The Re-Electrification of the Automobile: Trends and Motives in Hybrid and Electric Car Designs

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Abstract – **Before about 1920, electric automobiles were common. They vanished quickly after the introduction of mass-produced gasoline vehicles, but are now being revived in the form of hybrid vehicles. Hybrid designs of various types lead to dramatic improvements in efficiency and exhaust emissions. The paper reviews some alternative hybrid system designs, and discusses the rapid increase in electricity and electronics applications in today's automobiles. The engineering needs provide significant worldwide product opportunities.**

I. Introduction

Electric automobiles led the development of other automobiles, appearing in serious form in the 1880s and peaking in production after 1910 [1]. At the time, low speeds and limited range were not a severe concern: only urban areas had adequate roads, and intercity travel required train or coach transportation. The vehicles were clean, easy to use, and required much less maintenance than the gasoline and steam vehicles of the day. They were able to take advantage of a growing urban electrical infrastructure, and in many ways were the ideal match for city transportation needs.

Early electric cars reached the pinnacle of their development in the mid-1910s. Fig. 1 shows a 1914

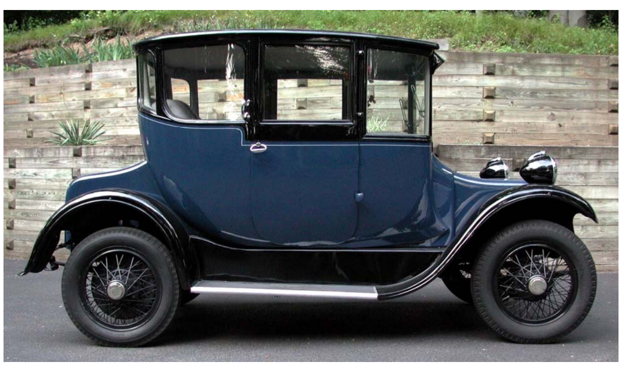

Fig.1. Detroit Electric automobile, 1914 model [2].

Detroit Electric, still in operation today. Although the disappearance of these designs is often linked with the invention of the electric starter in 1912, several authorities [3] argue that the low cost of gasoline at the time and the rapid acceptance of the mass-produced Ford Model T are more likely causes.

Hybrid electric vehicles also appeared very early. Ferdinand Porsche's early design [4], shown in Fig. 2,

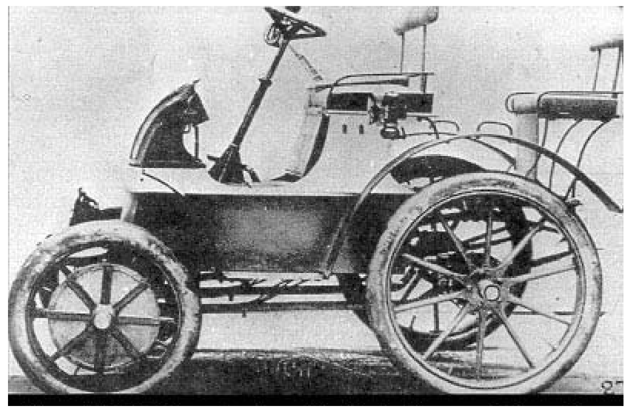

Fig. 2. The Lohner-Porsche hybrid vehicle (from www.hybrid-vehicle.org).

was featured at the 1900 World Exhibition in Paris. It used an internal combustion engine to power a generator, and had electric motors in the wheels for motive power. Other hybrid vehicles were developed before 1910. All had the advantages that they did not require gear shifting, since the engine operated a generator. Dc motor control had been established, and control of electric motors was feasible at the time. As in the case of all-electric vehicles, hybrid designs became less popular as the technology of fuel-driven engines and automotive systems improved.

It is well known that hybrid vehicle technology held its ground in many applications, and remains a significant industrial transportation system today. The diesel-electric locomotive appeared in the 1920s. It is a classic hybrid electric vehicle that uses a large diesel engine to drive an electric generator. Power from the generator is controlled and delivered to electric motors that provide motive force. Most ships, submarines, and large off-road trucks (such as mining haulers) use the same architecture. Diesel-electric hybrids exhibit the key advantages of a hybrid configuration:

- On-board energy is stored in the form of liquid fuel, with energy per unit mass far greater than batteries, flywheels, or other storage approaches.

- Mechanical energy is converted directly to electric form with no requirements for adjustable gearboxes, drive shafts, linkages, or other large mechanical connections.
- The engine is well-matched to its generator load, and can operate near its most efficient conditions.
- Energy in electrical form is readily controlled, even at levels of several megawatts.
- Conversion in electric machines is efficient, and such machines have excellent power-to-weight ratio.

Thus, while electric vehicles all but disappeared by 1920, diesel-electric hybrids have been the transportation system of choice at levels of about 500 kW and higher since that time.

