Automotive Materials: Technology Trends and Challenges in the 21st Century

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Abstract

The following article is an edited transcript based on the plenary talk given by Alan I. Taub of General Motors Corp. on November 28, 2005, at the Materials Research Society Fall Meeting in Boston.

Fuel economy requirements, emissions regulations, and the push for energy independence are key factors driving the auto industry to increase vehicle efficiency. The main avenues to efficiency improvement are powertrain enhancements and mass reduction. This presentation details how General Motors is developing advanced propulsion systems and using lightweight materials to achieve greater vehicle efficiency. Taub, who is executive director of General Motors Research and Development, outlines GM's strategy for advancing propulsion technology, from improvements in the internal-combustion engine to hybridization to full vehicle electrification. He then describes the company's efforts to use lightweight materials such as aluminum and magnesium alloys, high-strength steels, and composites to reduce vehicle weight. Also highlighted is GM's success in employing novel materials in the development of advanced vehicle and powertrain systems to achieve additional efficiencies. One example is the application of smart materials, which enable new features and functions by way of mechamatronic solutions (the integration of smart materials with mechanical systems and electronics). Key technical hurdles that must be overcome to increase the use of these materials by the automotive industry are also discussed.

Keywords: *composite, energy storage, environmentally protective, H, nanoscale, nanostructure, polymer.*

Introduction

There's good news and bad news about the overall growth potential of the automotive industry.

First, the good news: Owning an automobile and having personal mobility appears to be global and universal in nature. For me, anything that can be represented on a sigmoidal curve (Figure 1) has the force of a natural law, which in this case would be, "when people can afford personal mobility, they opt for it." The growth in world population and the growth in global affluence, particularly in developing countries, have very good implications for the automotive business. Today, 12% of the world's population owns a vehicle. By 2020, that figure could reach 15%, as shown in Figure 2. Factoring in the increased population, the result would be a 50% increase in vehicle ownership in the world. Those of us in the vehicle manufacturing businesses definitely want to be a part of that growth story.

Now, for the bad news: This phenomenal growth carries its own challenges and problems. How can we grow the "vehicle parc"—the number of registered active vehicles—to 1 billion vehicles without adversely affecting the planet we live on? Sustainable growth is the primary challenge for our industry. It is the theme that drives the technology agenda for General Motors and probably for most of the other automotive OEMs (original equipment manufacturers).

GM's sustainable growth agenda has several key components:

1. Fuel economy is one of the most critical challenges to our sustainability, and not just in the United States or in the aftermath of Hurricane Katrina. Almost 98% of automotive vehicles are powered by petroleum products. We worry not only about the sustainability of that supply, but also about whether its sources can be diversified, a development that we favor.
2. Emissions, both from our manufacturing plants and from our vehicles, are another major factor. Our emissions goal is to take the vehicle out of the environmental debate. That is another way of saying that our company is working toward achieving zero tailpipe emissions. We are attacking the problem not only at the tailpipe, but also from the full "wells-to-the-wheels" cycle. In the end, that vision could be enabled by the hydrogen economy and the fuel cell electric vehicle.
3. Infrastructure is yet another sustainability issue. Since the 1960s, the vehicle parc has been growing at a rate that is exceeding the number of roads available internationally. Congestion is one of the rate-limiting steps that we are addressing.
4. Safety is one of GM's primary sustainability objectives. The World Health Organization estimates that the number of annual traffic-related fatalities globally is about 1.2 million lives, including vehicle occupants, cyclists, and pedestrians. This number is growing, particularly in the developing world. On the positive side, we are going through a technology-enabled transformation that will vastly improve automotive safety. For the past 40 years, our focus has been to design vehicles so that in the event of a crash, the chance is maximized that the person will be able to walk away from the car or truck. To accomplish this, we have developed seat belts, air bags, and crush zones. Now, through technology such as electronics, controls, and software, we are moving toward the point where the crash could be avoided in the first place.
5. The experience of driving the vehicle, in terms of both safety and comfort, is another major factor in our industry. We are changing the driver–vehicle relationship through electronics technology. Today, our high-end vehicles have almost 30 microprocessors in them, as well as safety devices such as our OnStar mobile communications package, which provides 24-hour connection to an OnStar center. In the same way that iPods and Blackberrys have changed our daily lives in a personal way, electronic

