THE DESIGN, ELECTRIC VEHICLE SIMULATION PROGRAM, AND DUTY CYCLE FOR A COMPUTER-CONTROLLED BENCH TEST OF LEAD–ACID BATTERIES

U. WAGNER

T. U. München, Lehrstuhl für Energiewirtschaft und Kraftwerkstechnik, Arcis-Str. 21, D-8000 München 2 (F.R.G.)

Summary

The testing of traction batteries should not be carried out in accordance with the existing duty cycles for vehicles with combustion engines. It should be a test procedure adapted to the mode of operation of electric vehicles (EVs). Such a duty cycle can be developed from an analysis of the power profiles of an EV in urban traffic, which will probably be the main operational area of an EV.

The most important criteria for consideration when establishing a duty cycle are pointed out. The next phase would involve a generalization of the established test cycle, which can be achieved in a number of ways.

1. Introduction

The manufacturer of an EV must be able to estimate exactly the available energy of a traction battery, because it corresponds to the driving range of his product. The battery must therefore be tested in a manner which exceeds the usual capacity check with constant currents.

It is very important that a test procedure is developed which simulates the typical behaviour of an EV under actual driving conditions. It is therefore necessary to operate with cyclic power discharges. In an EV a particular power is required by the user without regard to the depth of discharge (D.O.D.) of the battery. This aspect must be considered when establishing a new duty cycle.

Worldwide, there are many test procedures for vehicles with internal combustion engines. They have been developed with regard to the special driving conditions of the respective country or they are only applied to a restricted class of vehicles. Additionally, they may have different objectives. In consequence, there are special tests for energy consumption, emission, or endurance.

In spite of all these differences existing duty cycles have one thing in common: they were all developed especially for the characteristics of combustion engine driven vehicles and do not take into consideration the fact that an EV is unable to fulfill the test requirements after a certain battery D.O.D. is exceeded. Furthermore, it must not be forgotten that an EV features more possible driving states, for instance, driving at nearly constant speed without taking power from the battery. The criterion to be tested in a traction battery is the power performance, which corresponds to the driving range of the EV under given traffic conditions.

The conclusion must be that it is inadvisable to use any of the existing duty cycles for battery testing.

2. Battery testing

Battery testing can be carried out using constant current as well as cyclic power discharges. Both methods serve a purpose, but the conclusions to be drawn differ greatly. This is explained in Fig. 1, which is an information flow chart for the selection and testing of batteries.

The EV manufacturer obtains information from the user — the intended application, and the rated values of available energy for different

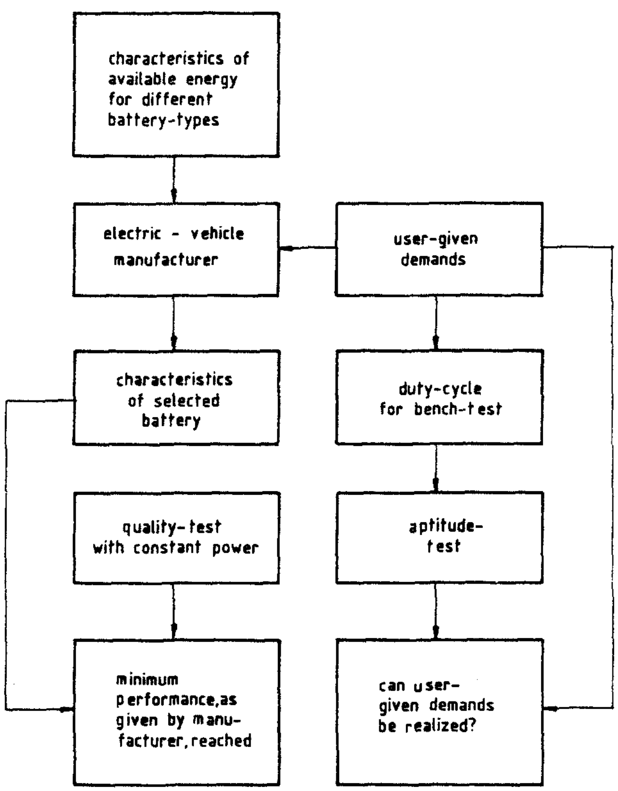

Fig. 1. Information flow chart for selection and testing of batteries.

battery products provided by the battery producer. He makes an approximate computation of the required mean power and the desired driving range. The result will be the minimum energy available at a certain power, which is compared with the rated values of battery specifications. Based upon these data the manufacturer makes his choice. The selection must be followed by a battery test. Here we must distinguish between two types of test methods.

