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Real-life EV battery cycling on the test bench

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Abstract

When choosing a battery system for EV applications, there are many parameters we have to take into consideration: technical parameters, operational experience, economic factors, material availability, and the environment (A. Pellerin, Elec. Hybrid Technol. 96, 68–75). In this paper, we want to concentrate on one parameter only: battery life. The lifetime of traction batteries can be expressed either in terms of number of cycles or in terms of calendar life. Both are important and they strongly depend on the mission profile of the vehicle. A lot of work has been concentrating on bench testing to study the cycle life of traction batteries using standard cycle profiles such as ECE15 or DST. We have learned, however, that the results obtained show significant differences to the results obtained with vehicle trials. After a short introduction talking about the importance of the on-board energy, the EV mission profile and the time factor, we discuss the parameters influencing cycle life: rest periods, ambient temperature, depth of discharge (DOD) or peak power demand, etc. In the second part of the paper, we present a 'complex four-season cycle' integrating the previously mentioned parameters to approach real-life vehicle conditions.

Keywords: EV; Traction battery; Test procedure; Cycle life

1. Introduction

1.1. Importance of on-board energy

The objectives for different parameters of traction batteries are specified by organizations such as the United States Advanced Battery Consortium (USABC) [1], quoting target values for cycle life of 600 cycles for the midterm and 1000 cycles for the long-term.

The cycle life necessary for a vehicle depends on the on-board energy: a vehicle equipped with a battery of 15 kW h (useful energy under normal driving conditions) and an energy consumption of 150 W h km^{-1}, has a range of 100 km. For a vehicle life of 100,000 km, 1000 nominal cycles are needed (1000 times the nominal energy discharged), corresponding to a cumulated discharged energy of 15 MW h. The same vehicle equipped with a battery of 30 kW h and the same energy consumption of 150 W h km^{-1} (the extra weight of the battery is compensated by a lower average discharge rate and therefore, a higher available energy) has a range of 200 km, therefore, only 500 nominal cycles are needed for 100,000 km, the cumulated discharged energy remaining obviously the same at 15 MW h.

The same battery module might be used for the two-battery configurations, therefore our objectives for this module and the complete traction battery are not the same as far as cycle life is concerned. In order to be precise, cycle life has to be expressed in nominal cycles or in cumulated discharged energy for a given battery configuration (See Fig. 1).

1.2. Importance of the mission profile

The cycle life available for a given battery technology might be very much dependent on the mission profile of the vehicle. Let us consider the same vehicle as mentioned above, introducing the power characteristics of the drive systems. Let us assume a peak power of 30 kW from the battery. The power/energy ratio in the first case is 30 kW/15 kW h = 2.0; in the second case 30 kW/30 kW h = 1.0. For the same vehicle, the same battery technology might have a different discharge profile, e.g., maximum discharge power, as a function of the on-board energy.

On the other hand, for the same battery technology and the same on-board energy, the discharge profile varies

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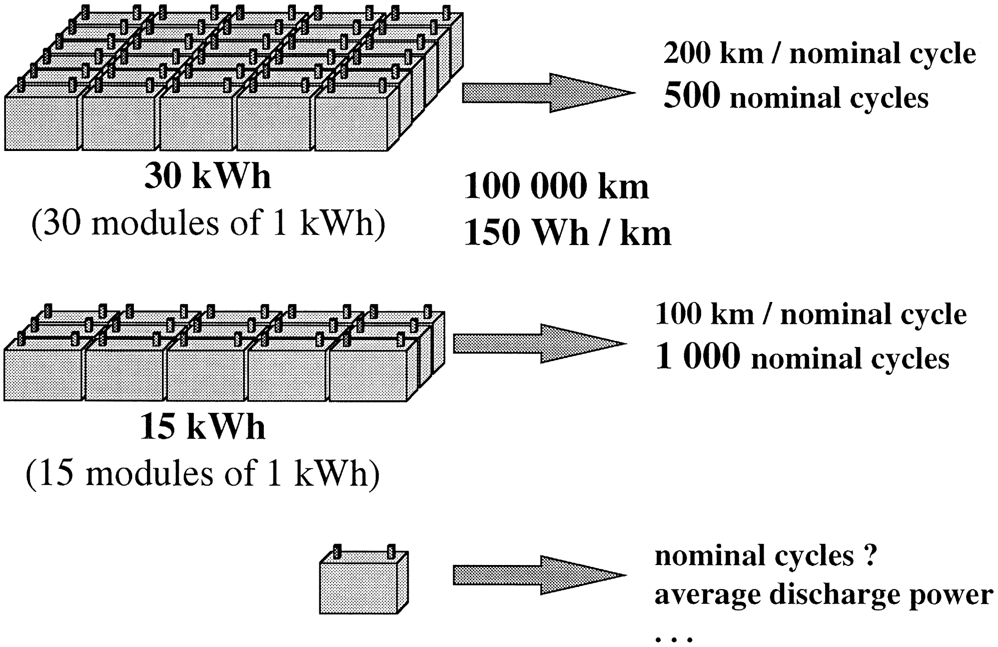

