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INTERNATIONAL
400 Commonwealth Drive, Warrendale, PA 15096-0001

SURFACE VEHICLE RECOMMENDED PRACTICE

SAE J1634

REV. APR1999

Issued 1993-05
Revised 1999-04

Superseding J1634 JUN95

Submitted for recognition as an American National Standard

(R) Electric Vehicle Energy Consumption and Range Test Procedure

Foreword—This document has also changed to comply with the SAE Technical Standards Board format. Definitions have changed to Section 3. All other section numbers have changed accordingly.

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1. ***Scope—***This SAE Recommended Practice establishes uniform procedures for testing electric battery-powered vehicles which are capable of being operated on public and private roads. The procedure addresses electric vehicles (EVs) only. It is the intent of this document to provide standard tests which will allow for determination of energy consumption and range based on the Federal Emission Test Procedure using the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Driving Schedule (HFEDS). Realistic alternatives should be allowed for new technology. Evaluations are based on the total vehicle system's performance.

Dynamometer test procedures are specified in this document in order to minimize the test-to-test variations inherent with track testing, and to adhere to standard industry practice for energy consumption and range testing.

2. ***References***

2.1 **Applicable Publications—**The following publications form a part of this specification to the extent specified herein. Unless otherwise specified, the latest issue of SAE publications shall apply.

2.1.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J1263—Road Load Measurement and Dynamometer Simulation Using Coastdown Techniques
SAE J1715—Electric Vehicle Terminology
SAE J2263—Road Load Measurement Using Onboard Anemometry and Coastdown Techniques
SAE J2264—Chassis Dynamometer Simulation of Road Load Using Coastdown Techniques

2.1.2 CFR PUBLICATION—Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

40 CFR Part 86—EPA; Control of Air Pollution from New and In-Use Motor Vehicles and New and In-Use Motor Vehicle Engines; Certification and Test Procedures
40 CFR Part 600—EPA; Fuel Economy of Motor Vehicles

2.1.3 OTHER—United States Advanced Battery Consortium—Electric Vehicle Battery Test Procedures Manual

3. Definitions

3.1 Curb Weight—The total weight of the vehicle with all standard equipment and including batteries, lubricants at nominal capacity, and the weight of optional equipment that is expected to be installed on more than 33% of the vehicle line, but excluding the driver, passengers, and other payloads; incomplete light-duty trucks shall have the curb weight specified by the manufacturer.

3.2 Battery—A device that stores electrical energy chemically.

3.2.1 BATTERY AMPERE-HOUR CAPACITY—The capacity of a battery in ampere-hours obtained from a battery discharged at the manufacturer's recommended discharge rate such that a specified cut-off terminal voltage (see 3.2.3) is reached.

3.2.2 STATE-OF-CHARGE (SOC)—The residual capacity in ampere-hours of a battery expressed as a percent of the battery ampere-hour capacity.

3.2.3 CUT-OFF TERMINAL VOLTAGE—The manufacturer-recommended minimum voltage as a function of load below which battery damage could occur.

3.3 Start-of-Test—The point during a test at which the vehicle key switch is first placed in the “on” position, after following applicable manufacturer “starting” procedures.

3.4 End-of-Test—The point (in time and distance) at which the vehicle has been decelerated to a rest (zero velocity) condition after the appropriate test termination criteria have been met and the key switch is placed in the “off” position.

4. Test Conditions and Instrumentation Common to All Tests—The following conditions shall apply to all tests defined in this document unless otherwise stated in specific test procedures.

4.1 Condition of Vehicle

4.1.1 Vehicles shall be stabilized as determined by the manufacturer and shall have accumulated a minimum of 1600 km (1000 miles), or the battery has been conditioned as specified in 4.2.1, but no more than 9978 km (6200 miles) on the Durability Driving Schedule as defined in 40 CFR Part 86, Appendix IV, Section (a) or an equivalent driving schedule.

4.1.2 Vehicles shall be tested with normal appendages (mirrors, bumpers, hub caps, etc.) for coastdown testing. Certain items (e.g., hub caps) may be removed where necessary for safety on the dynamometer. If any appendages are removed, the fact shall be noted.

