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Driving cycle testing of electric vehicle batteries and systems

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Abstract

Testing of batteries for electric vehicles (EVs) has two distinct focuses. For batteries, testing concentrates on optimizing battery performance and cycle life. It normally uses constant current or constant power and simple cycles. For EV systems, testing focuses on the total vehicle including the battery. This testing is multifaceted and usually involves a complex driving life cycle. These tests are demanding and require much higher physical and electrical performance than a constant-current cycling regime. Tests commonly used today are FUDS, SFUDS and GSFUDS life cycle profiles. These tests have shown to be a much better prediction of battery life cycle performance than is constant-current or constant-power cycling. Driving life cycle tests are one facet of the six characteristics considered when evaluating EV batteries and EV systems.

The testing of electric vehicle (EV) batteries and EV systems have dissimilar goals. In testing batteries for potential application in EV systems, one commonly starts with cells. These are put through the characterization steps of Table 1. These cell tests are then repeated by varying the environment as detailed in Table 2. The objectives of this testing are primarily to characterize and optimize the cell.

The testing of EV systems represents the testing of a complete vehicle platform as detailed in Table 3. The primary consideration in testing an EV system is range because it is the EV's major shortcoming. The specific energy (W h/kg) of the battery primarily determines an EV's range. A secondary consideration is acceleration. This is determined by the battery's specific power (W/kg) (peak power).

Testing of EV systems is done in the field on specific driving courses or in the laboratory on a dynamometer. In either case, testing complete EV systems is time consuming and expensive. Testing in the field requires precise control of all environmental

TABLE 1

Cell characterization tests

A h capacity (3 h rate)
Specific power (W/kg)
Specific energy (W h/kg)
Cycle life (80% DOD)
Utilization of active material (%)

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TABLE 2

Cell environment variables

Discharge (vary the rate and type)
Recharge (constant voltage or pulsed)
Cycling at various states-of-discharge
High and low temperature performance
Variation in cell geometry and electrolyte
Variation of raw materials and separators
Operation with mechanical vibration

TABLE 3

Testing electric vehicle systems

Complete platform
Propulsion system
Regenerative braking
Rolling resistance
Battery system
Range (km)
Acceleration

conditions, precise reproduction of all test parameters, extensive instrumentation and numerous hours of data analysis.

Testing in the dynamometer laboratory is much more precise but also requires many man hours and is costly.

Electrical tests have been developed to simulate real-life driving conditions in the laboratory. These tests have become the standard of the EV industry as a cost-effective means of comparing performance of cells and battery systems. The tests are complex power cycles representing theoretical driving profiles. They provide hard data without going to the dynamometer or the test track. Today, this equipment is all microprocessor-based hardware operated by sophisticated software programs. It has computer-based data acquisition which is put into graphical or spreadsheet format for evaluation and analysis.

The electrical tests that have been used to simulate real-life driving conditions have evolved from simple constant-current or constant-wattage cycles to stepped constant-wattage cycles, to the sophisticated average power integer concept of GSFUDS* (Table 4).

All of these tests are used to provide a means of comparing dissimilar battery systems or to evaluate enhancements to specific battery systems.

The US Department of Energy (DOE) has defined a specific EV platform which represents mid-1990s technology. It is called an Improved Hypothetical Lightweight Aerodynamic Low Rolling Resistance Van (IDSEP) [1]. The DOE has also established six criteria to characterize batteries suitable for powering the IDSEP van [2] (Table 5):

*FUDS: Federal Urban Driving Schedule.
GSFUDS: Generic Simplified Federal Urban Driving Schedule.
SFUDS: Simplified Federal Urban Driving Schedule.

