Energy Quarterly · Interview

The shift to advanced materials: GM's Alan Taub surveys future of the auto industry

Interviewed by **David S. Ginley** and **Arthur L. Robinson**

As vice president for Global Research & Development, Alan Taub oversees General Motors Co.'s seven worldwide science laboratories and has responsibility for GM's major corporate innovation programs and its global technology-collaboration network. As Taub sees it, the auto industry is in the midst of a paradigm shift. Today's vehicles represent more than a century of "refinement" of the "horseless carriage" that became the motorized version of the 19th century horse and carriage, but that ancient lineage is coming to an end. Thanks to the availability of new technologies ranging from communication networks to materials, the growing pressures of sustainability from energy and the environment (i.e., continuing availability of natural resources) as well as safety concerns and the need to compete in an emerging global market, companies like GM are transforming how to think about transportation.

***MRS BULLETIN:* Tell us about the challenges and opportunities that drew you to GM? How did your materials background help you in your new position?**
ALAN TAUB: I joined GM over a decade ago for a couple of reasons. It was pretty clear at the time that the automotive industry was about to change what we call the "DNA" of the vehicle; that the product which we had basically designed a hundred years before and had refined for a century was not going to be the product that we could use sustainably in the next century. Moreover, GM had gone through a near-death experience in the early 1990s, and it was pretty clear that it was trying to reinvent itself. Having lived through Jack Welch's transformation of GE, I thought it would be a great opportunity to also be part of the transformation at GM. I had anticipated it would take three to five years, but after 10 years and a bankruptcy in the middle, I think we have succeeded in reinventing the company while initiating the reinvention of the vehicle.

How has GM's near-death experience affected the company, and how has it affected R&D?
The company had some key structural issues that had to be resolved. As the market shifted in North America, we had too many brands, and our capacity was larger than needed. It took the bankruptcy to help the company address some of those issues. I think the remarkable part is how we kept both product and technology development in place during that tough time. As I said before, we're going through a transformation as an industry: in the product, in the way we interact with our consumers, and the whole nature of personal mobility. This shift is clearly technology-enabled, and, fortunately, our leadership and financiers understood that we needed to keep the product development and the technology pipeline alive, and I think we managed to do that.

Can you describe the changing global landscape as markets such as China turn their eyes toward personal mobility and how this will affect GM?
China is the fastest-growing market in the world. It's a very different market on the business side. We are there in a joint venture with an excellent partner. The environmental and resource sustainability required in the 21st century is being driven probably more by the developing world than the developed world. Around the world, per capita vehicle ownership scales with per capita income. Since incomes are growing much faster in the developing world, that is where we are seeing the fastest growth in vehicle sales. So the need to reinvent the product is as strong in the emerging markets as in the developed mature markets. Thanks to our global footprint for manufacturing and engineering and for research, we're attacking the problems of the developing world, and there will be different solutions.

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https://doi.org/10.1557/mrs.2012.63 Published online by Cambridge University Press

David S. Ginley (left) interviews Alan Taub.

Does serving both developed and developing worlds tend to bifurcate the product lines?

I think time will tell. If you look at what happened in China, for example, the market matured remarkably quickly, so that the Buick products we sell in China come off the same platforms we use in the rest of the world. As an industry, we started selling more vehicles in China than in the United States two years ago; that trend will probably never reverse, and it's anticipated in the not-too-distant future that industry sales in China will exceed Europe's and North America's combined. Moreover, some of the luxury brands are also predicting more sales in China.

At the other end of the product spectrum, we have our partnership with SAIC and Wuling, which is building and marketing a lower-end commercial vehicle that's already doing remarkably well. We introduced a new brand—Baojun, which is under Chevrolet—to hit the market more geared toward the lower tier cities in China and their developing areas. We'll have to see whether the product lines homogenize, but there's clearly room for a higher value product for the people with lower per capita income.

Do you see a similar thing happening in India?

We're doing well in India. The market is only now beginning to grow at a similar rate as in China, and the product mix is about the same. India will have some infrastructure issues. For example, China is investing in roads and infrastructure faster than India is. But basically this type of investment is taking place wherever accelerated growth is occurring—whether it's Brazil, Russia, India, or China—in everything from the luxury brands on down.