Fig. 1. Influence of the on-board energy.

from one vehicle to another. These differences might be due to different drive trains, aerodynamics, vehicle weight, vehicle performance characteristics such as acceleration and regenerative braking, etc.

In the first part of this paper, we are going to discuss the different parameters that have to be investigated to provide optimum battery integration and management, and therefore optimum battery performance on-board the electric vehicle.

1.3. Importance of the time factor

RENAULT has some first experience with its commercialized electric vehicles, with a typical driving distance

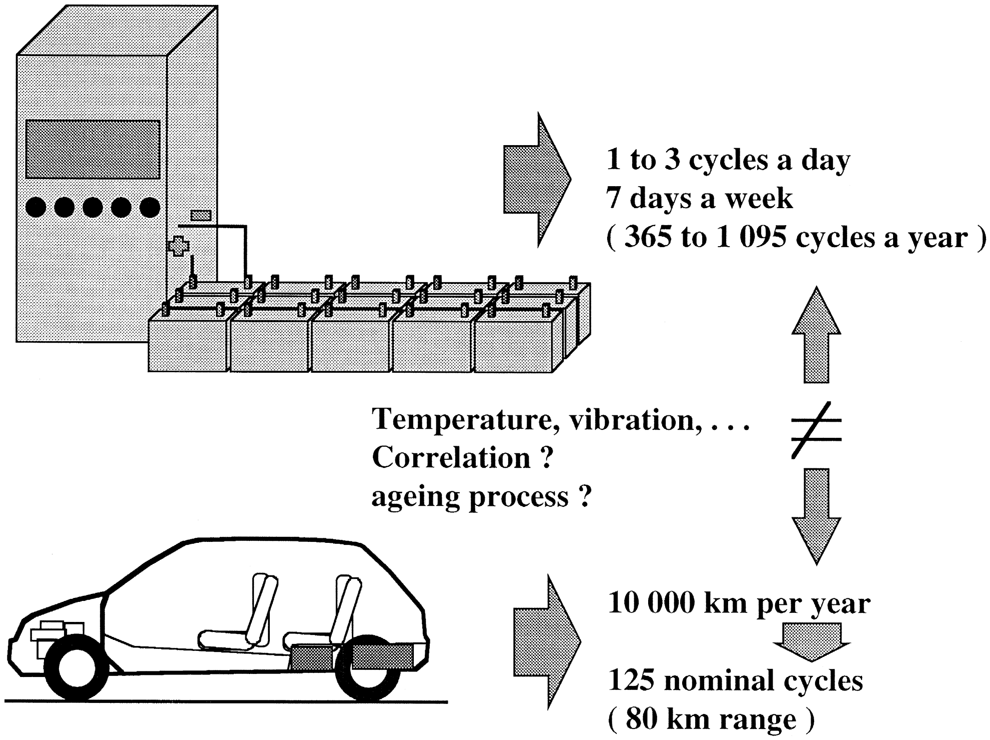

Fig. 2. Bench test–vehicle test.

rarely exceeding 10,000 km per year, corresponding to 125 nominal cycles only (typical vehicle range of 80 km). One might argue that the annual driving distance increases with an available driving range of more than 80 km. The USABC does also quote objectives for the calendar life of traction batteries: 5 yrs for the midterm, 10 yrs for the long-term, corresponding with our objective of 100,000 km and 10,000 km yr^{-1}.

