Experience feedback on electric vehicles of the French car fleet

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Abstract — *Nearly 10.000 electric vehicles appeared these 15 last years in the French car fleet. The main problem of reliability encountered on these vehicles comes from the batteries. Their high price and the low number of cycle in use (except on exceptional case), cause a kilometric cost two to three times superior than with a thermal vehicle. Some problems on the electronics and on the motor of traction were also noticed. Light vehicles, developing a power of approximately 15 to 20 kW with 60 km to 90 km of range, are well adapted to an urban use. Today the demand for electric vehicles by private users at reasonable price is keener than the offer. The CEA of Grenoble invests itself in the monitoring of electric vehicles in order to optimise electrics architectures and the storage of energy, thanks to more powerful batteries of Lithium Iron Phosphates type for example.*

INTRODUCTION

In France, the 10.000 electric vehicles manufactured are resulting from prototypes, and were born fifteen to twenty years ago. Currently all the productions are stopped and there remain only a few thousands of electric cars in circulation. Many are destroyed and some went toward foreign countries (the Scandinavians countries more particularly).
The aim of the suggested presentation 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 mains French manufacturers marketed several models of electric vehicles from 1990:
Express, Clio, Kangoo, AX, Saxo, Berlingo, 106, Partner.
All these vehicles have the open Ni-Cd batteries technology coming from the same supplier. Some cooled by air, others by water.
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).

Saxo and 106 are identical except some details of esthetics. It is the same between Berlingo and Partner.

Table 1: summary of the principal characteristics

Véhicules	Mass (kg)	Maximal Power (kW)	Voltage of batteries (V)
AX	950	20	120
Saxo/106	1 090	20	120
Clio	1 220	21	114
Express	1 230	21	108
Partner/ Berlingo	1 470	28	162
Kangoo	1450	30	132

Table 2: summary of the principal characteristics

Véhicules	Power (kWh)	Range (km)	Mass of batteries (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

2 COSTS OF IMPLEMENTATION OF AN ELECTRIC VEHICLE

Example of cost of using for an electric vehicle, like a Citroen Saxo (all the amounts indicated are including all taxes):
Energy consumption of the vehicle: 21 kWh/100 km.
Assumption of distance covered annually: 15 000 km, (200 ways of 75 km). The yearly consumption is 3 150 kWh, that mean:

- 195 € with the EDF “off-peak hours” rate,
- 325 € with the EDF “full hours” rate and for a private user.

Annual maintenance costs of the batteries (4 water filling): approximately 250 €.
The kilometric cost is:

- 0.0297 € with reloading in off-peak hours,
- 0.0383 € with reloading in full hours.

The electric vehicles sold by PSA were subjected to a maintenance leasing agreement for the batteries. And the current price reaches 165 €/month, that correspond to 1 980 €/year. If we include the batteries contract the kilometric cost become:

- 0.145 € with recharging in off-peak hours,
- 0.154 € with recharging in full hours.

The electric vehicles sold by Renault were not subjected to a maintenance leasing agreement for the batteries, but the vehicle was much more expensive.

To compare, an economic diesel vehicle in urban cycle (5.5 L/100 km) returns to:

- 0.077 €/km (price of the gas oil selected: 1.4 €/L).

The price of the leasing agreement battery induces a cost of use twice higher than that of a thermal vehicle. This cost is ten times superior that the electricity of recharging in off-peak hours.

Contrary to some wrong ideas, the maintenance of a Saxo or 106 electric is not cheaper than that of an equivalent thermal vehicle. That is due to the technologies of the equipment used: cooling pump to change every 20 000 km, brushes of the motor to be checked regularly and to change every 50 000 km approximately. Precisely to do 100 000 km the maintenance costs rise approximately:

- 1 200 € for a Clio 1.5 DCI 80,
- 1 400 € for an electric Saxo with the batteries contract which includes the water filling [4].

