Re-Inventing Carmaking With Truly Electric Cars

Using a Modular Car Architecture to Build New Cars and a New Carmaking Industry

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***Abstract*—If we replace our gasoline-engine cars with truly electric cars, we can build a new carmaking industry. A few huge, often financially troubled companies with slow-changing technology dominate today's industry. But we can build a new carmaking industry as big, bold, vibrant and fast-moving as the computer industry. A modular car architecture that builds on the advantages of an electric—not mechanical—power train is the key. Our "proof of concept" truly electric car has seven modules, each a "black box" with well-defined and simple mechanical, data and power interfaces to other modules. Making cars truly electric can give us dramatically new cars and a dramatically new carmaking industry.**

Keywords—Electric vehicles, modular design, carmaking

I. Introduction

In the light rain and darkness of 2:00 am on a spring morning in 1896, a woman stood watching her husband take an axe to the doorway of a small workshop that stood behind their house. He was making the door bigger.

Over the past three years, the man had put together four bicycle wheels, a buggy frame, and a hand-built gasoline engine to make a horseless carriage. But having finished his new "quadricycle," he found that it was too wide to get through the narrow door. Thus the axe.

Finally finished, the man got on the bicycle seat he had put on the buggy frame and drove the car off. The wife waited nervously until the man returned hours later. He told her that he stopped at the electric plant where he worked to repair the car, but otherwise the car worked well. They celebrated a bit, he drank a glass of milk, and they both finally went to bed.

The man was Henry Ford. His quadricycle was not the most technically advanced car of his time. But that quadricycle proved that a simple, reliable, rugged, lightweight, powerful gasoline-engine car could be made in a small home workshop from common parts. Proving that concept started Henry Ford on the way to influence cars and carmaking like no other single person.

Following Henry Ford's path, we have been working for the past three years on a new proof-of-concept car. The components in that "truly electric car" are not technically advanced. But it has a new architecture, different from the basic car architecture that has lasted since the 1920s.

We think we have proved the concept that a simple, reliable, powerful modular car can be made in a small garage from common parts. We also think our new modular architecture might powerfully influence future cars and the future carmaking industry. Here is why.

II. Summary

In this paper, we first look at how moving to truly electric cars can give birth to a whole new carmaking industry. We then look in concrete detail at how we built our "proof of concept" truly electric car.

A. A New Carmaking Industry

Moving from gasoline-engine cars with an integrated architecture to electric cars with a modular architecture can change the carmaking industry. Perhaps carmaking can become more like the computer industry, where technology advances rapidly and the industry prospers.

The computer industry has become the most vibrant in the world. But it was not always so. A few decades ago the computer industry was dominated by a few huge companies—most of them financially troubled—and computer technology changed slowly. Just like the carmaking industry today.

What changed? In a word, modularity. [1] Starting with the IBM 360 series of computers, IBM and other computer makers moved computing from a tightly integrated industry—where every computer was designed and built as an integrated product—to a more modular world.

Now besides the industry giants, a number of smaller companies could build innovative, experimental modules that fit right into more proven, established computer designs. Silicon Valley was born. And modularity powered the computer industry to become the most important industry today. [1]

Today's carmakers face challenges. Financial turmoil, bankruptcy, peak oil, global warming, government regulation and interference, maturing markets. All these things foreshadow even more difficult days ahead for an industry that has fallen far from the pinnacle in its heyday when management expert Peter Drucker called carmaking the "industry of industries." [2]

But the carmaking industry has trouble changing. Throughout their over hundred-year history, cars have been designed and built as integrated products. Today's cars—even with modern technology—have not evolved dramatically from their ancestors. At least when cars are compared to their computer counterparts, as seen in Fig. 1.

The integrated architecture of our cars has not only slowed the evolution of car technology, but has also slowed the evolution of the carmaking industry. Just when we need quick changes the most.

We want to change that. We have a new car architecture that will bring a new and better structure to the carmaking industry.