4.1.3 All accessories shall be turned off.

4.1.4 The vehicle shall be tested at loaded vehicle weight—curb weight plus 136 kg (300 lb).

NOTE—Trucks over 6000 lb GVW may be tested at curb weight plus one-half vehicle payload, defined as the adjusted loaded vehicle weight (ALVW).

4.1.5 Manufacturer's recommended tires shall be used. Tires shall be conditioned as recommended by the vehicle manufacturer and shall have accumulated a minimum of 100 km (62 miles) and have at least 50% of the original usable tread depth remaining. For dynamometer testing, tire pressures should be set at the beginning of the test at the pressure used to establish the Dynamometer Road Target Coefficients (see SAE J1263 or SAE J2263) and shall not exceed levels necessary for safe operation.

4.1.6 The lubricants normally specified by the manufacturer shall be used.

4.1.7 If the vehicle has a manual transmission, gears shall be shifted at the speed/load points reasonably expected to be followed by vehicles in use.

4.1.8 If the vehicle has regenerative braking, the regenerative braking system shall be enabled for all dynamometer testing, with the exception of coastdown testing (see 9.2.1). For dynamometer testing, if the regenerative braking level is adjustable, it shall be set according to the manufacturer's specification prior to the commencement of the test. The driving schedule speed and time tolerances specified in 6.3 shall not be exceeded due to the operation of the regenerative braking system.

4.2 Condition of Battery

4.2.1 The battery shall have been aged with the vehicle as defined in 4.1.1, or equivalent conditioning. The battery aging may be performed either with the vehicle or by using an equivalent bench aging procedure (Test procedure #2, Constant Current Discharge Test Series, in the United States Advanced Battery Consortium EV Battery Test Procedures Manual, Revision 2). The number of charge/discharge cycles for bench aging a lead-acid battery shall be equivalent to at least 1000 vehicle miles. Other battery technologies may use different battery aging periods, if supported by the manufacturer as being equivalent.

4.2.2 All batteries shall be cycled in accordance with the manufacturer's recommendations before starting testing. Battery ampere-hour capacity shall be verified to be within acceptable limits using the manufacturer's recommended procedure and shall be verified at least once following the completion of vehicle testing.

4.2.3 Full charge is to be established using manufacturer's recommended charging procedure and appropriate equipment.

4.3 Environmental Conditions

4.3.1 Temperature during vehicle and battery ambient soak/charge period shall be within the range of 20 to 30 °C (68 to 86 °F).

4.4 Dynamometer

4.4.1 Use of an electric dynamometer is required for electric vehicle testing. Electric dynamometers must have the capability of load adjustment at various vehicle speeds to allow for the simulation of on-road vehicle load versus speed characteristics.

4.4.2 The dynamometer $Dyno_{set}$ coefficients shall be determined based on SAE J2264 when using electric dynamometers, as modified in Section 9. If the vehicle is equipped with air conditioning, 10% (up to 1.4 hp) is to be added to the road load curve to account for the electrical energy use for air-conditioner operation. For the single-roll electric dynamometer, the loading will be increased by 10% by adjusting the coefficient of the velocity squared term in the equation (that is, C in $RL = A + Bv + CV^2$) based on the road load value at 80.5 km/h (50 mph). The magnitude of the A/C adjustment is calculated as 10% of the total dynamometer force at 80.5 km/h (50 mph). The "A" and "B" coefficients will remain constant. At the present time, EPA does not have a test procedure for electric vehicles, and CARB does not address what should be done to account for air-conditioner equipped electric vehicles. When either agency adopts a method for air-conditioner accounting, then this procedure should be revised to be consistent with the regulatory requirement.

4.4.3 Four-wheel drive or all-wheel drive vehicles shall be tested on a four-wheel dynamometer if both sets of wheels are powered. Otherwise, four-wheel or all-wheel drive vehicles will be tested in a two-wheel drive mode of operation per 40 CFR 86.135-90 (i).

