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Experience feedback on electric vehicles of the French car fleet – battery impact

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Abstract

Nearly 10.000 electric vehicles have emerged from the French car fleet during these 15 last years. The presentation details the accumulated experience on these vehicles, to highlight the technical points that limited the performances and to analyze the technological accessible progress. The reliability weakness of the batteries, and of course its cost effect, is the main problem that has been met with this kind of vehicles. The initial expensive price of batteries, combined with poor cycles endurance, induce a kilometric cost two to three times higher than the one of traditional gasoline vehicles. Some problems on the electronics and on the traction motor were also noticed. In CEA-LITEN the native Ni-Cd batteries of a Citroën AX was replaced with high security Lithium Iron Phosphate batteries.

Introduction

In CEA-LITEN, the LPAC laboratory has two activities. Firstly, it develops fuel cell systems for automotive applications, off-road ones and stationary gensets. The second activity of the laboratory concerns electric vehicles, with monitoring actions of existing electric or hybrid vehicles and development of battery stacks or power electronics for electric vehicles [1].

In France, the 10.000 electric vehicles were produced. Their conception results from prototypes born fifteen to twenty years ago. Now, electric car production from all French manufacturers has stopped, and only a few thousands of them remain in circulation. Many electric cars have been destroyed and others could be found outside France, especially in Scandinavians countries.

The aim of this paper is to detail the accumulated experience feedback on these vehicles, to highlight the technical points that limited the performances of these vehicles and to analyze the technological changes that make it possible to minimize these limitations.

1. Main vehicles and their characteristics

The two most famous French manufacturers have produced several series of electric vehicles since 1990: Express, Clio, Kangoo, AX, Saxo, Berlingo, 106, Partner.

These vehicles are all based on Ni-Cd batteries technology coming from the same supplier (SAFT). Some are air-cooled, others are water-cooled.

The motors are all D.C. current type with separated excitement, except for the Kangoo, which is driven by a wound rotor synchronous motor (separate excitation).

Vehicles	Mass (kg)	Power (kW) Nominal/ Maximum	Battery Voltage (V)
AX	950	11/20	120
Saxo / 106	1 090	11/20	120
Clio	1 220	16/21	114
Express	1 230	16/21	108
Partner / Berlingo	1 470	15/28	162
Kangoo	1450	15/30	132

Vehicles	Energy (kWh)	Autonomy (km)	Mass of battery (kg)
AX	12	100	260
Saxo / 106	12	80	260
Clio	11,4	70	250
Express	14,7	80	310
Partner / Berlingo	16,2	85	360
Kangoo	13,2	75	280

Saxo and 106, on one hand, and Berlingo and Partner, on the other hand, are very similar and present only few esthetic details.

2. POWER TRAIN

2.1. Batteries

Batteries are common to PSA and Renault vehicles: open Ni-Cd technology requiring of the regular water handing-over (ideally all 3.000 to 4.000 km rather than 6.000 to 8.000 km such from the calculator of the vehicle).

The express uses 18 modules 6 V/140 Ah cooled by air.

Kangoo embarks 22 modules 6 V/100 Ah cooled by air. This air cooling appears insufficient and badly distributed, taking into account the level of the thermal losses.

Clio is supplied with 19 modules 6 V/100 Ah, cooled by water with antifreeze agent.

The Saxo/106 uses 20 modules 6 V/100 Ah, cooled by water with glycol.

On Berlingo and Partner, the 27 batteries are cooled with water with glycol.

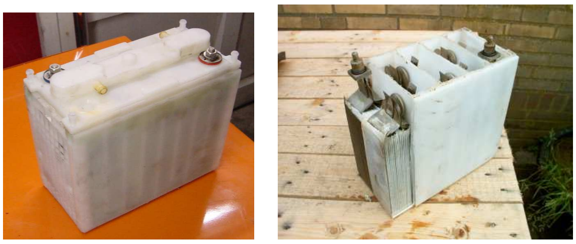

Fig. 1. Ni-Cd battery module

2.2. Electrical traction motors

PSA vehicles use motors of the same technology (D.C. current with separated excitation, reducing and differential by integrated epicyclical gear).

The motors of the Express and Clio are also with D.C. current and separate excitation but the differential reducer is not integrated.

Contrary to the other vehicles presented, Kangoo is driven by a three-phase wound rotor synchronous motor.

The motor with D.C. current with brushes is simple to control: the armature requires a simple reversible DC/DC converter.

An inverter drives the Kangoo synchronous motors.

For these two types of motors, a DC/DC converter regulates the excitement.

