ABSTRACT

In the last few years, almost every automotive OEM has announced the development of some sort of electric vehicles. Many of those have already been shown to the public, either as concept vehicles, or as pre-production demonstration vehicles. In order to support the development of this technology, FEV has, over the last 18 months, developed more than 20 different electric, or range-extended electric vehicles. All those vehicles are driving successfully on the road today, either as demonstration or fleet vehicles. The development of those vehicles was only possible through partnerships, and very close cooperation with key suppliers. In contrast to conventional powertrain technology, key components (e.g. battery, traction motor, electric HVAC, inverters) are not yet off-the-shelf technology and need further development and adaptation to the new vehicle concepts. Therefore, the integration of all partners has proven to be key to the rapid development of electric and hybrid vehicle technology.

An overview of some of the vehicles which have been developed at FEV is provided. In most cases, those key partners were already involved in the early concept definition phase. They were continuously involved as the projects evolved, in some cases even co-located into the FEV project center, to ensure best possible communication and resolution of issues.

INTRODUCTION

The electrification of the vehicle drivetrain is rapidly moving forward. Supported - and in some cases triggered - by government incentives, every vehicle manufacturer around the globe has started to develop hybrid and electric vehicles. However, despite all the publicity associated with electric vehicles, all forecasts show only a relatively small market penetration within the next decade. By 2015, the market share for electric vehicles - even with very optimistic views - will most likely be not larger than 1%. By 2020, this share could climb to 3%.

Nevertheless, despite the relatively small short- and medium term market opportunities, significant development effort is presently spent on this technology.

TECHNOLOGY

In general, the electrification of the powertrain is increasing rapidly. The introduction of micro, mild, and full hybrid vehicle - with or without plug-in capabilities -, plus the development of full electric vehicles makes it increasingly difficult for the consumer to understand the terminology “hybrid”, and to differentiate between the various technologies. For the purposes of this paper, we are focusing
only on electric vehicles, and range-extended electric vehicles (ReEV).

Whether it is an electric vehicle, or a range-extended electric vehicle, in either case the vehicle is propelled only by an electric motor. The additional combustion engine in the case of the range-extended electric vehicle is only used to generator electric energy via an attached generator (“series hybrid”). This arrangement is different to the conventional drivetrain installation, which has a direct mechanical connection between the combustion engine and the wheels (“parallel hybrid”). Therefore, with the conventional drivetrain, the operating condition of the engine is determined by the road load demand of the vehicle. In contrast, the engine operating condition of a series hybrid can be flexibly chosen, as the engine only drives the generator. Depending on the selected operating strategy, this electric energy is either used for recharging the battery, or is used to directly provide power to the electric traction motor (see Figure 2).

During the SAE World Congress 2009, the Hummer H3 Range-Extended Electric Vehicle (Figure 3) was shown for the first time. The vehicle was developed in cooperation with Raser Technologies, Inc. It features a 41 kWh Electrovaya battery, distributed into 3 modules. Vehicle testing results revealed a more than 40 miles all-electric range for this vehicle. If the down-sized combustion engine is used as a range-extender, the total range is extended to ~300 miles.

![Figure 3. Hummer H3 Range-Extended Electric Vehicle](image)

The other end of the spectrum in respect to vehicle size is the Fiat 500 city car (Figure 4), which was also developed as a range-extended electric vehicle. The vehicle features a 12 kWh battery, and gives the vehicle a 60 miles all-electric range. Due to the packaging restrictions of this very small car, the integration of the range-extender module created particular challenges. In addition, experience has shown that the NVH characteristics of the range-extender module is one of the most critical aspects of a ReEV. Therefore, it was decided to use a small 20 kW rotary Wankel engine as a range-extender engine. As this engine is only driving a directly attached generator, the corresponding flexibility allowed the installation under the rear seat (Figure 5).

![Figure 4. Fiat 500 Range-Extended Electric Vehicle](image)

**VEHICLE EXAMPLES**

Over the last 18 months, FEV has developed more than 20 electric vehicles and range-extended electric vehicles for various customers and applications. All of those vehicles are driving today successfully on the road, either as demonstration or fleet vehicles. Examples of those vehicles are the following pictures.
The Dodge Caliber was converted into a range-extended electric vehicle, with a target of 40 miles all-electric range (Figure 6). Key specifications are the 21 kWh battery, and a 125 kW traction motor. This vehicle was developed to showcase potential modularity of the electric drive concepts. It can either be used as pure electric vehicle, or, with the addition of a range-extender module, as a range-extended electric vehicle.

- Electric Vehicle with 125 kW motor
- 21 kWh Li-Ion battery
- All-Electric Range ~ 40 miles
- With 75 kW Range-Extender: total range of ~300 miles

The Renault Laguna was developed for Better Place, a California-based company which is developing swappable battery technology, as well as the charging infrastructure for electric vehicles. FEV was tasked by Better Place to develop a fleet of electric vehicles for use in Better Place's visitor center in Israel (Figure 7). Besides the conversion of the vehicles to all-electric vehicles, one of the key tasks of this program was the achievement of the European Single Vehicle Approval through TÜV Rheinland, which certifies that these vehicles are roadworthy and safe to be driven on public roads in Europe.

