SAE International®	SURFACE VEHICLE RECOMMENDED PRACTICE	SAE	J1634 OCT2012
		Issued	1993-05
		Revised	2012-10
		Superseding	J1634 OCT2002

Battery Electric Vehicle Energy Consumption and Range Test Procedure

RATIONALE

The procedure has been revised in order to provide new methods for testing Battery Electric Vehicles (BEVs). These methods are intended to both improve testing efficiency and provide a practical testing methodology that can be easily adapted to accommodate future testing enhancements.

FOREWORD

Historically, the determination of range and energy consumption for Battery Electric Vehicles has relied on a Single-Cycle Test (SCT) methodology. The SCT requires that a vehicle be repeatedly driven over the same speed vs. time profile (i.e., drive cycle) until the vehicle's battery energy is completely exhausted. The long and indeterminate nature of the SCT places significant logistical strains on test facilities, a situation that will worsen as battery technology advancements enable even greater range capability. It is also possible that additional test cycles - beyond the currently required UDDS ("City") and HFEDS ("Highway") cycles - will be necessary in order to better characterize the effects of temperature and accessory loads on range performance, making the SCT paradigm even less practical. For these reasons, a Multi-Cycle Test (MCT) procedure has been developed.

The MCT method enables range and AC energy consumption determinations for multiple drive cycle types using a single full depletion test. This is accomplished by measuring: (1) the DC energy consumption for each included cycle type, and (2) the battery's useable DC energy content. Given the total energy content of the battery, the range for each drive cycle type follows directly from its respective energy consumption. Similarly, the appropriate quantity of AC recharge energy attributable to each drive cycle can be determined according to its respective DC energy consumption. The MCT method is applicable to vehicles powered by lithium ion batteries and tested using the existing standard drive cycles; new battery technologies, new drive schedules, or significantly different vehicle designs should be evaluated to determine if method remains applicable.

Significant reductions in the testing resources needed to produce both a City and Highway range determination are possible using the MCT method. For example, a BEV with a 150 mile unadjusted UDDS range would consume about 18 ½ hours of total dynamometer test time in order to perform the necessary City and Highway SCT tests. The same City and Highway range determinations could be accomplished in about 4 ½ hours using a single MCT (a reduction of over 75%). Given a 200 mile UDDS range, the differential between the on-dyno test times increases further to 24 ½ hours and 5 ½ hours, respectively, for the SCT and MCT. These estimates do not account for the additional savings that accrue from the elimination of one of the two recharging periods required by the SCT procedure. Additionally, the MCT test sequence can easily accommodate new test cycles and may be combined with supplementary partial-depletion tests, enabling further streamlining opportunities relative to the SCT when applied to more complex or comprehensive testing scenarios.

1. SCOPE

This SAE Recommended Practice establishes uniform procedures for testing battery electric vehicles (BEV's) which are capable of being operated on public and private roads. The procedure applies only to vehicles using batteries as their sole source of power. It is the intent of this document to provide standard tests which will allow for the determination of energy consumption and range for light-duty vehicles (LDVs) based on the Federal Emission Test Procedure (FTP) using the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Driving Schedule (HFEDS), and provide a flexible testing methodology that is capable of accommodating additional test cycles as needed. Realistic alternatives should be allowed for new technology. Evaluations are based on the total vehicle system's performance and not on subsystems apart from the vehicle.

NOTE: The range and energy consumption values specified in this document are the raw, test-derived values. Additional corrections are typically applied to these quantities when used for regulatory purposes (Corporate Average Fuel Economy, vehicle labeling, etc.).

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J1263 Road Load Measurement and Dynamometer Simulation Using Coastdown Techniques

SAE J1711 Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles

SAE J1715 Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) 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 United States Government Printing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-0000, www.gpoaccess.gov.

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

United States Environmental Protection Agency, Specifications for Electric Chassis Dynamometers, Attachment A, RFP C100081T1, 1991.

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, consisting of one or more electrochemical cells electrically connected in a series and/or parallel arrangement. Often used as shorthand for traction battery, a battery that provides power to propel a vehicle. Traction batteries are typically electrically rechargeable, with charge power supplied from the electrical grid through a charger, from energy captured from regenerative braking, and/or from power generated by a fuel-powered engine.

3.2.1 Battery Ampere-Hour Capacity

The capacity of a battery in A•h obtained from a battery discharged at the manufacturer's recommended discharge rate such that a specified cut-off terminal voltage (see Section 3.2.3) is reached.

3.2.2 State-of-Charge (SOC)

The residual capacity in A•h of a battery expressed as a percent of the battery ampere-hour capacity.

3.2.3 Cut-Off Terminal Voltage

The manufacturer-recommended minimum operating voltage of the battery. This voltage can be either a function of load and/or temperature, or an absolute minimum.

3.3 FULL CHARGE (FC)

The battery state associated with maximum off-board stored energy capacity established by using the manufacturer's recommended charging procedure and appropriate equipment. The charger should indicate full charge by an easily read indicator somewhere in or on the vehicle and/or charger connections. The state must be indicated to the vehicle tester and also be achieved repeatedly from test to test for accurate and reliable calculations of AC kW•h energy consumption.

3.4 FULL DEPLETION TEST (FDT)

A test that fully depletes the useable energy content of a vehicle's battery. The test begins with the battery at a full charge and terminates when the remaining battery energy is insufficient to allow the vehicle to satisfactorily maintain the prescribed drive trace.

3.5 PARTIAL DEPLETION TEST (PDT)

A test that does not fully deplete the useable energy content of a vehicle's battery.

3.6 SINGLE CYCLE TEST (SCT)

A full depletion test consisting of multiple phases of the same drive cycle (i.e., drive schedule).

3.7 MULTI CYCLE TEST (MCT)

A full depletion test consisting of multiple phases of one or more drive cycles. The MCT enables the determination of range and energy consumption for multiple drive cycles using a single full depletion test. Data from the MCT can also be used to make range determinations for additional drive cycles that are not included in the MCT, but that are run in a standalone PDT.

3.8 AC RECHARGE ENERGY (Eac)

The AC energy, measured in AC W•h, from the power outlet required to return the battery to full charge after a test. This measurement must include energy needed to power charging equipment (e.g.,, EVSE).