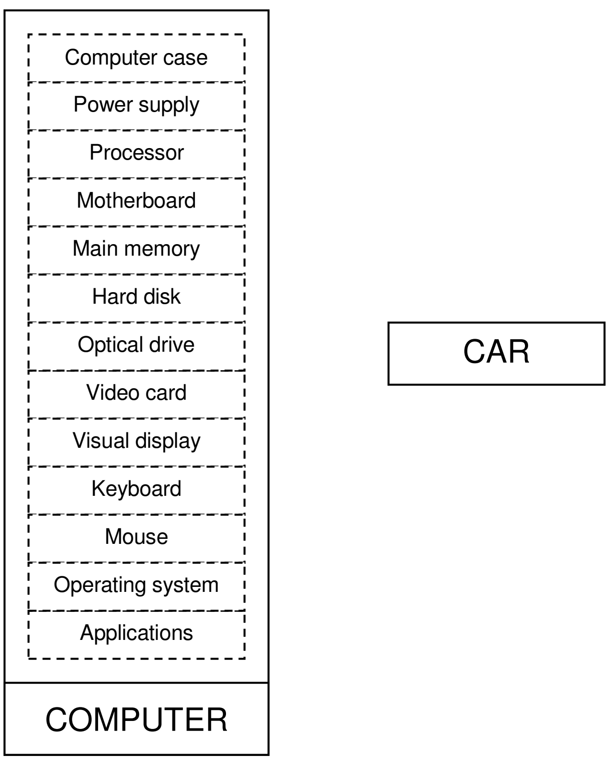

Figure 1. A desktop computer's modular architecture compared to a car's integral architecture

B. *Our New Car Architecture*

The basic architecture of a car has changed little since the 1920s. Our architecture does differ. We have designed a truly electric car, one that builds on the advantages an electric power train can give. Our "proof of concept" truly electric car has seven modules:

- car operating system
- driver control unit
- motor controllers
- wheel/motors
- car body
- car chassis
- electric power unit

Each module is designed as a "black box." Specifically, "what" the module does is defined. Each module must perform one or more functions of the car. But "how" the module performs the function is left up to the module designer. [1]

The modular architecture also strictly defines the interfaces between modules. Three types of interfaces connect modules together to form a complete car:

- mechanical
- data
- power

For the modules and interfaces to work well as an architecture, two things are particularly important. First, no two modules can perform the same function. [1], [3] For example, the electric power unit cannot add structural support to the car chassis. That is not its function. The car chassis must itself provide all the structural support needed, and must not rely on any other module to do any part of the car chassis's function.

Second, to preserve the independence of each functional module, the interfaces must be as simple and as limited as possible. As much as can be trimmed from each interface must be trimmed, until only the bare minimum remains. [1]

Details of each module and its interfaces appear below.

C. *Why No Modularity Before Now?*

If modularity brings such big benefits, why has the carmaking industry shied away from moving to modularity? Carmakers do use modular assemblies in some cases, and have made efforts to be more modular. But given the nature of the mechanical power train, it is very difficult (but not impossible) to build a conventional gasoline engine car that is modular. [4]

Only truly electric cars unleash the power of modularity. Companies in this new carmaking industry can produce the kind of innovation, and the kind of vibrancy, that the computer industry has shown. With that, carmaking might once again become the industry of industries.

III. THE CARMAKING INDUSTRY

A. *Integrated Cars Give Carmaking Its "Vertical" Nature*

In the early days of carmaking, more than 2,000 carmakers sprang up in the United States alone. Now, though, American carmakers have shrunk to a handful. Heavily regulated by governments for safety reasons, carmaking has become a capital-intensive industry that requires hundreds of millions of dollars and many years to get a new car on the road.

Carmakers today all make an integrated product. That means that the car is designed as an integrated whole. All parts are chosen and assembled to be part of just one car. As a rule (rarely broken), even similar parts and assemblies for one car cannot be used in another, even very similar, car. Even a simple seat, for example, cannot usually be taken out of one car and put in another.

Most in the carmaking industry see progress in making cars more integrated, not more modular. [5] That makes some sense. As noted in more detail below, modularity brings drawbacks as well as benefits.

More important, gasoline cars are complex, powerful mechanical machines. In a gasoline car (unlike electric cars), power cannot be transmitted by a simple wire. To transmit power, a complex transmission and series of belts bring the engine's power to the drivetrain and to other areas of the car.

As shown in Fig. 1 above, an integrated product like a car is very different from a modular product, like a desktop computer. A modular product has individual modules—with structure separated by function—that have simple, well-defined interfaces between them. [3]

For example, with the desktop computer shown in Fig. 1, you can buy each of the individual modules separately and use it with the other modules. Most of the modules how have "plug and play" interfaces that connect the modules together. That lets people upgrade and repair their computers more easily.

