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Computers on Wheels?

In the early 2000s, a metaphor borrowed from consumer electronics helped electric vehicle enthusiasts, Silicon Valley engineers, and policymakers reinvent the automobile.

In the early 2000s, electric vehicles (EVs) fell victim to what some observers characterized as one of the most heinous and irresponsible acts of industrial vandalism in American history. After leasing several thousand EVs to customers, many of whom grew to love their cars, automakers recalled and destroyed or otherwise disposed of almost all of them. As documented by filmmaker Chris Paine in the 2006 film *Who Killed the Electric Car?*, General Motors' brazen cancellation of its popular EV1, then the world's most advanced automobile, became seared in the popular consciousness. Embittered by what they saw as a corporate conspiracy against common sense and environmental rectitude, EV proponents pushed back. Enthusiasts had long homebrewed their own EVs, and the death of the electric car sparked a fresh round of do-it-yourself activism.

This activism, informed in large part by the information technology (IT) revolution, played a major role in enabling the EV revival that began in the late 2000s and early 2010s. Guided by experience with materials, systems, and modes of organizing innovation from the world of IT, the movement spawned a powerful metaphor: the EV as a computer on wheels. This idea would cast the electric car in the glow of Silicon Valley's unparalleled success, breathing new life into the EV project and sustaining it until public policy intervened to secure its future in the mid-2000s.

While the analogy of the EV as a kind of large mobile device proved a fruitful thought experiment in sorting through the problems of developing new products, it was not easy to translate into industrial engineering practice. Ultimately, though, the consumer electronics industry and public policy accomplished an end run around the automaking establishment to reinvent the EV.

An off-the-shelf car

The origins of the EV revival are often traced to a pair of Silicon Valley engineers who founded Tesla, a company now widely regarded as a peer of tech giants such as Apple, Google, and Amazon. Around 2000, newly wealthy from developing one of the first electronic books, Martin Eberhard and Marc Tarpenning pondered the fate of the EV. Eberhard believed all-battery EV propulsion was the most efficient way to convert energy for automobile use and that automakers had, with the exception of the EV1, deliberately designed most EVs to fail by making them ugly and underpowered—and in the process had misinformed the public about the technology's potential. To change public attitudes, Eberhard and Tarpenning envisioned building and commercializing the electric supercars that mainstream automakers claimed could not be built and commercialized—initially for wealthy customers and then for average motorists once costs had been trimmed.

The pair professed little knowledge of battery or automobile engineering, but a trend in IT industrial management seemed to offer a solution. As Silicon Valley deindustrialized, starting in the early 1970s, developers of consumer electronics began to integrate off-the-shelf components into new products, a management model that emphasized marketing and logistics over research and development. Dell Technologies founder Michael Dell, who did much to commodify the computer, referred to this approach as virtual integration.

Eberhard saw that the auto sector was deindustrializing too, and believed that something like virtual integration could also work in that context. If a commercial EV could not easily be scratch-built, reasoned Eberhard, perhaps one could be assembled from components available on the open market. The technologies that most interested him were the induction motor (desirable because it induced a magnetic field to generate mechanical motion and dispensed with the need for a costly permanent magnet) and the rechargeable lithium-ion cells used to power laptop computers and other handheld devices. Eberhard and Tarpenning calculated that a pack of such cells would have sufficiently high energy density to give an induction motor-equipped EV unprecedented acceleration and range.

These ideas were not entirely new. Politicians had been intrigued by the possibility of applying the methods of the semiconductor and electronics sectors in other industries, including automaking, at least as far back as the Clinton administration, which introduced this concept in policy discourse in the early 1990s. Car companies had been experimenting with induction motors since the 1960s, and in the 1990s Toyota and Matsushita adapted commodity cells for use in the first-generation hybrid electric Prius. The novelty of what Eberhard and Tarpenning envisaged lay in combining these elements with lithium power in an all-battery EV.

Steering away from an anticipated crisis

Positioning the EV as a kind of IT product made sense to tech investors at the time. In the early 2000s, venture capitalists were ready to diversify. In part, this was a consequence of the dot-com bubble bursting in 2000 and 2001, which wiped out $5 trillion in paper wealth. In the ensuing recession, there was further apprehension about the direction of IT.