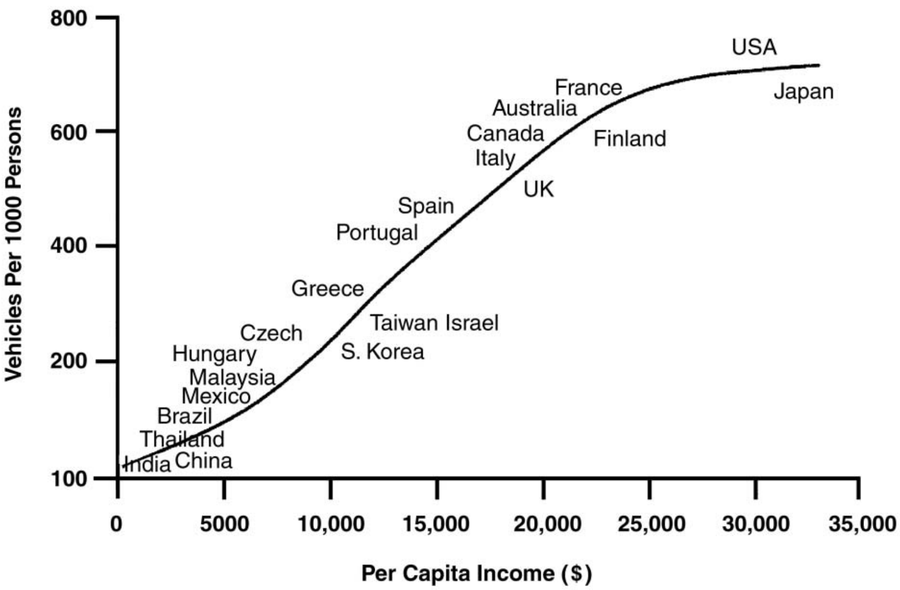

Figure 1. Relationship of vehicle sales to per capita income. Vehicle ownership correlates almost directly with rising per capita incomes. As a result, increasing affluence in both the developed and developing countries is expected to drive substantial increases in vehicle sales in the future.

vehicle controls will alter the entire "look and feel" of driving. Because of sophisticated on-board software, we are getting ever closer to our goal of being able to personalize and adapt each vehicle to the individual.

Cost also weighs in as a critical factor in the sustainability equation. The era when automobiles were a cost + margin = price business ended around the mid-1990s. Since then, vehicle purchase prices have been leveling around the world, resulting in a reversal of the equation, to price – margin = allowable cost. To continue the trend of a growing vehicle parc, we must achieve increasingly lower costs while delivering ever-increasing features and functionality.

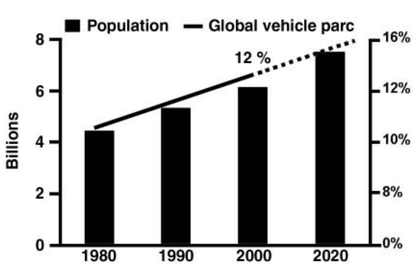

Figure 2. World population and the global vehicle parc. Vehicle ownership is a universal, but largely unmet, aspiration. Today, only about 12% of the world's population owns a vehicle. By 2020, with 15% of 7.5 billion people projected to own an automobile, the global vehicle parc could surpass 1 billion vehicles. Source: U.S. Census Bureau International Population Database, GM Global Market & Industry Analysis.

Considering that we have a broad array of challenges in the auto industry, I have decided to selectively concentrate on two of these challenges—advanced propulsion and advanced materials. These topics are reflected in a number of other sessions presented at this meeting.

Advanced Propulsion Systems

The primary challenge in improving automotive propulsion systems is achieving better fuel economy while retaining or improving performance. For every unit of energy that is delivered to the wheels to move the vehicle during city driving, nearly eight units of energy in gasoline are required. The example in Figure 3 is based on city driving, the most demanding kind of use.

Improving the Internal-Combustion Engine

The greatest energy loss is in the efficiency of the engine. The internal-combustion engine has been developing and maturing for more than 100 years, but it can still be further improved.

As a result of research that is taking place today at laboratories and universities around the world, we can now visualize the entire combustion event inside the cylinder. Coupling that capability with flow modeling, thermal chemistry, and advanced electronic controls, we can control a combustion event at each angle degree of the crank turn.

From a holistic point of view, it is possible to squeeze an additional 10–20% efficiency out of the gasoline engine, today's conventional powertrain. As an example, we were able to provide our new fleet of light-duty trucks with "active fuel management." Since highway driving requires only about one-half of the engine cylinders, we have learned how to turn half of them off once the truck hits the highway, reducing the throttling losses.

Technologies like this start to attack the efficiency equation. Of course, with internal-combustion engines, there is always a certain amount of efficiency loss because of cold starting and because the engines are usually operating in transient, versus steady-state, mode.

Introducing Hybridization

The next step in improving engine efficiency is to examine other energy losses in the propulsion system, in particular, the losses at idle and in kinetic energy. For GM, the current response is to introduce hybridization into our fleet.

First, hybrid technology allows shutting off the engine when the vehicle is not moving and running the accessories off the battery. The second major advantage of hybrid technology is the recapture of kinetic energy. Historically, the kinetic energy of a 4000-pound vehicle moving down the road has been turned into heat in the brakes. Hybridization allows that energy to be recouped through regenerative braking, which involves converting the vehicle's kinetic energy during deceleration into stored electrical energy.

With improvements in conventional powertrains—that is, gasoline and diesel engines—as well as hybridization, we will be able to improve the fuel efficiency of our fleet by as much as 30–35%.

To take advantage of these efficiency improvements, GM has an aggressive plan for rolling out its own hybrids. We have chosen to put the hybrid powertrains on the most fuel-consuming vehicles—our large trucks and SUVs.