An integrated product, by contrast, has a design that treats the product as a whole. That gives the best performance and efficiency, but at the expense of simplicity. For example, with the car shown in Fig. 1, you can only buy the car, and not individual modules. You can buy parts for the car, but they are parts for that specific car, not functional modules that can be used in a variety of cars. And the interfaces between the parts are complex. [3]

The modular and integral designs for a nail clipper given by Ulrich and Eppinger [3], shown in Fig. 2, show the difference between the two approaches. But view that comparison with a little caution. That comparison is exaggerated to prove the point, and it does not really illustrate the tradeoff between simplicity (modular design) and performance (integrated design) that we focus on.

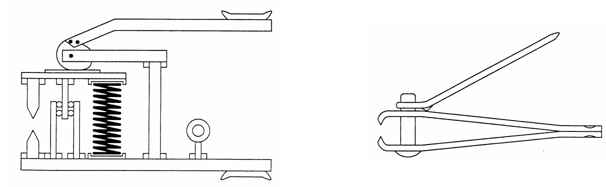

Figure 2. A nail clipper, with modular design (left) and integral design (right). From [3].

Some have noted that the nature of firms follows from the nature of the products that the firms make. [6] Similarly, the integrated nature of the car has led to carmaking being an integrated, vertical industry. When a complex product like a car is designed as an integrated product, the relationships between the various parts of the car are complex. That makes the distinction between functions loose and the interfaces between parts haphazard. That is exactly contrary to a modular design.

Given complex interactions among functions and the parts that perform them, a carmaker today must make sure that everything fits well, and works well, together. That means careful design and testing through an intricate, parallel process of designing, engineering and building a car. And that takes a big company, one with deep pockets and enough cash to last for the many years needed to get a new car on the road so that it can sell to make money.

That leaves us with a vertical carmaking industry like that shown in Fig. 3. There are only a few huge companies—three based in the United States—that build and sell more than a few cars. Even those three struggle, with two of them going bankrupt in 2009. General Motors and Chrysler were saved only by the unprecedented involvement of the United States government that saw GM nationalized and Chrysler given away to a foreign company. That all makes it hard to call the American carmaking industry the "industry of industries."

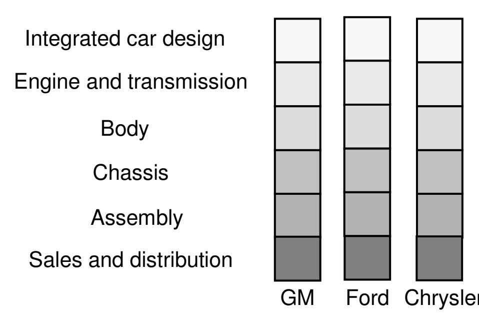

Figure 3. The vertical American carmaking industry.

B. *Turning "Horizontal" Like the Computer Industry*

Somewhat surprisingly, the nature of the product becomes reflected in the structure of the industry. An integrated product means an integrated and vertical industry. A modular product means a modular and horizontal industry.

The computer industry also used to be very vertical. As shown in Fig. 4, only a few huge companies built and sold only complete, integrated products. All the hardware and all the software—operating system and application programs alike—were designed and built by the computer maker, and sold only as a complete computer. [7]

With modularity, that all changed. Now computer companies did not need to build a complete computer, both hardware and software, to have something to sell. They could get a product to market more quickly and by spending less money by designing, building and selling a module rather than a computer.

The effects were dramatic. New companies started to jump into the market, finding investors willing to fund them. These companies experimented with new technology that the older, more conservative companies found too risky. The market value of computer companies, taken together, soared. [1] Innovation exploded. So did profits.

The success story of the computer industry has seen no equal. As shown in Fig. 5, the computer industry changed in structure from vertical to horizontal. [7]

Going modular affects an industry in two important ways. First, the move can speed up technological change by increasing experiments. Second, the move can make the industry more vibrant by lowering barriers to entry.

With a modular car design, we believe carmaking can become like the computer industry: innovative and profitable. By reducing the barriers to entry of new companies, and by encouraging experimentation, a new horizontal carmaking industry can be born. A vibrant new industry can grow up alongside a more troubled one.