For bench testing, most laboratories carry out 1 to 3 cycles per day, 7 days a week, resulting in some 365 to 1095 cycles per year. For a DOD of 80% normally used in this kind of test, we obtain 292 to 876 nominal cycles per year. As we can see, this is totally different from EV reality (≤ 125 nominal cycles), where we observe long standstill periods, partial discharges, etc. As a consequence, the results obtained differ from vehicle testing (see Fig. 2).

However, it is clear that during research and development it is not possible to carry out cycling tests for prototypes at a rate of 125 nominal cycles per year only. We have the problem of not having the time available to verify the calendar life of a product that is expensive and that is undergoing continuous development. It is therefore, necessary to develop accelerated lifetime tests with proven correlation to forecast expected calendar life.

To conclude, we have to understand clearly the influence and correlation of accelerated bench test cycling and the ageing of a battery. A compromise has to be found between winning time on one hand, and obtaining all necessary information for the real vehicle application on the other.

In the second part of this paper, we discuss the approach of a ‘complex cycling’ profile to reach our objective.

2. Study of parameters influencing cycle life

2.1. Reference cycle

A lot of work has been concentrating on bench testing to study the cycle life of traction batteries using standard cycle profiles such as SAE 1227a [2], SFUDS [3], ECE15 or DST. Despite the continuous improvement of these cycles, we have learned, however, that the results obtained show significant differences to the results obtained with vehicle trials. Previous work with lead-acid batteries showed a cycle life on the bench of more than 700 cycles (TC69 WG3) [4], whereas only 300 cycles were obtained with the same battery on the electric vehicle.

In order to study different mission profiles, it is necessary to establish a reference cycle for further comparison. The cycle profile used is the TC69 WG3 (see Fig. 3). This dynamic discharge profile is very simple to use. It consists of a total discharge time of approximately 2 h and 30 min (for 100% DOD), and corresponds roughly to a suburban driving pattern. However, we have to accept the drawback of not having one step representing regenerative braking.

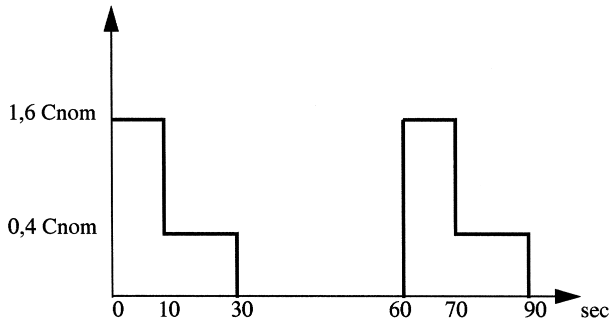

Fig. 3. Discharge with reference cycle TC69 WG3.

1. Normal charge (8 h)
2. Rest period of 1 h
3. Discharge TC69 WG3 (reference cycle), 80% DOD

11 = 1.6 C_{nom}	10 s
12 = 0.4 C_{nom}	20 s
13 = 0	30 s

4. Rest period of 1 h

This reference cycle can easily be modified to study the influence of one specific parameter, e.g., we examine the influence of the peak power demand by replacing the current step 11 by P_{max}. It is obvious that all test samples have to be as close in initial performance as possible to allow comparison and conclusion.

We establish a test plan, varying only one parameter at a time. The electrical data such as internal resistance variation, average discharge voltage, capacity evolution, energy efficiency, temperature, etc. have to be analysed and compared between different tests. The idea is not to obtain the life cycle capability of a system, we are more interested in studying the evolution of the identified parameters and the ageing process during testing. Once the cycling is completed, the active material has to be analysed in close collaboration with the battery manufacturer (post-mortem analysis).