By the 1990s, research at GM had lost much of its luster but since then has steadily improved. How were you able to turn things around?

When I graduated in the late 1970s, what was known as GM Research was one of the world's preeminent laboratories. It was in the same league as Bell Labs, IBM, and GE. As the company went through its financial difficulties in the 1990s, budget pressures were everywhere, and the research organization contracted dramatically. With the beginning of the restructuring of the company, the opportunity to rebuild the research laboratory was there. When I arrived, the good news was that the core of the talent had not left, and the "cream of the crop" was still there to build on. We moved ahead in three ways.

First, during the 1990s, while many corporate industrial laboratories were still the bastions of deep technical work, they also had now aligned themselves more closely to the roadmaps of the companies, and so there was more applied research to strengthen the relationships of the labs to engineering. This was probably the least difficult of our challenges, but we made it happen.

Second, during the contraction that occurred, the GM organization had become internally focused, while the other industrial labs were setting up open innovation networks. So we changed our business model in two ways: We moved from the then current five percent of the budget spent outside GM to adopting a goal of 30 percent to fund universities, joint work with national labs, and the supply base. And together with Boeing, we entered into a 50/50 joint venture to run the old Hughes Research Laboratories, so we own that together and manage it at the intersection of aerospace and automotive technology. Not only is this intriguing, but it's highly leveraged and working well. In this way, we started a much more open innovation network.

Finally, we also decided to globalize our laboratory footprint. General Motors was the world's first automotive industrial research laboratory and for obvious reasons was located in the Detroit area. We had remained in southeast Michigan on one site for 80 years, but we decided to globalize to get people with different perspectives. At the time, more than 50 percent of the researchers located in the Warren lab were born outside the United States. Over 98 percent of them, however, graduated from a U.S. graduate school. And I have a belief that the way you conduct research is very much driven by how you were taught in graduate school. All this resulted in a more homogeneous approach to invention. By opening up labs in other

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places around the world—Bangalore, Shanghai, outside Tel Aviv, and other places such as upstate New York—we achieved a diversity of inputs that has served us well: world-class talent working where they want to work and living in different environments.

Many industries have shifted their research portfolio balance more toward applied research. What does the portfolio balance look like for GM?
First of all, we are an applied-research organization. We do explore white space phenomenon that can impact the industry, but every project we do has a potential payoff, either something we'll put in our plants to improve productivity or cost, something we'll use in a propulsion system, a new product feature, or a tool for more effective product development. However, the nature of our industry is GM works together with the supply base to develop breakthrough technologies. In the end, GM does the system integration, but in order to be the best at the things we do, we try to understand the entire process. In the case where GM buys the components but builds the vehicle, we have to have an understanding of everything that goes into the car. For electronic controls and software, which by the end of this decade will be 40 percent of the value added to the vehicle, we need to understand communication protocols and the fundamentals of electrical architecture in order to provide the guidance for the final engineering implementation. So we won't do esoteric research, but we will cover everything from understanding the breakthroughs to consulting with engineering on the final implementation. We do a lot of the fundamental work in conjunction with universities. At any point in time we probably have almost 400 active research projects with universities around the world where we are able to obtain fundamental knowledge that will apply for our business.

