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Electric Propulsion

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In the beginning of the 20th century, there were three candidate propulsion systems to replace the horse and buggy for personal transportation: steam, electric, and internal combustion engines. There were several reasons why the internal combustion engine won out. One was the invention of the electric starter first put in production in 1912. The driver no longer needed strength to crank the engine. Together with the Bosch ignition, major contributions made to the car business by the electrical engineers were combustion engine and electrical starters. Electric lights followed and then the radio in the 1930—the Motorola. But what really spelled the death of the electric car was the discovery of low-cost petroleum, the ability of oil refiners to crack heavy crude into gasoline, and the development of powerful, efficient engines using custom-made fuels in the 1920s, 1930s, and 1940s. Greatly contributing, of course, was the genius of manufacturers such as Henry Ford, which reduced the cost of making mass-produced automobiles so that many could afford them.

Exhaust Emissions

The car industry grew into mammoth size, dominated by the United States and Europe, and in many ways helped win World War II. It produced thousands of tanks, trucks, and airplanes in World War II and created the famous general purposes vehicle that became the jeep. But clouds were on the horizon, starting with smog in Los Angeles. After a lot of research, it was established that smog was caused by a combination of the atmospheric conditions in Los Angeles and emissions from cars, primarily oxides of nitrogen and unburned hydrocarbons. Laws were established to limit exhaust emissions, but this constitutes a fascinating story for another time.

Smog and pollution reawakened interest in electric vehicles. The problem was the energy stored in a battery. By this time, several batteries had been investigated, from Edison's nickel iron battery to various, more exotic batteries such as nickel cadmium and silver zinc. For automotive use, the only candidate was the conventional lead-acid design used for the starting lighting and ignition (SLI) battery. Even today, lead-acid batteries have an energy storage capability of about 40 Wh/kg, compared with about 12,000 Wh/kg for gasoline. Even if the efficiency of the drive between battery and wheels is four times that of fuel to wheels in an internal combustion engine, the energy storage problem is apparent.

THE NEXT SET OF VEHICLES WERE A TRIO OF ELECTRIC, HYBRID, AND CONVENTIONAL VEHICLES DESIGNED AND BUILT TO MEET THE NEEDS OF URBAN COMMUTERS.

Electric Vehicles

I joined General Motors (GM) Research Labs in 1965, and the first project I worked on was a 1966 Corvair converted to electric drive. In spite of the bad publicity associated with the Corvair, the electric drive conversion was a remarkable exercise in R&D. It had silver-zinc batteries that, although expensive, were the only batteries that could provide performance; an induction motor drive; and a combination voltage modulator and inverter that we called a modulating inverter. The inverter used silicon-controlled rectifiers (thyristors) that had been invented only eight years earlier [1]. Our partner and supplier was Westinghouse, and it was exciting to receive them, test them, and put them in the drive. We did not fully understand the problems of voltage transients and switching losses, and we used to go through a lot of them.

The vehicle had the same performance as its gasoline vehicle, although with limited range. Of course this was an R&D exercise, since the cost of the battery, which was in limited production, was several times the cost of the conventional vehicle. For the next 40 years, battery performance limited the development of electric vehicles. Almost every conceivable combination of elements

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was tried and failed to meet the basic four criteria for success:

- *Energy density*: How far a vehicle could go on one charge?
- *Power density*: What is the top speed and acceleration?
- *Cycle life*: How many years or miles would the battery last?
- *Cost*: Would customers buy it?

Unlike today, the primary interest in those days was pollution, and because most of the electricity production was from high-sulfur coal, there were many discussions on how effective electric cars would be in achieving the design objective. Basically, did people in Los Angeles care if the Four Corners power station in Utah caused acid rain?