In fact, we introduced our first hybrid system in 2003 for transit buses after our Allison transmission business came up with a new hybrid transmission architecture called a "two-mode." The first mode is used for launching the vehicle after a stop and driving at low speeds, when more power is needed; the second mode is used for cruising at highway speeds, when less power is required. A bus, with its numerous stops and waits, is the perfect application for hybrid technology, because hybridization stops fuel loss when the

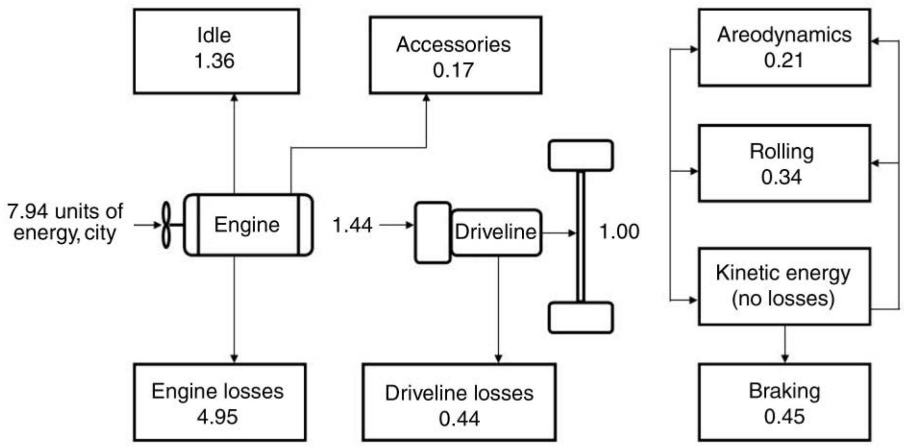

Figure 3. Energy distribution for a typical mid-sized vehicle. Each number represents the energy units used in an urban test cycle (city driving). Out of 100% of the fuel's energy input, only about 13% reaches the vehicle wheels. Essentially, every subsystem and component on the car has to get lighter and better.

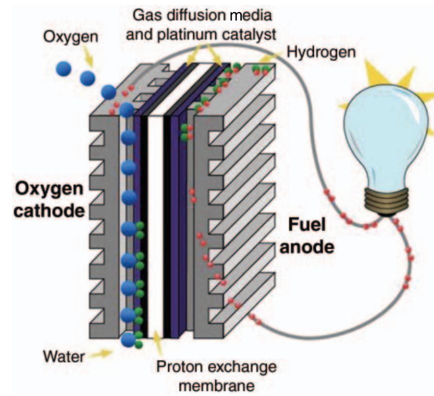

Figure 4. The proton exchange membrane (PEM) fuel cell preferred for automobile applications consists of a hydrogen fuel anode, an oxygen cathode, and a membrane made from a specialized polymer–electrolyte material. Green dots are hydrogen, blue are oxygen, and red are electrons.

vehicle is idling and recaptures kinetic energy through regenerative braking. Hybrid technology is resulting in a 25–50% improvement in fuel economy, depending on driving conditions.

In 2007, we will begin offering a new hybrid powertrain intended for use in our mid-sized SUVs and sedans. We also are downsizing the two-mode from our bus system and plan to roll out this new system on our full-sized trucks in 2008.

Reducing costs in hybrid vehicles is still difficult to achieve, however, because it involves carrying essentially two systems: an internal-combustion engine and an electric drive system. Even though both systems are downsized, it is difficult to run them in combination at equivalent cost to a conventional gasoline engine. We believe that the fully electric vehicle, powered by the fuel cell, will enable that.

Moving Toward Full Electrification

GM's foray into electric propulsion took place in 1996, when we commercialized a fully electric vehicle, the EV1. The first test markets were California and Arizona, and we leased about a thousand of our electric vehicles to customers in these states. This was a big technology gamble, and in the end the marketplace rejected it.

Some in the automotive business believe that the ultimate lack of success with EV1 resulted from the limitations of battery technology. GM had counted on a breakthrough in battery energy density, that is, the number of kilojoules that can be stored in the battery as a function of its size and weight. Although most people actually drive less than 100 miles in a day, the marketplace saw the limitations of a 100-mile range as a flaw. The lack of a charging infrastructure was also an issue.

Now, ten years later, we may be on the threshold of that battery breakthrough. Indications from some research areas show that lithium-ion battery technology may have achieved not only some cost breakthroughs, but also (and more importantly) a fast recharge rate and good cold-weather performance. Supercapacitors also have great potential and could represent a paradigm shift for our hybrid-electric vehicle advancements.

Hydrogen-Powered Fuel Cells

While GM's first electric car failed to ignite the market, the company did not back off from its goal of achieving full vehicle electrification. Instead, when we could not acquire enough energy density in the battery, we sought an alternative technology in the hydrogen-powered fuel cell. The goal was to use gaseous hydrogen to achieve the required energy density in a fuel cell. The vehicle would still be fully electric but would operate in a different way to get capacity and energy in range.