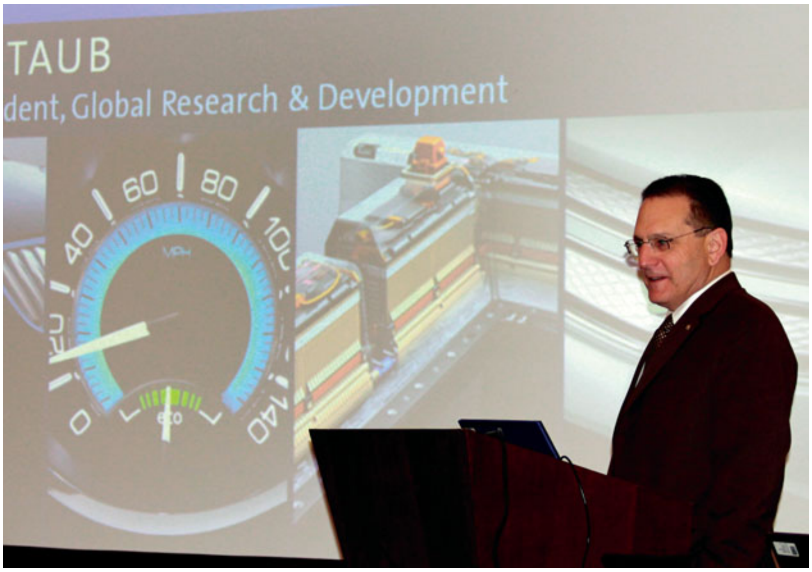
I hasten to add that the labs I lead do everything from propulsion to electronics to advanced materials. But if you look at where the breakthroughs are needed, they're primarily materials-enabled, and that's everything from sensors and lighter-weight materials to energy storage and energy conversion (that is, the battery and fuel-cell field). These will all come via materials substitution, inventing new materials at the molecular level and applying breakthrough materials. The future of the industry is in the hands of the materials scientists probably for the first time in its evolution. This is an intriguing time for a materials scientist to be leading the lab.

What are some of the materials-related research advances achieved during your tenure that are now in the marketplace?
First, we have made the vehicle lighter. The first stage of light-weighting was the mechanical engineers' domain, based on topology optimization and making joining technology more efficient; but it quickly moved into the introduction of advanced materials. Our researchers led in some of the high-strength steel implementations in the early days of that technology, but it was in the movement to aluminum and magnesium that we have really led the industry, particularly on casting technology for both materials. We also have made several innovations in composites, particularly in the Corvette, which uses our ultraviolet-stabilized, exposed carbon fiber. So the introduction of advanced lightweight materials, where there's the opportunity to take out 20–30 percent of the total weight of the vehicle, including as much as 40 percent of the body weight—50 percent if we could get low-cost carbon fiber to work—is something we are very proud of.

In addition, for a period of time GM was the largest user in the world of nanomaterials. Our researchers had invented a way to basically exfoliate a naturally occurring clay into single layers (something like graphite but with mineral structure), a surfactant that kept it from agglomerating when it was put in a resin, and then molding it into plastic parts. It is one of the fastest structural materials implementations I've seen in any industry. We partnered with a clay supplier, a resin maker, and a molder. As one of the few advances that has given us the combination of lighter weight, lower cost, and

GM's Shanghai-GM (SGM) assembly plant, a joint venture with the Chinese company SAIC.

https://doi.org/10.1557/mrs.2012.63 Published online by Cambridge University Press



Alan Taub presents his award talk on vehicle electrification at the Acta Materialia Materials and Society Award Forum held at the 2011 MRS Fall Meeting in Boston.

easier forming, discovery has really made some good inroads. As an aside, I'm so jealous. I almost wish I could be reincarnated and start my career now in materials science. The tools that these new researchers have to examine and build and design materials at the atomic and molecular levels are mind-boggling.

More recently, we have moved into "smart" materials such as shape-memory alloys—those that change shape or stiffness based upon changes in heat or the magnetic or electrical field. The number of motors that are put on the vehicle for the convenience of the driver was on its way from dozens to well north of a hundred. Motors use a lot of power; they take up a lot of space; and they weigh a lot. Our researchers realized that they could make things move without a motor using smart materials. We had had some experience with it in vehicle suspension systems with magneto-rheological fluids that changed the viscosity with magnetic field. Probably the next breakthrough was shape-memory alloys. Those had been invented when I was in graduate school, and I remember that for about a decade, its application was limited to trick spoons. After the medical industry then refined the material in its processing for stents, our researchers realized, "Hey, wait a second; another industry has matured that material. Can we take advantage of it for applications and scale it up?" We have filed almost 300 patents, and we have shown the media our first generation of potential technologies. In the not-too-distant future, we're going to be announcing the first commercial automotive application.

All in all, in everything from smart materials to self-healable vehicles to light-weighting, there's not a component on the vehicle that we're not reinventing. I'm not sure, other than in the first 10 years of the auto industry, that anybody's been able to say this until recently.

