased cross-sectional areas, steel thread inserts, cast-in steel crossties, or bolt-on reinforcing caps. If independent cylinder valve actuation is included in these new designs, the weight of the valves might need to be reduced to improve dynamic response. This might push forward the development of lightweight valve materials such as titanium alloys, intermetallics, or ceramics. The drive to reduce turbocharger lag, which can be experienced as a hesitation in acceleration by a driver, might drive both heavy- and light-duty engine manufacturers to explore high-temperature lightweight materials to reduce rotating mass.

Both heavy- and light-duty engine manufacturers likely will have a number of common materials issues, such as the need for improved gasket sealing resulting from increased cylinder pressures. Likewise, light-duty fuel injection systems might face material and actuator demands similar to those used in heavy-duty applications. However, with increasing use of alternative fuels in light-duty applications, manufacturing of some components of the fuel system might need to transition away from traditional aluminum alloys to corrosion-resistant alloys such as stainless steel. The exhaust system components might also face the same material limitations encountered by the heavy-duty sector, but the use of solid-state waste-heat recovery might require additional materials development for components and heat exchangers.

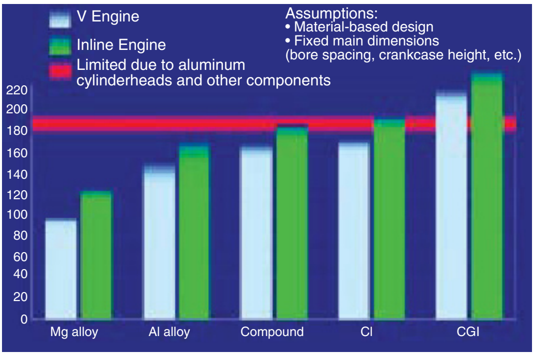

Figure 3. Cylinder pressure limits for various engine block materials.[18]

Materials might be required to address unexpected noise, vibration, and harshness (NVH) issues with the new combustion regimes. Some of the most promising techniques for increasing efficiency and mitigating emissions result in unacceptable noise levels being generated by the engine. To mitigate these adverse affects, engine manufacturers might explore the use of lightweight alloys such as magnesium, which has a different natural frequency than steels and, therefore, a dampening effect that can reduce NVH issues in some components.

Further complicating the material needs of future powertrain materials will be the need to help offset the additional weight of hybrid-drive and battery systems associated with new powertrain configurations. Also, at some time in the future, fuel cell powertrains might replace internal combustion engine powertrains.

Hybridization and Electric Drives

Hybridization is achieved by adding an electric drive system to a conventional vehicle or even a fuel cell vehicle.[19] The electric drive system (**Figure 4**) can include a motor, generator, power electronics (inverters and controllers), and a means for storing electrical energy (batteries and/or ultracapacitors). Hybrid electric vehicles (HEVs) achieve lower fuel consumption than conventional vehicles with internal combustion engines in several ways.[20] By recapturing the kinetic energy of a decelerating vehicle (while the engine speed is decreasing) and using regenerative braking instead of friction breaking, the fuel economy of a typical vehicle can be increased by 10%.[21] Regenerative braking works as follows: As a driver brakes in a hybrid or electric car, the kinetic energy, normally dissipated as heat, supplies power to a generator. The generated electrical energy then charges the energy storage system every time the brakes are applied. The stored energy is subsequently used to accelerate the vehicle, requiring less fuel use and thus leading to more efficient operation. The availability of an electric motor for launch assist and quick engine restarts allows the engine to turn off during stops, thus reducing fuel consumption at idle by 5–10%. Because the combination of a motor and an engine