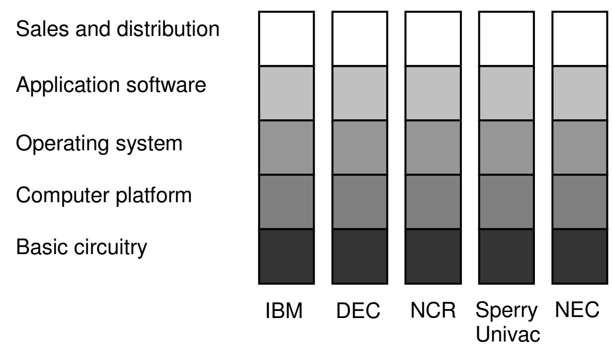

Figure 4. The old vertical computer industry. From [7] (modified).

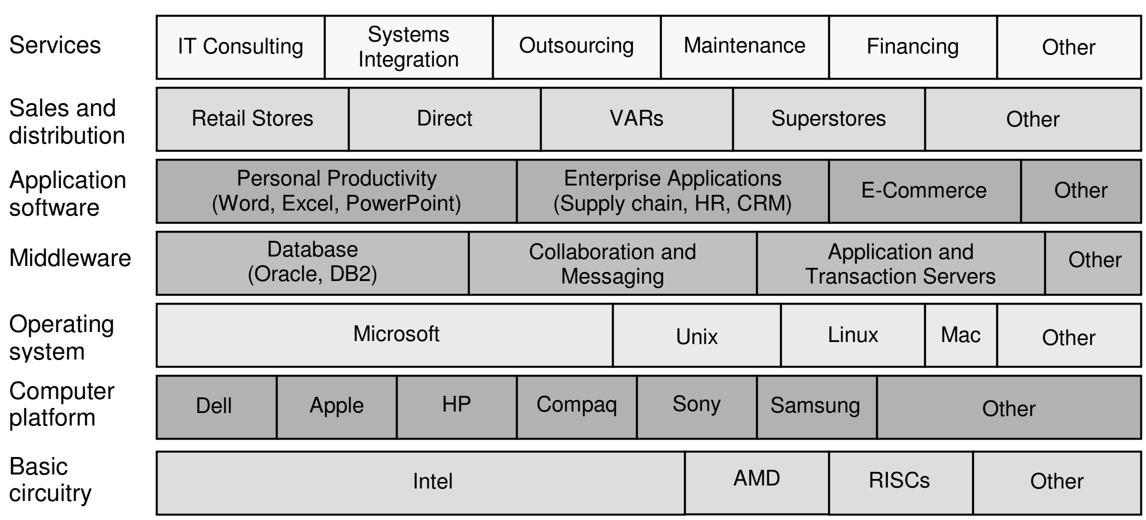

Figure 5. The current horizontal computer industry. From [7] (modified).

IV. PROOF OF THE TRULY ELECTRIC CAR CONCEPT

To prove the concept of a truly electric car, we designed and built a car using off-the-shelf parts.

Karl Ulrich [8] defines "product architecture" as:

(1) the arrangement of *functional elements;*

(2) the mapping from *functional elements* to *physical components;*

(3) the specification of the *interfaces* among interacting physical components.

Product architectures vary on a spectrum between the two poles of modular and integral designs. In a modular architecture, all functional elements map to just one set of physical components. Interacting physical components have few and narrow interfaces. A modular product will have interchangeable physical components, with standardized interfaces. Just like desktop computers and bicycles.

Contrast that with an integral architecture. There, functional elements map to physical components in a complex way, not one-to-one or many-to-one. Interfaces between the physical components that act together are also usually complex, called "tightly coupled." For an integral product, if one functional element or component changes, that will usually force a change in other nearby elements or components for the overall product to work correctly.

Our car tends very much toward the modular end of the product architecture spectrum. So to design the car, we identified its functions, split the functions into independent modules, and created well-defined and simple interfaces for connecting the modules.

Our objective was not to produce a prototype car that we would actually make and sell. Nor was it to produce the best performing car possible. Instead, we wanted to focus on design. We wanted to show how a car could be split into functional modules connected through simple interfaces.

Let us describe, in concrete fashion, the design of our "proof of concept" truly electric car. At the time of this writing, the modules for the proof-of-concept car have all been individually designed, built, and to some degree at least, tested. They work. But they have not yet been assembled and tested as a whole car.

Of course, not all modular cars have to follow this exact architecture.

A. The Seven Car Modules

We describe below the function and our implementation of each module of our proof-of-concept car. Fig. 6 shows the basic mapping that makes this architecture work.