3.9 DISCHARGE ENERGY (Edc)

The net DC energy output of the battery, in DC W•h, measured while a vehicle is driven over a test cycle. The equation for calculating vehicle DC energy is given in Equation 1, however, in practice it is expected that this calculation will typically be performed internally by a power analyzer as specified in Section 4. Battery voltage measurements made by the vehicles own on-board sensors (such as those available via a diagnostic port) may be used for calculating discharge energy if these measurements are equivalent to those produced by applicable external measurement equipment, such as a power analyzer.

$$Edc = \frac{1}{3600 \times f} \times \sum_{j=0}^{n} V_j \times i_j \qquad \text{(Eq.1)}$$

TABLE 1 - EQUATION SYMBOL EXPLANATIONS

Symbol	Symbol Represents	Units
V_j	Battery DC bus voltage	Volts
i_j	Battery current	Amps
$\sum_{j=0}^{j=n} V_j \times i_j$	The sum of the product of battery voltage and current flow into and out of the battery throughout the length of the test and/or cycle	Watts
f	The frequency of current measurements	Hertz
n	Number of samples	-

NOTE: The current measurement point for the battery(ies) current must be selected such that any and all of the current flowing through the battery(ies) is measured, including current associated with regenerative braking.

3.10 PHASE AND CYCLE DISCHARGE ENERGY ($Edc_{[cycle]\_i}$, $Edc_{[cycle]}$)

The phase discharge energy, measured in DC W•h, is the discharge energy associated with a specific phase of a test. The phase discharge energy is given by $Edc_{[cycle]\_i}$, with [cycle] indicating the drive cycle type and subscript "i" indicating the phase number (i.e., the run order of the phase relative to other phases of the same drive cycle type). The cycle discharge energy is the summation of phase discharge energies for all phases of the same drive cycle type. For example, Edc_{UDDS_2} indicates the phase discharge energy for the second UDDS driven during a test, and Edc_{UDDS} is the summation of discharge energies for all UDDS phases contained in the test.

$$Edc_{[cycle]} = \sum_{1}^{\text{number of phases of given cycle}} Edc_{[cycle]\_i} \qquad \text{(Eq. 2)}$$

3.11 TEST DISCHARGE ENERGY (Edc_{total})

The sum of the discharge energies, measured in DC W•h, for all phases of a test, inclusive of all drive cycle types.

$$Edc_{total} = \sum^{\text{all test phases / cycles}} Edc_{[cycle]} \qquad \text{(Eq. 3)}$$

3.12 USEABLE BATTERY ENERGY (UBE)

The useable battery energy is defined as the total DC discharge energy (Edc_{total}), measured in DC W•h, for a full depletion test (section 3.4). The useable battery energy represents the total deliverable energy the battery is capable of providing while a vehicle is driving a test cycles on a chassis dynamometer.

$$UBE = Edc_{total}\big|_{FDT} \qquad \text{(Eq. 4)}$$

The UBE that is determined during the MCT is generally applicable to other tests consisting of the cycles listed in Section 6, provided the test temperature is at or above 10°C (50°F).

3.13 ENERGY CONSUMPTION (ECac, ECdc)

Energy consumption is the energy used by the vehicle in traveling a particular distance. Two types of energy consumption are used in this procedure: (1) AC energy consumption calculated using AC recharge energy, measured in AC W•h, and, (2) DC discharge energy consumption calculated using DC discharge energy, measured in DC W•h. Energy consumption is energy per unit distance, represented as AC W•h / km (W•h / mi) or DC W•h / km (W•h / mi)

$$ECac = \frac{Eac}{\text{distance travelled}} \qquad \text{(Eq. 5)}$$

$$ECdc = \frac{Edc}{\text{distance travelled}} \qquad \text{(Eq. 6)}$$

3.14 FULL RECHARGE ENERGY (FRE)

The total recharge energy is the AC recharge energy, measured in AC W•h, needed to return the battery to full charge in the recharging period immediately following a full depletion test. Battery recharge energy is measured as specified in Section 7.2.5.

$$FRE = Eac\big|_{FDT} \qquad \text{(Eq. 7)}$$

Full recharge energy for a test and recharge conducted at -7°C (20°F) is designated by FRE_{20}.

3.15 RECHARGE ALLOCATION FACTOR (RAF)

The ratio of the full depletion AC recharge energy (FRE) and the full depletion DC discharge energy (UBE). The RAF is used to allocate the measured AC recharge energy to the individual test phases based on the DC discharge energy expended in each phase. This factor enables AC energy consumption determinations for multiple drive cycles using a single recharging event.

$$RAF = \left.\frac{Eac}{Edc_{Total}}\right|_{FDT} = \frac{FRE}{UBE} \quad \left(\frac{AC, W \cdot hr}{DC, W \cdot hr}\right) \qquad \text{(Eq. 8)}$$

The RAF, UBE and FRE that are determined using the Combo MCT are generally applicable to other tests consisting of the cycles listed in Section 6, provided the ambient test temperature is at or above 10°C (50°F).

3.16 DC DISCHARGE AMP-HOURS (C_D)

The net DC A•h discharged from the battery during a test.

NOTE: The measurement points for the battery(ies) must capture any and all of the current flowing into and out of the battery(ies) during vehicle operation, including current associated with regenerative braking.

3.17 DC RECHARGE AMP-HOURS (C_C)

The net DC A•h delivered to the battery during the recharge period immediately following the test where C_D is measured.

NOTE: The current measurement point for the battery(ies) current must be selected such that any and all of the current flowing through the battery(ies) is measured during the recharge event.

3.18 CHARGE RECOVERY (CR)

The ratio of total post-test DC recharge (C_C) to the total DC discharge (C_D). Charge recovery is used to evaluate the equivalence of the pre- and post-test charge.

$$CR = \frac{|C_C|}{|C_D|} \qquad \text{(Eq. 9)}$$

3.19 ELECTRIC VEHICLE SUPPLY EQUIPMENT (EVSE)

The conductors, including the ungrounded, grounded, and equipment grounding conductors and the electric vehicle connectors, attachment plugs, and all other fittings, devices, power outlets, or apparatuses installed specifically for the purpose of delivering energy from the premises wiring to the electric vehicle.

3.20 BATTERY ELECTRIC VEHICLE (BEV)

A vehicle that receives its power solely from batteries, unlike a hybrid vehicle that may receive a portion of its power from a separately-fueled power source, such as an internal combustion engine.