II. Reappearance

Electric and hybrid vehicles began to reappear in the 1960s and 1970s based on two trends. First, silicon power electronic devices simplified electrical energy control. Second, increasing gasoline prices and supply volatility drove a new round of innovation. Silicon power electronic device improvements are the most important story today. Sophisticated electric motor controls at levels up to 200 kW are available commercially. At the opposite extreme, power electronics can now control small motors and lamps for all ranges of automotive applications.

The pinnacle of electric vehicle redevelopment has been the General Motors EV1, a two-seat electric sports car with exceptional performance. A view is provided in Fig. 3. Although this vehicle generated wide interest

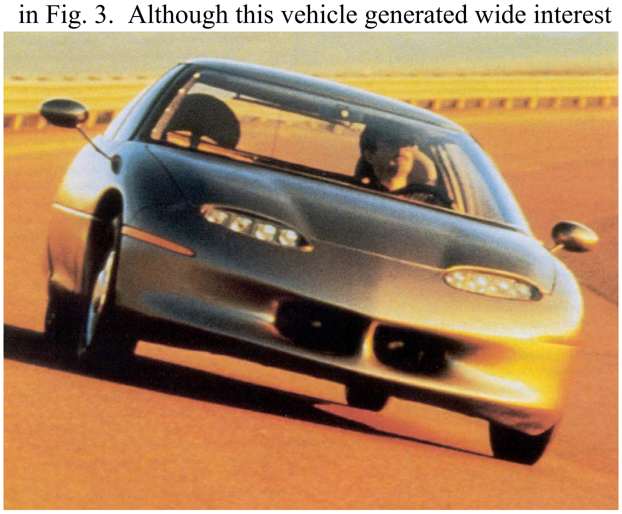

Fig. 3. General Motors EV1 vehicle (from www.gmev.com).

and consumer demand, it was never seriously marketed by General Motors. The vehicles were recalled when difficulties appeared with the battery chargers, and apparently nearly all have since been destroyed by the manufacturer.

The EV1 showed the promise of modern electric vehicle designs:

- A small induction motor was able to deliver 102 kW in a tight traction package, and set a new standard for traction power-to-weight ratio.
- High-performance motor control supported smooth operation and high torque. A modified EV1 set the land speed record for electric vehicles.
- A paddle-style contactless charging system showed new ways to manage electrical safety.
- Energy recovery during braking was smooth and efficient.
- Consumers who tested the car were invariably impressed by the performance, quietness, and smooth operation.

The drawback was the heavy battery pack. Even with almost 600 kg of batteries, the typical range was less than 150 km. Although this range is adequate for many commuters, it was thought to be too low for mass markets.

More recently, improvements in lithium-ion batteries are encouraging further consideration of all-electric cars [5]. Even the best batteries, however, are unlikely to store more than 300 W-hr/kg. Gasoline stores about twenty times as much energy per unit mass, so the best batteries yield far lower range than conventional cars. In principle, lithium batteries support most commuting needs. If rapid recharge becomes feasible, long trips might be within reach of the technology.

Fuel cell vehicles are sometimes discussed as a long-term electric vehicle technology that overcomes the limitations of batteries. The emergence of fuel cell vehicles has been delayed by high cost, limited capability of materials, and the lack of a hydrogen infrastructure. In the automotive size range, fuel cells are unlikely to be more than about 50% efficient in converting from fuel to electrical output [6]. Since a high-quality diesel engine with electric generator load can exceed 40% efficiency on the same measurement basis, fuel cells at best offer a modest improvement over conventional technologies. The high development cost and need for a hydrogen infrastructure are substantial barriers to broad adoption of fuel cell cars. A thorough examination of diesel-electric hybrids suggests that the conventional engine-generator arrangement looks interesting compared to possible fuel cell systems.

The main advantage of hybrid vehicle arrangements, including the long-established diesel-electric system, is the flexibility of electrical control. Expanded availability and functionality of power electronics across all power ranges has opened new opportunities in this arena. As a result, electrical demands in automobiles have been increasing [7]. Increasing numbers of car models include electric windows, seat controls, heated windshields, and other general electrical features. New automotive designs are likely to use major electrical subsystems such as electric power steering [8], air conditioning, and water pumps. Active suspensions, in development for about twenty years [9], are heavy users of electric power.

On the border between conventional cars and hybrid cars is the use of an integrated starter-alternator (ISA) [10], such as the device in Fig. 4. An ISA-based

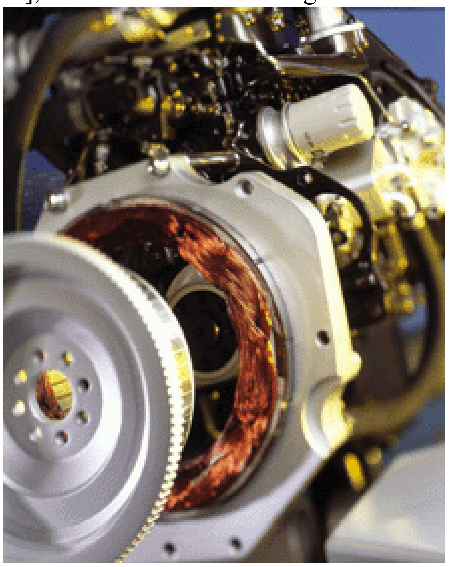

Fig. 4. Partially assembled ISA (*Mechanical Engineering Magazine* online, April 2002).

architecture makes it relatively convenient to start and stop an engine on demand. This technique avoids fuel consumption during stops and idling, and appears likely to become a widely-used approach in the next few years. ISA methods have increased in sophistication. Some proposed designs use the fast torque response of the electric machine to cancel a portion of the torque ripple in the combustion engine [11].