The efforts of Eberhard, Tarpenning, and others suggested that the next big thing could be transportation, and developments in the IT sector reinforced this thinking. Progress in computing technology and IT more generally is often linked with Moore's Law, the miniaturization trend named for Gordon Moore, the cofounder of Fairchild Semiconductor and Intel, who in 1965 observed a correlation between falling costs and increased transistor density in silicon chips. Moore and many other experts perceived this trend to be in a permanent state of crisis, which they understood in terms of the anticipated physical barriers to scaling. But long before this could happen, manufacturers faced the problem of overproduction. Integrated circuits were first used in military applications and entered civilian markets via cheap and relatively rudimentary devices such as electronic wristwatches and pocket calculators. By the late 1970s, Moore worried that scaling was outstripping the capacity of those markets to absorb commodity microchip production and predicted that the next major applications of chips lay in homes and automobiles.

Eberhard and Tarpenning did not explicitly frame the all-battery EV as a solution to fears about the oversupply of semiconductors. Instead, the pair led the way in suggesting that an important avenue of growth for IT lay in electric automobility. To realize this goal, the entrepreneurs drew on the communitarian energy of Silicon Valley start-up culture, engaging collaborators who contributed capital, expertise, and technology.

Cadging commodity cells

Virtually integrating EV production turned out to be a difficult task, largely because the borders separating programming, consumer electronics, and automaking proved less porous than Eberhard and Tarpenning had assumed. The lithium cells the pair sought to acquire were composed of highly combustible organic electrolytes and metal oxides that required safety controls to prevent them from overheating and triggering a very hot fire that could not easily be extinguished. Such cells had already been involved in fires in mobile devices, and by the early 2000s they were drawing increasing regulatory scrutiny. Very large battery packs of the sort Eberhard and Tarpenning were planning contained vastly more incendiary material than packs for mobile devices, and required even more sophisticated safety controls. The pair started sketching the architecture of such a system around 2001.

From the perspective of electronic and automotive parts suppliers, however, the benefits of participating in this new venture were unclear. Suppliers worried about the legal ramifications if their components were implicated in malfunctions. For that reason, Eberhard maintained, makers of lithium cells had hitherto refused to sell to EV enthusiasts. Auto parts suppliers were also reluctant to do business with Eberhard and Tarpenning because the volume of EVs they initially proposed to produce was far short of commercial scale.

Still another complicating factor was that virtually all cell manufacturing was then based abroad and rooted in a corporate culture largely closed to outsiders. By the turn of the millennium, decades of globalization had concentrated semiconductor and computer design in the United States, semiconductor production in Taiwan and South Korea, and much of the rest of the consumer electronics industry in Japan, whose semiconductor industry increasingly served domestic consumer goods manufacturers producing a wide array of applications and their subsystems, including lithium-ion cells. Eberhard learned that in Japan, sales decisions were made not by dedicated sales staff (as in the United States) but by plant managers, and the only way to engage them was to forge personal relations on the ground.

After many visits to Japan, Eberhard eventually managed to win over electronics company Sanyo with an argument that aligned the business plan he and Tarpenning were developing with the business model of cell manufacturers. In his pitch to a Sanyo factory manager, Eberhard reasoned that just one of the vehicles he was proposing required as many cells as 2,000 notebook computers, meaning that 1,000 such cars would require as many cells as two million notebooks. Intrigued, the manager allowed Eberhard to demonstrate his and Tarpenning's ideas for battery pack management and safety systems.