Fuel cells operate by a process that is electrolysis in reverse—getting hydrogen and oxygen to combine to generate electricity (Figure 4). The proton exchange membrane (PEM) fuel cell preferred for automobile applications consists of a hydrogen fuel anode, an oxygen cathode, and a membrane made from a specialized polymer–electrolyte material. At the anode, hydrogen molecules split into protons and electrons. The electrons that are generated can perform electrical work as they pass through a circuit to the cathode. The protons, meanwhile, migrate through the membrane to the cathode, where they are reunited with the electrons and then combine with oxygen to create water. The only other byproduct is heat. In a vehicle, multiple fuel cells are connected in series to create a fuel cell stack capable of providing the electricity required to power the vehicle. The electricity propels the electric motor, which turns the vehicle wheels. When fueled by pure hydrogen, a fuel cell car is a zero-emission vehicle, because it produces no exhaust emissions or greenhouse gases. This seemingly simple technical breakthrough is, like every breakthrough, materials-enabled. I work in what is basically a mechanical–electrical engineering company and I need to keep reminding my co-workers that the world is made of materials.

In working toward our vision of a hydrogen-powered fuel cell, we faced several challenges. The first was packaging the fuel cell in a conventional vehicle. The fuel cell had to be designed so that the propulsion system would not end up taking all the cargo and passenger space. Because of the nature of our product, system engineering requirements mandate achieving a certain energy density and a certain weight density to produce the 75 kW needed to propel the vehicle. Not only have we demonstrated that principle, we have also exceeded that target. We have shown the possibility of packaging and designing a fuel-cell-powered vehicle with numerous advantages over a conventional powertrain-driven vehicle. We have developed fuel tanks for storing liquid and gaseous hydrogen. And we have designed vehicle systems to be operated electronically—or, as we say in the industry, "by wire." Many of the constraints inherent in mechanical systems, with all of their driveline connections, are eliminated.

Our efforts to package our fuel cell propulsion system into a fairly conventional vehicle resulted in the HydroGen3 (see Figure 5). The HydroGen3 is a converted Opel Zafira minivan from which the internal-combustion engine and fuel tank were removed and replaced with a fuel cell propulsion system and either a compressed hydrogen tank or a cryogenic liquid hydrogen storage system.

In addition to the HydroGen3, we have also created a revolutionary vehicle design that we call the "reinvented" automobile. Our AUTOnomy vehicle, which debuted in January 2002, was the first to be designed around a fuel cell system and by-wire controls. We followed it with the Hy-wire vehicle, introduced in September 2003, and, most recently, the Sequel concept car, which debuted in January 2005 (see Figure 5). The Sequel is the first fuel cell vehicle capable of being driven 300 miles between fill-ups, and this range is for a five-passenger SUV.

Once we reduced the fuel cell to a manageable size and weight, we faced additional challenges. First, we needed to assure the durability of the fuel cell. Because of the way a fuel cell is structured, a single pinhole in the membrane can disable it. Second, because our industry is operating in a competitive environment, our target is to develop a fuel cell propulsion system at the same $50/kW cost associated with today's conventional internal-combustion engines.

Fuel Cell Development Challenges

In addressing the fuel cell durability and cost issues, we are looking at three major areas:

Our first area of concern is catalyst materials. We need to find ways, just as we did for the engine catalytic converter, to reduce platinum catalyst loading for the fuel cell. In addition, we need to improve the support system for the catalyst itself, particularly for corrosion problems.

The membrane is the second area we need to address. Because fluorinated membranes are costly, we are searching for a different material system that will allow us not only to control the cost and structural performance of the membrane, but also to allow the membrane to work at higher temperatures where we can gain more efficiency, particularly at heat extraction and at lower humidities.

One of the largest system challenges posed by the fuel cell stack today is controlling humidification. Current membranes lose function at low humidity because protons are carried by water. To the extent that we can get a membrane and catalyst system that will work at lower humidities, we will change both the economics and the system engineering of the fuel cell itself.

Diffusion media, the third area of the fuel cell stack that we are developing, controls much of the flow and mechanical performance of the stack. A solution would be an optimized diffusion medium, realized through top-notch research relative to hydrophilic and hydrophobic coatings.

Hydrogen Storage Challenges

Another problem that arises in adapting fuel cells for vehicles is hydrogen storage. This area, more than any other, needs to capture the attention of the world's materials community. Ironically, when I was in graduate school, hydrogen storage activities were very prominent, driven to a great extent by the space program. Today, this research area is re-emerging, and it presents a major opportunity for scientists because hydrogen storage is the potential Achilles' heel for our fuel cell strategy.

Right now, we are pursuing four options for solving the hydrogen storage problem. Each area has its challenges, and all of them are materials-based.

First, we are looking at compressed gas, which is the default storage medium today. Compressed gas packages hydrogen efficiently but is too costly because it involves high-strength carbon fiber in the composite tank. For 20 years, GM has been waiting for a breakthrough that would lower carbon fiber costs, which could completely change the research parameters not just for fuel cells but for automotive bodies as well.

An alternative is to use liquid hydrogen storage. We have been able to show that it packages well and we have built vehicles that run on it. Of the various options, it probably constitutes the best financial solution. The drawbacks associated with liquid hydrogen storage are based on fundamental physics and thermodynamics. We do not know how to take advantage of the energy we use to liquefy the hydrogen once that hydrogen is in the fuel tank. About half of the efficiency we get from the fuel cell stack, which is by definition twice as efficient as the best internal-combustion engine, is lost in liquefying the hydrogen. To counteract that, we are developing a hybrid approach that we call cryopressure, which is a combination of liquid storage and compressed storage.