What do you see as some of the emerging materials science areas important to GM?

Clearly, the number one challenge now is energy storage. We need to shift toward vehicles that are powered by renewable sources rather than petroleum and in that way take the tailpipe out of the environmental debate. In the past two to three decades, we have doubled the efficiency of our power train, but if you look at the growth of the vehicle market, we have not moved fast enough to power our vehicles with diverse renewable fuels. We need to wean ourselves off petroleum, and we believe the end game is electrification of the propulsion system. If you look at what it takes to do that, at this point we know we can package an electric propulsion system, and we can meet durability requirements. The big challenge is raising its value for consumers. That means everything from better batteries, better hydrogen storage, more efficient fuel cells and better catalysts, and lower costs. For motors, we have to develop a magnet material not based on rare earths. For power electronics, we need much faster switching devices that are normally in off-states, so we're looking at III–V semiconductors such as GaN.

Next, consider the electronic control software revolution. Silicon technology was supposed to asymptote twice already, but the materials scientists keep inventing their way out of it. In a world where memory is so inexpensive that you'll never need to delete any piece of information, and with communication networks having become so prolific that you know where everything is and where you're connected wirelessly, and all that computing power is in the cloud, it's still fundamentally the transistor and other things that enable this capability. We started spending more on silicon than steel years ago.

The last one I'll mention is biomimetics. When it comes to "bio" anything, other than, say, biofuels, what's the relevance to automotive? What we've latched onto is biomimetic, mimicking how nature does it. The way we tend to build things today is not very efficient. We'll cast a big structure and then machine away most of it. Name anything in nature, other than maybe the Grand Canyon, that's biologically based and would waste that much material and energy. Now, are we ready to throw some microbes in a glass and produce a vehicle? No, but I do think self-assembling structures within vehicles will come.

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Would you say that computational horsepower has finally gotten to the point that it can become predictive rather than explanatory when it comes to materials?
We don't have the luxury of time to solve the environmental and resource sustainability issues of our products. We're at the point now where I can design a vehicle with most of its key attributes in the computer and then do validation prototype testing. But when it comes to some of the fundamental materials breakthroughs like our use of smart materials, it's still empirical and Edisonian, and then the theory catches up later. We have got to change that. We need to model and design materials virtually, including their thermodynamic behavior, their metastable behavior, the evolution of microstructures during processing, and so on. We're only now catching up with the design tools, so this is clearly an area of major breakthrough. Fortunately, the cost of computing has dropped tremendously, and this has opened up some new possibilities, such as combining computation with combinatorial experimentation where the ability to predict and rapidly validate new materials allows the study of thousands of alternative variations, which is a huge advantage. In other areas, we would like to study hydrogen storage or catalysis, where key properties are dominated by defects. We really need to master that next stage of modeling: dilute constituents and dilute defects.

What are the options for improving the efficiency of gasoline engines still further before moving to the all-electric end game you referred to?
First, it depends on what you consider the internal combustion engine. Let's start with the more efficient version, diesel. The challenge in diesel is cleaning up emissions and doing that without dramatically increasing costs and without decreasing the efficiency. As in gasoline engines, when you start including after-treatment systems to address the knocks and soot issues, you have to run combustion differently. At the same time, we think we can start dramatically closing the gap between gasoline and diesel efficiency. There's another 20 percent fuel economy improvement that we can get in a base gasoline engine by improved combustion, lower friction, and other changes.

At that point, the base architecture of the internal combustion engine has probably gone as far as you can take it. So we're looking at alternate architectures. Something called "split-cycle engines"—where you separate the compression and ignition events—offer the opportunity for another step change in efficiency in the base engine. Beyond that, you can couple it with partial electrification, what we call "hybrid." The hybrid allows you to overcome idling losses. When you have an engine designed to move a large vehicle down the road and do it efficiently, it turns out having that same engine operate efficiently under low loads is problematic. It would be more efficient to shut off the engine in idle and run the accessories off the battery, and then when you step on the throttle, turn on the vehicle engine so that you haven't lost a beat. And we've done that in a way that the consumer does not see it. You then add regenerative braking and use the electric motor–combustion engine balance to effectively let the engine run more efficiently. If you combine all those together, you're somewhere north of 30 percent improvement over where we are today. But the end game of full electrification will be even more efficient.