3.21 INTERNAL COMBUSTION ENGINE VEHICLE (ICEV)

A vehicle that receives a portion, if not all, of its power from an internal combustion engine (including HEVs and PHEVs).

3.22 MPGe

Miles per gallon equivalent. This parameter is generally used to quantify a fuel economy for vehicles that use a fuel other than gasoline or diesel. This value represents the miles a vehicle can drive with the energy equivalent to one gallon of gasoline. At the time of this document's publication, 33705 Watt hours per gallon of gasoline is accepted and used by the EPA for fuel economy labeling purposes.

3.23 CYCLE

The specific speed vs. time profile associated with test phase (e.g.,, UDDS, HFEDS, etc.), used synonymously with drive cycle or schedule. Also refers to specific groupings of phases of the same drive cycle type, for example: City (UDDS phases), Highway (HFEDS phases).

3.24 PHASE

A time period consisting of a specific subset of the overall test duration. Phases are typically delineated by a single occurrence of a drive cycle (or in some cases by a predefined subset of a drive cycle). The phase number indicates the run order of a phase within a test relative to other phases of the same drive cycle.

3.25 TEST

A test consists of a series of phases that run in succession until the end-of- test criteria are met.

3.26 START-OF-TEST

The point during a test at which the vehicle power switch is first placed in the "on" or "run" position, following applicable manufacturer "starting" procedures.

3.27 END-OF-TEST (EOT)

The point (in time and distance) at which the vehicle has been decelerated to a rest (zero speed) condition after the appropriate test termination criteria have been met and the vehicle power switch is placed in the "off" position.

4. TEST CONDITIONS AND INSTRUMENTATION

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), 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 All accessories shall be turned off except those required by the test procedure.

4.1.3 For testing on a 2WD dynamometer, the vehicle shall be tested at Equivalent Test Weight (ETW), which is assigned according to its Loaded Vehicle Weight (LVW) (curb weight plus 136 kg (300lbs)). (40 CFR Part 86.129)

NOTE: Trucks over 3856 kg (8500 lb) GVW may be tested at curb weight plus one-half vehicle payload, defined as the adjusted loaded vehicle weight (ALVW).

4.1.4 If the vehicle has regenerative braking, the regenerative braking system shall be enabled for all dynamometer testing, with the exception of coastdown testing (e.g.,, SAE J2264). Sections 4.4.2 and 4.4.3 provide additional guidance on proper implementation of regenerative braking for track and dynamometer testing.

4.1.5 If the vehicle is equipped with an Antilock Braking System (ABS) or a Traction Control System (TCS) and is tested on a two wheel dynamometer, the vehicle's ABS or TCS may inadvertently interpret the non-movement of the set of wheels that are off the dynamometer as a malfunctioning system. If so, modifications to the ABS or TCS shall be made to achieve normal operation of the remaining vehicle systems, including the regenerative braking system.

4.2 Condition of Battery

4.2.1 The battery shall have been aged with the vehicle as defined in Section 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 aging periods may be used for non-lead-acid battery technologies, if supported by the manufacturer as being equivalent.

4.2.2 All batteries shall be cycled in accordance with the vehicle manufacturers 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.

4.3 Environmental Conditions

4.3.1 Ambient temperatures during vehicle and battery ambient soak, test, and recharge period shall all be within the range of 20 to 30 °C (68 to 86 °F). For tests performed at other temperatures (such as an SC03 or Cold UDDS) refer to the appropriate Federal Regulation to determine soak and test temperature requirements. In general, the pre-test and post-test soak/recharging period should be conducted at the same ambient temperature.

4.3.2 Cold temperature testing requires the vehicle and battery ambient soak, test, and re-charge period remain within the temperature range specified in CFR 86.230-11(C).

4.4 Dynamometer

4.4.1 Dynamometers used for testing BEVs shall have the capabilities specified in 40 CFR Part 86.108-00.

4.4.2 Dynamometer coefficients shall be determined as specified in SAE J2263 and J2264, with the following provisions:

a. Vehicles equipped with regenerative braking systems that are activated only when the brake pedal is depressed require no special actions for coastdown testing on the test track or dynamometer. Vehicles equipped with regenerative braking systems that are automatically actuated during decelerations (without brake pedal input from the driver) shall have regenerative braking disabled during the deceleration portion of coastdown testing on both the test track and dynamometer. Methods to disable regenerative braking on both the test track and the dynamometer shall be determined by the manufacturer.

b. The dynamometer's inertia simulation shall be set as specified in 40 CFR Part 86-129-00. If the effective rotational mass of the vehicle differs significantly from the estimates given in SAE J2263 and J2264 (1.5% of test mass per axle), the actual effective mass should be experimentally determined. If the vehicle does not have a mechanical neutral, the manufacturer shall prescribe procedures and calculation methods for coastdown and road-load determination that correctly account for the actual rotational inertia.

4.4.3 Four-wheel drive, all-wheel drive, or vehicles with regenerative braking on only one axle are preferably tested on four-wheel drive dynamometers. If tested on two-wheel drive dynamometers or in two wheel drive mode, the vehicle must be properly configured per 40 CFR 86.135-90. The vehicle should be configured in such a way as to account for any significant additional regenerative braking due to the loss of friction braking on the non-regenerative axle. Dynamometer assisted braking shall be turned off during testing.

4.5 Test Instrumentation

This section provides a list of instruments that are required to perform the tests specified in this document, , except for distance measurements which must be within ±0.5% of the total distance traveled. Coastdown measurement instrument accuracy is described in SAE J2263 or SAE J2264, as applicable.