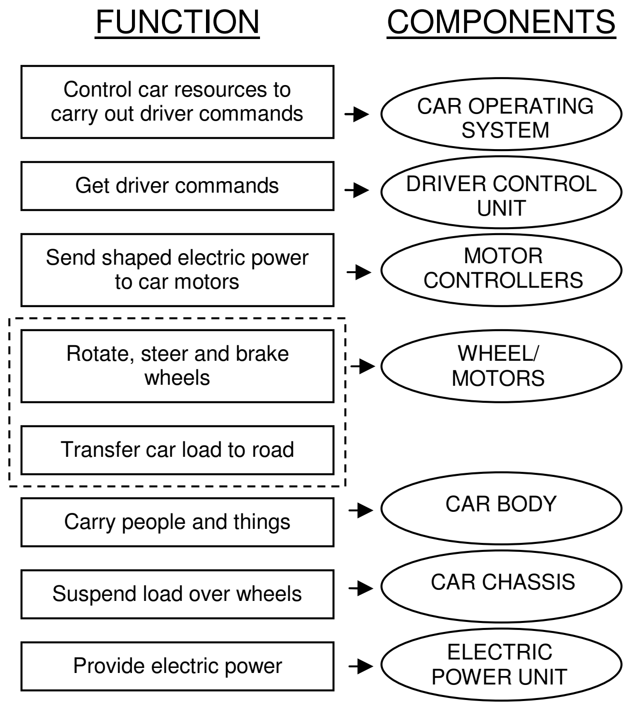

Figure 6. Mapping of car functions to car components.

Car Operating System

- Function: The car operating system controls all the resources of the car to carry out the car driver's commands. To steer the car, for example, a driver will put in a steering command using the driver control unit. The driver control unit will convert the command to a data signal sent to the car operating system. The car operating system will process the command to get the correct signal to send to the wheel/motors, which will then move the wheels the correct amount to steer the car as the driver wants.
- Implementation: The car operating system has hardware, software and networks. The hardware consists of a laptop computer running Windows 7 and several Arduino microcontrollers. The software is custom software written in C++. The networks include Universal Serial Bus (USB) and Serial Peripheral Interface (SPI).

Driver Control Unit

- Function: The driver control unit gets commands from the driver and sends them to the car operating system. For example, steering, speed and braking commands.
- Implementation: The driver control unit consists of a two-axis joystick made by Logitech that has a USB cord to connect to the car operating system's laptop computer.

Motor Controllers

- Function: The motor controllers shape the electric power from the electric power unit and send it to the wheel/motors to generate the speed desired by the car's driver. The motor controllers also need to provide the wiring between the electric power unit and the wheel/motors.
- Implementation: The two motor controllers are 48-Volt golf-cart type motor controllers from Alltrax. Each of the two rear wheel/motors has its own motor controller.

Wheel/Motors

- Function: The wheel/motors provide steering, speed and braking for the car.
- Implementation:

  The two front wheel/motors have steering and brakes, but do not have traction motors to turn the wheels. These wheels came from a 1991 Ford Ranger pickup truck. Each wheel has its own independent steering linkage, with a small electric motor in place of a steering wheel. The hydraulic brakes were replaced by electric trailer brakes.

  The two rear wheel/motors have speed and brakes, but do not have steering. Each wheel has its own electric motor, a 48-Volt motor that weighs 12.7 kilograms and provides 5 kilowatts continuous, and up to 15 kilowatts for short periods. The hydraulic brakes were replaced by electric trailer brakes.

Car Body

- Function: The car body carries the car's driver, plus (possibly) other passengers and cargo. It also provides the lights, horn and other accessories for safety. Thus, its most important features are safety, comfort and fashion. The latter is more important than it might seem. Indeed, the car body will be what we see as being the car, and appearance is largely what sells cars.
- Implementation: The car body consists of the cab and bed of a 1991 Ford Ranger pickup truck. We gutted the cab—removing the steering wheel, the seats, the dashboard, and everything else—down to the bare metal. We then had a lot more space to use, and are putting back seats and carpet as needed to make the space safe and attractive.

Car Chassis

- Function: The car chassis mechanically connects most modules together. In particular, it suspends the car body above the wheel/motors.
- Implementation: The car chassis consists mainly of the chassis from a 1991 Ford Ranger pickup truck. As the engine, transmission and differential were all torn off the chassis, largely only the frame remained. As the solid rear axle made it hard to connect wheel/motors, the rear axle was removed and an independent rear suspension from a 1997 Ford Thunderbird was welded in its place.