TABLE 4

Electric vehicle life-cycle tests

Test conditions	Type of test
Constant current	US National Electrical Manufacturers' Association (NEMA)
Stepped constant power	US Society of Automotive Engineers (SAE), FUDS, SFUDS
Stepped average power integer	GSFUDS

TABLE 5

Characteristics of batteries for IDSEP-van

Performance
Amortized OEM cost
Ruggedness
Resource consumption
Safety/environment
Likelihood of success

1. Performance – average useable energy capacity per cycle (end-of-life when 70 to 80% of capacity remains).
2. Amortized OEM Cost – ratio of OEM battery cost to cumulative energy capacity over the useful life.
3. Ruggedness – including tolerance to overcharge, overdischarge, to single cell failures, reliability and maintenance frequency/complexity.
4. Resource consumption – net DC-DC energy efficiency and types, quantities, costs and sources of fabrication materials.
5. Safety/environment – gauging the level of hazard the battery may pose to the EV driver, passengers and general public.
6. Likelihood of success – measures maturity and technical barriers to commercialization.

Some degree of testing is utilized in all six of these criteria. Battery cycle life is the greatest area of concentration in testing. A life-cycle capacity loss of 20 to 30% results in a performance degradation that constitutes the end of the useful life of the battery, the point at which it can no longer fulfill its design mission.

Early constant-current cycle life tests have been replaced by complex profiles that more accurately simulate an EV duty cycle. Review of the 1991 BCI presentation on Electric and Hybrid Vehicles by Mr K. F. Barber, Director of Electric and Hybrid Propulsion Division of the US Department of Energy, indicates that the most common EV life cycle tests are SFUDS and FUDS in that order [3].

The FUDS test is 1372 s in length and has continuously varying power levels [4] (Fig. 1). It requires costly test hardware and the data-recording requirements are significant. The test is used to define the battery performance in the IDSEP-van characterized earlier.

Cole [1] provided a characterization of the FUDS test as detailed in Table 6. A simplified form of this test called SFUDS was also detailed by Cole (Fig. 2). It is

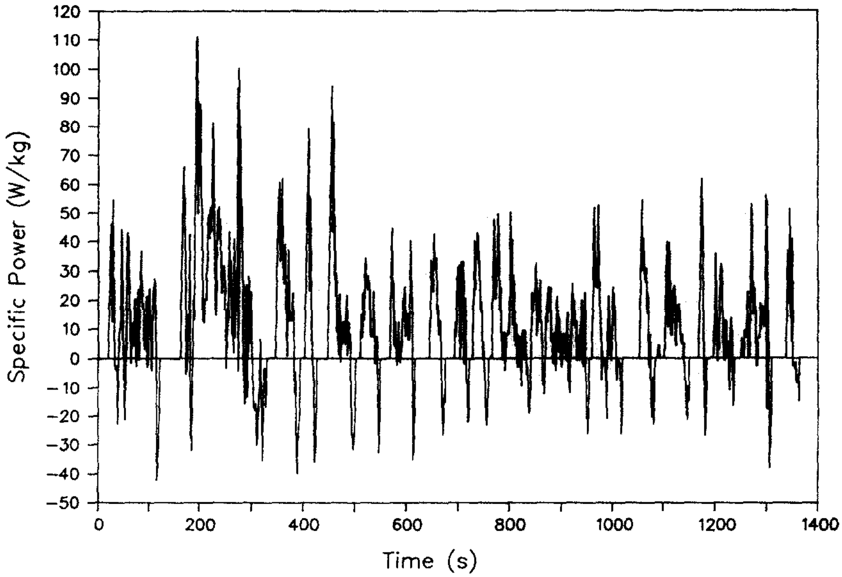

Fig. 1. FUDS driving cycle.

TABLE 6

FUDS cycle

Power (W/kg)	
average	10.1
maximum	79
Speed (km/h)	
average	31.2
maximum	91.1
Energy consumption (W h/km)	225
cycle time (h)	0.38
cycle distance (km)	11.9

referenced to the same IDSEP-van. The SFUDS test is composed of 20 steps and 6 power levels (Table 7).

A comparison of FUDS to SFUDS indicates they produce very similar results.