4.6 General Instrumentation

Equipment referenced in 40 CFR Part 86.106 is required, where appropriate. All measurements shall be NIST-traceable (National Institute of Standards and Technology). The following instruments are either additionally required or recommended for as-needed usage:

a. A DC wideband voltage, Ampere, and Watt-hour meter (power analyzer): Voltage and current of the battery pack are measured directly with this meter. It shall be installed in such a way as to measure all current leaving and entering the battery pack (no other connections upstream of the measurement point). Ampere-hour meters using an integration technique shall have a maximum integration period of 0.05 s, so that abrupt changes of current can be accommodated without introducing significant integration errors. Total accuracy of current and voltage measurements shall be 1% of the reading or 0.3% of full scale, whichever is larger. Instruments shall not be susceptible to offset errors while measuring current, because very small current offsets can be integrated throughout the cycle and provide erroneous energy or ampere-hour results.

b. A DC wideband Ampere-hour meter: If voltage sensing is not available, then one should optionally measure A•h without directly sensing voltage. In this case, the voltage shall be monitored (logged) from vehicle network data.

c. An AC Watt-hour meter to measure AC recharge energy (if applicable): It shall be installed in such a way as to measure all AC electrical energy entering the charger. The AC Watt-hour meter shall have a total accuracy of voltage and current of 1.0% of the reading or 0.3% of full scale whichever is larger.

d. An instrument to measure the pedal position (or an equivalent indicator of the driver's acceleration demands) for US06 dynamometer load adjustments (when applicable).

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

5. DATA TO BE RECORDED FOR ALL TESTS

Table 2 lists the data and parameters that must be recorded in order to perform the SCT and MCT test procedures described in this document. The determination of certain items in this table may inherently require the measurement of intermediate quantities not explicitly listed (e.g., current, voltage).

TABLE 2 - REQUIRED PARAMETERS TO BE RECORDED

Item	Parameter/Measurement	Description	Units
1	Battery Ampere-Hour Capacity	Section 3.2.1	DC A•h
2	Ambient Test Temperature	-	°C (°F)
3	Time, Soak Start	Pre-test soak period	-
3	Time, Soak End	Pre-test soak period	-
4	Time, Test Start	-	-
5	Distance Driven (Total)	-	km (mi)
6	Distance Driven Per Phase ($D_{[cycle]\_i}$)	-	km (mi)
7	Discharge Energy[1] (Edc)	Net DC Watt-Hours discharged during test (Section 3.9)	DC W•h
8	DC Discharge Amp-Hours (C_D)	Net DC A•h discharged (Section 3.16)	DC A•h
9	Time, End of Test	-	-
10	Vehicle Charging Mode	If multiple settings available	-
11	Time, Start of Charge	Time connected to EVSE	-
12	Power Outlet Voltage	Nominal AC voltage at power outlet	AC Volts
13	AC Recharge Voltage[2]	Real-time RMS voltage measured at power outlet (1 sample per minute minimum)	AC Volts
14	AC Recharge Energy (Eac, FRE)	Total AC Energy from power outlet (Sections 3.8, 3.14)	AC W•h
15	DC Recharge Amp-Hours (C_C)	Net DC A•h returned to battery (Section 3.17)	DC A•h
16	Time, End of Recharging Period	Time Full Charge (FC) is achieved	-

[1]Optional for SCT [2]Recommended

6. DRIVE SCHEDULES

There are five driving schedules (also known as drive cycles) referenced in this document which are required by the EPA and the California Air Resources Board during emissions and fuel economy certification of ICEVs. They are the Urban Dynamometer Driving Schedule (UDDS), the "Cold" UDDS, the Highway Fuel Economy Driving Schedule (HFEDS), the US06 Driving Schedule (US06), and the SC03 Driving Schedule (SC03). Additionally, a constant-speed cycle is defined for use in this procedure.

NOTE: At the time of this document's publication, only the UDDS and HFEDS tests are required for BEV certification in the United States & Canada.

6.1 UDDS

The Urban Dynamometer Driving Schedule is defined in 40 CFR Part 86, Appendix 1. It has a duration of 22 min, 52 s. It is used to represent vehicle city driving.

6.2 HFEDS

The Highway Fuel Economy Driving Schedule is defined in 40 CFR Part 600, Appendix 1. It has a duration of 12 min, 45 s. It is used to represent vehicle highway driving.

6.3 US06

The US06 Driving Schedule is defined in 40 CFR Part 86, Appendix 1. It has a duration of 9 min, 56 s. It is used to represent vehicles driving at high speeds and accelerations. Dynamometer load reduction for low-powered vehicles may be used in accordance with 40 CFR Part 86.108 00(b)(2)(ii).

6.4 SC03

The SC03 Driving Schedule is defined in 40 CFR Part 86, Appendix 1. It has a duration of 9 min, 56 s. It is used to represent vehicle operation with air conditioning.

6.5 “Cold” UDDS

Same as UDDS schedule. The test is performed in cold ambient conditions as defined in 40 CFR Part 86, Subpart C

6.6 Constant Speed Cycle (CSC)

The constant speed cycle is used to rapidly deplete battery energy, and consists of a steady-state speed schedule of 90km/h (55mi/h). The initial acceleration to 90km/h (55 mi/h) - or 90% of maximum sustainable speed if a vehicle cannot reach 55mph – must be smooth and accomplished within 1 min of the key switch being placed in the "on" position. The vehicle’s speed must be held within the tolerances defined in Section 6.7. The CSC may be broken into distinct sub-phases of at least 5 min (unless the test termination criteria are met before this time) and no longer than 60 min. A 5-30 min key-off soak must be performed between each CSC sub-phase.

6.7 Speed Tolerance

The speed tolerance at any given time on these driving schedules is defined by the upper and lower limits, as described in 40 CFR (Part 86.115-78).

6.8 Speed Tolerance Violations

Speeds that violate the speed tolerance may constitute an invalid test; however, for an entire full depletion test procedure consisting of many test phases, infrequent speed excursions that exceed the speed tolerance described in Section 6.7 are acceptable, if due to driver variability. The criterion for a valid full depletion test is: no more than one violation of the tolerances referenced in Section 6.7, per test phase. Individual violations should not exceed a tolerance of ± 4 mph of the target speed within a 2s period. Additional allowances for tire slippage, brake spikes or other vehicle and/or dynamometer-related anomalies shall be considered according to §86.115-78. Vehicles with a maximum speed capability that is less than the maximum speed on the drive cycle shall be operated at maximum available power (or full throttle) when the vehicle cannot achieve the speed trace within the speed and time tolerances specified in section 6.7. Good engineering judgment shall be used in applying this speed tolerance allowance given the additional demands on personnel associated with testing BEVs.