The *quality test* may be a capacity check at constant current, until a specified voltage is reached. Nevertheless it is preferable to determine the available energy using a constant power test in order to include voltage changes *versus* D.O.D. — characteristics.

The *ability test* determines whether, under the harsher conditions of a cyclic power discharge, the battery is still able to satisfy the user's demands. The ability test must be carried out by the EV manufacturer. It should be a power-controlled test, because extreme power variations in combination with the time constants of the different polarisation voltages would cause unpredictable results.

The ability test should take place in a laboratory. This allows the tests to be repeated several times and helps to hold down the cost of measuring and controlling devices. Moreover, measurements in the field would require more test personnel.

3. Procedure

The development of a duty cycle for a computer-controlled bench-test must now be considered. It must be based upon a knowledge of the characteristics and operational modes of an EV. It should be mentioned in this context that IfE and FfE at Munich have had an EV at their disposal for about 3 years. Power- and speed-profiles have been recorded during an extended series of tests in urban and highway traffic, on a straight road along the Munich regatta course, and on test stands.

The results of this investigation have been summarized in a large-scale simulation program which computed energy and power balances for every component of the EV. In addition to other functions, this program can be used to compute energy consumption for the usual duty cycles (ECE, FAKRA). The results were compared with actual values and were found to be satisfactory.

A second, more interesting, feature of the program, was the calculation of power profiles for given speed tests by means of a process computer. The microcomputer is combined with a transistor-controlled discharging device for the battery, this allows a cyclic discharge with arbitrary power tests. The principle of the test stand is shown in Fig. 2. The discharge current ranges between 0 and 400 A at 80 V.

Figure 3 shows the current profile during a test cycle, which is a series of 4 microcycles with different final velocities. The microprocessor surveys battery voltage and current. If the voltage drops below its rated value at 80% D.O.D., an automatic load reduction takes place.

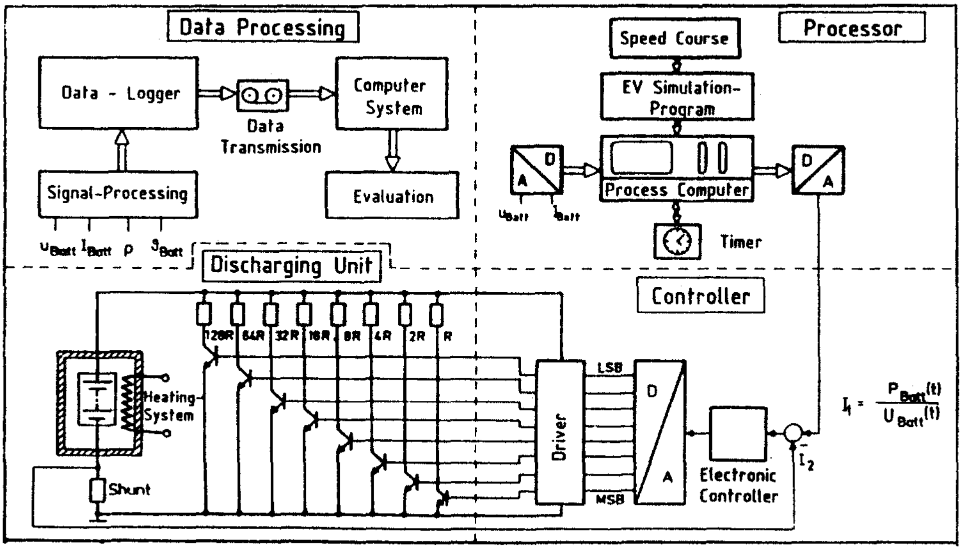

Fig. 2. Process-computer controlled discharging unit 0 - 400 A/80 V.