If the ISA is large enough to permit energy recovery during braking, the combined system becomes a *mild hybrid* [12]. The Honda Insight, the first modern hybrid car on the North American market, has been termed a mild hybrid by many experts. The car, shown in Fig. 5, uses an ISA architecture to maximize

Fig. 5. Honda Insight mild hybrid (from www.familycar.com).

fuel economy from its engine. It has a lightweight two-seat chassis.

The ISA-based mild hybrid architecture is one example of a *parallel* hybrid vehicle system. In a parallel arrangement, the multiple energy forms are brought together in mechanical form. In a typical system, this means an engine and electric machine both interact with a transmission or drive shaft. Perhaps the simplest form, a "through the road hybrid," has a conventional internal combustion drive train on one axle and an electric drive train on a separate axle. A much more sophisticated parallel system can be found in the Toyota Prius (Fig. 6) and the more recent Ford

Fig. 6. Toyota Prius (first North American version).

Escape hybrids [13]. In this system, the engine and main electric machine are connected through a sun-planet gear set. This arrangement provides a degree of independence between the two energy sources.

The diesel-electric drive train is an example of a *series* hybrid vehicle architecture. In a system of this type, the multiple energy resource are brought together in electrical form. This has the advantage of decoupling the engine from vehicle performance, since the engine drives a generator rather than an axle. The Toyota and Ford drive trains achieve a degree of operation in this regard by providing a second electric machine to serve as a generator. Series designs offer energy source flexibility. Fuel cell vehicles, for example, are series hybrids. Turbine-generator series hybrids have also been constructed.

Comparisons between parallel and series hybrids involve subtle details. For example, if a combustion engine requires a fixed speed and load power for highest efficiency – as is usually the case for very large diesel engines or for turbines – a series architecture is probably the right choice. The engine operates a generator alone, and the operating condition can be set by control rather than by vehicle functions. If the combustion engine provides substantial dynamic variability, such as provided by variable valve timing and other advanced features, then a parallel or ISA architecture is likely to be suitable.

Hybrid designs also require design tradeoffs unfamiliar to experienced automotive engineers. For example, the Toyota Prius is designed to greatly enhance its emissions performance. Vehicle operation in the first few minutes emphasizes engine warm-up and management of the catalytic converter. The engine is permitted to start and stop frequently once it is warm. This avoids any extra emissions when engine power is not needed. The engine itself follows the Atkinson cycle, slightly more efficient than the conventional Otto power cycle. This method is hard to use in conventional cars because it sacrifices torque performance. The present model Toyota Prius meets both the aggressive "super ultra low emission vehicle" (SULEV) target and more recently established "partial zero emission vehicle" (PZEV) levels. These represent about a 90% exhaust emissions reduction compared to conventional vehicles.

The Honda Insight, in contrast to the Toyota, is designed for high fuel economy. Its ISA arrangement assists an efficient small engine. Brief power peaks are picked up by the electric motor. Braking energy is recovered to the battery pack. The combined result is the most efficient present production car.

III. Other Electrical Considerations

The growth of electrical aspects in cars is rapidly reaching a limiting condition. The conventional 12 V system supports no more than about 2 kW with reasonable efficiency and component size [14]. The move toward a high voltage system, nominally 42 V, is progressing [15,16]. This voltage can support up to 10 kW of electrical resources. While 10 kW is not sufficient for full hybrid operation, it supports an ISA function. Vehicles with 42 V ISA architectures are in development by Toyota and others.

A 42 V system is of interest because it can improve working levels and functionality across a whole range of electrical devices. Electromechanical actuators for engine valves, for example, have been demonstrated for 42 V power. A complete set of electromechanical actuators would lead to a "camless" engine and support a complete re-engineering of combustion engines. This suggests long-term possibilities that would substantially enhance vehicles fuel economy.

IV. Conclusion

Electric vehicles were common a century ago, and hybrid designs also entered the market in the early 1900s. Although electric vehicles all but disappeared after the explosive growth of the Ford Model T, hybrids have continued on in the form of large diesel-electric drive trains. Today, innovations in power electronics have extended the benefits of hybrid cars to the full range of vehicle sizes. The result is a renaissance of electric and hybrid cars. In addition, power electronics is expanding the possibilities for more general electricity use in automobiles. Applications such as electric power steering, integrated starter-alternators, and active suspensions require more and more power. The emerging 42 V architecture supports power levels up to about 10 kW, enough for these new functions although not enough for full hybrid architectures.

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