6.9 Intra-test Pauses

The following pauses are used for tests requiring repeated pairs of drive cycles:

- City: 2 x UDDS. Between each UDDS, the vehicle shall soak for 10 min ± 1 min
- Highway: 2 x HFEDS. Between each HFEDS, there is to be a 15-s key-on pause
- US06: 2 x US06. Between each US06, there is to be an key-on pause for 90-s ± 30-s,
- SC03: 2 x SC03. Between each SC03, the vehicle shall soak for 10 min ± 1 min

7. SINGLE CYCLE RANGE AND ENERGY CONSUMPTION TEST (SCT)

7.1 Purpose of Test

The purpose of this test is to determine either the total City or total Highway range and energy consumption for a BEV when operated on a chassis dynamometer over repeated UDDS or HFEDS driving cycles, respectively. This is a full-depletion test where the vehicle is driven until the useable energy content of the vehicle's battery is completely exhausted. It is the intent of this section to provide standard procedures for testing BEVs so that their performances can be compared when operated over standard drive cycles. This procedure is recommended for vehicles with a range capability less than 97 km (60 miles).

7.2 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.

7.2.1 Preconditioning

Preconditioning should consist of repeatedly driving the vehicle driven through one or more of the standard emissions test cycles referenced in this document until the vehicles battery is fully depleted (a full depletion range test may be used to satisfy this requirement). This method is recommended to ensure that the subsequent recharge event produces a repeatable battery energy capacity prior to the test; however, a preconditioning sequence that does not fully deplete the battery but consists of at least one UDDS or HFEDS cycle is also acceptable if it results in equivalent pre-test useable battery energy.

Following the preconditioning drive, the vehicle, battery, and thermal management system, if any, shall be soaked for at least 12 h and not more than 36 h. The vehicle shall remain on charge for the duration of the soak period, and the soak shall not end before full charge is reached. Upon completion of the soak, the vehicle shall be moved (pushed or towed - not driven) into position on the chassis dynamometer. The vehicle drivetrain shall 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. The dynamometer test must begin no more than one hour after the vehicle is taken off charge.

NOTE: The 12 to 36 hr flexibility in soak duration provided in section 7.2.1 is considered appropriate for testing at 20 to 30 °C (68 to 86 °F). However, for testing conducted -7°C (20°F), inconsistent soak times (or time between unplugging the vehicle and starting the test) could result in undesirable variability in pre-test battery pack temperatures, potentially impacting test results.

7.2.2 Range and Energy Consumption Dynamometer Test

The vehicle shall be repeatedly operated over one of the following pairs of drive cycles:

City Test: 2 x UDDS

Highway Test: 2 x HFEDS

The cycle pairs are repeated until the end-of-test criteria have been satisfied (Section 7.2.3) as shown in Figures 1 and 2.

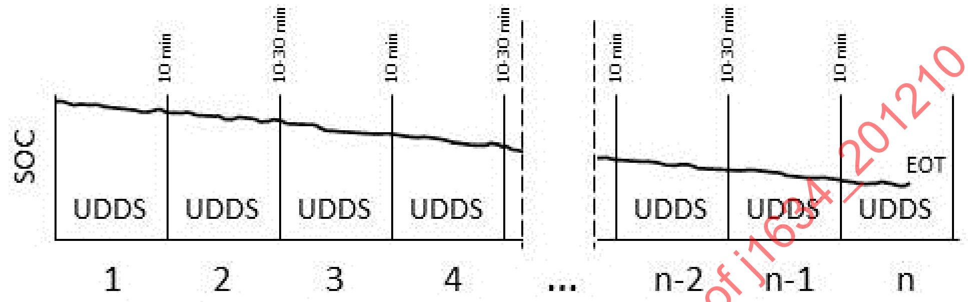

FIGURE 1 - REPEATED CITY TEST

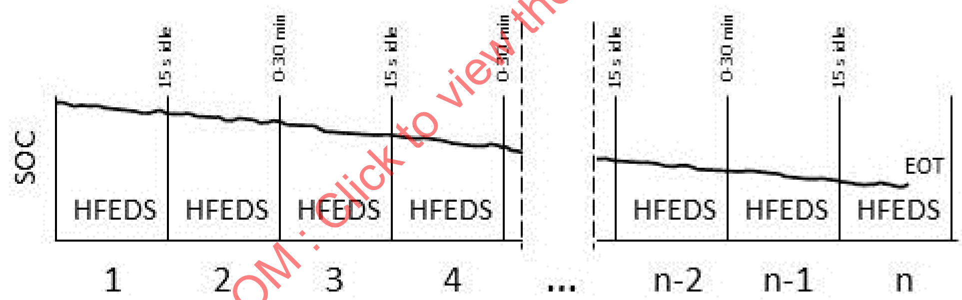

FIGURE 2 - REPEATED HIGHWAY TEST

The required intra-test soak times are given in 6.9. Between each cycle pair the vehicle must soak for: 10 to 30 min for the City test, and 0-30 min for the Highway test (as shown in Figures 1 and 2). During all soak periods, the key or power switch must be in the "off" position, the hood must be closed, the test cell fan(s) must be off, and the brake pedal not depressed. Test site ambient temperature shall be maintained in accordance with 4.3.1. Dynamometer coastdown "quick checks" are not required.

DC discharge A•h (C_D) must be measured during the entire dynamometer test procedure (driving phases and soaks) in order to validate the equivalence of the pre- and post-test charge.

7.2.3 End-of-Test (EOT) Criteria

The test termination criterion for the full-depletion range and energy consumption test is defined as follows:

(a) For vehicles capable of meeting the prescribed speed vs. time relationship of the applicable drive cycle, the test termination criterion for the full-depletion range and energy consumption test is defined as when the vehicle - due to power limitations - is incapable of maintaining the speed tolerances as defined in Section 6.8 while the driver is attempting to follow the drive schedule, or, the manufacturer determines that the test should be terminated for safety reasons, (e.g., excessively high battery temperature, abnormally low battery voltage, etc.). When the test termination criterion has been satisfied, the driver shall immediately apply the brake and decelerate the vehicle to a stop within 15 seconds. The total distance travelled once the vehicle has reached zero speed is the vehicle range.

(b) For vehicles that are not capable of meeting the prescribed speed vs. time relationship of the applicable drive cycle for the initial phase of that cycle (i.e., the phase that begins with the vehicle fully-charged) and operated at maximum available power, the test terminates when the following criterion is satisfied: 1) when the vehicle, while operated at maximum available power or "full throttle", is unable to reproduce the best-effort speed vs. time relationship established by the vehicle in the first phase of the test. The applicable drive tolerances for the best-effort trace are provided in Section 6.7. Note: The speed tolerance violation criteria given in Section 6.8 do not apply to the best-effort trace for low-power vehicles.