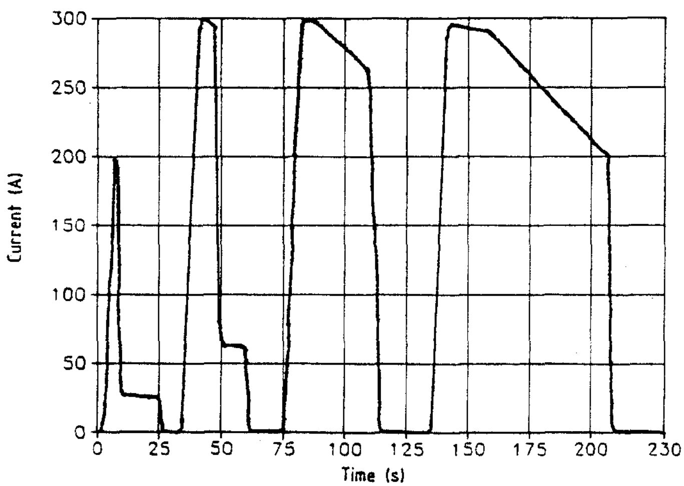

Fig. 3. Current profile during one cycle. Depth of discharge = 60%.

If the reduced power is insufficient to accelerate the vehicle at more than 0.5 m s^{-2}, the test is considered to be at an end.

Control of the discharge process requires considerable programming effort. One special EV was provided with all the available information and characteristics necessary for the computation of the power demand. Due to the time and effort involved, an attempt was made to simplify the test specification. One method was to analyse the actual power curves and to extract all the information relevant to the available energy of the battery.

The method was divided into three steps:

(i) Statistical analysis of the actual power and speed curves.

(ii) Reduction of the power tests to a few, discrete power classes.

(iii) Synthesis of the results to a duty cycle that considers every relevant aspect involving available energy.

3.1. Statistical analysis of power curves in urban traffic

Because driving in urban traffic is probably the most typical operational mode for an EV, development of the duty cycle will be discussed in that context.

First, some important requirements of the duty cycle must be agreed:

— the maximum battery power must be part of the power test;

— standing time must be considered;

— regenerative braking is not simulated;

— average power (without regenerative braking) must be observed.

3.2. Frequency analysis of power classes

Figure 4 shows the frequency distribution of discrete power values reduced to classes with a cell width of 10 kW. Operating with this class interval, the resulting error with respect to average power can be neglected. If the cell width is chosen as being greater than 10 kW, the result may be changed to an unacceptable degree. Figure 4 shows that the 30 kW class is only rarely found. From this it follows that there is a gap between the power class required to drive at maximum speed and the maximum motor power. Everything points to the fact that whenever possible, the vehicle is

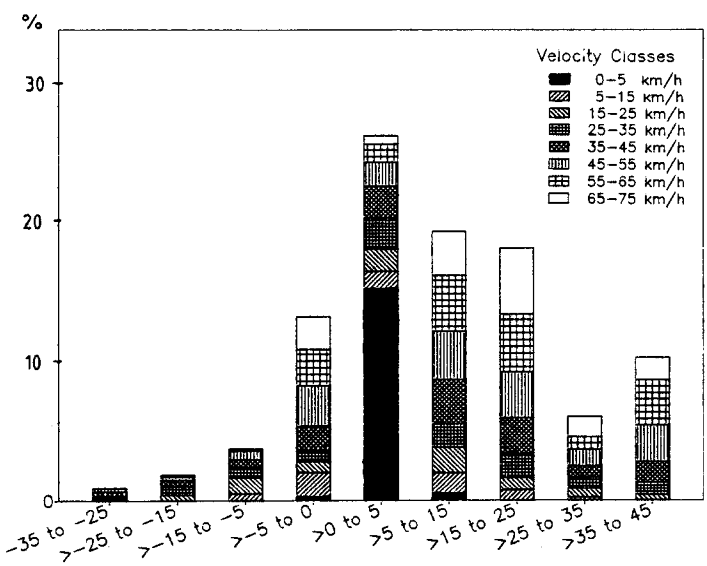

Fig. 4. Frequency distribution of power and velocity.