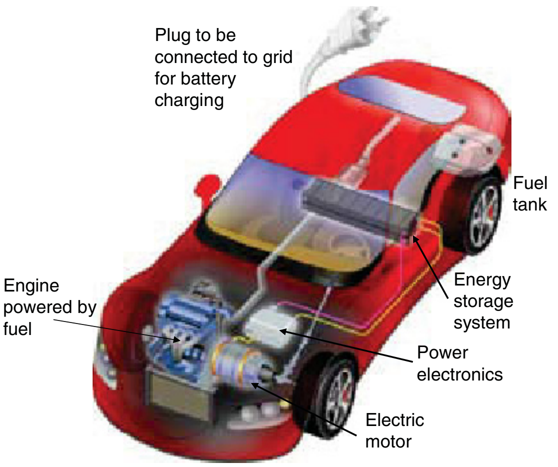

Figure 4. Components in a plug-in hybrid vehicle. (Without the plug and the on-board charger, the components represent a hybrid electric vehicle.)

provides power for acceleration, the engine could be downsized to meet only top speed and grade requirements; this could provide another 10–20% improvement in fuel economy.[22] Overall, hybridization could improve fuel economy by 20–50%. (For example, the combined EPA-rated city/highway fuel economy of a 2007 Toyota Hybrid Camry at 39 mpg is 30% higher than a conventional 2007 Camry at 27 mpg.[23]) Each of the major hybridization components entails corresponding materials challenges.

Energy Storage

The electrical-energy storage systems for HEVs must be smaller, lighter, longer-lasting, more powerful, more energy dense, and less expensive than today's batteries if these advanced vehicles are to significantly expand into the markets around the world. Thus, the energy storage systems offer the most challenging material issues, particularly those for plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles. Materials in PHEV energy storage systems have the more challenging task of withstanding many shallow charge/discharge cycles (as in HEVs) and many deep charge/discharge cycles (as in electric vehicles).[24] The article by Whittingham in this issue covers the general topic of electrical-energy storage materials issues, but some challenges are related specifically to transportation applications, namely, safety, calendar life, and cold-start operation. Many automotive researchers believe that lithium-ion batteries are the choice for electric drive applications for the next 10–15 years, so the focus is on improving their low-temperature performance and safety.[25] The major components of batteries are cathodes, anodes, separators, and electrolytes. To improve the safety of lithium-ion batteries, researchers and developers are investigating new cathodes such as nanophase iron phosphate[26] or mixed oxides and new anodes such as new forms of carbon/graphite that are less active than today's carbon materials. Other components to be improved include lithium titanate ($Li_4Ti_5O_{12}$) anodes;[27] separators with better melt integrity, lower shrinkage, and shutdown functionality such as ceramic-coated Teflon; and nonflammable electrolytes.[25] Given that the use of alternative cathodes, anodes, separators, and electrolytes might reduce the performance and/or life of the battery, other researchers are investigating the possibilities of depositing atomic layers of protective materials on existing high-performing anodes and cathodes and using additives to reduce the flammability of electrolytes.[28] Still, internal electrical shorts that develop over many months, although rare, pose the most challenging materials and design issues for lithium-ion batteries in vehicles.[29] Researchers are developing models and test methods to understand this failure mode in order to propose solutions.[30] At temperatures below freezing, the power capability and, to a certain extent, the available energy of lithium-ion batteries decrease. For consumer acceptance, a lithium-battery-powered vehicle must be able to start at −30°C. Some of the limitation is attributed to the interface between electrolyte and active materials.[31] In general, changes in the active material and electrolyte have not, to date, significantly improved the poor low-temperature performance. Therefore, to improve performance, electrolyte formulations based on $LiBF_4$ in carbonate and ester mixtures are being investigated.[32] Moreover, methyl butyrate is being tested as an additive that can decrease the viscosity of the electrolytes to enhance their wetability properties in the separator (allowing for better electrolyte coverage), thus leading to improved low-temperature performance.[25]

Electric Machine and Power Electronics

The cost and weight of motors/generators and power electronics (inverters and converters) need to be decreased and their power density increased to facilitate greater penetration of HEVs into the vehicle marketplace.[33] One path to reducing the overall cost of the traction drive system (i.e., the electric machine and power electronics) is to eliminate the 65–70°C auxiliary additional coolant loop presently utilized in commercial HEVs such as the Toyota Prius[34] (**Figure 5**) or Ford Escape. Researchers are investigating approaches that use the existing internal combustion engine cooling system and take the water/ethylene glycol coolant directly from the radiator at 105°C to cool the power electronics.

