EXAMINATION OF BATTERY-RELATED ELECTRIC VEHICLE TRACK AND FIELD MEASUREMENTS

EDWARD J. DOWGIALLO, JR.

Electric and Hybrid Vehicle Systems, U.S. Department of Energy, 1000 Independence Avenue, S.W., Washington, DC 20585 (U.S.A.)

RUSS J. KEVALA

Electric Vehicle Site Programs, The Aerospace Corporation, Washington, DC (U.S.A.)

Introduction

The U.S. Department of Energy Electric and Hybrid Vehicle Program activities include on-the-road evaluation of electric vehicles (EVs) by site operators at several locations throughout the United States. Daily vehicle operation, and maintenance logs and energy input data are recorded by these site operators, which provide useful operating information about the EV fleet of more than 500 vehicles.

In evaluating improved products and components or in assessing the capabilities of vehicles equipped with different batteries, however, more detailed engineering data are required. To acquire the needed data and to understand the differences in performance observed under field and laboratory conditions better, an onboard instrumentation system is essential.

Experience has shown that EV batteries do not exhibit the same performance under field conditions as that obtained on the test track, dynamometer, or in the laboratory. Many in the EV research and development (R&D) community believe that the differences are significant, but direct comparisons are few. On the basis of driver-generated data, LaBelle of Argonne National Laboratory (ANL) found that the average daily distance traveled in the field was typically only half the range obtained on the test track [1].

To make direct comparisons, certain types of data are necessary; they include

Site Characteristics: Road and environmental conditions, trip time and distance, stops per mile, percent times at each velocity and grade, preventive and problem maintenance hours, and a.c. and d.c. energy consumption per mile.

Vehicle Characteristics: Vehicle weight, range, and acceleration times; and gradeability, mechanical power, regeneration, and component characteristics.

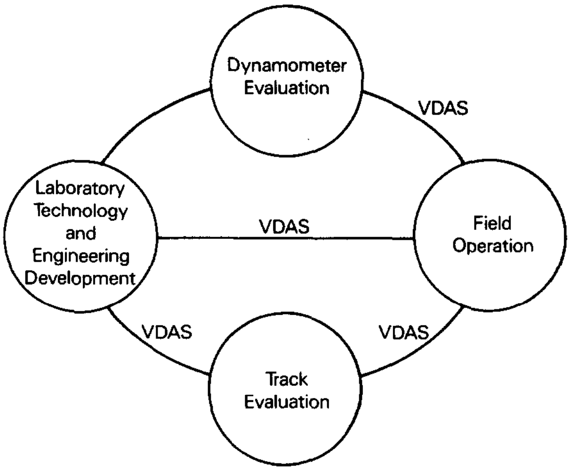

Fig. 1. EV battery development cycle.

Traction Battery Characteristics: Capacity, power, life, state of charge, and temperature effects.

Charger Characteristics: Efficiency, charging profile, and a.c. energy into charger.

A diagram of the EV development cycle from the laboratory to field operation is shown in Fig. 1. The diagram shows areas where an onboard instrumentation system such as the Versatile Data Acquisition System (VDAS) would help facilitate the refinement of an EV system by comparing technical information acquired at the different stages of development. Ultimate successful development of EVs will necessitate close cooperation among the three stages of technology development and a greater understanding of the relationships between battery data collected in laboratories and track and field tests.

Versatile data acquisition system

VDAS [2, 3] is designed to acquire dynamic mechanical and electrical data in a compressed format, performing preliminary computations and tabulations with an onboard microprocessor. It can output the data on demand or store it continually for up to 1 month for off-line presentation. VDAS should help facilitate the refinement of an EV system by comparing technical information acquired at different stages of EV development.

This paper presents some preliminary data acquired by means of VDAS units mounted on vehicles being tested on a test track and in the field. These data are compared with independently generated battery data supplied by the manufacturers and from laboratory testing. Future efforts are being aimed at continuing this investigation under more controlled and carefully planned conditions to afford a more accurate comparison of the parameters and their variation among laboratory, dynamometer, track, and field conditions.