A more sophisticated version of the SFUDS has also been developed by Cole [4] to provide a test that is not vehicle specific. It is based on the SFUDS and is called the GSFUDS (Fig. 3). GSFUDS uses the concept of average power, P_{ave}, which is calculated by dividing the net energy out of the battery by the time duration of the discharge (less open-circuit rest periods between cycles). P_{ave} is used as the single parameter which defines the cycle and, simultaneously, the characteristics of an electric vehicle which a traction battery powers. The other factors which affect P_{ave} are related to vehicle speed. Since the speed versus time profile is held constant, it is hypothesized that the normalized power ratio P/P_{ave} will not change significantly from vehicle to vehicle. This can be seen in the comparison of Table 8.

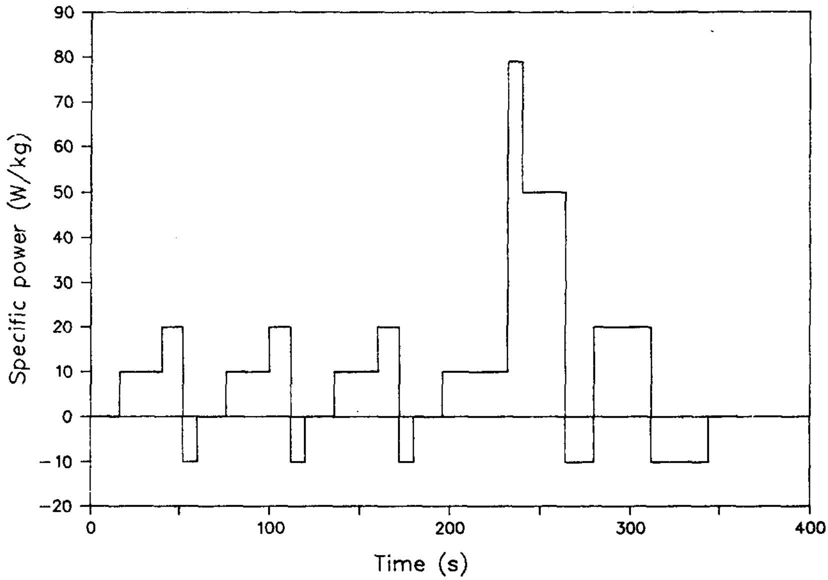

Fig. 2. SFUDS driving cycle.

TABLE 7

FUDS, SFUDS cycle

	FUDS	SFUDS
Power (W/kg)		
average	10.1	9.9
maximum	79	79
Speed (km/h)		
average	31.2	30.6
maximum	91.1	87.5
Energy consumption (W h/km)	225	224
cycle time (h)	0.38	0.1
cycle distance (km)	11.9	3.1

The GSFUDS test has the same 20-step cycle with 6 power levels as does SFUDS. It uses whole integers of the ratio P/P_{ave}. The main advantages of this test are that it is much simpler than the FUDS test and it is not vehicle specific as is the SFUDS test.

Reviewing the state of EV battery testing from the literature reflects how data can be used, correctly or incorrectly, to infer a result. In the presentation: Development status, performance and life data for the horizon design, by Electrosource, Inc. [5] a life-cycle regime of constant current to 80% DOD followed by a constant-current/constant-voltage recharge to 107% of A h discharged yielded almost 800 cycles. Using this data it was inferred that this charge/discharge cycle would provide a range of at least 80 miles. However, this projection using a constant-current cycle may not be an appropriate extrapolation. Budney and Andrew [6] noted that using the SFUDS driving