Higher temperature coolants impose significant operating and reliability challenges for the electrical components used in these systems, which are already taxed by high internal self-heating as a result of their elevated operating currents. Operation at extreme temperatures imposes unique design and materials challenges for both the power electronics and the electric machines.[35]

In addition to the selection of appropriate materials, manufacturing improvements are needed. The cost of permanent magnet motors could be reduced by design and manufacturing

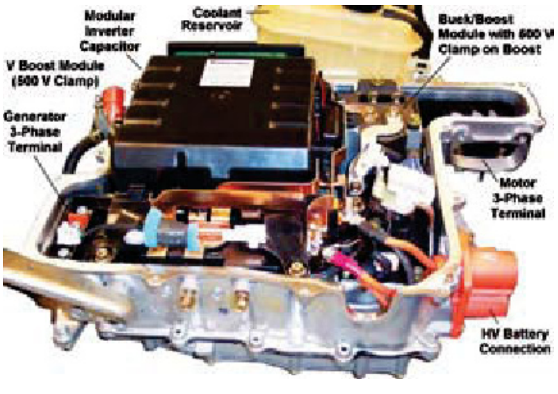

Figure 5. Overview of packaging of 2004 Toyota Prius Hybrid inverter/converter. *Note:* V Boost is voltage boost, and HV is high-voltage.

improvements, as well as elimination or reduction of the number of magnets and/or the amount of lamination material. One area of research is currently focused on improvements to sintered and bonded magnets.[36] Bonded magnets are attractive from a manufacturing perspective because they can be injection molded to desired shapes with possibly lower manufacturing costs. However, because of the epoxies required to hold the flakes together, bonded magnets have lower energy products than sintered magnets and might not be qualified to as high a temperature. Further research is needed to improve the mechanical strength and reduce the magnetic saturation of bonded magnets at elevated temperatures. Increasing the temperature of the coolant, although beneficial from a cost perspective, will create many challenges for electric propulsion systems. As the operating temperature of a motor approaches the Curie temperature of the magnets, the intensity of the magnetic field decreases rapidly toward zero, so it might be necessary to develop special magnetic materials with higher Curie temperatures.[35] (Note that the Curie temperature, by definition, is the temperature above which a material is no longer magnetic.)

The performance and lifetime of many power electronics components degrade rapidly with increasing temperature.[37] Silicon power devices typically can be operated at junction temperatures of up to 125°C or even 150°C. Increasing the coolant inlet temperature reduces the ability to cool silicon devices, so either the current going through them has to be reduced or more silicon devices must be used. Alternatively, wide-bandgap semiconductors such as silicon carbide or gallium nitride could be used at higher temperatures, but they are much more expensive and the technology is not yet mature. Further research to reduce costs is needed, along with manufacturing improvements to maximize yields.

Other challenges regarding power modules include component packaging for higher temperatures, which involves the reliability and durability of wire bonds and solder joints both at high temperatures and over repeated power cycling. In addition, thermal interface materials (TIMs) pose a major bottleneck to the removal of heat from high-power components.[38] Materials with high dielectric strengths and high thermal conductivities are needed. Inverter packages still predominantly use thermal grease to improve the flow of heat through various packaging layers. Resistance to heat flow is caused by material thickness, low thermal conductivity, material voids, and poor surface contact between material layer interfaces. The thermal grease layer can contribute 40–50% of the total thermal resistance of the different layers in the electronics package. Uniform application of the TIM, pumping out during thermal cycling, and drying out of the grease are known problems with existing thermal greases. Reducing the thermal resistance of the TIM can significantly aid in meeting the thermal requirements for advanced automotive systems. **Figure 6** shows the different layers constituting a typical insulated-gate bipolar transistor (IGBT) package in an inverter. In this case, the silicon die is soldered to the direct-bond copper (DBC) layer, which is composed of an aluminum nitride layer sandwiched between two copper layers. In a typical IGBT package, the DBC layer is attached to the aluminum heat sink by an interface of thermal grease. Because of manufacturing variability, the DBC layer and cold plates have surface irregularities that lead to voids in the surface-to-surface contact. These irregularities contribute to added thermal resistance known as contact resistance. The thermal grease is used to help fill these gaps and provide improved thermal contact. The interface material in inverter packages typically ranges from 25 to 100 µm in thickness and is a major contributor to the thermal resistance in the package. Polymers with embedded metal-coated particles and carbon nanotubes grown on copper substrates are among the materials being investigated to replace thermal grease.[38]