7.2.4 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.

7.2.5 Recharging

Within 3 h of operating the vehicle over the test cycle, the vehicle shall be placed on charge and the battery recharged to full capacity in order to measure full AC recharge energy (FRE) and DC recharge A•h (C_C). Full charge is to be established using the manufacturer's recommended charging procedure and appropriate equipment. If the vehicle is equipped with a charger, that charger shall be used. Otherwise, the vehicle shall be charged using an external charger recommended by the vehicle manufacturer. If multiple charging power levels are available, the vehicle shall be recharged at the power level recommended by the manufacturer. If not specified by the manufacturer, the recharging power level expected to be most widely utilized by end users shall be selected. Once the correct power level has been determined for a vehicle, it shall be consistently used for all pre- and post-test recharging events. Note: All the AC energy supplied to the vehicle from the electrical grid must be measured, including all energy used to power charging equipment (e.g., charger, EVSE, 12V battery charger, etc.).

For vehicles that require less than 12 hours to reach Full Charge (FC), FRE and C_C are determined by measuring the AC Recharge Energy (Eac) and DC Recharge Amp-Hours (C_C) for a 12 hour period following the connection of the vehicle to the EVSE. For vehicles requiring more than 12 hours to reach FC, the data collection period shall continue until FC is achieved. The 12 hour minimum data collection period is intended to better replicate expected in-use charging practices (i.e., overnight charging) and to provide a standard time period that can be used quantify any ancillary recharging loads, such as those resulting from battery thermal conditioning.

Recharging must be conducted at the same nominal ambient temperature as the pre-test soak/charging period. 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. The recharging period must appropriately quantify the energy used to condition or prepare the vehicle or cabin for testing during the pre-test soak/charging period (e.g.,, cabin preheating or heating of seating surfaces, battery heating/cooling)

7.2.6 Full Charge Verification

The equivalence of the pre- and post-test battery charge must be verified using the charge recovery definition in Section 3.18. Since the net A•h required to return the battery to a full charge during the recharging event must be greater than or equal to net A•h discharged by the battery during a FDT, the charge recovery ratio should be ≥ 1 for most battery types. Since the determination of full charge verification must also take into account error in the associated measurement devices, the pre- and post- test charge events can be considered equivalent if the charge recovery is greater 0.97.

$$CR = \frac{|C_C|}{|C_D|} \geq 0.97 \quad \text{(Eq. 10)}$$

7.3 Range ($R_{[cycle]}$)

Range for the SCT is defined as the total test distance driven, measured in km (miles), from the beginning of the test until the point where the vehicle reaches zero speed after satisfying the EOT criteria (Section 7.2.3).

$$R_{[cycle]} = \text{Total Distance Driven} \quad \text{(Eq. 11)}$$

The City range is total distance driven on repeated UDDS cycles (Section 7.2.2).

$$R_{City} = R_{UDDS} = \text{Total Distance Driven on City Test} \quad \text{(Eq. 12)}$$

The Highway range is the total distance driven on repeated HFEDS cycles (Section 7.2.2).

$$R_{Highway} = R_{HFEDS} = \text{Total Distance Driven on Highway Test} \quad \text{(Eq. 13)}$$

7.4 AC Energy Consumption ($ECac_{[cycle]}$)

AC energy consumption serves as an efficiency and cost-of-operation metric, and is also used to determine MPGe for fuel economy labeling purposes. Energy consumption for the SCT test is defined as the full AC recharge energy (FRE) measured during the post-test recharging period (Section 7.2.5) divided by the appropriate range value (Section 7.3).

$$ECac_{[cycle]} = \frac{FRE_{[cycle]}}{R_{[cycle]}} \quad \text{(Eq. 14)}$$

Using Eq. 14, the City energy consumption is calculated by:

$$EC_{City} = ECac_{UDDS} = \frac{FRE_{UDDS}}{R_{UDDS}} \quad \text{(Eq. 15)}$$

Using Eq. 14, the Highway energy consumption is calculated by:

$$EC_{Highway} = ECac_{HFEDS} = \frac{FRE_{HFEDS}}{R_{HFEDS}} \quad \text{(Eq. 16)}$$

8. MULTI-CYCLE RANGE AND ENERGY CONSUMPTION TEST (MCT)

8.1 Purpose of Test

The purpose of this test is the determination of multiple range and energy consumption values using a single, continuous test procedure where a vehicle is operated on a chassis dynamometer over repeated driving schedules. This is a full-depletion test where the vehicle is driven until the useable energy content of the vehicle's battery is completely exhausted. It is the intent of this section to provide standard procedures for testing BEVs so that the performance can be compared when operated over standard drive cycles. This procedure is recommended for vehicles with a range capability greater than 97 km (60 miles).

8.2 Test Methodology

The MCT consists of a fixed number of dynamic drive cycles combined with constant-speed driving phases. The fixed drive cycles are used to determine the energy consumption associated with specific and established driving patterns. The constant-speed driving schedules, which are located in the middle and the end of the test, are intended to: 1) reduce test duration by depleting the battery more rapidly than the established certification drive schedules, 2) improve the robustness of the energy determination by minimizing the impact of drive style variation, and 3) prevent inconsistent triggering of EOT criteria that can occur at high power-demand points when a BEV is following a dynamic drive schedule at low states-of-charge. Figure 3 illustrates how multiple drive cycles (UDDS, HFEDS and CSC) are combined in the Combo MCT test.