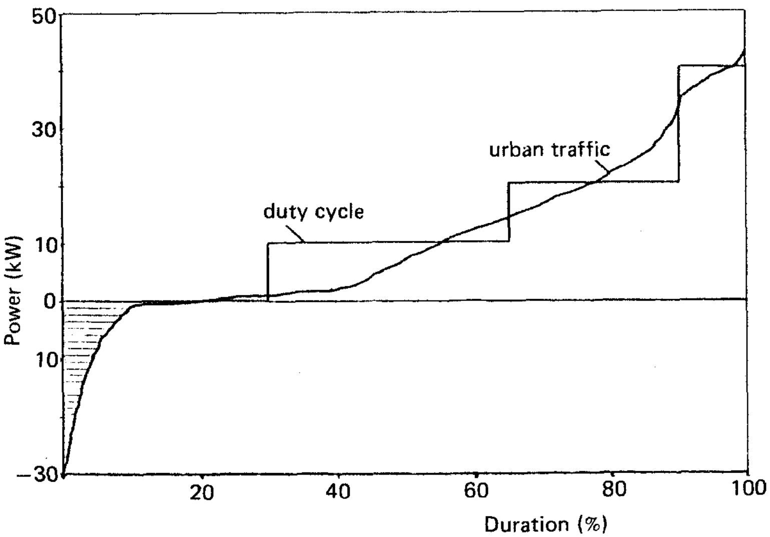

Fig. 5. Power duration curve.

accelerated at maximum power, which is not surprising when the low power/weight ratio of 13 W kg^{-1} is taken into consideration.

The average power without regenerative braking is 12.5 kW.

The power duration diagram (Fig. 5) is also helpful when establishing a duty cycle. Care must be taken that the duty cycle duration curve approximates to the diagram of the original values.

Several power stage combinations have been examined: is was evident that at least 4 power classes were needed.

One power block is given by the maximum motor power (class 4 = 40 kW) which appears for around 10% of the cycle duration. During standstill (10%) and regenerative braking (20%) the battery will not be producing power (class 1 = 0 kW). The 30 kW power class will be disregarded because of its infrequent occurrence.

The remaining 10 and 20 kW power stages must be timed in a manner such that the mean power during the complete cycle averages 12.5 kW.

The following power classes and respective durations have been arrived at from the values of Fig. 5.

class 1 0 kW = 30% (=10% + 20%)
class 2 10 kW = 35%
class 3 20 kW = 25%
class 4 40 kW = 10%.

The corresponding duration curve is shown in Fig. 5.

3.3. Duty cycle derivation

The duration of a complete duty cycle must be determined: it is defined as the average time between two stops. In an analysis of speed *versus* time curves, the duration of one cycle was computed as 100 s, the average time of standstill being 10 s.

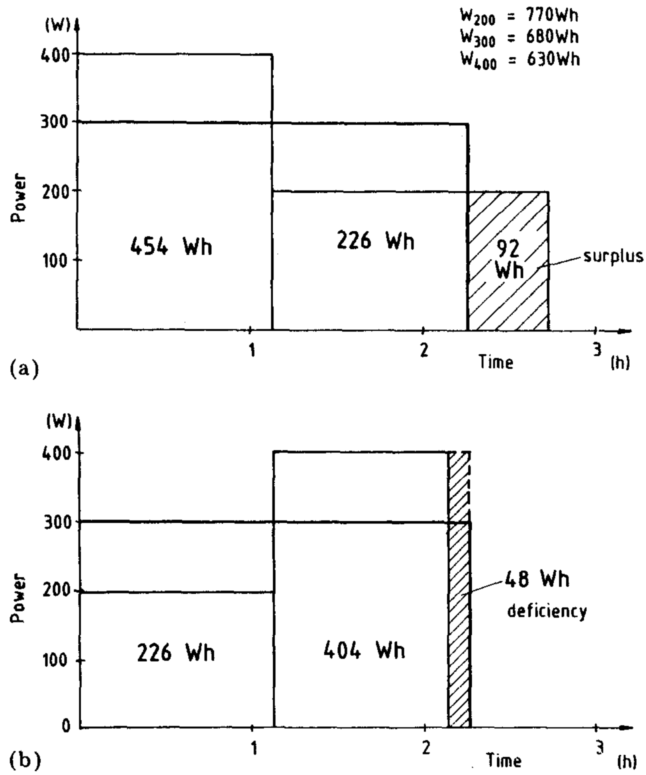

Fig. 6. Practical example of power block sequences. (a) 400 W for 50% of the time and 200 W for 50% of the time; (b) 200 W for 50% of the time followed by 400 W for 50% of the time.