Electric Power Unit

- Function: The electric power unit provides the electric power needed by the traction motors to move the car. It also provides the electricity needed to run car systems like lights and computer hardware. Finally, it includes a power bus—wiring that makes electric power available at various points within the car.
- The electric power unit has four 12-Volt deep-discharge lead acid batteries wired in series to provide 48 Volts. It also has another 12-Volt deep-discharge lead acid battery to provide power to accessories.

B. *The Interfaces (Mechanical, Data and Power)*

To encourage experimentation, each module is made as independent as possible, and kept a "black box" that performs a specified function in an unspecified way. But the modules must operate together to form the car, so they must be connected, even if those connections—or interfaces—are kept as simple as possible. That means mechanical, data and power interfaces must connect the modules together.

Mechanical Interfaces

All of the mechanical interfaces are simple. None of the mechanical interfaces require welding. None require mechanical power to be provided by one module to another. That means that all modules can be easily connected and disconnected. Using simple equipment and unskilled people, we think our proof-of-concept car can be built or unassembled in an hour.

For example, one interface is between the car body and the car chassis. The interface specification includes:

(a) the dimensions of the contact surfaces between the body and chassis;

(b) the positions and sizes of the bolts and holes to hold them together;

(c) the maximum force the interface can bear.

In our proof-of-concept car, the driver control unit can be used anywhere in the car body. The wheel/motors sit in a box bolted to the car chassis. The car body bolts to the car chassis. The motor controllers are mounted on a board bolted to the car chassis. The car operating system sits in a box in the car body.

Data Interfaces

The data interfaces need to define the data that must be exchanged between modules, and to provide a bus over which the data flow.

In our proof-of-concept car, the driver control unit gets braking, steering and speed input from the driver. The driver control unit senses driver input to the joystick 100 times each second and translates that into a number. Steering is from -100 (far left) to 0 (center) to 100 (far right). Braking is from 0 (none) to -100 (full brakes). Acceleration is from 0 (none) to 100 (full throttle). Direction is 1 (forward), 0 (park) or -1 (reverse).

The driver control unit sends that data to the car operating system on a data bus. The car operating system processes that data and in turn sends signals to the two motor controllers (speed) and to the wheel/motors (steering and brakes). The same numbers are used, and the signals are again sent 100 times each second.

Power Interfaces

Compared to a gasoline car, power interfaces in our proof-of-concept car are simple. An 8-gauge wire power bus provides 12-Volt power at various points in the car. The 48 Volts for the traction motors comes through 2/0-gauge heavy wiring.

V. Future Generations

Our proof-of-concept car does not rival the performance of a conventional gasoline-engine car. But we believe that truly electric cars can quickly evolve to perform much better than gasoline cars.

Why is that? A modular architecture allows a system integrator to mix and match modules for best results, based on price and performance. Companies expert in fields outside of carmaking can contribute their best technology for use in a car. Different modules need different technology, and these technologies will evolve at different speeds.

Development of each module can take place in parallel and independently. That means the technological generations of a car can evolve like rabbits do with their rapid multiplying, not like elephants with their long generations. New technology in one module can be put into cars immediately, without waiting for or coordinating with evolution in the technology of other modules.

That power of parallel development is what drives software development, which has become modular out of necessity. Complex software—like Linux and other operating systems—now all depends on modular development. That same power will allow truly electric cars to improve rapidly.

How rapidly? That is hard to say. Predictions are hard to make, especially about the future. But for example, by upgrading all of the modules of our proof-of-concept car, using existing technology we think we can build a car that uses a gasoline-powered generator to produce electricity so that the car can:

- Go 100 miles per U.S. gallon of diesel fuel
- Go from 0 to 100 miles per hour in 10 seconds
- Go 1,000 miles on one tank of gas
- Sell for a total price (for all 7 modules) of $35,000

To achieve these goals, we would put a 17 kW motor in each wheel, each with an adaptive motor controller mounted onboard the car chassis. Power would be supplied by a combination of generator and battery. The generator would need to operate at about 50% efficiency, and the car as a whole would need to get about 5.5 miles per kilowatt hour of electricity.