Characteristics of the motors:

Vehicles / motors	Type	Power (kW) Nominal/ Maximum	Torque (Nm)
AX / Saxo / 106	DC	11/20	127
Partner / Berlingo	DC	15/28	180
Clio / Express	DC	16/21	125
Kangoo	AC	15/30	165

Vehicles / motors	Voltage (V)	Current (A) Nominal / Maximum	Speed (rpm)
AX / Saxo / 106	120	110/200	6 700
Partner / Berlingo	162	110/200	6 700
Clio / Express	114	150/190	-
Kangoo	132	110/220	9 500

2.3. Electronic control units for PSA vehicles

All electronics devices of the vehicle are gathered in an aluminium box cooled by water (cold plate on the lower face).

<u>Characteristics of the 12 V converter:</u>

- Input voltage 120 V or 162 V.
- Output voltage 14.1 V.
- Output current: 70 A maximum.

The load of the battery 12 V occurs in the following cases: ignition key in position APC or battery of traction in load or voltage of battery < 11 V.

Technology: Mosfets transistors; galvanic insulation.

<u>Characteristics of the traction battery charger:</u>

- Input voltage: mains 230 V 50 Hz
- Maximum input current: 10, 13 or 14 A RMS configurable with the diagnostic tools (“Elit” at Citroen).
- Correction of the power-factor.
- Output current controlled: 0, 5, 10 or 15 A approximately according to the programmed loads.

The technology is traditional for a PFC charger of this power: an elevator “boost” including the function of correction of the power-factor (PFC), followed by a DC/DC conversion with galvanic insulation realized with an “H bridge”. The semiconductors selected are Mosfets (figure 2).

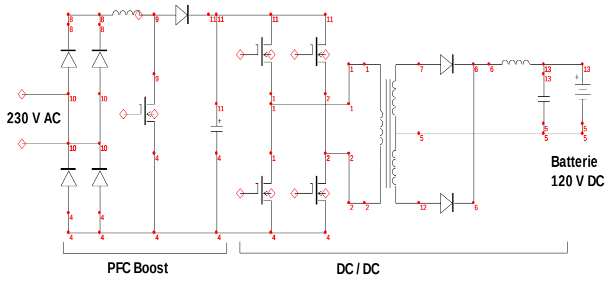

Fig. 2. synoptic diagram of the battery charger of traction

The computer generates a PWM signal to control the charge of the battery according to the programmed loads.

Characteristics of the motor converter:

The driving information of the vehicle is exchanged between the calculator and the electronic card of the converter. Measurements and the control of the main currents and of the excitement are done on this card.

A medium power converter drives the excitement of the motor. This converter with two 20 A rated relays allows choosing the rotational speed of the motor and its direction.

A high power converter controls the current in the rotor of the motor for the acceleration and braking phases.

The control strategy of the currents in the rotor and the inductor depends on the rotational speed of the motor:

- In acceleration phase from 0 to 1 600 rpm, the excitement current is fixed at 11 A. The armature current is cut out so that its mean value can vary between 0 and 200 A according to the position of the accelerator.

- In phase of acceleration from 1 600 to 5 500 rpm, the full voltage of the battery is applied to the armature while the excitement current is cut out so that its mean value varies from 11 to 1.2 A according to desired speed.

Deceleration is managed in the following way:

- From 5 500 rpm to 1 600 rpm the excitement current grows from 1.2 to 11 A and the battery is charged by currents varying respectively from 165 A at 5 500 rpm to 75 A at 1 600 rpm (accelerator pedal completely slackened).

- From 1.600 rpm to 0 the braking converter raises the voltage in order to keep on recharging the battery with 75 A at 1 600 rpm towards 0 at null speed.

- The action on the brake functions differently: the battery is charged at 75 A from 1 600 rpm down to 300 rpm.

Technology of the converter:

The switching function for the current of traction and braking is entrusted to an IGBT module (Insulated Gate Bipolar Transistor) Toshiba 400 A/600 V. This component integrates two IGBT (arm of bridge), each one with a diode in anti parallel, noted T, F, DF and DT on figure 6. One of the components provides the function of buck converter (acceleration at low speed), the other makes it possible to carry out the boost converter function (deceleration at low speed). The switching function of the excitement current is done by an IBGT of smaller power (case TO 220).

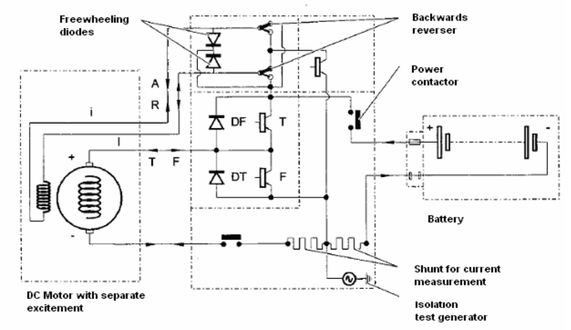

Fig. 3. : synoptic diagram of the converter

A contactor opening on two poles ensures galvanic insulation between the battery of traction and the electronics of motor control (figure 3).