Integrating the powertrain

The other key component of Eberhard and Tarpenning's electric supercar was the powertrain. In the early 2000s, Eberhard discovered AC Propulsion (ACP), an engineering research company cofounded by Alan Cocconi and Wally Rippel, engineers who had made major contributions to the Impact, a concept car built by AeroVironment and GM in the late 1980s that served as the prototype of the EV1. Impact utilized induction motors and an onboard charger integrated into the powertrain. GM's decision to design the EV1 with an off-board charger caused Cocconi to quit the project and start ACP with the goal of developing integrated EV powertrain technology. The company sold this technology to established automakers who used it for demonstration purposes and in so-called compliance cars that the California Air Resources Board had compelled them to produce through the zero-emission vehicle mandate of 1990, which itself had been inspired by the original Impact concept car. This arrangement sustained ACP's research and development operations and allowed car companies to invest minimal resources in the all-battery EV format they despised

Eberhard and Tarpenning aimed to license ACP technology and integrate it, along with the battery pack they were conceptualizing, into the chassis and frame of a sports car adapted from the Lotus Elise. In July 2003, Eberhard and Tarpenning founded Tesla Motors, named for Nikola Tesla, the inventor of the induction motor. Jeffrey Brian (JB) Straubel, an electronics engineer who had also patronized ACP, was later hired to develop the battery pack. Having assembled the components for an EV prototype, Eberhard and Tarpenning sought the capital to build it. With major investors cautious in the wake of the collapse of the tech bubble, the EV entrepreneurs embraced Elon Musk, a programmer who, like them, had managed to make and keep a fortune in the tech boom and believed that the next big thing was transportation. He also had links to ACP through Straubel, a friend who later became Tesla's chief technology officer. In 2004, Musk committed $6.5 million, becoming chair of Tesla Motors and its single largest shareholder in one stroke. The new partnership was short-lived. By 2007, Musk had assumed sole control.

Public policy and the EV revival

In succeeding years, Musk sank much of his personal fortune into Tesla, keeping it afloat as the company struggled and earning Musk credibility in enthusiast circles. However, public policy played an important and under-recognized role in shaping the financial conditions for the EV revival. While the Bush administration had promoted hydrogen fuel cell electric propulsion at the expense of first-generation all-battery EVs, the success of the hybrid Prius, and variants modified by activists for plug-in capability, caused policymakers to reverse course. Support for large-battery plug-in EV technology came through the Energy Policy Act of 2005 and the Energy Independence Act of 2007.

By 2008, the stage was set for the rebirth of the EV. That year, the Roadster hit the market as Tesla's first semi-commercial offering. It was the first purpose-built, serially-produced, all-battery EV to take to US roads since the EV1, and was followed by Nissan's all-battery electric Leaf in 2010. These cars had the ill fortune of launching during the Great Recession, but both greatly benefitted from the Obama administration's stimulus initiative, a continuation of earlier efforts by the federal government to encourage US EV manufacturing. Clean car technology initiated by a vision of virtually integrated start-up innovation was now the darling of the federal government, which became intent on expanding EV adoption through national industrial-technological dirigisme.

Over the course of the 2000s and 2010s, under three presidential administrations, the federal government spent many billions of taxpayer dollars on advanced power source technoscience, incentives for consumers, networks of chargers, and a domestic cell manufacturing complex, stoking demand for EVs and helping Tesla become (for a time) the world's largest manufacturer of EVs and the most valuable car company by market capitalization.

Automobile as mobile device

How significant were IT analogies in shaping the contemporary electric vehicle? In the years following the demise of the EV1, initiative in US EV development came from actors outside the automaking establishment, for whom IT was the lodestar of advanced industrial innovation. For them, the idea of the EV as a mobile device served as a heuristic that facilitated engagement with new and unfamiliar technologies. It also helped them make common cause with policymakers who had long seen electronics, and semiconductors above all, as vital to US economic competitiveness and national security. In retrospect, it appears that IT metaphors helped marshal resources and keep the EV dream alive in the bleak post-EV1 years.

While the EV renaissance is savored with more than a little schadenfreude by those who nurse a grudge against Detroit, innovation maxims derived from IT may well have obscured the real complications of developing EV technology. For all their points of similarity, EVs and mobile electronic devices are significantly different in terms of scale, complexity, and, importantly, lifecycle. Repurposing commodity cells originally designed for consumer electronics applications was problematic because such cells were designed to last the lifetime of mobile devices—generally a few years at most. Cell chemistries had to be modified for EV applications, and later generations of cells were designed specifically for use in EVs.