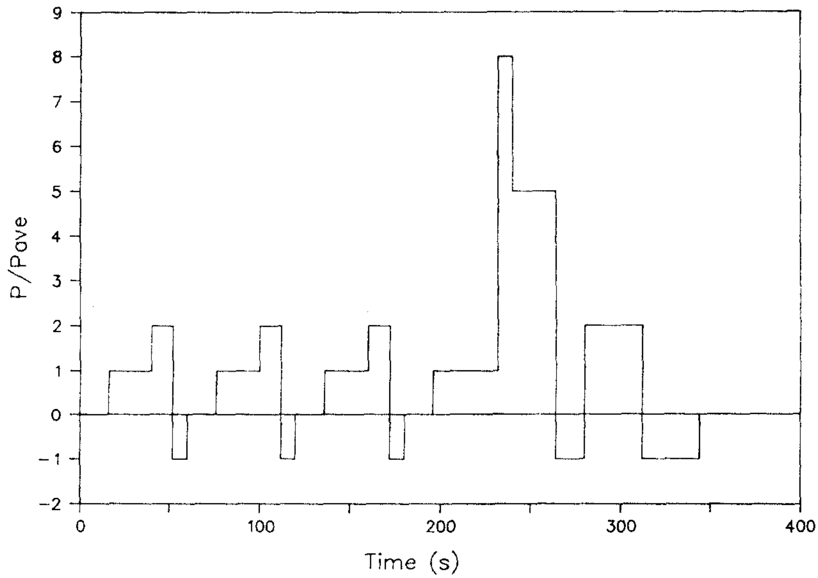

Fig. 3. GSFUDS driving cycle.

TABLE 8

	Cycle		
	FUDS	SFUDS	GSFUDS
Power (W/kg)			
average	10.1	9.9	10
maximum	79	79	80
Speed (km/h)			
average	31.2	30.6	31.3
maximum	91.1	87.5	87.7
Energy consumption (W h/km)	225	224	223
cycle time (h)	0.38	0.1	0.1
cycle distance (km)	11.9	3.1	3.1

cycle compared to a constant-current cycle placed tremendous stress on the active material resulting in premature capacity degradation and an abbreviated cycle life. They also noted that the transient power nature of the SFUDS profile forces a severe depression in the voltage to levels markedly lower than those reached by constant current. They went on to note that experimental life-cycle data from Argonne National Laboratory supports the hypothesis that, compared to constant-current cycling, the SFUDS regime provides a better measure of performance in an actual EV environment. It also is more demanding of the battery. Budney and Andrew noted that, compared with constant-current cycling, available capacity decreased under simulated EV driving profiles and the resultant cycle life was reduced by as much as 67%.

TABLE 9

Testing electric vehicle batteries and systems

A h capacity
Constant power discharge
Specific power (W/kg)
Specific energy (W h/kg)
Peak power (kW)
Internal resistance (Ω)
FUDS and SFUDS cycle performance
Thermal characteristics
Regenerative backing characteristics
Cell voltage variability

An excellent example of EV battery and EV system testing is provided by Burke [7] in his report on the testing of a sodium–sulfur battery. He tested both cells and the battery. The tests are detailed in Table 9.

He also studied variability between discharge voltage of banks of cells and how it affects battery pack performance and life. The paper includes a discussion of packaging. It details limitations of the present battery system and potential areas for future improvement. We suggest this is an excellent model for testing EV batteries and EV systems.

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References

1 G. H. Cole, *A Generic FUDS Battery Test Cycle for Electric Road Vehicle Batteries,* Idaho National Engineering Laboratory, SAE Technical Paper Series, No. 891664.
2 *National Program Plan for Electric Vehicle Battery Research and Development, Technical Plan,* Idaho National Engineering Laboratory, DOE/ID-10219, Aug. 19, 1989.
3 K. F. Barber, *World Technology Panel, Electric and Hybrid Vehicles,* BCI 1991 Convention, Washington, DC, Apr. 24, 1991.
4 G. H. Cole, *A Simplified Battery Discharge Profile Based Upon the Federal Urban Driving Schedule,* Idaho National Engineering Laboratory, *9th Electric Vehicle Symp., Toronto, Ont. Nov. 13, 1988,* pp.
5 B. Jay, A. Datta and C. Lankford, *Development Status, Performance and Life Data for the Horizon Design,* Electrosource, Inc., in 7th *Annual Battery Conf. Applications and Advances, Long Beach, CA, Jan. 1992.*
6 P. Budney and M. Andrew, *Flow-by Lead/Acid — Improving the Performance Standard for EV Battery Systems,* Johnson Controls, Inc., SAE Technical Paper Series, 900135, 1990.
7 A. F. Burke, *Charge/Discharge Characteristics of a Full-Size Sodium–Sulfur Battery for an Electric Vehicle,* Idaho National Engineering Laboratory, *in 7th Annual Battery Conf. Applications and Advances, Long Beach, CA, Jan. 1992.*