The best solution ultimately may lie in finding a solid-state material for hydrogen storage. Recently, a number of materials systems have been discovered that are increasing, by a factor of two, the amount of hydrogen storage density over existing solid-state storage materials. A breakthrough has already been achieved in that we now have materials with close to the right storage density. The conundrum we face is that we cannot release and charge those materials quickly enough. In addition, the materials systems that have good thermokinetics have poor thermodynamics.

Figure 5. GM's fuel cell vehicles.

Finding a breakthrough class of materials that circumvents these problems may be just a matter of time. Given today's impressive breakthroughs in combinatorial experimental techniques, the world's research infrastructure has the capability to accomplish this fairly quickly. In the "good old days," the ability to successfully analyze 10 alloys in a year meant that a researcher was doing productive breakthrough work. Today, our researchers can sputter-deposit an entire phase diagram for a ternary alloy and perform submillimeter site characterization in a week. Right now, they are limited not by the experiment, but by their data analysis techniques and the quantum mechanics that guide the selection. Based on these advances, the materials community is now able to develop the kinds of materials that will solve our energy storage media problems.

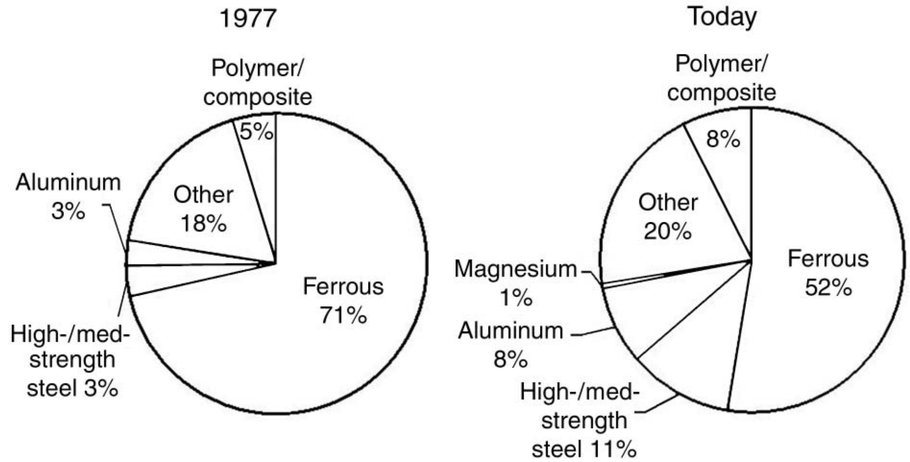

Figure 6. The use of lighter-weight materials in a typical automobile has doubled between 1977 (left) and today (right). The "other" category includes glass, rubber, and ceramic materials.

Advanced Materials

So far, this discussion has centered on the materials challenges associated with engine efficiency—how fuel economy can be achieved through hybridization or by fully electrifying the vehicle. Now I would like to discuss what impact the weight of the vehicle has on fuel economy, and what materials challenges are posed by weight.

For every 10% reduction in vehicle mass, fuel economy is improved by 6%, which illustrates the significant leverage of vehicle weight. Over the past 30 years, the industry has reduced the weight of its vehicles by about 30%. That weight reduction came from smarter design and materials substitutions. Currently, the improvements from good mechanical engineering design are continuing, while the advantages to be gained from materials substitutions have just begun to gather momentum. A large range of materials is now being developed that will significantly change the nature of materials usage in vehicles.

Steel versus Lighter-Weight Materials

Since 1920, the composition of vehicles has been three-quarters low-carbon steel. Except for the substitution of plastic for wood, this basic materials distribution of vehicles remained the same until 1975, when the entire equation changed. Today, high-strength steel represents about one-third of the steel on the vehicle (Figure 6). According to GM's agenda, in five to seven years, high-strength steel will represent 80% of the steel on the vehicle. Metallurgists will recognize the challenges inherent in that goal, including the fact that high-strength steel is stronger and more difficult to form, heat-treat, repair, and weld.

Aluminum

Today, other lighter-weight materials, in particular, aluminum, magnesium, and high-strength plastics, are increasingly replacing steel in cars. GM is the most aggressive user of aluminum and magnesium in the industry, measured by the number of pounds of these materials we have on each vehicle. We use these materials because they provide better performance for the cost in terms of fuel economy. Many of our closures—for example, hoods—are now made from aluminum.

This use of aluminum has posed difficulties. Aluminum conducts heat more easily than steel, but it also has lower electrical resistivity and thus requires a lot more current for welding. For example, when we started the changeover to aluminum in the early 1990s, had we decided to convert just half of our plants from steel to aluminum, we would have had to change the electric capacity of the plants to accomplish it. We therefore developed alternative joining approaches. Indeed, we have learned how to weld, form, and paint aluminum, and we have learned about its corrosion and durability characteristics.

Aluminum in general has lower ductility and therefore lower formability than steel. The black dots in Figure 7a represent the simulated major and minor strains that occur in various parts of the sheet when it is formed (in this case, we are looking at an inner panel of the lift gate for one of our Malibu MAXX cars; see Figure 7b). We faced the issue that some parts that could be made in steel could not be made in aluminum. On the other hand, some automotive parts were so difficult to form that they could not be fabricated even in steel. Sometimes the only solution was to break the part into two pieces, a move that displeased our designers.