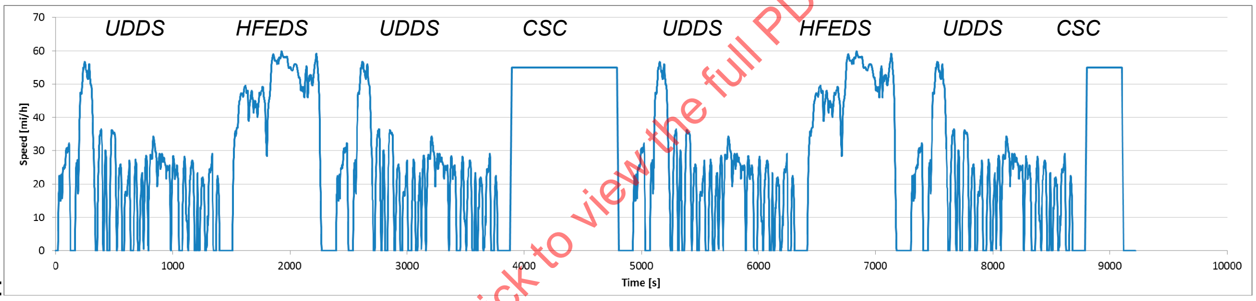

FIGURE 3 - COMBO MULTI-CYCLE RANGE TEST: SPEED VS. TIME PROFILE

In addition to measuring the cycle-specific energy consumption, the MCT also allows for the determination of cycle-specific range. Determining the range for a given cycle type requires knowledge of both the energy consumption for the drive cycle and the total energy content of the test vehicle's battery. The MCT method makes use of an in-situ determination of the battery's useable DC energy content (UBE) that - when combined with a drive cycle's DC energy consumption - can be used to determine the range for that cycle. The general equation describing this method is given in Eq. 17.

$$R_{[cycle]} = \frac{Distance_{[cycle]}}{Edc_{[cycle]}} \times UBE = \frac{UBE}{ECdc_{[cycle]}} \quad \text{(Eq. 17)}$$

The UBE determined from the Combo MCT may also be applicable to cycles listed in Section 6.6 for test temperatures ≥ 10°C (50°F), even though these cycles are not part of the Combo MCT. The ability to use a single UBE value across multiple drive cycle types – thus eliminating the need to run a separate, full-depletion test for each drive cycle - is enabled by the fact that the total deliverable battery energy has been shown to be sufficiently robust with respect to the standard dynamometer drive schedules. This property enables range determinations for cycle types that are not included in the MCT sequence from which the UBE was derived, for example the US06 or SC03, thus minimizing the need to run additional full depletion tests for these cycles (see Appendix A for specific applications). This ability to use a single energy content value (within appropriate test temperature constraints) is applicable to lithium ion batteries and the existing standard drive cycles listed in Section 6. New battery technologies, new drive schedules, or significantly different vehicle designs should be evaluated to determine if this property remains applicable.

The AC energy consumption for each drive cycle included in the MCT is determined using the Recharge Allocation Factor (Section 3.15) and the cycle-specific DC energy consumption as shown in Eq.18:

$$ECac_{[cycle]} = \frac{FRE}{UBE} \times ECdc_{[cycle]} = RAF \cdot ECdc_{[cycle]} \quad \text{(Eq. 18)}$$

The AC energy allocated to each cycle type is effectively proportional to that cycle's DC discharge energy. The RAF determined from the Combo MCT may also be applicable to cycles listed in Section 6.6 for test temperatures ≥ 10C (50F), even though these cycles are not part of the Combo MCT. Test cycles performed at -7C (20F) may require UBE and FRE determinations that are performed at the actual test temperature.

8.3 Combo Range and Energy Consumption Test

8.3.1 Test Procedure

The Combo MCT is used to determine both the City and Highway range and energy consumption values using a single, continuous full depletion test, and is to be conducted subject to the test conditions and data requirements of Sections 4 and 5.

8.3.2 Preconditioning

For 25°C (75°F) ambient temperature City and Highway range testing, the preconditioning shall follow the requirements specified in Section 7.2.1. For tests performed at other ambient temperatures refer to the appropriate Federal Regulation to determine soak and test temperature requirements.

8.3.3 Test Sequence

The combo MCT range test consists of four UDDS cycles, two HFEDS cycles and two CSC cycles. The test sequence, shown in Figure 4, is characterized by four distinct segments: 1) Sequence 1 (S_1), the initial UDDS-HFEDS-UDDS sequence, 2) the mid-test CSC depletion phase (CSC_M), 3) Sequence 2 (S_2), the second UDDS-HFEDS-UDDS sequence, and 4) the end-of-test CSC (CSC_E).

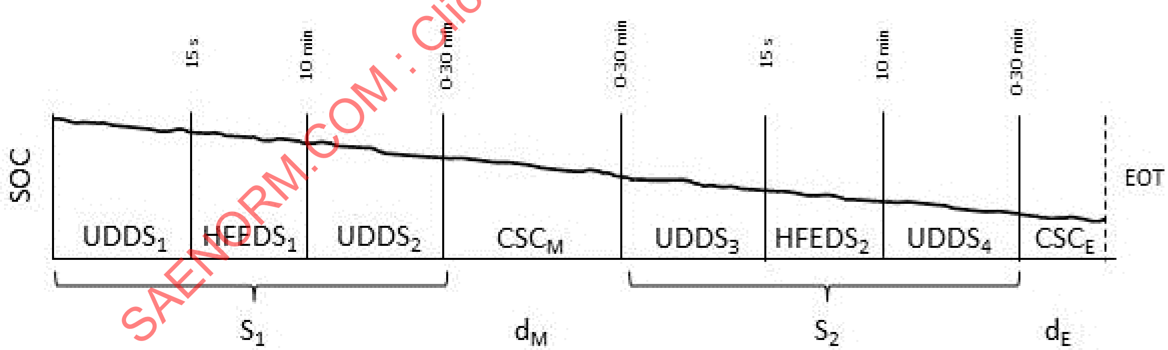

FIGURE 4 - COMBO MULTI-CYCLE RANGE TEST SEQUENCE

The UDDS and HFEDS cycles provide the cycle-specific DC energy consumption values (at both high and low states-of-charge) needed in order to calculate City and Highway range and AC energy consumption. These dynamic drive cycles make up 81.31 km (50.52 miles) of driving distance; the remainder of the vehicle's UBE is depleted using CSC phases, which deplete battery energy more rapidly than UDDS or HFEDS cycles.

The CSC_M phase is located between S_1 and S_2.This placement enables−given a sufficiently long duration for the CSC_M−the vehicle's performance on the UDDS and HFEDS to be quantified for both high and low states of charge. Since the CSC_M distance (d_M) that is required to ensure that S_2 is conducted at a "substantially" lower SOC condition than S_1 will depend on the range capability of the test vehicle, good engineering judgment should be applied in order to select an appropriate CSC_M distance. In general, a d_M should be selected such that it will result in a CSC_E distance (d_E) that is 20% or less of the total driven distance for the Combo MCT. Recommended methods for determining the length of d_M both prior to and during a test are given in Appendix B.