GM technician checks a lithium-ion battery pack for the Chevrolet Volt at GM's battery laboratory in Michigan.

Do those improvements all translate well to vehicles powered by biofuels like ethanol?
Betting that the infrastructure will come as well as advanced biodiesel and bioethanol fuels, we chose to start making our fleet biofuel-compatible and now lead the industry. Our flex-fuel vehicles in Brazil and the United States can run with 100% and with 85% ethanol fuels, respectively. There are some extra challenges in doing that, including engine modifications, owing to both wear of the engine and corrosion issues. At this point, the industry, and GM in particular, is prepared for the move to biofuels. The next question is how do we do it in such a way that the infrastructure and

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the vehicle fleet move in tandem and do it consistently around the world? We are betting that both the biofuel infrastructure and particularly the development of advanced biodiesel and cellulosic bioethanol will come. And there will be issues around fuel quality that we'll have to work with the energy suppliers to handle.

Electric cars are a radical departure from the past. What are the big challenges for taking this path?

First, there's the challenge of the electric vehicle itself. We define electric vehicles as vehicles where the wheels are powered by electric motors. There are two ways you can produce electricity for the motors: plug in to the grid to charge a battery, or store hydrogen for use in a fuel cell. Let's start with the plug-in. The batteries, while improved dramatically with lithium-ion technology, are still burdened with a low energy density that only allows us to get limited range in a pure battery-powered electric vehicle. We're going to produce our Chevrolet Spark as a pure electric vehicle. But we have gotten our consumers accustomed to a 300-mile range and a five-minute refueling time at the service station. So while we are working hard on battery improvements, there have to be markets where a limited-range small vehicle makes sense. On the other hand, we have also come up with the idea of coupling the electric vehicle to an onboard charging system powered by a gasoline engine, as in the Chevrolet Volt or the Opel Ampera. The reception to that innovation has been tremendous because it gives you the best of both worlds. It took us awhile to have our consumers understand what the Volt really does, but everybody who's getting one loves it. The challenge remains, though, of getting the cost down to a level where consumers will find value.

How do you see a large-scale implementation of electric vehicles occurring, including a workable infrastructure?

On the infrastructure side, there are several challenges. First, we did a limited rollout of the Volt in selected parts of the country because we had to educate our dealers, and we had to educate the first responders who would need to answer emergency calls. More importantly, we learned that we had to set up a system so that someone who bought a Volt and wanted more charging capacity than a 110-V home outlet provides could conveniently and without undue waiting be able to install a 220-V charger, which is faster. It turns out almost every municipality, every city, every town around the country has different codes, different inspection systems, and we had to engage a third party who would expedite the process for permits and help the consumer install the charging device.

We also need to look at the effect on the electric-power grid. As long as you're not charging the vehicles at 4:00 pm on a hot, humid day in August, the excess capacity of the grid would accommodate up to 50 million electric vehicles with minimal impact on electric generation. Eventually, the base grid might start to notice electric vehicles, but for a while, utilities will see electric vehicles as an opportunity to utilize off-peak capacity. Where there will be issues, even for such off-peak charging, is at the local substation and the transformer in front of your home. When they were developed, many suburban areas weren't set up to be running air conditioning and charging vehicles off the same transformer, and so infrastructure investment will be required at the local level. Additional investment will be needed as the computerized smart grid starts working, with its ability to efficiently manage electricity service based upon current capacity and demand.

As the smart grid is being developed, we're working with the various government agencies to ensure that someday the batteries or fuel cells on the vehicle could be part of the solution. I think the shorter term opportunity is the potential to take used batteries out of electric vehicles and reuse them in battery farms for storage, whether the power source is solar or wind. I think there's very little doubt that battery farms will start to be implemented along with wind and solar farms. The question is will they use new batteries developed for that application or reuse vehicle batteries?

What needs to be done so that you'll have the well-trained workforce that you are going to need?