3. Reliability problems

3.1. Power electronics problems

Generally, the thermal aspects of power electronics were not sufficiently taken into account in the design of these power electronics.

For example on PSA vehicles, the weak point is the thermal management of the battery charger which suffers particularly.

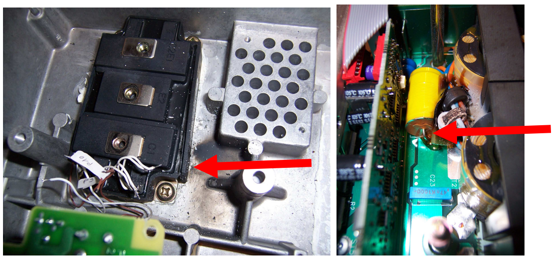

Fig. 4. IGBT and polypropylene capacitor having overheated

3.2. Electric motor problems

Information collected tends to show that there could have had manufacturing problems concerning the commutator of the traction motor. By warming up, the commutator would become deformed, causing sparks between the brushes and the commutator segments, involving the fast degradation of this one and a premature wear of the brushes. Thanks to the monitoring of electric vehicles, we also note that the motor works regularly beyond its range of nominal output power while the car is going up a slope.

The armature of the engine is cooled by air flow. However, ventilation does not include any filter. That causes pollution of the commutator and brushes. Some defects of insulation may occur because of the graphite dust generated by the wear of the brushes and transported by the air flow of the cooling.

3.3. Batteries of traction problems

The batteries of traction used (open Ni-Cd technology) encounter various problems with a lot of different root causes. The comprehension of the causes of failure is difficult and dubious.

The experiment shows that some profiles of use make recurring breakdowns:

- The systematic recharge of the battery as soon as the vehicle is being parked, without taking into account energy gauge or the long periods of non-utilization, battery plugged for loading, causes the “metallization of the plates” followed by an internal short-circuit (figure 5).

- The high depth discharges of the batteries contributes to keeping a good range of the vehicle, but can lead to the destruction of the weakest elements. The monitored voltage of the whole battery (with a lighting indicator in the instrument panel when the recharge is necessary) does not make it possible to detect a block of 6 V which would be weak. Therefore its voltage may be reversed.

- The calculator (according to the number of overloaded energy) orders the frequency of water filling of the batteries. An open Ni-Cd Battery supports the overload quite well, but this causes the electrolysis of the water contained in the electrolyte. The requests for maintenance of the batteries (put out of water) by the calculator are too much spaced, and overheating of the emerged plates can then occur.

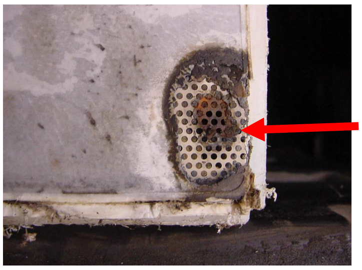

Fig. 5. : Degradation of the separators, follow-up of fusion.

The filling of water every 3 000 to 4 000 km rather than 6 000 km is desirable.

Some well used batteries of 2001 (regularly charged and discharged, used in rather fresh temperatures, frequent filling of water) allow, now, Berlingo to travel more than 200 000 kms.

4. Operating costs

4.1. Operating costs of the Electric Citroen Saxo

Energy cost

Taking into account the following input data:

- Energy consumption: 21 kWh/100 km
- Distance: 15 000 km/year (200x75km)
- Electricity price in France,
  - "off-peak hours": 0.062€/kWh
  - "full hours": 0.103€/kWh
- 4 water filling a year: 250 €

leads to an energy operating cost of:

- 0.0297 €/km "off-peak hours" charges
- 0.0383 €/km "full hours" charges.

Saxo maintenance cost

Despite some common ideas, the maintenance of the electric Saxo is not cheaper than the maintenance of a similar gasoline vehicle, but this is due to some unsuitable technology choices:

- cooling pump has to be changed every 20 000 km
- motor brushes have to be changed every 50 000 km

The maintenance cost then reaches 1 400€/100 000km or 0.014€/km.

Battery lifetime cost without leasing agreement

An electric Saxo includes 20 Ni-Cd 6 V/100 Ah modules. The battery price reaches 7 000 € and the battery is specified for 120 000 km (1 500 cycles of 80 km).

But, battery lifetime is in fact highly linked to how it is used and charged.

A lot of batteries haven't even run more than 30 000 kms, whereas some others have run up to 200 000 kms.

The overall costs of use are obviously radically different between these two extreme cases.

Assuming:

- 7 000€ battery price
- **500 cycles** of 70km (**35 000km**) lifetime due to the misused of the battery (long storage period battery at full charge, high operating temperature).

leads to a lifetime cost of 0.2€/km and a lifetime of 28 months.