2.2. Influence of discharge power

The available discharge power, continuous and instantaneous, is one of the most important parameters for the performance characteristics of the vehicle (acceleration, top speed). This specific discharge power for the battery might be a function of the on-board energy, the DOD, the temperature, battery age, cumulated discharged energy, etc.

In order to study the influence of the peak power demand, we have to take three parameters into consideration: the value of the peak power value, its duration and the frequency of the peak power demand. We modify our reference cycle and change the discharge step 11 to I_{max} (see Fig. 4).

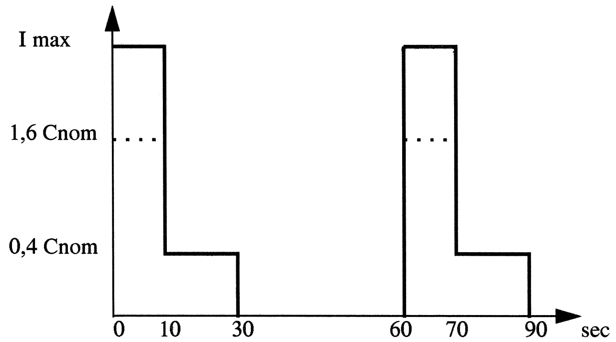

Fig. 4. Discharge with reference cycle TC69 WG3, modified for Peak Power value.

Example: peak power value
Fig. 3 Discharge with modified TC69 WG3, 80% DOD

11 = I_{max}, limited by U_{min}	10 s
12 = 0.4 C_{nom}	20 s
13 = 0	30 s

Example: peak power frequency
Fig. 3 Discharge with modified TC69 WG3, 80% DOD

11 = I_{max}, limited by U_{min}	5 s
12 = 0.4 C_{nom}	20 s
13 = I_{max}, limited by U_{min}	5 s
14 = 0	30 s

The value of I_{max} is provided by the battery manufacturer. For U_{min} we use 2/3 OCV, unless stated otherwise.

We know that this parameter is most important for advanced battery systems with high specific energy, e.g., Li-ion, NaNiCl2 (ZEBRA). To satisfy the proposed energy demand of 15 kW h, we require an approximate battery weight of 200 kg (ZEBRA, $\geq$ 75 W h kg^{-1}) and 125 kg (Li-ion, $\geq$ 120 W h kg^{-1}). For a given peak power of 30 kW, we require a specific peak power of 150 W kg^{-1} for ZEBRA and 240 W kg^{-1} for Li-ion (power/energy ration = 2). We notice the importance of the installed energy. The lower the installed energy, the higher the specific peak power. If we increase the peak power and/or reduce the battery energy, we approach the battery specifications of hybrid vehicles with a high power/energy ratio of 5–20. [5]

First initial tests of the systems show their peak power capability, compatible with our example. However, we have to study the influence of a repetitive power demand on cycle life to ensure the values provided by the battery manufacturer are truly useful peak power.

2.3. Regenerative power

It is well known that regenerative braking increases driving range, up to 25% for an urban driving cycle. Furthermore, regenerative braking reduces maintenance for the brake pads. However, little is known on the influence of strong regenerative braking on cycle life. We therefore introduce a high percentage of regenerative braking (up to 30% to emphasize the phenomena) into the reference cycle: 12 and 14, with 12 = 14 = −0.5 C_{nom}. In reality, we might have a regenerative braking current well above this value.

Example: regenerative power
Fig. 3 Discharge with modified TC69 WG3, 80% DOD

11 = 1.6 C_{nom}	10 s
12 = −0.5 C_{nom}, limited by U_{max}	5 s
13 = 0.4 C_{nom}	20 s
14 = −0.5 C_{nom}, limited by U_{max}	5 s
15 = 0	30 s

The power capability of a battery system has to be investigated in two directions: for discharge and for charge. The battery of a hybrid vehicle, for example, with a relatively low battery energy, has to be capable to accept high regenerative power and fast recharge.