4.4.3.1 For four-wheel or all-wheel drive vehicles tested on a four-wheel drive dynamometer, the dynamometer inertia weight shall be selected with the nearest available inertia weight which equals or exceeds the loaded vehicle weight.

4.4.3.2 For four-wheel drive vehicles tested on a two-wheel drive dynamometer and for two-wheel drive vehicles, dynamometer inertia weight shall be selected with the nearest available inertia weight which equals or exceeds 1.015 times the loaded vehicle weight. The addition of the 1.5% is to account for rotating inertia, mainly the nondriven wheels, not accounted for under static conditions. The value of 1.015 may not be suitable for all vehicles. If an actual or estimated value for rotating inertia is known for the particular vehicle being tested, the more accurate value should be used.

4.4.4 During dynamometer operation, a fixed speed cooling fan shall be positioned so as to direct cooling air to the vehicle in a manner consistent with the accepted practices for simulating road conditions. The fan capacity in general shall not exceed 2.5 m^3/s (5300 ft^3/min), but auxiliary fans may be employed if needed to more closely duplicate on-road conditions.

4.4.5 If the dynamometer has not been operated during the 2-h period immediately preceding the test, it shall be warmed up for 15 min by operating it at 48 km/h (30 mph) using a nontest vehicle or as recommended by the dynamometer manufacturer.

4.5 Test Instrumentation—This section provides a list of instruments which are required to perform the tests specified in this document. The overall error in recording or indicating instruments shall not exceed ±2% of full scale, except for distance measurements which must be ±0.5% of total distance traveled. Coastdown measurement instrument accuracy is described in SAE J1263 or SAE J2263/J2264, as applicable.

4.5.1 GENERAL INSTRUMENTATION—All instrumentation must be National Institute of Standards and Technology (NIST) traceable. The following classes of instruments are typical of those required for the tests outlined in this procedure. Instruments used should meet the minimum or equivalent requirements provided in 4.5.

a. Ammeter
b. AC kilowatt-hour meter
c. DC wideband watt-hour meter or watt-time recorder (optional)
d. DC wideband watt meter (optional)
e. Vehicle speed versus time recorder
f. Distance versus time recorder
g. Tire pressure gauge
h. Ambient temperature versus time meter

4.5.2 Wideband instruments (bandwidth of at least 10 times that of the maximum fundamental frequency) are required where pulsed power electronics are implemented. Any watt-hour meter using an integration technique shall have an integration period of less than 0.05 s so that short bursts of regeneration energy and current can be accommodated without causing integration errors.

4.5.3 The dynamometer shall measure vehicle speed and integrate distance accurate to 0.5% of maximum vehicle speed and 0.5% of actual distance.

5. Data to be Recorded for All Tests

5.1 General

5.1.1 Vehicle identification (manufacturer, model, year) and configuration (description of any nonstandard vehicle features; e.g., sunroof, oversize exterior mirrors, etc.).

5.1.2 Vehicle accumulated mileage at the start and end of test.

5.1.3 Curb weight and test weight.

5.1.4 BATTERY

a. Manufacturer
b. Type
c. Nominal capacity rating
d. Previous history of the battery, including chronological age, number and nature of charge/discharge cycles, description of the last discharge and recharge processes (including a description of the charging system utilized if not supplied by the vehicle manufacturer), and a brief description of known adverse usage conditions.
e. State-of-charge (A-hr) of the battery at the start-of-test using the definition in 3.2.2.

5.1.5 Motor type and rating.

5.1.6 Motor controller type.

5.1.7 Overall drivetrain ratio(s), and drivetrain ratio(s) used during test, and vehicle speed at shift points if manual transmission.

5.1.8 Tire manufacturer, design, size, and pressures at start of test.

5.1.9 Range of ambient temperature during test.

5.1.10 Soak and charge duration.

5.1.11 Date and starting and ending times of test.

5.1.12 List of all instrumentation used in test (manufacturer, model no., serial no.) and the last calibration date of the instruments (where applicable).