The corresponding cost is: **1.4 €/kWh.**

Assuming:

- 7 000€ battery price
- **1 500 cycles** of 70km (**105 000km**) lifetime thanks to optimal operating conditions (water filling frequency twice than the manufacturer specification, low temperature of use, normal use without too deep discharge, no storage at full charge).

leads to a lifetime cost of 0.067 €/km and a lifetime of 7 years.
The corresponding cost is: **0.47 €/kWh.**

Battery lifetime cost with leasing agreement

The PSA maintenance leasing agreement of the batteries cost 1 980 €/year (including 4 water filling a year)

Assuming 15 000 km/year and excluding the water filling annual cost lead to a battery lifetime cost of 0.115 €/km.

Total costs:

The total cost can be estimated with or without the PSA leasing agreement cost.

With the PSA leasing agreement the total cost is comprised between 0.159€/km and 0.168€/km.

Without it, the total cost, including battery lifetime cost, is comprised between 0.111€/km and 0.252€/km.

4.2. Operating costs of traditional Diesel car

Energy cost

An economic diesel car in urban cycle uses 5.5 L/100 km.

Assuming a gas oil price of 1.4€/L, the energy cost reaches 0.077 €/km.

Car maintenance cost

For a Clio 1.5 DCI 80 the maintenance cost is roughly 1 200€ per 100 000km or 0.012 €/km.

Total cost

The total cost is 0.089€/km.

4.3. Cost conclusion

Energy cost of electric car is roughly half the energy cost of similar diesel car.

Maintenance costs are close, but electrical car design can be easily improved to be very reliable.

Battery lifetime cost is high and the range is very large depending of the battery use.

Mainly, **the total cost is two or three time more important than a diesel one**. Only in the best case, the Saxo total cost and the diesel car cost are close.

Battery lifetime improvements must be achieved in order to provide a more attractive total cost.

(Notice that these results are related to energy, electric and petroleum, costs)

5. Results of monitoring from an original electric Citroën AX

The energy stored in the batteries of our AX in real use is **8.7 kWh instead of 12 kWh.** The same ratio was found on the Kangoo, measured by the Idaho National Laboratory [2].

The efficiency of charging/discharging the batteries is good, up to **85 %.**

The efficiency of the charger is **only 80%.** This value is low compared to current commercial products available.

The original vehicle AX includes 3 batteries packs:

- A rear pack with 11 modules (154 kg).
- A lower front pack with 6 modules (84 kg).
- An upper front pack with 3 modules (42 kg).

The total mass of the batteries ready to use with water cooling and electrolyte is:

280 kg instead of 260 kg (the packaging is included).

The real energy/mass is: **31 Wh/kg.** This value is very low but it includes all the battery system and the packaging.

6. CEA batteries developments with LiFePO4 technology

The CEA has been working for 8 years on Lithium Iron Phosphate battery technology.

This technology has a good security level and its price is going down. The performances are very good for urban electric vehicles due to the low internal resistance and high number of cycles.

The cost of wear may become as low as 0.3 €/kWh, which will be cheaper than the lead acid batteries technology.

In CEA Grenoble, the replacement of the original Ni-Cd batteries by lithium iron phosphate batteries has been successfully done on an electric vehicle demonstrator (Citroën AX which is one of the lightest vehicles).

The total weight of the new battery system is less than half of original one (138 kg).

The AX mass is now 810 kg, about the same value as for a thermal engine version.

The car gives now very good accelerations.

The energy stored is 10.5 kWh in only 2 packs instead of 3:

- A rear pack (72 kg).
- A lower front pack (66 kg).

The new energy/mass is: 76 Wh/kg, including all the battery system and the packaging.

The measurements of the new kilometric range of the car are in progress.

7. Conclusion

A new departure for the development of electric vehicles is update today.

The power electronics can be designed to ensure a high level of reliability.

The batteries remain the most important point and should be studied firstly to ensure a cost of stored/restored energy lower than 0.5 €/KWh, (to be competitive compared to the thermal vehicles) and a good security level. The purchase cost must be controlled; the number of cycle in real use (temperature range) must reach 1 000 to 2 000 cycles.

The lithium iron phosphate technology battery which offers an intrinsic high level of safety and which exists industrially today is a good candidate for this need. In CEA, the replacement of the original Ni-Cd batteries by lithium phosphate batteries is done. The weight is now 810 kg compared to 950 kg initially.

Weak range is not a blocking point for urban vehicles. Maximum speed is also sufficient (approximately 90 to 100 km/h). Therefore, a power of approximately 15 to 20 kW on a light vehicle is suitable.

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[1] “Experience feedback on electric vehicles of the French car fleet”.IFP conference “advanced in hybrid powertrains 2008”.

[2] “Hybrid Electric and Plug-in Hybrid Electric Vehicle Testing Activities” from the Idaho National Laboratory
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