Test conditions

Tests of a prototype VDAS were performed on a closed-loop test track at the Belvoir R&D Center near Washington, D.C. Two EVs, a Unique Mobility Electrek 2+2 and an Electric Vehicle Associates (EVA) Evcort, were driven at constant speeds of 25, 35, 45, and 55 mph (40, 56, 72, and 88 km h^{-1}) and SAE J227a Electric Vehicle Test Procedure driving schedules B, C, and D. The 6750 ft. (2.06 km) track includes 900 ft. (274 m) of 2.5 - 5.0 percent upgrade and 1200 ft. (366 m) of 3.2 - 3.6 percent downgrade. The drivers were instructed to continue a test run until the vehicle could no longer maintain 95 percent of the cruise speed on the level portion of the track.

Field tests were performed on a Jet Industries 600 Electravan at Sandia National Laboratories (SNL) at Albuquerque, New Mexico, and on a South Coast Technology (SCT) Volkswagen Rabbit equipped with nickel/iron batteries at Northrop Corporation at Hawthorne, California. During these tests, which are continuing, the vehicles were used for general daytime use by company employees and charged at night. Table 1 lists the traction batteries and weights of the vehicles tested.

TABLE 1

Electric vehicle batteries tested

Vehicle	Traction battery	Battery weight (kg)	Gross vehicle weight (kg)
Unique Mobility Electrek 2+2	16 3-cell modules, Eagle-Picher Industries 3KQ-11 tubular plate lead–acid	487	1526
EVA Evcort	18 3-cell modules, Globe lead–acid Gel/Cell	495	1790
Jet 600 Electravan	16 3-cell modules, ALCO-2200 lead–acid	580	1494
SCT Rabbit	80 cells, Eagle-Picher Industries VNF-270 nickel/iron	673	1750

Track and field measurements

Vehicle range and battery energy

Figure 2 shows the distance traveled by the Unique Mobility Electrek as a function of the amount of energy removed from the traction batteries. Each data point represents a separate run on the track at a constant speed of 35 mph (56 km h^{-1}). The wide variation in distances traveled, even at the same nominal speed, shows how much driver technique, environmental conditions, battery age, and actual vehicle weight during the run, can affect the useful range of the vehicle. These variations become larger as the distances

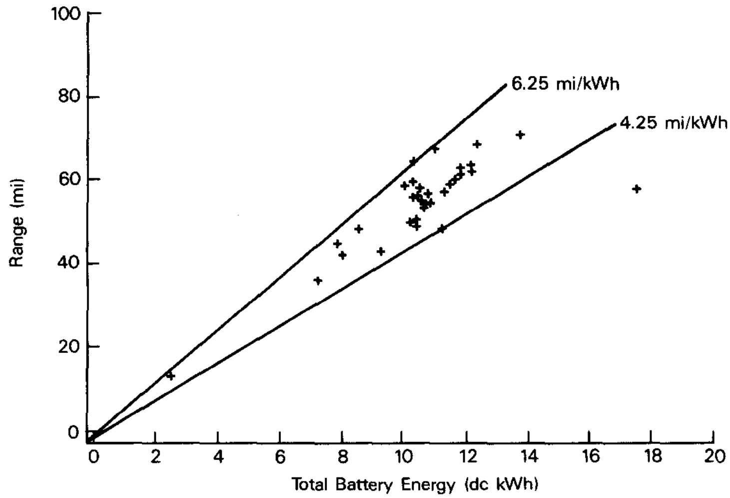

Fig. 2. Range as a function of d.c. kW h (Electrek at Belvoir R&D Center).

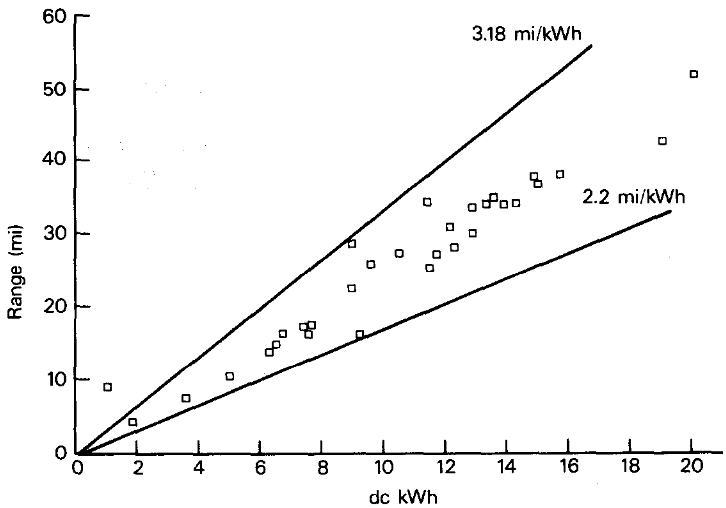

Fig. 3. Range as function of d.c. kW h (SCT Rabbit on field runs).