Quick Plastic-Forming of Aluminum

To find a viable parts-fabrication method that would not destroy the integrity of the design, we sought help from the aerospace industry. We borrowed a technique called superplastic forming, which lends itself well to manufacturing a small number of parts, for example, 50–100 fuselages a year. At GM, we tend not to think about anything below 10,000 units a year, and we prefer runs of about 100,000 units. We discovered, however, that without going into the full superplastic regime, we could make parts using some conventional aluminum alloys that did not need high-cost processing. We identified a "quick plastic-forming range" (QPF range) that now allows us to form parts in aluminum that cannot be formed in steel.

We went into QPF production quietly five years ago, and then announced it two years ago when we started using it to form parts on the Malibu, one of our highest-volume cars. QPF allows us to make a lift gate in a single piece, in aluminum, with a significant weight savings compared with making the part from two pieces of steel. More importantly, the QPF technique provides an intersection of art and science that works well from a technology standpoint and can produce an "edgy" look that satisfies our designers. A good example is the trunk lid on our Cadillac STS (Figure 8). With QPF, we can fabricate the trunk lid in a single piece without sacrificing the clean, sharp edge. QPF is the kind of technological breakthrough we need to build on so that we can apply it to other parts of the vehicle.

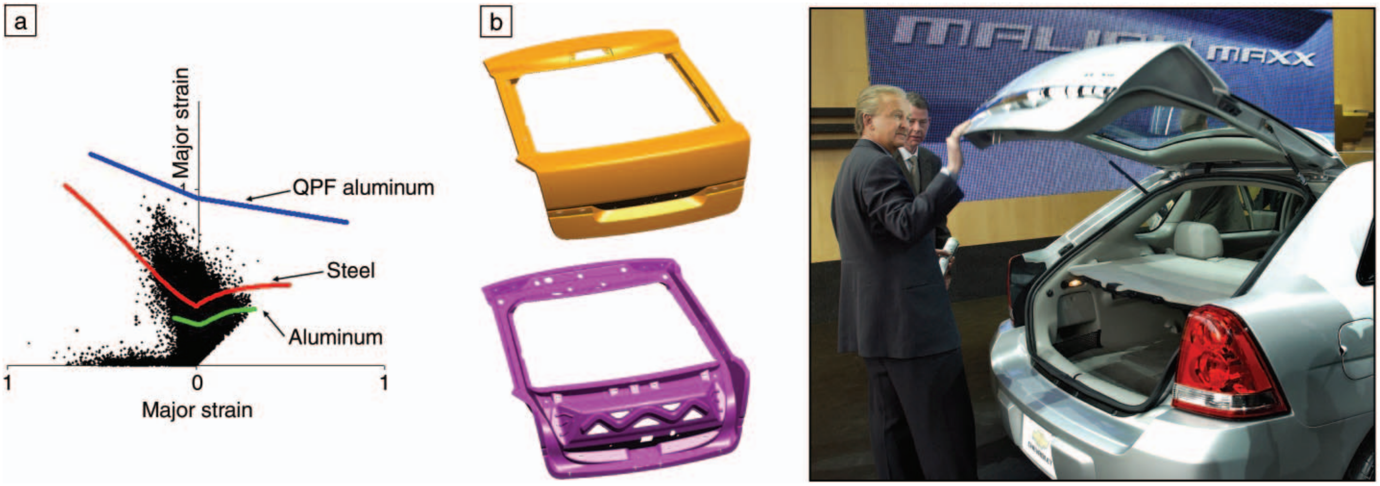

Figure 7. (a) Strain data from (b) the inner panel of the lift gate for the Malibu MAXX. Data on the graph in (a) demonstrate that a conventionally stamped steel or aluminum sheet could not have been used to produce the inner panel design because of the strains, represented by the black dots, that would occur in fabrication; the part could only be stamped using GM's quick plastic-forming (QPF) aluminum process.

Figure 8. Quick plastic-forming (QPF) technology provides an intersection of art and science that can produce an "edgy" look that satisfies GM's designers. A good example is the trunk lid on the Cadillac STS. With QPF, the trunk lid can be fabricated in a single piece without sacrificing the clean, sharp edge.

Magnesium Castings

I mentioned earlier that GM is one of the most aggressive users of magnesium in the automotive industry. In 2004, we produced more than two million units in the form of magnesium instrument panels. Like aluminum, magnesium posed problems that we were able to solve. As a result of another technological breakthrough, we learned how to make the largest magnesium castings in the world, producing instrument panels 5 feet long, 4 mm thick, and weighing 27 pounds. Because our panels are covered by plastic, you can't see that they are composed of an integrated single casting of magnesium, which ultimately yields higher performance at a lower weight with better packaging.

Thermoplastic Olefin

One class of materials whose use is accelerating for automotive applications is thermoplastic olefin (TPO). GM is using TPO in increasing amounts because it enables us to differentiate the styling of the fascia we put on external parts of our vehicles, and to do it with a low-cost investment. Like other lighter-weight materials, TPO poses challenges, in terms of processing quality, cost, and strength.