Because we have a global footprint for product development, we're concerned about the technology-ready workforce around the world, but the United States right now is of particular concern. The United States has created one of

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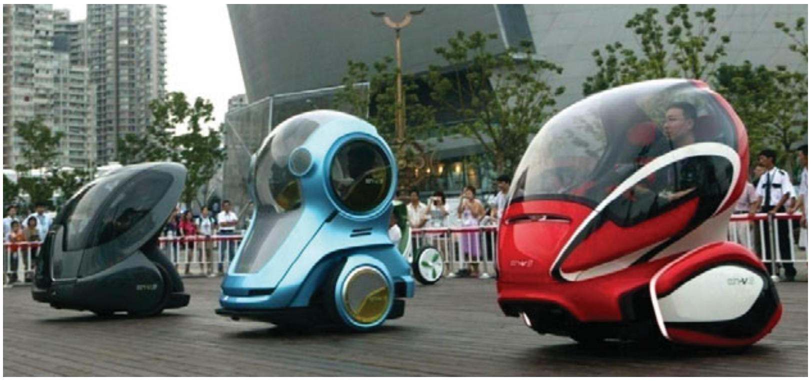
the best STEM [science, technology, engineering, and mathematics] school systems in the world, if not the best, but U.S. students are underrepresented. Moreover, the pipeline for a domestic STEM-educated workforce is an issue, and not just for the graduate schools. If you want to work on the automotive assembly line today, you have to be quite sophisticated technologically to run the machines, and we're already starting to see shortages in our service base—the technicians who work on the vehicles. We've also got to balance the pipeline with gender and underrepresented minorities, in part because you want the workforce that develops your technologies and designs to reflect the consumer population and thereby be in touch with its needs and desires. Underlying it all, at the elementary through high school levels, we've got to fix STEM. At GM specifically, we've set up a battery engineer program at the University of Michigan, and we're in cooperation with the university to train a workforce. We also work with community colleges to get the technician workforce ready.

The hydrogen-fuel-cell option for electric vehicles seems to have dropped out of sight. What is happening with hydrogen-powered cars?
First, I would say the current emphasis on plug-in electrics is augmenting the fuel-cell agenda. We have been on the path and committed to electrification of the vehicle since the 1990s. We learned a lot from the EV1, which was our first commercial introduction. One of the things we learned was how to make vehicles quieter. When you don't have engine noise, you start to hear the hydraulics and all the other sounds. Learning how to quiet the vehicle down was a lesson we applied throughout the fleet. Relative to electrification, we learned about the consumer's range anxiety, so if you start out with an 80-mile range, as we did with the EV1, people won't buy it. When the EV1 was launched, the breakthrough battery at the time was nickel-metal hydride, which was then going to improve indefinitely. When we saw their materials properties leveling off, however, we realized that limited range would remain a problem.

Well, there's another way to make and store electrons on a vehicle: hydrogen storage and a fuel-cell stack. When we began that journey, the system was a hundred times too large, a hundred times too heavy, and a thousand times too expensive. We set out on a 10-year journey to solve those problems, and we've made a lot of progress; today, we can package our next-generation fuel-cell stack in roughly the same space as a conventional engine. Hydrogen storage is still a challenge, and we've kept that activity on track. However, the improved but still limited range enabled by the introduction of lithium-ion batteries has allowed us to go back to the plug-in while we're continuing to develop the fuel cell.

How difficult will it be to develop an infrastructure for hydrogen-powered cars?
One of the challenges plug-in electric vehicles has is the need to bring the plug to within five feet of every vehicle. We've done analyses of what it would take to put a hydrogen infrastructure in place. In this case, we're taking advantage of centralized fuel stations because, using compressed hydrogen gas, we can fill a fuel-cell vehicle within the same five minutes that you spend at the gasoline pump today. So by our analysis, the number of stations you'd need to put in for the introduction of fuel-cell vehicles is far from overwhelming; it just requires the will to do it. In fact, Japan and Germany have committed to that infrastructure. Southern California seems to be stepping up, and there is an active program in Hawaii perhaps because the self-contained nature of the island might make the infrastructure easier to implement. The infrastructure is a one-time investment. The vehicle is a recurring cost and a recurring impact on the environment. I personally believe the best vehicle solution (plug-in, fuel cell, or other) will drive which infrastructures go in rather than the other way around, but it takes a cooperative event: there's a role for governments, there's a role for energy companies, and there's a role for us.