The parameter 'regenerative braking' shows the importance of our overall approach: the peak power on discharge has to be specified within the product definition by marketing experts; in contrast, the management of regenerative braking is a more technical decision. The car manufacturer has to be aware of what is visible to the final customer (acceleration, available discharge power), and what is of less importance for the customer, but possibly as important for the optimal functioning of the battery system (regenerative power).

2.4. Depth of discharge

Concerning the depth of discharge (DOD), there are in general two possibilities: a fleet operator, with a daily use that is repetitive, therefore the battery is always discharged down to a similar DOD. The private user, however, has a mission profile which might vary at random from low to high DODs.

We have to use our reference cycle and go to a low DOD (e.g., 20%), thus accumulating a high number of cycles (but not nominal cycles!). The average battery voltage during discharge is higher than for a discharge at 80% DOD, and the battery is in the charge mode for a higher percentage of time, as the normal end of charge for all battery technologies consists of a low charging power.

Many papers have dealt with the so-called memory effect for alkaline and lead-acid batteries, which has been observed mainly on vehicle trials. This specific test allows us to verify this phenomenon more scientifically on the bench and to investigate its importance for the latest battery technologies: NiMH, NaNiCl2, and Li-ion.

2.5. Partial charge

As for the DOD, the vehicle battery might be fully charged regularly, or might be frequently charged without reaching a fully charged state. This might cause problems for the electrochemistry or the state of charge indication, and in consequence there might be an influence on battery life. We therefore have to modify our cycling profile, using some partial charges at various DODs and a complete charge only from time to time.

We believe that this kind of cycle profile has been used very little up to now, except for hybrid vehicle battery testing. In reality it might well happen that we use partial charging during the day to increase the daily driving range. This seems true especially for vehicles with a relatively low range, that is vehicles equipped with a battery energy of less than 15 kW h.

2.6. Rest periods after charge and discharge

As indicated in our reference cycle, we most often use a fixed rest period after charge and discharge: typically 1 h. The electric vehicle, however, will be most often 'used' in the rest mode, whereas on the test bench the charge mode is predominant (the charging time is normally longer (approximately 8 h) than the discharge time (approximately 2 h).

We have to modify the reference cycle and investigate long rest periods after charge. For alkaline and lithium batteries, this is important for the self-discharge or capacity loss (reversible or irreversible) and depends on the ambient temperature. For hot batteries we are more interested to measure the thermal discharge, i.e., the energy required to keep the battery at its operational temperature.

Concerning the rest periods after discharge, we have to investigate, for example, the effects of sulfatation for lead-acid batteries, or the cooling down of hot batteries (once the battery is discharged and not connected to the mains).

2.7. Deep discharge

Normal vehicle operation excludes the complete discharge down to 100% DOD, because this means vehicle breakdown. However, experience from vehicles equipped with lead-acid batteries showed that the driver might drive the vehicle until he comes to a standstill, waits for some moments and continues to drive until he comes again to a standstill (taking advantage of diffusion effects of the lead-acid battery, but severely damaging the battery). This shows the importance of well studied end of discharge strategy for the vehicle electronics and driver interface.

Deep discharge might also happen due to problems with the state-of-charge indication. Within our reference cycle, with a discharge down to 80% DOD, we integrate a deep discharge down to 100% and beyond (up to 0 V) every x cycles ($10 < x < 100$). In fact, this test combines the study of the influence of a deep discharge on cycle life, but also takes into consideration safety aspects under abnormal conditions.

2.8. Conclusion

We have to be very careful in the specification of our test procedures and the interpretation of the obtained results. When emphasizing the influence of one parameter at a time, we have to be cautious in choosing the right value in order to understand the effects it might have on the electrical test results during cycling. Furthermore, we have to be careful in assuring the overall test conditions to ensure the reproducibility of our test results.

Cycling is not necessarily carried out until the end of life criteria, but might be stopped once a certain number of cycles is obtained, for example 500 nominal cycles. At the end of the test a postmortem analyses is carried out in collaboration with the battery supplier, to analyse the ageing mode of the battery caused by the specific test.