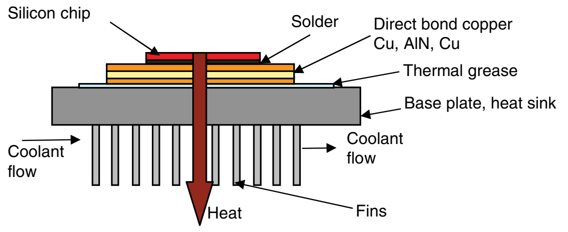

Figure 6. Different layers constituting the insulated-gate bipolar transistor (IGBT) package in an inverter.

Another research approach under investigation to protect the power electronic components from high-temperature peaks is to use phase change materials (PCMs) to store excess heat from transient power peaks. Examples of PCM candidates based on 125°C coolant environment are erythritol, $MgCl_2$, rhombic sulfur, acetanilide, and ammonium acetate.[33] (Phase change materials are also being applied as building materials. See the article by Judkoff and the accompanying sidebar by Bonfield in this issue for a discussion of PCMs in this context.)

Polymer-film capacitors currently are used to absorb ripple currents in inverters to smooth the voltage level and protect the batteries from high transients, which contribute to reduced lifetimes. These capacitors lose their capacity and degrade more rapidly as their operating temperature rises.[35] High-dielectric-constant glass ceramic material is a potential candidate for capacitor applications in inverters. Research is ongoing to improve the reliability and longevity of ceramic capacitors and to mitigate their undesirable failure modes. Another area of research involves the use of ferroelectric thin films on metal foils, which can be embedded into printed circuit boards in the power electronic module. This approach can result in significant reductions in the volume of the power module. Other challenges include high-volume production quality and long-term reliability/durability of the components when subjected to the harsh automotive environment.[33]

Tires and Rolling Resistance

Road transportation depends heavily on tires. Key ingredients of tires are natural rubber (which comes from rubber tree), synthetic rubber/carbon black (which come from petroleum), and steel.[39] Sixty percent of the expense of tire production is attributed to petroleum prices. Materials research on tires is directed toward improving rolling resistance while maintaining the life and handling, reducing or reusing the natural rubber content, and reducing the energy required in production. One of the key ways to improve automotive efficiency is to reduce the rolling resistance of vehicle tires. This is not a measure of a tire's traction or "grip" on the road surface, but rather simply indicates how easily a tire rolls down the road, minimizing the energy wasted as heat between the tire and the road, within the tire sidewall itself, and between the tire and the rim.[40] Detailed modeling has indicated that a 10% reduction in tire rolling resistance should yield fuel savings of about 1–2%, depending on driving conditions and vehicle type.[41] According to research for the California Energy Commission, about 1.5–4.5% of total gasoline use could be saved if all replacement tires in use had low rolling resistance.[42] This translates roughly into average savings of up to 30 gallons of gasoline per vehicle per year, or $2.5–7.5 billion worth of national average gasoline savings in the United States.

Future

The future of road transportation vehicles is very exciting. Future vehicles will be more energy efficient, have less pollution, and provide fuel flexibility. Lightweighting and hybridization will play key roles in improving fuel economy. In addition to new and improved designs, new materials or improvements in existing materials for vehicle structures, powertrains, energy storage systems, motors, power electronics, and tires will make lower fuel consumption and pollution possible.

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