5.1.13 The method used for the battery verification test and the results obtained.

5.1.14 Any deviation from test procedure and reason for deviation.

5.2 Dynamometer Data

5.2.1 Description of dynamometer used (including drum or roll diameter, number of rolls, distance between roll axes, if applicable, and method of vehicle restraint).

5.2.2 Dynamometer road load power set points or equation.

5.2.3 Dynamometer inertia weight setting.

5.2.4 Actual miles driven for each test cycle.

***6. Test Cycles*—**The test cycles provided are the United States Environmental Protection Agency (EPA) UDDS and the HFEDS driving schedules.

6.1 UDDS—The UDDS driving schedule is described in Appendix I of 40 CFR, Part 86 nd represents city driving. It consists of a series of non-repetitive idle, acceleration, cruise, and deceleration modes of various time sequences and rates. The UDDS has a duration of 1372 s and is 12 km (7.45 miles) long with an average speed of 31.5 km/h (19.6 mph) and a maximum speed of 91.2 km/h (56.7 mph).

6.2 HFEDS—The HFEDS driving schedule is described in 40 CFR, Section 600.109(b) and represents highway driving. A single HFEDS schedule is 764 s in duration and is 16.4 km (10.2 miles) long. The average speed is 77.8 km/h (48.3 mph) with a maximum speed of 96.4 km/h (59.9 mph).

6.3 Speed Tolerance—The speed tolerance at any given time on the UDDS and HFEDS driving schedules is defined by the upper and lower limits as described in 40 CFR part 86.115-78 and Appendix I of 40 CFR part 86. The upper limit is 3.2 km/h (2 mph) higher than the highest point on the trace within 1 s of the given time. The lower limit is 3.2 km/h (2 mph) lower than the lowest point on the trace within 1 s of the given time. Speed variations greater than the tolerances (which may occur during gear changes) are acceptable provided they occur for less than 2 s on any occasion.

7. Vehicle Energy Consumption When Operated on Selected Driving Patterns

7.1 Purpose of Test—The purpose of this test is to determine the energy consumed by a test vehicle when operated on a dynamometer over repeatable driving cycles. It is the intent of this section to provide standard procedures for testing EVs so that the performance can be compared when operated over fixed driving patterns. Two test sequences can be performed (UDDS Test Cycle for a "city" energy consumption measurement and HFEDS Test Cycle for a "highway" energy consumption measurement), however, both test cycles do not need to be performed.

7.2 Definition of Energy Consumption—Energy consumption is the energy used by a vehicle in traveling a particular distance. In an electric vehicle utilizing an electrically rechargeable battery, there is always a certain amount of the total AC energy supplied to the battery which is not available for vehicle propulsion due to charger and battery inefficiencies or other vehicle maintenance requirements. Energy consumption may be measured two ways. The vehicle DC energy consumption measure is optional and can be used to characterize the energy consumption of the charger and powertrain.

$$\text{Vehicle AC Energy Consumption} = \frac{\text{AC Energy to Charger for Recharge}}{\text{Distance Traveled}} \qquad \text{(Eq. 1)}$$

with units of AC Wh/km (AC Wh/mile)

$$\text{(Optional) Vehicle DC Energy Consumption} = \frac{\text{DC Energy from Battery while driving}}{\text{Distance Traveled}} \qquad \text{(Eq. 2)}$$

with units of DC Wh/km (DC Wh/mile)

7.2.1 VEHICLE AC ENERGY CONSUMPTION—The AC energy from the power outlet required to return the battery to full charge after testing shall be divided by the range of the vehicle on the particular test cycle. This quotient shall be reported as the Vehicle AC energy consumption of the electric vehicle for the particular conditions of the test.

7.2.2 VEHICLE DC ENERGY CONSUMPTION (OPTIONAL)—Vehicle DC energy consumed by the electric vehicle on a driving cycle shall be measured with a wideband watt-hour meter or a data logger. If a watt-hour meter is used, the total energy consumed from the start of the test to the defined end-of-test shall be recorded. For vehicles with regenerative braking, two W-h meters shall be used: one to measure the energy taken from the battery, and the second to measure energy returned to the battery by regenerative braking. Both the gross vehicle DC energy consumption (watt-hours from the battery divided by the distance traveled) and the net vehicle DC energy consumption (watt-hours from the battery during driving minus the watt-hours returned to the battery from regenerative braking, divided by the distance traveled) shall be reported for each driving cycle.