traveled increase; therefore, most of the data points lie within a wedge-shaped area with upper and lower bounds defined by energy "efficiencies" of 0.16 and 0.235 kW h $miles^{-1}$ (0.1 and 0.15 kW h km^{-1}).

Figure 3 shows the distances traveled in the field at Northrop as a function of the energy discharged by the nickel/iron battery. Most data points fall within a wedge-shaped, 0.31 and 0.45 kW h $miles^{-1}$ (0.19 and 0.28 kW h km^{-1}) region. Note that the field runs were not conducted at a constant speed, and the nickel/iron battery vehicle weighs considerably more than the Electrek with lead–acid batteries.

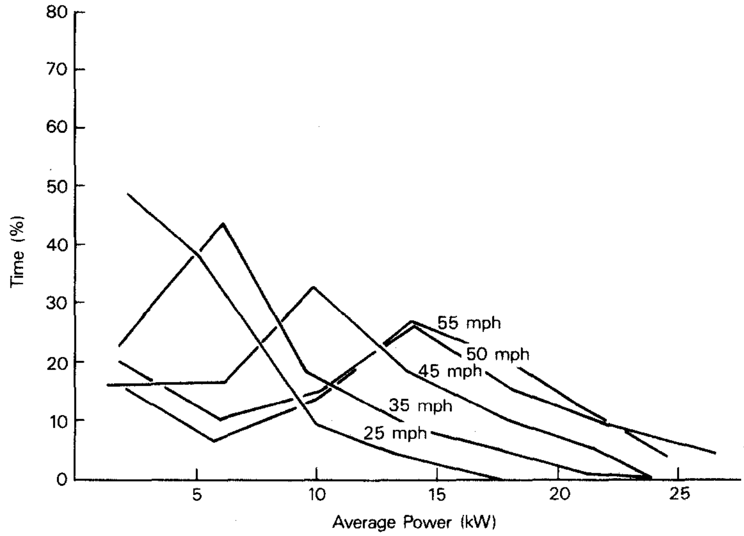

Fig. 4. Electrical power requirements at various speeds (Electrek on Belvoir test track).

Battery power requirements

Figure 4 shows the percent of the total time spent at various electrical power levels for the Electrek. Each data point is an average for all track runs at the speed shown. The percent time spent at peak power decreases as the speed increases. The peaks for 50 and 55 mph (80 and 88 km h^{-1}) coincide, indicating that the limits of battery power for negotiating the 5 percent upgrade at constant speed may have been reached for this EV at 50 mph (80 km h^{-1}).

A similar plot for the SCT vehicle at Northrop clearly showed that power levels under 2 kW were required for approximately 35 percent of the mission. Higher power levels up to 25 kW were required for short periods of time. It is this higher power level requirement that generally limits the available range of the vehicle, because the battery is unable to deliver the higher powers after it is partially discharged.

For the Jet 600 vehicle at SNL, VDAS records showed that when peak power was being delivered to the motor, the battery voltage dropped from the nominal 96 V to only 35 V. This decrease indicated a possible cell reversal in the battery pack that had not been sensed by the driver.

Mechanical power for acceleration and climbing grades

VDAS senses the acceleration vector of the vehicle. At constant speeds on level roads, the value of the acceleration vector is zero. A positive or negative value of acceleration would be proportional to the mechanical power (excluding road load) required or absorbed by the vehicle in negotiating grades and in accelerating and decelerating. This "dynamic" mechanical power is recorded in a matrix with the electrical power and velocity.