We think we can get that type of performance from reasonably priced equipment that exists now. But it will not be easy. It may not even be possible. Only the future will tell.

VI. Drawbacks to Modularity

Making modular cars can bring big advantages, as discussed above. But modularity can also bring drawbacks that must be considered. [9] We present above the positive attributes of their approach, but we cannot ignore the potential drawbacks or how these would be mitigated. Those we address here.

A. Carmaking Issues From Modularity

For most of us, cars are typically the second largest investment after houses. That means we have high expectations on warranty, maintenance and service, and on long-term availability of parts. The current approach to car design and manufacture focuses on meeting consumer requirements in these areas. Carmakers have set the bar very high for reliability, especially in the last decade.

If cars become just a collection of modules, who will be responsible for meeting the high expectations consumers have for warranty, maintenance and service? As well as other important factors such as safety and resale value?

Based on how the computer industry functions, we think these problems can be worked out. With truly electric cars, carmakers may well become system integrators and sellers, rather than makers. Much like Dell, who does not make any computers. Rather, a buyer orders a computer from Dell, who has parts made and assembled by other companies, and then has the completed computers shipped to buyers.

Of course, cars are not computers, and the carmaking industry is not the computer industry. The word "crash," for example, means something a lot different, and often a lot deadlier, for a car than for a computer. We cannot predict whether or how consumer expectations will be met by truly electric cars. Only the future will tell us that.

B. Technical Issues From Modularity

Some believe that while modularity may power the computer industry, things are different in industries like the car industry. [10] They argue that there are fundamental reasons, based on natural phenomena, that keep mechanical design from approaching the ideal of computer and electronics design. Daniel Whitney, for one, persuasively makes this case. [4]

Certainly today's cars have designs that are increasingly integrated, making car design much more complex than in the past. Car buyers increasingly look at things like noise, vibration and harshness in judging the quality of cars. Those things can be controlled best in integrated designs.

That argument has some merit. Some products—like jet airplanes—have severe weight, space and energy constraints. With those constraints, parts must be designed to do multiple jobs, often sharing functions. A wing, for example, may serve as a provider of lift, a control surface, and a fuel tank. Interfaces also become highly coupled, with welding and close fits compared to the looser interfaces of modular parts.

Are cars too much like jet airplanes to be designed, built and sold as single-function modules connected by loosely coupled interfaces? Or must cars have functions shared by many subsystems, with a highly integrated architecture to optimize performance?

Based on our experience designing and building our proof-of-concept car, we are optimistic. We believe that unlike gasoline-engine cars, truly electric cars can perform well with a modular architecture. Here too, however, we cannot know now whether that will be the case.

VII. Conclusion

By moving to modularity, we can make truly electric cars and give birth both to new cars and a new carmaking industry. Car technology can change as rapidly as computer technology. A new carmaking industry can turn horizontal, as shown in Fig. 7, and evolve to be as vibrant and profitable as the computer industry. Both trends will be welcome in an industry that has fallen far in recent decades, even as it faces challenges more pressing than ever.

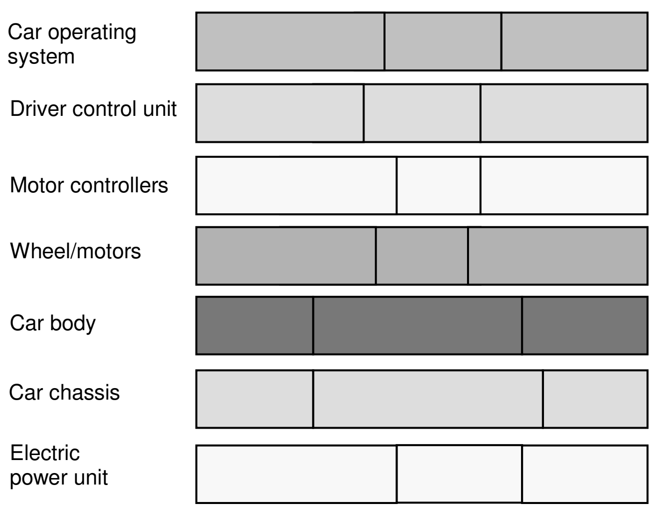

Figure 7. The new horizontal carmaking industry.

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Motor Controllers	Edward Durney
Wheel/Motors	Alan Durney
Car Body	Carolyn Ipson
Car Chassis	Larry Ipson
Electric Power Unit	Carl Durney

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