It is also important to evaluate the costs associated with the wear of the batteries of traction. An electric Saxo/106 uses 20 modules Ni-Cd 6 V/100 Ah. The price of the whole of these batteries rises approximately at 7 000 €. The documentation of the vehicle specified a batteries lifetime of approximately 120 000 km (1 500 cycles of 80 km).

The reality was quite different: the batteries of some vehicles did not even do 20 000 km (in 4 years), others go to more than 150 000 km. This variation is related to the profile of use of the batteries and the frequency of the maintenance. The overall costs of use are obviously radically different between these two extreme cases.

We calculate the costs with two realistic averages with cycles of 70 km:

Low assumption: the battery is misused (long storages charged, temperature of use raised and maintenance corresponding to the manufacturer specification) and will carry out only 500 cycles. The car will do 35 000 km.
The restored energy is: 5 000 kWh [(1)].
(10 kWh consumed by discharge on 12 kWh theoretically available in the battery of a Saxo or 106 are 80% of depth of discharge).

The corresponding cost is: 1.4 €/kWh [(2)].
The kilometric cost of wear of the batteries is: 0.2 €/km [(3)].
Lifetime of the battery on the assumption of 15 000 km/an: 28 months.

High assumption: the battery is used under optimal conditions (put out of water twice more frequent than the manufacturer specification, low temperature of use, regular use without too deep discharge, no storage completely charged). In this case the battery will be able to reach or exceed the 1500 announced cycles. The car will run 105 000 km.
The restored energy is: 15 000 kWh [(4)].
The corresponding cost is: 0.47 €/kWh [(5)].
The kilometric cost of wear of the batteries is: 0.067 €/km [(6)].
Lifetime of the battery on the assumption of 15 000 km/an: 7 years.

We know one user who changed these batteries with more than 200 000 Kilometers for 5 vehicles of his fleet.

Conclusion concerning the costs:
The high cost and the low number of cycle in real use of open Ni-Cd batteries used on these electric vehicles (except exceptional case) causes a kilometric cost two to three times superior than a thermal vehicle.

The cost of implementation becomes equivalent or lower than a diesel vehicle if the battery of traction ensures 1 500 cycles under the real conditions of use.

(1) 10 kWh X 500 = 5 000 kWh.
(2) 7 000 € / 5 000 kWh = 1.4 €/kWh.
(3) 7 000 € / 35 000 km = 0.2 €/km.
(4) 10 kWh X 1 500 = 15 000 kWh.
(5) 7 000 € / 15 000 kWh = 0.47 €/kWh.
(6) 7 000 € / 105 000 km = 0.067 €/km.

3 THE CHAIN OF TRACTION

3.1 The 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 during the discharges under strong currents or of the load of equalization of the elements.
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 antifreeze agent. The water pump operates with a D.C. current motor with brushes that requires to be replaced every 20 000 km.

On Berlingo and Partner, the 27 batteries are cooled with water with antifreeze agent circuit that is circulated by a pump using a brushless motor without maintenance.

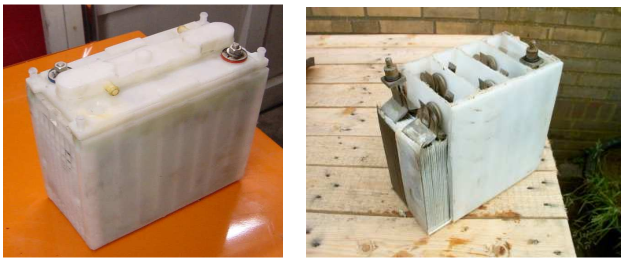


Figure 1 et 2: module of batterie Ni-Cd.

3.2 Electrical motors of traction

PSA vehicles use motors of the same technology (D.C. current with separated excitation, reducing and differential by integrated epicyclical gear) but the power is different for the Saxo/106 and Berlingo/Partner.