GM has found a way to use nanocomposites to overcome these problems. For the past five years, we have been the largest user of nanomaterials in the world (Figure 9). Our technology is based on taking a naturally occurring smectite clay and chemically treating it so that it actually exfoliates down to single molecular sheets. We learned how to process the clay without agglomerating the sheets, which means that we now have a reinforcement that is at the nanometer scale.

TPO nanocomposites constitute another case of science lagging behind engineering. We were able to make these materials work quickly by creating partnerships with several suppliers—a molder, a resin supplier, and a particulate supplier.

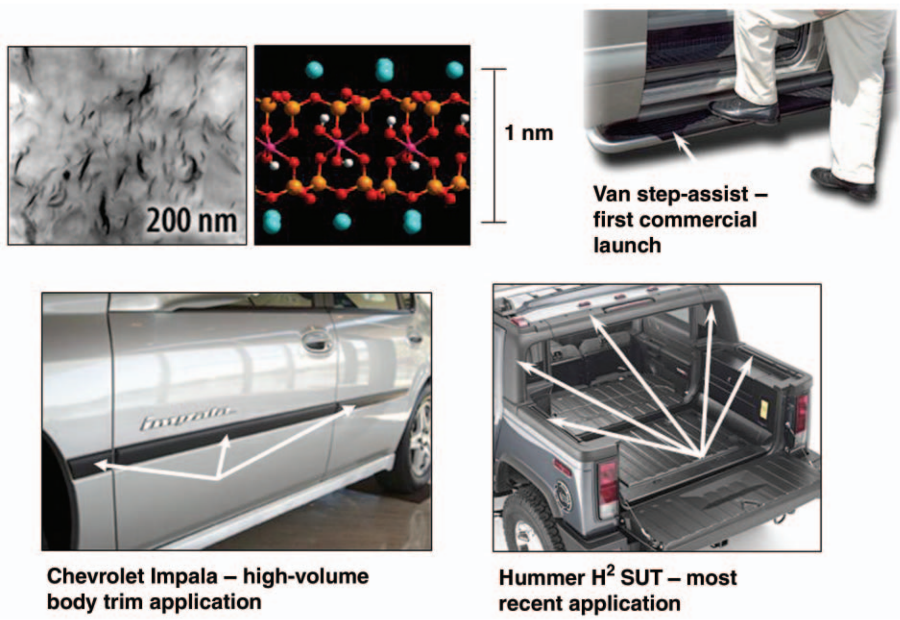

Figure 9. GM nanocomposite applications. The image at upper left is a transmission electron micrograph of smectite clay filler dispersed in thermoplastic olefin; the schematic beside it shows the atomic structure of smectite clay (blue = sodium ions, red = oxygen atoms, gold = silicon atoms, magenta = aluminum atoms, and white = hydrogen atoms). SUT stands for "sport utility truck."

Even today, however, we still do not fully understand why our nanomaterials work so well. We do know that one of the results is anomalous strengthening—the modulus is greater than what we expect from calculations using current theories. In addition, we are achieving lower weight, lower costs, and higher quality, with a larger processing window.

At this point, some high-quality research is needed to tell us why we are getting anomalous strengthening. We could use that information to guide some materials substitutions and to help us tailor the interfaces so we can reduce costs even further. The anomalous strengthening of nanometer-sized particulate for structural applications is just one more automotive materials area that is ripe for development.

Although we utilize lighter-weight materials in many of our vehicles, our materials flagship vehicle is the Chevrolet Corvette. It contains multiple aluminum and magnesium parts, including hydroformed aluminum frame rails and roof bow, magnesium roof frame and engine cradle, carbon-fiber floor pan, and titanium valves and connecting rods. We have even used balsa wood in a Corvette floor, in the Z05 model.

Smart Materials

The real paradigm-changer for our industry, outside of the propulsion system, is the introduction of smart materials. These materials have historically been the domain of the aerospace industry, where typically one can spend $100 per pound for certain parts, or $1000 per pound on a satellite.

When it comes to vehicles, however, one is able to spend only about $1.50 per pound. Fortunately for the automotive industry, certain smart materials applications are approaching volume production at costs that we can afford.

We have accomplished that by integrating smart materials with certain mechanical–electrical solutions. Consider the concept of mechatronics, where mechanical and electrical engineers combine their areas of expertise to devise new types of solutions. An example of that would be General Motors' variable valve timing engine technology. We have taken this idea a step further with a solution that we call "mechamatronics," which integrates mechatronics with smart materials.

One of the primary results of this smart materials research will be an explosion of opportunities—the development of different materials systems that can give us actuation not by motors or gears, but by heat, magnetic field, or electricity. When we can change the shape of something with heat, magnetic field, or current, we can change the way we do our fundamental designs.