7.3 Test Procedure—The dynamometer test defined in this procedure is to be conducted subject to the test conditions and data requirements of Sections 4 and 5.

7.3.1 PRECONDITIONING—The vehicle, battery, and thermal management system, if any, shall be soaked at ambient temperature before the start of test for at least 12 h and not more than 36 h, and shall remain on charge for the duration of soak. Soak shall not end before full charge is reached. Within 1 h of the end of soak/charge period, the vehicle shall be moved (pushed or towed—not driven) into position on the dynamometer. The vehicle drivetrain should be in a "cold" condition at the start of this test; therefore, the vehicle shall not be rolled more than 1.6 km (1 mile) between the end of the charge/soak period and the start of this test.

7.3.2 TEST CYCLES—The vehicle may be tested over one or both of the following two test cycles. The vehicle should be preconditioned prior to each cycle and recharged after each cycle to obtain the system AC energy consumption for the cycle. Dynamometer coastdown "quick checks" are not part of energy consumption test.

7.3.2.1 UDDS Test Cycle—The vehicle shall be operated over two successive UDDS cycles as described in 6.1, with a 10-min soak with key switch in the "off" position, the hood closed, and test cell fan(s) off after each UDDS cycle, until the vehicle is no longer able to maintain the speed or time tolerances (see 8.3). Vehicle system DC energy consumption may be recorded during the test cycles.

7.3.2.2 HFEDS Test Cycle—The vehicle shall be operated through two HFEDS cycles described in 6.2. The HFEDS cycles are to be separated by 15 s at zero speed with the key switch "on" and the brake pedal depressed and followed by a 10-min soak with key switch in the "off" position, the hood closed, and test cell fan(s) off. This test sequence will be repeated until the vehicle is no longer able to maintain either the speed or time tolerances (see 8.3). Vehicle system DC energy consumption may be recorded during the test cycles.

7.3.3 Within an hour of operating the vehicle over the test cycle, the vehicle battery shall be recharged to full capacity according to the manufacturer's recommended procedure to measure the vehicle AC energy consumption. Charging is required for a minimum of 12 h and is complete when the manufacturer's end-of-charge criteria are met.

If the vehicle must be moved to a separate charging location at the end of the test, it shall be pushed or towed, not driven.

7.4 Special Reporting—The following data, in addition to the data requirements in Section 5, should be reported for each test sequence performed.

7.4.1 Recharge time.

7.4.2 AC watt-hours supplied to battery charger during recharge following test.

7.4.3 The calculated system AC energy consumption.

7.4.4 DC watt-hours returned to battery during recharge following test (optional).

7.4.5 DC watt-hours discharged from the battery during test (optional).

7.4.6 DC watt-hours returned to battery (regenerative) (optional).

7.4.7 The calculated vehicle DC energy consumption (optional).

8. Vehicle Range When Operated on Selected Driving Patterns

8.1 Purpose of Test—The purpose of this test is to determine the overall range of an electric vehicle when operated on a dynamometer over repeated driving cycles. Two test sequences can be performed (UDDS test cycle for a "city" range and HFEDS test cycle for a "highway" range). Both test cycles need not be performed.

8.2 Test Procedure—The dynamometer tests defined in this procedure are to be conducted subject to the test conditions and data requirements of Sections 4 and 5. Recording of battery discharge, battery recharge, and regenerative data is optional for the range test.

8.2.1 PRECONDITIONING—The vehicle, battery, and thermal management system, if any, shall be soaked at ambient temperature before the start of test for at least 12 h and not more than 36 h, and shall remain on charge for the duration of soak. Soak shall not end before full charge is reached. Within 1 h of the end of soak/charge period, the vehicle shall be moved (pushed or towed—not driven) into position on the dynamometer. The vehicle drivetrain must be in a "cold" condition at the start of this test; therefore, the vehicle shall not be rolled more than 1.6 km (1 mile) between the end of charge/soak period and the start of test.