Characteristics of the motor for Saxo/106:

- Nominal power: 11 kW from 1 600 to 5 500 rpm.
- Maximum power: 20 kW.
- Maximum torque: 127 Nm from 0 to 1 600 rpm.
- Maximum speed: 6 700 rpm.
- Safety over speed: 8 000 rpm limited by electronics
- Nominal voltage: 120 V.
- Nominal current: 110 A.
- Maximum current: 200 A.
- Excitation voltage: 90 V.
- Maximum excitation current: 11 A.
- Number of brushes: 4.
- Forced air-cooling with 2 modes according to the temperature of the motor.
- CTN temperature sensors drowned in the inductor.
- Ratio of reduction: 1/7.2.
- Speed for 1000 rpm = 13.96 km/h.
- Mass of the unit: 72 kg.

Characteristics of the motor for Berlingo/Partner:

- Nominal power output: 15 kW from 1.650 to 6.500 rpm.
- Maximum power: 28 kW from 1.650 to 6.500 rpm.
- Maximum torque: 180 Nm from 0 to 1600 rpm.
- Maximum speed: 6.700 rpm.
- Safety over speed: 8.000 rpm limited by electronics.
- Nominal voltage: 162 V.
- Nominal current: 110 A.
- Maximum current: 200 A (5 min).
- Excitation voltage: 120 V.
- Maximum excitation current: 11 A.
- Number of brushes: 4.
- Forced air-cooling with 2 modes according to the temperature of the engine.
- CTN Temperature sensors drowned in the inductor.
- Ratio of reduction: 1/7.18
- Speed for 1.000 rpm = 15.11 km/h.

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

Characteristics of the motor for Express and Clio:

- Nominal power output: 16 kW at 2 000 rpm.
- Maximum power: 21 kW at 2 000 rpm.
- Torque with starting: 125 Nm.
- Motor mass alone: 75 kg.
- Number of brushes: 8.

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

- Maximum power: 30 kW from 1 850 to 9 500 rpm.
- Permanent nominal power output: 15 kW.
- Maximum torque: 165 Nm from 0 to 1 850 rpm.
- Maximum speed: 9 500 rpm (103 km/h).
- Nominal voltage: 132 V.
- Temperature sensors in windings of the stator.
- Motor mass alone: 60 kg.

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

3.3 Electronic units of control for vehicles PSA:

All the electronics devices of the vehicle is gathered in an aluminium box cooled by water (cold plate on the lower face).
The unit includes three systems of power for the energy transformation, a DC power contactor and a calculator as shown on the following diagram (example chosen for Partner or Berlingo; figure 3):

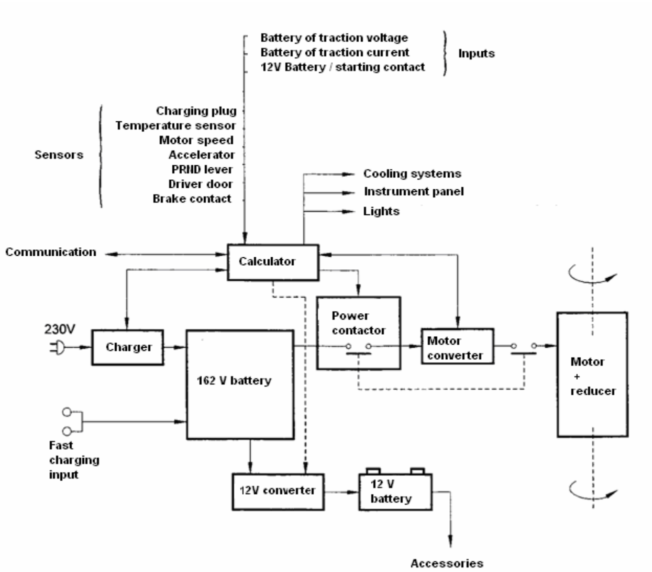


Figure 3: diagram of architecture of electronic unit for Berlingo/Partner.

The calculator collects information of various sensors (temperature, speed, etc) and takes measurements of driving current and voltage of the battery 162 V. Notice that we name "battery 162 V" all 27 blocks of 6 V in series. This precision is important because the calculator checks only the total voltage of the battery. There is no intermediate measure on a group or on every module of 6 V. The problem of that absence of monitoring is that weaker elements may reverse their polarity under strong discharge currents.