In addition to this, the power block sequences must be very carefully fixed, because they can have a significant influence on the available battery energy. A practical example of this is shown in Fig. 6.

The values given in Fig. 6 show that the battery is capable of supplying 680 W h when being discharged at 300 W. The available energy in a cyclic discharge with an *average* power of 300 W is then determined theoretically.

When operating at 400 W for half the time and at 200 W for the rest, there is an energy surplus of 13% compared with constant power discharge (Fig. 6(a)). On reversing the 200 and 400 W block sequences, a deficiency of 7% will result (Fig. 6(b)).

Though applying the same mean and absolute power, significant differences in available energy can result. In the example chosen they amount to 20% of the constant power discharge value. This makes obvious the importance of the power stage sequences, particularly when approaching end of discharge.

In reality, arbitrary combinations of power sequences are possible. The duty cycle sequence is arranged in such a manner that the desired average

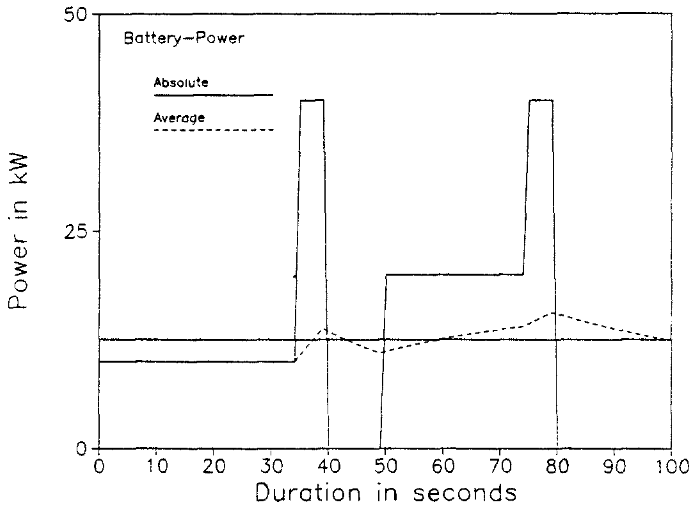

Fig. 7. Duty cycle for bench test of EV battery.

power value is reached as early as possible within the cycle and no large deviations from this average occur.

A duty cycle satisfying all the established demands is shown in Fig. 7. The mean power only varies around 20%.

4. End of discharge criteria

Another important item when establishing a duty cycle is the conditions for end of discharge — modern EV have a voltage controlled power reduction, therefore the same principle should be applied to the test procedure.

If the required power cannot be supplied, the respective section will be prolonged until the necessary amount of energy is achieved. The extension must not exceed the duration of the following section reserved for standstill on regenerative braking. This is not a hard condition to fulfil, so, as a second criterion an absolute power minimum should be fixed, for instance, 50% of motor power.

5. Duty cycle generalization

The derivation of this cycle was accomplished by analyzing the power profiles alone. A correlation between power and speed data does not enter into this procedure. In order to apply the established duty cycle to other vehicles and batteries, it must be defined in more general terms. Two methods are possible:

— Test description by speed profiles.
— Adaptation of the power curve to motor power and power/weight ratio of the vehicle to be tested.

Another method worthy of investigation consists of an analysis of power gradients and average duration of power functions. With this method a more exact approximation of the duty cycle to the actual circumstances can be achieved. This will produce a much more complex test specification, however, because the technical data of the EV must be considered to a greater degree (for instance, the type of gear).

6. Conclusion and further procedure

The established duty cycle is considered to be the most simple version of a test specification. It is a means of determining the power performance of traction batteries for EV in urban traffic. It was developed by theoretical analysis of actual power curves and will be applied to a 96 V battery in a real-time bench test.

The bench test will be used to compare the results with actual measurements. If necessary, the duty cycle will be modified in order to achieve a still better correspondence between field and laboratory tests.