An ideal vehicle would expend 0.746 kW of electrical power to produce a change of 1 hp. It was found that the average slope of a plot of measured dynamic mechanical power *versus* electrical power at constant speeds on the test track was slightly steeper than 0.746 kW hp^{-1} due to the internal losses in the electrical system.

Battery temperature

Figure 5 illustrates battery temperature as a function of elapsed time for the three SAE J227a driving schedules (*i.e.*, B, C, and D). The temperature rises faster as the power increases with speed from the B (20 mph) through the C (30 mph) to the D (45 mph) driving schedules.

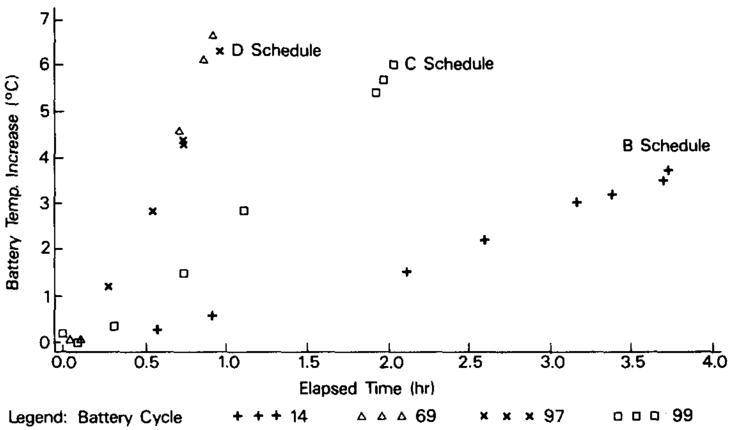

Fig. 5. Battery temperature increase as a function of elapsed time, effect of drive schedule (Electrek).

Charge history

VDAS records the complete charge history, as well as ambient and battery temperatures. This record is very useful for assessing potential problems associated with charging procedures and for optimizing charging routines in the field or in the laboratory.

Comparison with laboratory data

Battery energy and power

Eagle-Picher Industries (EPI) and KW Battery Company provided data on 3KQ-11 battery voltages under constant current discharge conditions. A Ragone plot showing the specific energy as a function of specific power level derived from these data is shown as the solid line in Fig. 6. Each point on the plot represents the total energy available from the battery when discharged completely at a constant power level. This condition is approximated during a battery discharge in an EV traveling at constant speed on level ground.

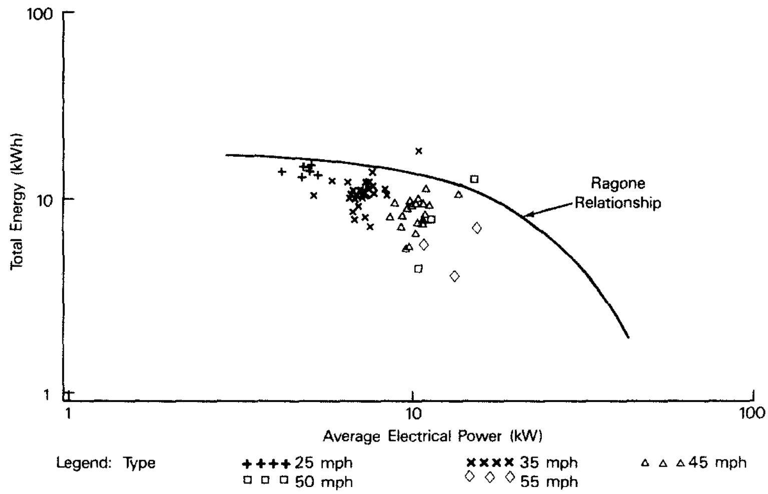

Fig. 6. Total electrical energy at average electrical power levels (Electrek on Belvoir test track).

Although these requirements are not met under the test conditions, an average electrical power for each constant speed track run was computed for the Electrek by taking a time-weighted average of the electrical power in each 4 kW interval. The measured energy data for each average power level are also shown in Fig. 6. The measured track data fall mostly below the Ragone line and cluster around increasingly higher power levels as the average test speed increases.