The calculator controls indications of the instrument panel: speed of the vehicle, remaining energy in the battery, instantaneous consumption (ECO), indicators, etc.

Figure 4: instrument panel PSA

<u>Characteristics of the 12 V converter:</u>
- Input voltage162 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. Cooling by aluminium sole screwed on the cold plate.

<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.
- Output voltage imposed by the voltage battery (unloaded: 285 V approximately).

The technology is traditional for a charger with sinusoidal taking away 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 5).

The cooling is made by broad aluminium sole screwed on the water plate.

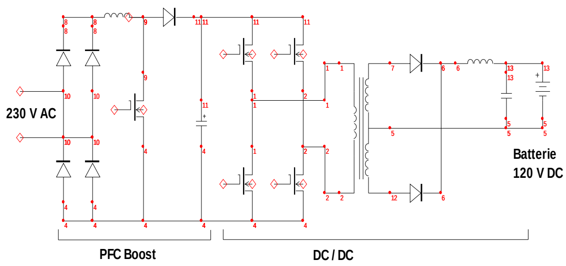


Figure 5: synoptic diagram of the battery charger of traction.

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

Normal load (for Berlingo/Partner):
- Charge at constant power to inject the energy necessary to the battery so that it reaches its rated capacity of 100 Ah (current of approximately 15 A).
- Push a constant current of 5 A to overload the battery of 15% (15 Ah) at the end of the cycle of a normal load.

Charge with equalization (the load of equalization takes place all the 10 normal loads):
- Charge at constant power to inject the energy necessary to the battery so that it reaches its rated capacity of 100 Ah (current of approximately 15 A).
- Push a constant current of 5 A during 5 hours to balance the batteries, which corresponds to an overload of 25%. This phase of overload generates many losses (nearly 1 kW) during 5 hours.

Maintenance charge before the water filling of the batteries or charge for initialization after replacement of defective modules:
- Charge at constant power to inject the energy necessary to the battery so that it reaches its rated capacity of 100 Ah (current of approximately 15 A).

- Push a constant current of 10 A during 5 hours to increase the temperature of the batteries, then generation of a pulsed current 0 - 10 A: 10 A during 2 minutes then 0 during 28 minutes and so on. In this phase the temperature of the batteries remains high and the process of electrolysis continues what maintains high level of electrolyte in the elements. Thus the demineralised water filling can be done without risk of overflow of electrolyte during followings charges.

<u>Characteristics of the motor converter:</u>

The relative data with the displacement of the vehicle are exchanged between the calculator and the electronic card of the converter. Measurements and the instructions of the currents and of excitement are done on this card.
A medium power converter drives the excitement of the motor. This converter with 2 relays allows choosing the speed and direction of rotation of the motor.
A high power converter controls the current in the rotor of the motor for the phases of acceleration and braking.

The strategy of control of the currents in rotor and in inductor depends on the speed revolution of the motor:
- In phase of acceleration 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 current of recharge of the battery varies 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 continue to recharge the battery under 75 A at 1 600 rpm towards 0 at null speed.
- The action on the brake is differentiating than the last point of the recharge of the battery at 75 A goes from 1 600 rpm up to 300 rpm.

Technology of the converter:
The switch of 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 (phase of acceleration at low speed), the other makes it possible to carry out the boost converter (phase of deceleration at low speed). The switch of the excitement current is carried out by an IBGT of smaller power (case TO 220).

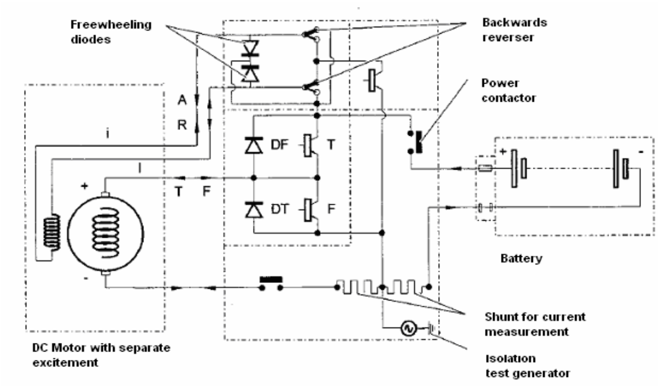


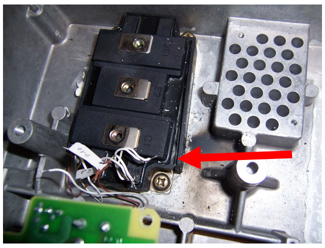
Figure 6: synoptic diagram of the converter