8.2.2 TEST CYCLES—The vehicle may be tested over one or more of the following cycles. the vehicle should be preconditioned with the battery in a fully charged condition prior to each cycle.

8.2.2.1 UDDS Test Cycle—The vehicle shall be operated over two successive UDDS cycles as described in 6.1. A 10-min soak will follow each UDDS cycle. The key switch is placed in the "off" position, with the hood closed and the test cell fan(s) off during soak periods, and the brake pedal shall not be depressed. This test sequence will be repeated until the test termination criteria are met. Then the distance traveled "city range" shall be recorded and the vehicle shall be decelerated rapidly to a stop.

8.2.2.2 HFEDS Test Cycle—The vehicle shall be operated over two successive HFEDS cycles described in 6.2. The two *HFEDS* cycles are to be separated by 15 s at zero speed with the key switch "on" and the brake pedal depressed. A 10-min soak will follow the two HFEDS cycles. The key switch is placed in the "off" position, the hood closed, the test cell fan(s) off during soak periods, and the brake pedal shall not be depressed. This test sequence will be repeated until the test termination criteria are met (see 8.3). Then the distance traveled "highway range" shall be recorded and the vehicle shall be decelerated rapidly to a stop.

8.3 Test Termination Criteria—The UDDS and HFEDS were developed for and are used in the emissions and fuel economy testing of internal combustion engine powered vehicles. They are defined as best-effort tests; i.e., speeds lower than those prescribed are acceptable provided the vehicle is operated at maximum available power during such occurrences. Electric vehicles, in general, display decreasing acceleration and top speed capabilities as the batteries become increasingly discharged. Using the UDDS or HFEDS cycles for a driving range test with a best-effort performance criterion would enable the vehicle to continue the test until it could no longer move at all, as long as it was still being driven at maximum available output power. A driving range obtained from such a test would have little value. Therefore, the test termination criterion for the range and energy consumption test is defined as when the vehicle is unable to accelerate fast enough to maintain the speed tolerances as defined in 6.3 while the driver is attempting to follow the driving schedule. The total distance travelled before the test termination criteria is reached, is the vehicle range.

8.3.1 OTHER MANUFACTURER-SPECIFIED TEST TERMINATION CRITERIA—Other earlier test termination criterion may be specified by the vehicle manufacturer. For example, to prevent battery damage, the vehicle manufacturer may specify a battery characteristic such as terminal voltage under load to be the test termination criterion.

8.4 Special Data Recording—In addition to recording the data specified in Section 5, the following data shall be reported.

8.4.1 The criteria used to define test termination.

8.4.2 The distance the vehicle traveled before the test termination criteria were met.

8.4.3 If the optional energy consumption was measured, recharge energy and time and the system AC and DC energy consumption.

9. Coastdown Testing

9.1 Purpose of Test—The purpose of this procedure is to determine the road load force on a vehicle as a function of vehicle velocity so that accurate simulation of the road load force on a chassis dynamometer can be accomplished.

9.2 Test Procedure—Vehicle road force required information is to be determined from coastdown tests which are performed to SAE J1263 or J2263 requirements with the following modifications.

9.2.1 Vehicle regenerative braking shall be disabled during coastdown testing, minimizing any changes to the mechanical system.

9.2.2 Presently no procedure exists for vehicles that cannot obtain the vehicle speeds required in SAE J1263 and SAE J2263/J2264. When determining the road load power setting for these vehicles, good engineering practice should be used to modify these procedures for the lower speeds to determine the road load power setting.

9.3 Data to be Recorded—Data recording requirements shall be the same as those specified in SAE J1263 and SAE J2263/J2264.

10. Notes

10.1 Marginal Indicia—The change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions have been made to the previous issue of the report. An (R) symbol to the left of the document title indicates a complete revision of the report.

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