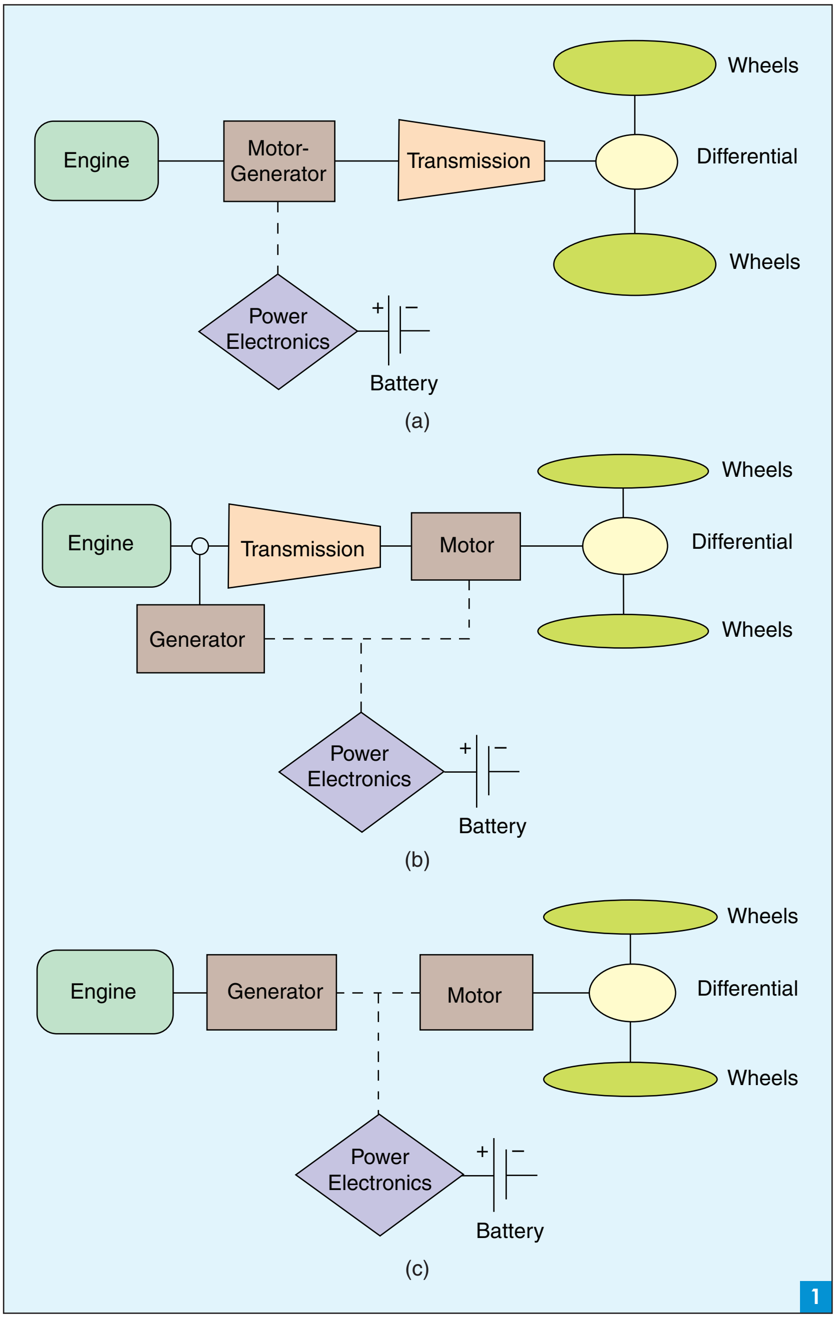
The next vehicle we built was a hybrid that used a Stirling engine driving a generator that charged the batteries and drove a dc motor. The dc motor was a step back in technology compared with the induction motor of the Corvair, but we were trying to reduce cost. The Stirling engine is an external combustion engine that was chosen because of low emissions. I think we said at the time that driving this vehicle in Los Angeles would clean the air by eliminating hydrocarbon emissions produced by conventional cars. Clearly, this vehicle did not make it to production because of cost. Also, our colleagues in engine development were able to meet emission standards as they got tighter and tighter.

> THE STIRLING ENGINE IS AN EXTERNAL COMBUSTION ENGINE THAT WAS CHOSEN BECAUSE OF LOW EMISSIONS.

The next set of vehicles was a trio of electric, hybrid, and conventional vehicles designed and built to meet the needs of urban commuters. These vehicles also demonstrated that the conventional vehicle had the lowest cost and highest performance and could meet emissions requirements, which in the 1970s was the primary driver. In those days, there were price wars, and we could buy gasoline at 25 cents a gallon.

I continued to work on electric propulsion until the mid-1980s when I frankly decided it was not worthwhile, even for a researcher, to develop automotive electric drives until a better battery was available. We felt that once a battery was developed in the lab, we could quickly develop the drive and build it in existing factories before GM could build a plant to make batteries in the required volume. Others in GM thought otherwise and went ahead with the EV1. This was a pure electric vehicle using lead-acid batteries that was offered for sale or lease in California and Arizona in 1996. Its real-world range would be 20–30 mi, and its battery life was doubtful. In 1999, the original lead-acid batteries were replaced with nickel metal hydride (NiMH) batteries that offered a longer range but at much higher cost. Unfortunately, GM had to withdraw it from the market, which created a public relations disaster culminating with the movie by Michael Moore "Who Killed the EV1." In my opinion, the EV1 should never have gone to market.