How significantly do you think that design of the vehicle will evolve once you move to fuel cells or electric vehicles?
One of the beauties of electrified vehicles is the design flexibility. While the Volt's underlying architecture is basically an electrified version of the Chevy Cruze, with future electric cars, designers will be able to put the power plant anywhere as they think about a dedicated electrical architecture. In addition, with future accident-prevention technologies, release from



GM's concept of an autonomous vehicle, reinventing personal urban mobility with the electric, networked vehicle (EN-V).

https://doi.org/10.1557/mrs.2012.63 Published online by Cambridge University Press

many safety constraints is going to change how vehicles are designed. If you think about how you design a vehicle today, just imagine the packaging exercise: You put your mannequins in a virtual interior representing the vehicle; you put in your propulsion system; and then you design your passive safety structure—all the things you need to add to the vehicle to enable it to be safe. Now imagine a world where the propulsion system is electric, you're going by wire instead of mechanically connected. We're moving into an era of electronic controls and software where we can make vehicles that won't crash, so you're no longer constrained with passive safety structures. The designers are now free to totally reinvent the vehicle.

Once I have made a vehicle that doesn't crash, I can add more capability. Take a look at the concept vehicle that we rolled out at the Shanghai World Expo in March 2010. We call it EN-V—an electric and networked vehicle—and it drives itself; it is what we call an autonomous vehicle. We designed it for the megacities of the future where parking is at a premium. These are small vehicles, extremely lightweight, driven by wire, and electrified.

The representation of the evolution of the automobile that I like to draw starts with a horse and carriage. Next I show a station wagon or sedan. Just like the carriage, it has four wheels, rows of seats, and people facing forward, and the engine is in the front replacing the horse. But now reinventing the vehicle, particularly for the developing world, means we're not evolving from the horse and wagon; we're providing personal mobility in the form of an automobile for people who are used to a bicycle. If you think in that way, it's a very different concept of personal mobility.

How do you make the transition to autonomous vehicles in a society that has been conditioned for a century to think that driving cars is fun?

First of all, I'm a believer in autonomous on demand. A vehicle is a very irrational purchase. If you think about it, next to your home, it's the most expensive of cumulative purchases you make in your lifetime, and people care what it looks like. They care about the color. Vehicles are not commodities, so as we solve the technology challenge of environmental and resource sustainability in the 21st century, it's important that we maintain the emotional connection to the vehicle. So whether it's the design or the joy of driving—look there are times when I need to be on a conference call or I want to let go of the wheel, but there are times when I want to have some fun driving—it's a question of autonomous on demand.

In fact, when I used to think of the challenges of bringing autonomous driving to fruition, I was always of the belief that it would be the technology that got us there. Could we get the sensors right to give full awareness? Would we be able to get control of the vehicle right? I think our roadmaps for that are pretty robust and will bear fruit by the end of the decade. It's the unpredictable engagement and disengagement of the human in the loop that is turning out to be the problem that makes our roadmaps not yet robust enough. But that's a transition that we need to manage because people want to be included.

How do you educate consumers about the environment and sustainability so they can make an informed choice?

In the end, there's one universal truth that we strongly subscribe to: the consumer makes the decisions, not us. And so it will be a gradual shift, but the move toward autonomous is coming, the move to electrification is coming, and the move to the networked vehicle is coming. The features that provide comfort, convenience, or infotainment tend to be consumer pulls. When it comes to environmental and sustainability features, where there's an incremental cost or inconvenience to the consumer, these are harder sells. Today with our advanced propulsion systems and our alternate energy systems, we can't deliver a product that is price-competitive with conventional vehicles. So our challenge is to get that cost to a level where the consumer will value it. Typically it takes us about three generations of invention and scale-up to start meeting consumer value, and today we're in generation one. This is something the industry needs to accomplish in partnership with governments, with the supply base, and with our customer. It's not an option; making our products sustainable in the 21st century is a must-do. Whoever integrates environmental and resource sustainability into the best personal mobility solution will win the hearts and minds of the consumer. □

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