The above list of parameters might not be exhaustive (e.g., fast charge or temperature might well be very interesting and are used in the 'complex four-season cycle', described below), but we believe that the parameters used in our test definition help to identify the most critical points of a battery technology for traction applications. It is the car manufacturer's role, in collaboration with the battery suppliers, to provide optimum control and management parameters for the battery system on-board the electric vehicle. These control parameters have to be integrated within the battery management system (BMS) or the vehicle management unit (VMU).

3. 'Complex four-season cycle'

This complex cycle consists of a number of charge/discharge cycles using no longer a fixed pattern as proposed in the reference cycle. We propose a combination of all the parameters, previously studied individually:

Rest periods	5 min → 72 h
Charging time	1 h (fast charge) → 8 h (normal charge)
DOD	20% → 100% DOD
Interrupted discharge	
Partial charge	
Ambient temperature	$-5°C \rightarrow +35°C$

3.1. Ratio cycles / nominal cycles–calendar year / test year

Our complex cycle consists of 85 charge/discharge cycles for one given temperature, corresponding to 57 nominal cycles and a duration of approximately 6 weeks. The four seasons, thus one calendar year, is reduced to a duration of approximately 24 weeks, i.e., 6 months.

We obtain for one calendar year:

2 simulated years
680 charge/discharge cycles
456 nominal cycles

We notice that we do not achieve our initial objective of reducing significantly the number of nominal cycles per year. However, our complex cycle allows us to introduce some of the real life conditions of the electric vehicle and to save time (compromise between representative testing and time available). For a 15 kW h battery, we would have to cycle for approximately 24 months to obtain 1000 nominal cycles and thus 15 MW h (100,000 km). For the same cumulated energy (driving distance), and for a 30 kW h battery, the required time would be just over 12 months.

As mentioned before, we had difficulties in comparing the cycle life of lead-acid batteries obtained on the bench and on the vehicle. With the 'complex four-season cycle', for example, we are able to reproduce the reduced cycle life of only 300 cycles observed on the EV, mainly due to the longer rest periods of the complex cycle compared to conventional life cycle tests.

3.2. Influence of the ambient temperature

In order to simulate the calendar life, we introduce the four seasons of the year by modifying the ambient temperature of the test.

spring	(+20°C)
summer	(+35°C)
autumn	(+10°C)
winter	(−5°C)

We do not want to represent one specific geographical area, we rather try to integrate the variation of ambient temperature into a cycle life test. Traditional test procedures might propose to carry out life cycle tests at different temperatures. However, little is known about the influence of a regular temperature variation during the cycling test.

3.3. Analysis of the complex cycle

The complex cycle allows us to study in detail: (1) the influence of rest periods lasting up to 72 h (Monday effect, self-discharge, temperature, energy consumption for hot batteries, etc.), (2) the influence of fast charging (energy rechargeable, temperature evolution, etc.), (3) the influence of interrupted discharge (energy availability, temperature evolution, energy consumption for hot batteries, etc.), (4) the memory effect (available energy after frequent partial discharge), (5) the precision of a state-of-charge algorithm (if a gauge is available, the state of charge calculation is monitored by the bench), (6) the energy efficiency of the battery system,

$$\eta = \frac{\text{energy discharged}}{\text{charged energy} + \text{energy consumption of auxiliaries}}.$$

The importance of the above parameters might vary from one temperature to another, or their importance change with an increase of the cumulated discharged energy. The energy efficiency of the electrochemistry is surely a function of the applied cycle profile. However, for the overall energy efficiency of a battery technology, we have also to take into account the battery auxiliaries.

4. Conclusions

We propose in this paper a new approach for test procedures concerning battery bench testing for EV application. We have to clearly identify all possible parameters influencing the functioning of the cell electrochemistry or complete battery system. Once the parameters have been identified for a given vehicle specification, we have to study them individually to optimize the battery utilization on the EV.

In a second step, lifetime data have to be obtained by a complex cycle using real life vehicle data if possible together with a simulated driving pattern taking into account the parameters discussed before. Only this approach allows to obtain test bench data that are representative of vehicle data and to draw conclusions concerning the aptitude of a given battery technology for a specified vehicle utilization.

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