A contactor opening on two poles ensures galvanic insulation between the battery of traction and the electronics of control of the engine (figure 6 represents only one pole of the contactor).

4 FREQUENT PROBLEMS OF RELIABILITY

4.1 Problems involved in the power electronics:

Generally, the thermal aspects 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 (approximately 70% of the breakdowns; figure 8). Then comes the converter (approximately 20% of the breakdowns; figure 7), and after the converter 12 V and the calculator.



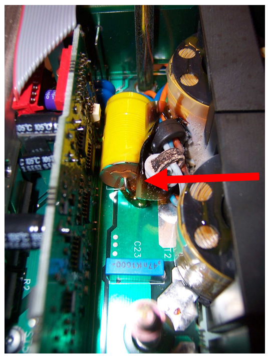


Figure 7: module IGBT destroyed *Figure 8: condenser polypropylene having overheated until its destruction.*

The battery charger is also a weak point on the Clio. A specific capacitor of filtering (under dimensioned and very stressed while running) ages prematurely and causes chronic breakdowns on this equipment (figure 9) [2].

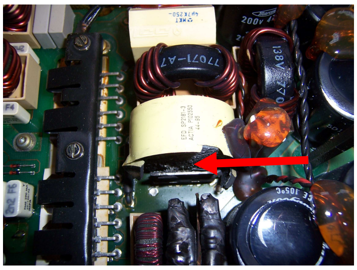


Figure 9: sight of the accused condenser.

4.2 Problems involved in the engine of traction:

Information collected tends to show that there would have been problems of manufacture about the commutator of the motor of traction. 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 beach of nominal output power on the going up roads.
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 cooling [1].

4.3 Problems involved in the batteries of traction:

The batteries of traction used (open Ni-Cd technology) encounter various problems from very varied origins. 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 been parked and without taking account of the gauge of energy in the instrument panel or the long periods of non-utilization, battery plugged for loading, causes the “metallization of the plates” followed by an internal short-circuit (figure 10) [1].
- The high depth discharges of the batteries take part to keep a good range of the vehicle, but can lead to the destruction of the weakest elements. The monitored voltage of the whole battery (with lighting an 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 likely to see its voltage being reversed [2].
- The calculator (according to the number of overloaded energy) orders the frequency of water filling of the batteries. A Battery Ni-Cd 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, which causes the overheating of the emerged plates.

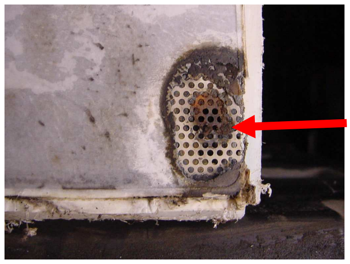


Figure 10: degradation of the separators, follow-up of fusion.

The filling of water every 3 000 to 4 000 km rather than 6 000 km is desirable [1].
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 km [3].

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 cost of purchase must be controlled; the number of cycle in real use on the range of temperature 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.
Weak range is not a blocking point for urban vehicles. Maximum speed is also sufficient (approximately 90 to 100 km/h). For that, a power of approximately 15 to 20 kW on a light vehicle is suitable.
The CEA of Grenoble is doing actions of monitoring on electric vehicles and hybrids. This work makes it possible to optimise electric architectures and the storage of energy.
In addition, the replacement of the original Ni-Cd batteries by lithium phosphate batteries is in progress on an electric vehicle demonstrator (Citroën AX which is one of the lightest vehicles).

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