IN REAL-WORLD DRIVING, THE PERFORMANCE IS LESS SPECTACULAR.



Based on product announcements from the major auto manufacturers, there appear to be three likely candidate schemes for hybrid electric vehicles. (a) Parallel, (b) Split, and (c) Series hybrids.

Throughout the 1980s and 1990s, various individuals and companies experimented with electric and hybrid vehicles. But, the market was experiencing a major shift. GM, Ford, and Chrysler were losing market share. The Europeans were moving ahead, but Toyota, Honda, and Nissan were gaining ground by leaps and bounds.

In 1997, Toyota made a brilliant strategic decision in unveiling the Prius Hybrid. It was a superbly engineered vehicle and gave it a phenomenal fuel economy rating of about 50% higher than the vehicles of similar size and performance. It was very expensive to build, and while I was not privy to actual numbers, my guess is that Toyota lost money on every vehicle they sold. The cost was high because they used NiMH batteries, brushless dc motors with rare-earth magnets, and, of course, the electric drive was in addition to the engine that was not significantly smaller. The strategy was brilliant because it moved Toyota from a maker of stodgy, reliable, and fuel-efficient cars to a technology leader at the time when people were beginning to worry about the cost of petroleum and its long-term availability. Also, with volumes that stayed below 20,000 units per year, the cost penalty was a good investment considering the pages of free publicity that this green vehicle generated. I suspect that even today, the primary business value of this vehicle to Toyota may be in the phenomenal publicity that it brings to the company.

Electric Hybrids

Based on the success of Prius, stimulated by the increase in the price of oil last year, every car manufacturer has announced hybrid vehicles of various types. It will be interesting to see which technology succeeds. If we define electric hybrids as vehicles with an internal combustion engine, a battery, and an electric drive, there are broadly three types:

- *Parallel hybrids* (see Figure 1): An electric motor generator is directly connected to the engine either through a belt in the simplest case or in place of the flywheel. It acts as a generator, charging the batteries when not all the engine power is needed to propel the vehicle, and as a motor to provide boost for acceleration. Thus, it allows the engine to operate more efficiently and permits the recovery back to the battery of some of the energy that would normally be dissipated in the brakes. Examples of these are the Chevy Malibu and the Honda Insight.
- *Split hybrids*: The engine and a generator are connected through a planetary gear set, with the third shaft going to the wheels. The generator output is connected to the battery, and a second electrical machine, connected to the wheels, gets power from the battery through power electronics. Thus, there are two ways to drive the vehicle: an engine directly through the planetary gear and an electrical path through the generator, battery, and motor. This allows the engine to operate at an even higher efficiency, because its load and speed can be somewhat decoupled from the vehicle needs. A problem is that some of the energy has to flow through the electrical branch with losses in the electrical machines and power electronics. Even so, for a given driving schedule, it can be optimized. The Prius shows great improvements for the Environmental Protection Agency (EPA) test schedules. In real-world driving, the performance is less spectacular. GM developed a more complex system to overcome this deficiency for large sport utility vehicles (SUVs).
- *Series hybrids*: In this case, the engine is completely disconnected from the wheels, and, thus, its performance can be completely optimized. The engine drives a generator that charges the battery and provides power to a motor to drive the vehicles. However, this entails double-energy conversion: engine mechanical to electrical to mechanical, to drive the wheels. One version of this is the GM Volt, which has a large battery and a charger that can be connected to 110 V power. This allows the vehicle to operate using the electric drive only, and thus for trips up to 40 mi (determined by the size of the battery) uses no gasoline. According to GM, this will be in production in 2010. It has generated a lot of interest, and manufacturers are coming out with various versions of plug-in hybrids all the way to pure electric cars.

Although steam cars are no longer in the picture, the beginning of the 21st century is similar to the 20th: a battle between electric and internal combustion engines.

Reference

[1] E. L. Owen, "SCR is 50 years old," *IEEE Ind. Applicat. Mag.*, vol. 13, no. 6, pp. 6–10, Dec. 2007.

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