Crucially, however, the useful lifetime of electric motors is potentially much longer than that of even the most robust batteries because electric motors do not physically degrade over time in the manner of electrochemical energy storage devices. Indeed, the temporal mismatch between the motor and the battery may have been the main reason the global automaking establishment (not just Detroit) was skeptical about the all-battery EV. Given that the battery is the single most valuable EV component, the temporal mismatch implied that battery-making would become the most lucrative aspect of any commercial-scale EV program. The auto industry perceived this scenario as threatening to its century-old business model, a key factor in the resistance of car companies to the zero-emission vehicle mandate.

Other assumptions about electric vehicles, influenced at least to some degree by IT metaphors, grew out of the fact that the all-battery EV utilizes fewer moving parts than vehicles powered by the internal combustion engine (ICE). It is widely believed that this quality enables such vehicles to convert energy more efficiently than ICE vehicles and hence have lower operating costs—at least if battery replacement is not factored into the equation. But it also gave rise to the fallacy that the all-battery EV is easier to build than ICE vehicles. The reality is that costly and sophisticated technologies are required to fabricate all types of high-performance EVs. One industrial engineer I interviewed held that ensuring quality control of EV cells involved hundreds of thousands of line items of failure mode and effects analysis and entailed manufacturing complexity he believed was greater than for the ICE. Cell defects can compromise the safety of the battery pack and vehicle.

Integrating battery packs into EV powertrains entails another layer of systems complexity. Of course, systems issues are by no means exclusive to EVs. Automakers have increasingly treated all cars, including ICE vehicles, as computers on wheels, stuffing them with ever-larger quantities of computer hardware and software designed to manage everything from energy conversion to entertainment to the act of driving itself. This results in systems dynamics—and occasional failures—that are not always well understood.

Conceptualizing EVs as computers on wheels may also have obscured the impact that a growing EV fleet could have on electrical infrastructure. As EVs proliferate, their collective recharging may create peak loads higher than the grid was designed to supply. Risk analyst Robert N. Charette notes that certain EV-dense municipalities may soon have to make major infrastructure investments as EV recharging ages local power transformers and shortens their service lives. Such problems trace back to public policies that were intended primarily to improve air quality by means of clean car technology and that failed to consider the network effects of utilizing the advanced propulsion automobile as a vehicle of environmental regulation.

The distributed industrial complex informed by the IT worldview that produces the EV and that concentrates research, development, and design in Western (primarily US) enterprises and manufacturing in Asian enterprises has proven surprisingly resistant to reform. An important goal of the American Recovery and Reinvestment Act of 2009 was the development of domestic EV manufacturing, an objective that implied some degree of decoupling from Asian EV supply chains. However, some stimulus money intended to build domestic cell capacity went to manufacturers owned by Asian companies, bolstering them and virtual integration as a business practice. In effect, stimulus accentuated rather than mitigated the geocultural division of labor and capital in the global consumer electronics industry. When establishment automakers grudgingly followed Tesla and Nissan's lead and began producing large-battery plug-in EVs, most chose to outsource cells that they integrated into battery packs of their own design. Some, such as Ford, have begun to outsource even battery packs.

Policy efforts to decouple US industry from dependence on Asian supply chains have continued under the Biden administration, this time targeting China, now the world's largest maker of EV batteries and EVs. This has thrown some planned US-China joint ventures into question, but the degree to which supply chains can be unwound, shortened, and localized remains unclear. Although some Chinese cell and battery enterprises may be prevented from doing business directly in the United States, most American EV cell manufacturing is performed by joint ventures involving US automakers and Japanese and South Korean suppliers with various ties to China of one kind or another. And it seems probable that globalization, and the trend in the global automaking establishment's loss of initiative to policymakers and the IT sector in dictating the technological agenda, will continue into the foreseeable future—if only because offshoring and outsourcing have hitherto enabled US capital to reap the lion's share of profits. For all the systems integration issues that can arise when automobiles are treated literally as computers on wheels, that metaphor and the modes of innovation and manufacturing it reflects and reinforces—above all, virtual integration—well suit the financial and industrial relationships the West and Asia have coproduced over the last 40 years.

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