NOTE: The CSC_M may be omitted for vehicles that are projected to meet the maximum CSC_E distance recommendation without a CSC_M (i.e., vehicles with relatively short range capability).

The test is concluded with a CSC (CSC_E) to enable a more consistent triggering of the end-of-test criterion and to prevent step changes in the range determination that have been observed when dynamic cycles with varying power demands are used to end a FD test.

8.3.4 Dynamometer Test

The vehicle shall be operated over the test sequence described in Section 8.3.3. The required soak times (also shown in Figure 4) are as follows: 15s key-on pause between $UDDS_1$ and $HFEDS_1$, and $UDDS_3$ and $HFEDS_2$; 10 min key-off soak between $HFEDS_1$ and $UDDS_3$, and $HFEDS_2$ and $UDDS_4$; 0-30 min optional soak preceding and following the CSC phases. The CSC_M and CSC_E portions of the test may be segregated into distinct sub-phases with associated soak periods as described in Section 6.6. During all soak periods, the key or power switch must be in the "off" position, the hood must be closed, the test cell fan(s) must be off, and the brake pedal not depressed. Test site ambient temperature shall be maintained in accordance with Section 4.3.1. The test is terminated when end-of-test criteria in Section 7.2.3 have been satisfied during the CSC_E. Dynamometer coastdown "quick checks" are not required

Within 3 hours of completing the test, the vehicle must be placed on-charge following the requirements specified in Section 7.2.5.

DC discharge energy (Edc) and DC discharge amp-hours (C_d) must be measured for the entire test.

8.4 Phase Scaling Factors

The phase scaling factors determine the contribution of each phase's energy consumption value to the total energy consumption for a given drive cycle type. Application of the generic phase scaling factors given in Eq. 19, 20, and 21, results in a cycle-specific energy consumption that is equivalent to the taking an un-weighted average of the individual energy consumption values for each phase:

$$K_{[cycle]\_i} = \frac{1}{n_{[cycle]}} \quad \text{(Eq. 19)}$$

$n_{[cycle]}$ is the total number of measured test phases of a particular cycle type and the subscript "i" is the phase run order within a given cycle type. For the UDDS and HFEDS phases contained within the MCT sequence, the generic phase scaling factors are defined as follows:

$$K_{UDDS\_i} = \frac{1}{n_{UDDS}} = \frac{1}{4} (i = 1, 2, 3, 4) \quad \text{(Eq. 20)}$$

$$K_{HFEDS\_i} = \frac{1}{n_{HFEDS}} = \frac{1}{2} (i = 1, 2) \quad \text{(Eq. 21)}$$

8.4.1 SCT-Equivalent UDDS Phase Factors

It has been observed that in certain BEV applications the energy consumption of the first UDDS is significantly higher than that of subsequent UDDS phases, likely due to regenerative braking limitations at high states-of-charge and/or “cold start” parasitic losses. For the SCT, the relative impact of this effect is minimal because the contribution of the first UDDS to the overall test result is diluted by the inclusion of many additional UDDS phases (13+ for a vehicle with a 160 km (100 mi) range). However, for the MCT the vehicle’s performance on first UDDS has a much greater impact on the total UDDS results since the test sequence includes only four UDDS phases. In order to make the City MCT results equivalent to those produced from the City SCT, the following SCT-equivalent cycle scaling factors are used in the City range and energy consumption equations:

$$K_{UDDS\_1\_e} = \frac{Edc_{UDDS\_1}}{UBE} \quad \text{(Eq. 22)}$$

$$K_{UDDS\_2\_e} = K_{UDDS\_3\_e} = K_{UDDS\_4\_e} = \frac{1 - K_{UDDS\_1\_e}}{3} \quad \text{(Eq. 23)}$$

Under this formulation, the relative contribution of first UDDS phase to the total UDDS energy consumption is proportional to its fraction of the total discharge energy (UBE), thus replicating the relative impact of the first phase that is inherent in the City SCT. Equal weightings are then assigned to UDDS phases 2, 3, and 4 as shown in Eq. 23 (since the scaling factors are simply a normalized weighted average, they must have a sum equal to 1).

8.5 DC Discharge Energy Consumption

DC discharge energy consumption is required in order to calculate range and AC energy consumption for the MCT. It is to be determined uniquely for each phase of the test - with phases of the same drive schedule differentiated by a subscript indicating relative phase order within the drive schedule type - and is defined as the ratio of discharge energy to distance traveled:

$$ECdc_{[cycle]\_i} = \frac{Edc_{[cycle]\_i}}{D_{[cycle]\_i}} \quad \text{(Eq. 24)}$$

Where $D_{[cycle]\_i}$ is the driven distance for the phase.

The total DC energy consumption for each drive cycle is calculated by summing the product of the phase scaling factor and the respective DC discharge energy consumption for all phases of a given cycle type.

$$ECdc_{[cycle]} = \sum [K_{[cycle]\_i} \cdot ECdc_{[cycle]\_i}] \quad \text{(Eq. 25)}$$

The City discharge energy consumption, using the SCT-equivalent scaling factors in Section 8.4.1, is then

$$\begin{aligned} ECdc_{City} &= (K_{UDDS\_1\_e} \cdot ECdc_{UDDS\_1}) + (K_{UDDS\_2\_e} \cdot ECdc_{UDDS\_2}) \\ &+ (K_{UDDS\_3\_e} \cdot ECdc_{UDDS\_3}) + (K_{UDDS\_4\_e} \cdot ECdc_{UDDS\_4}) \end{aligned} \quad \text{(Eq. 26)}$$

The Highway discharge energy consumption, using the generic scaling factors in Section 8.4, is then

$$\begin{aligned} ECdc_{Highway} &= K_{HFEDS\_1} \cdot ECdc_{HFEDS\_1} + K_{HFEDS\_2} \cdot ECdc_{HFEDS\_2} \\ &= \frac{ECdc_{HFEDS\_1} + ECdc_{HFEDS\_2}}{2} \end{aligned} \quad \text{(Eq. 27)}$$