**UNIQUE TEST FACILITIES**

The development of new powertrain and drivetrain technologies for electric vehicles requires in many cases completely different test facilities compared to conventional powertrains. OEMs, suppliers, and engineering companies have to adapt their test facilities to the new requirements. As an example, instead of test cells for fired engine operation - with fuel supply, exhaust stack, emission measurement equipment, etc. -, now electric motor test rigs are used, with battery emulation systems to simulate the battery, and typically much higher dyno speed capabilities (Figure 8).

Other examples of new requirements for test facilities are adaptations of existing test facilities for use with electric powertrains. In most cases, this at least leads to the addition of battery emulation systems, for example in the anechoic NVH test cell, or the vehicle chassis dyno, to make them suitable for hybrid and electric vehicles.
**NVH DEVELOPMENT**

Even though an electric vehicle is considered to be very quiet, it still requires significant NVH development effort. In vehicles with conventional powertrains, the engine noise is the primary noise and excitation source, and can mask a lot of other noise sources. Examples are low-level ticking or pump noises, which only become audible in very few cases if these noises become excessive, and exceed the threshold noise limit of the engine masking noise. However, with electric vehicles, this masking noise is missing, making any - even low-level - noise immediately apparent to the driver. Consequently, noise sources now need to be addressed which rarely have been a concern before.

![Vehicle Interior Noise - Comparison of Conventional Powertrains to Electric Powertrains](image1)

*Figure 9. Vehicle Interior Noise - Comparison of Conventional Powertrains to Electric Powertrains*

Figure 9 quantifies this noise issue of electric vehicles. Compared are the typical FEV Scatterbands for vehicle interior noise for both, vehicles with conventional powertrains and electric vehicles (actual measurements performed at FEV). At low and medium vehicle speeds, the electric vehicle is about 10 dB A quieter, i.e. about ¼ of the noise. At higher speeds, the share of wind and tire noise (which are independent of the powertrain concept) are increasing, causing the difference to be reduced.

This noise issue becomes even more apparent for a range-extended electric vehicle, which can operate as electric vehicle, as well as with an operating engine. When the vehicle transitions from electric drive to engine operation, the driver can experience a sudden ~10 dB A noise increase, without any obvious input from the driver. Therefore, one of the major challenges of an ReEV application is to make this transition as smooth as possible. And, preferably, make the engine noise so low that the driver does not even recognize that it is running. Due to the fact that the engine has no direct connection to the wheels, the engine operating conditions can be flexibly chosen, with a compromise of parameters like fuel economy, vehicle performance, battery state-of-charge (SOC) and NVH.

**ENERGY MANAGEMENT**

Due to the fact that electric vehicles have limited energy storage capability in the batteries, the highest priority is to use as much as possible of this electric energy for driving, in order to get the highest possible range. However, as every vehicle has additional energy consumers (controllers, pumps, power steering, heater, air conditioning), the optimization of energy management becomes a top priority task with an electric vehicle development. Collaboration between component suppliers and OEMs are becoming even more important than in the past to find the optimum balance. Therefore, also new technologies like solar roofs to generate additional electric energy, or low-consumption LED lights are finding their way into vehicles.

![Energy Consumption of Electric Vehicle During Drive Cycle, w/ and w/o Heater](image2)

*Figure 10. Energy Consumption of Electric Vehicle During Drive Cycle, w/ and w/o Heater*

In order to quantify the effect, Figure 10 documents the impact of the accessory electric power demand on the available battery energy. In this case a vehicle was driven in pure electric mode during an FEV-developed user cycle (duration about 1 hour). With the addition of the heater and other electrical consumers (i.e. controllers, coolant pumps, power steering) about 17% of the electric energy in this drive cycle was used for “non-propulsion” energy, reducing the available range of the vehicle accordingly. An additional heating-up of the vehicle due to the ambient temperature would have further increased the “non-propulsion” energy.
Figure 11 shows a corresponding representation of the results of the energy consumption. About 6% of the battery energy is required for the essential accessories, which includes coolant pumps, controllers, power steering, etc. The addition of the heater increases this “non-propulsion” energy share to 17%, i.e. about 11% are used to keep the vehicle interior warm. This share is even higher with lower ambient temperatures.

**SUMMARY/CONCLUSIONS**

The introduction of electric vehicles to the market is moving ahead, but it is not without challenges. Every time a new technology is introduced, the question of market acceptance and reliability needs to be evaluated. However, in the case of electric vehicles, it is not only the vehicle technology, but also the corresponding infrastructure needs to be in place at the same time, and be fully functional. Similar to a set of gears, if one gear fails, the whole system will not work (Figure 12). Therefore, the aspect of collaboration between all parties is essential to a successful market entry of the electric vehicle.

**REFERENCES**


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