We have already commercialized two of the applications to come out of this smart materials research. The first application is magnetorheological fluid (MRF) (Figure 10). Basically, we developed a way to take iron particles, put them into suspension, build magnetic yokes around them, and then change the viscosity by orders of

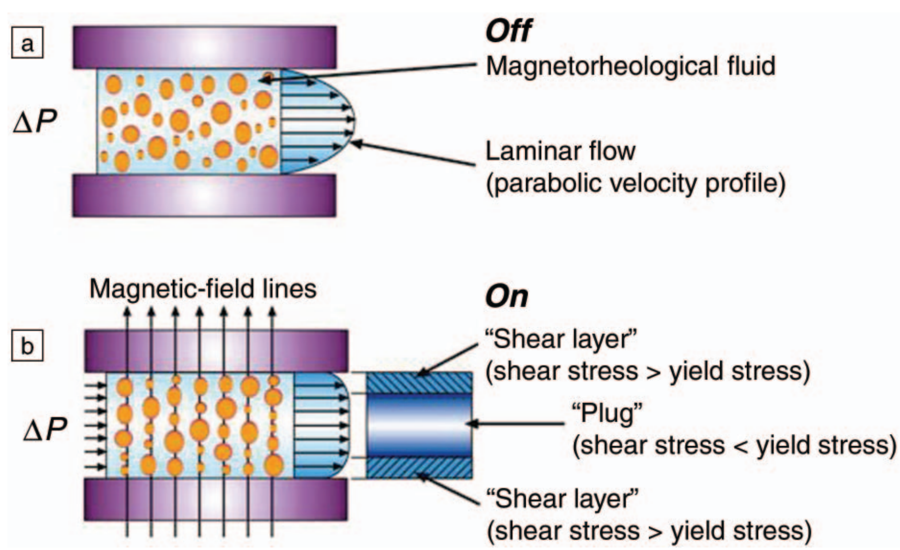

Figure 10. GM mechamatronic application to shock absorbers: magnetorheological fluid (MRF). MRF is a suspension of fine magnetizable particles in a synthetic oil. (a) In the off state, MRF is a random dispersion of magnetizable particles exhibiting Newtonian rheological behavior (shear stress = viscosity × shear rate). (b) In the on state, the applied magnetic field aligns the metal particles into fibrous structures, and the MRF rheology changes from Newtonian to Bingham plastic (shear stress = yield stress + viscosity × shear rate). The yield stress is controlled by the applied magnetic field. P is pressure.

magnitude by turning the magnetic field on and off. As a result, we can replace a single-state hydraulic system with an advanced system that allows us to make real-time changes in the damping characteristics of clutches and shock absorbers by the application of a magnetic field.

We have applied this concept to our truck fan clutch as a way to achieve fuel economy. We are also proud of the way we used magnetorheological fluid in our shock absorbers (Figure 10). In GM's Magnetic Selective Ride Control system, MRF is used as a working medium within a fluid-based shock absorber. By controlling the current to an electromagnetic coil inside the piston of the shock, the MRF allows for any damping state between the low forces of "off" and the high forces of "on." The result is continuously variable real-time damping for enhanced vehicle ride and handling performance. This technology allows us to make real-time adjustments to the viscosity of the shock absorber material. Vehicles with these shock absorbers offer a smoother ride than those with conventional shocks. Improved dynamic damping can also help maintain correct vehicle ride height in preparation for collisions and thereby help reduce the risk of under-ride, where a vehicle slides partially or completely under a higher vehicle in a crash. These examples represent the introduction of mechamatronic systems into our vehicles.

Conclusion

The issues I have discussed, from sustainability to safety to lower costs, are the ones driving the agendas for automotive technologies. There is a role for the materials community in each of these agendas.

The automotive industry is, after all, no longer built around bending steel. We need to have the best minds working on the latest solutions to reach our goals of improving fuel economy and reducing emissions. The automotive field represents a major area of opportunity for materials researchers, a concept I have been promoting for more than 20 years. This particular MRS meeting, with about one-third of its sessions relevant to our industry, has borne that out. I hope that all of you will take advantage of this opportunity and help us develop the next generation of automotive materials.

Alan I. Taub *is executive director of General Motors Research and Development in Warren, Mich., where he is responsible for GM's seven science laboratories in Michigan and India. These laboratories focus on a wide range of technologies, including advanced powertrain systems, computer-based design and analysis systems for vehicle engineering, electronics and information-based vehicle systems, new materials and fabrication processes, more environmentally friendly fuels and lubricants, and more efficient emission control systems. Taub was named to his current position in 2004.*

Before joining GM in 2001, Taub worked for Ford Motor Company. In his tenure with Ford, he managed the materials science department, where he was responsible for advanced automotive body, chassis, and powertrain materials. He later managed North American vehicle crash safety for Ford and vehicle engineering for the Lincoln brand. Taub joined Ford from General Electric, where he had worked for nearly 15 years in research and development and ultimately managed GE's materials properties and processes laboratory.

Taub was elected to membership in the National Academy of Engineering in 2006. He holds a BS degree in materials engineering from Brown University and master's and PhD degrees in applied physics from Harvard University. He was a member of the USCAR Automotive Composites Consortium (1993–1997) and served on the Materials Technical Team for the Partnership for a New Generation of Vehicles (1995–1997). He has been an active member of MRS and serves on the advisory boards of several institutions, including Harvard, Brown, the Massachusetts Institute of Technology, Northwestern University, and the National Science Foundation. He holds 26 patents and has authored more than 60 papers.

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