Battery depth of discharge

When minimum battery voltage is reached during a run, VDAS records the instantaneous battery current and power, as well as dynamic mechanical power, velocity, distance traveled, and elapsed time. The minimum battery voltage is reached when the battery is nearing the end of its useful capacity and power is needed by the vehicle to maintain minimum acceptable performance. The depth of discharge (D.O.D.) at this "peak" power thus defines the maximum level to which the battery may be discharged safely. The depth to which the traction battery has been discharged at the end of a run is an important parameter that controls battery life expectancy, vehicle range, and minimum performance.

For the Electrek at 35 mph (56 km h^{-1}), the average minimum battery voltage recorded on VDAS during the track tests was 74 V at 183 A. From laboratory measurements, this condition represents an 80 percent D.O.D. for the 3KQ-11 tubular plate battery when discharged at the same average power level as during the 35 mph runs. (See Range Prediction.) This condition typically occurred when the vehicle had traveled 96 - 97 percent of the total distance, and the vehicle was negotiating the 5 percent upgrade while trying to maintain the constant 35 mph (56 km h^{-1}).

Range prediction

A method of predicting the range of an EV from laboratory-measured battery characteristics has recently been proposed by Hornstra of ANL [4]. If the average velocity and power needs of the vehicle for a given mission are known, the battery Ragone and peak power *versus* D.O.D. relationships can be used to predict the maximum safe distance (in terms of gradeability and acceleration needs) which the vehicle could be expected to travel.

For the Unique Mobility Electrek traveling at a nominal 35 mph (56 km h^{-1}) around the test track, VDAS data showed that the average vehicle speed during four runs was actually 33 mph (52.8 km h^{-1}). During these runs, the vehicle range averaged 60 miles (96 km) and battery power averaged 5.8 kW. The Ragone relationship for the EPI 3KQ-11 battery (the solid line in Fig. 6) gives the corresponding average energy as 15 kW h. Thus, ideally, the battery is capable of providing the average power need for 15/5.8 = 2.6 h. The maximum depth to which the battery may be discharged safely (safe D.O.D.) for 35 mph (56 km h^{-1}) runs on the test track was estimated earlier at 80 percent. The projected vehicle range under these conditions then would be:

$$\begin{aligned} \text{Vehicle range} &= \text{Safe D.O.D.} \times \text{battery discharge time} \times \text{average speed} \\ &= 0.8 \times 2.6\ \text{h} \times 33\ \text{mph}\ (52.8\ \text{km h}^{-1}) \\ &= 69\ \text{miles}\ (110\ \text{km}) \end{aligned}$$

This projected range falls within the actual distances of 50 - 70 miles (80 - 112 km) traveled by the vehicle during these runs.

Actual field experience has caused EV users to restrict their mission requirements to allow a significant margin of safety. The method outlined above predicted a range of 57 miles (91 km) for the SCT EV with nickel/ iron batteries, but actual use varied between 14 and 37 miles (22 and 59 km). When the vehicle was driven in the field until the battery was fully discharged, a range of 53 miles (85 km) was obtained.

Conclusion

The preliminary data acquired by means of VDAS on vehicles on a test track and in the field have highlighted the practicality of obtaining meaningful data on battery energy and power requirements, as well as other vehicle characteristics such as range, speed, and acceleration capabilities.

Acknowledgement

The authors acknowledge the support and encouragement of Dr K. Friedman of the U.S. Department of Energy throughout the course of the analysis presented in this paper.

References

1 S. LaBelle, Recent developments in electric vehicle technology, *64th Annu. Meeting, Transportation Research Board, Washington, DC, January 14, 1985.*

2 E. J. Dowgiallo, Overview of electric vehicle testing with emphasis on an innovative approach, *Paper 8119, EVC Symp. VI, Baltimore Convention Center, Baltimore, MD, 1981.*

3 R. J. Kevala and Q. Y. Kwan, Analysis of electric vehicle operational data from versatile data acquisition systems, Paper No. 850227, *Int. Congr. Exposition, Society of Automotive Engineers, Detroit, MI, February 25 - March 1, 1985.*

4 F. Hornstra, A simple methodology for obtaining battery discharge times (or vehicle ranges) for arbitrarily structured load profiles, *1st Int. Workshop on Battery Testing, Heidelberg, F.R.G., Sept. 29 - Oct. 2, 1985;* this issue of *J. Power Sources, 17* (1986) 284.