Annex A2: Test Procedure for Measuring Fuel Economy and Emissions of Low Carbon Emission Buses Powered by Charge Sustaining Hybrid Powertrains

TABLE OF CONTENTS

1. Scope

This document provides an accurate and reproducible procedure for simulating the operation of buses powered by charge sustaining hybrid powertrains on dynamometers for the purpose of measuring emissions and fuel economy.

A hybrid vehicle is defined as having both a rechargeable energy storage system (RESS) capable of releasing and capturing energy and an energy-generating device that converts consumable fuels into propulsion energy. This procedure specifically includes batteries, capacitors and flywheels, although other types of RESS can be evaluated by following the guidelines provided. The procedure also provides a detailed description of state of charge (SOC) correction for charge-sustaining HEVs in order to correct for changes that occur over the length of the test. It should be noted that most buses addressed in this recommended practice are expected to be powered by engines that are certified separately for emissions. In these cases the engine certification procedure appears in Regulation 77/88/EC.

This test procedure does not make specific provisions or recommendations for testing of bus emissions with air conditioning deployed because the complexity of such tests is significant. All auxiliary loads will be turned off during the test, unless they affect the normal operation of the vehicle.

The intention is to test the vehicle in it's normal road-going condition and operating strategy as far as reasonably practical, within the constraints of the equipment and cycle. Potential exceptions to this include antilock brakes and traction control. Any aspect of vehicle operation which needs to be modified for the test shall be discussed with the test centre and recorded in the test report.

The procedure requires the calculation of Well-to-Wheel (WTW) Greenhouse Gas (GHG) emissions in order to determine if the vehicle qualifies as a Low Carbon Emission Bus.

The vehicle will be tested over the Millbrook London Transport Bus (MLTB) drive cycle representing intermediate-speed bus operation in London. Details of this cycle can be found in Appendix 1 of this document.

Alternative cycles may be used as detailed in the Vehicle Accreditation Requirements document.

Regulated emissions (HC, CO, NOx and PM) and carbon dioxide shall be sampled over the entire cycle and the results presented as gm/km.

For all buses, the concentration of nitrous oxide (N_2O) shall be determined using Fourier Transfer Infra-Red spectroscopy (FTIR) techniques.

For all buses, the concentration of methane (CH_4) shall be determined by separate analysis.

2. Definitions and Terminology

BATTERY -- A device that stores chemical energy and releases electrical energy.

BATTERY C/3 CURRENT RATE -- The constant current (Amperes) at which the battery can be discharged from its rated capacity in three hours to its manufacturer's recommended minimum. Battery manufacturers typically provide ratings from C/1 to C/6. These ratings have no direct impact on this recommended practice.

BATTERY DEPTH OF DISCHARGE (DOD) -- The percentage of rated capacity to which a cell/battery is discharged. State of charge (SOC) % + DOD% = 100%.

BATTERY RATED AMPERE-HOUR CAPACITY -- The manufacturer-rated capacity of a battery in Ampere-hours, obtained from a battery discharged at the manufacturer's recommended discharge rate (C/1 - C/6) such that a specified minimum cut-off terminal voltage or state of charge is reached.

BATTERY STATE OF CHARGE (SOC) – Based on the actual measured energy content of a battery and expressed in Ampere hours, or as a percentage of the battery's maximum rated Ampere hour (Ah) capacity.

CAPACITOR -- A device that stores energy electrostatically and releases electrical energy.

CAPACITOR STATE OF CHARGE (SOC) – Based on the actual measured energy content of a capacitor and expressed as a percentage of the capacitor's maximum rated voltage squared (V^2).

CHARGE-SUSTAINING HEV -- A charge-sustaining HEV derives all of its energy from on board fuel under normal usage. Over a short period of time charge-sustaining hybrid-electric vehicles may be either charge depleting or charge increasing. The definition means that that in the long term (24 hours) a RESS charge is sustained. The procedure includes provisions for calculating SOC corrections in the short term that reflect emissions from the vehicle as if it was charge sustaining in the short term.

CONSUMABLE FUEL -- Any solid, liquid, or gaseous material that releases energy and is depleted as a result.

ELECTROMECHANICAL FLYWHEEL -- A device that stores rotational kinetic energy and can release that kinetic energy to drive the vehicle, either directly, or via an electric motor-generator system.

ELECTROMECHANICAL FLYWHEEL STATE OF CHARGE (SOC) – Based on the actual measured energy content of an electromechanical flywheel and expressed as a percentage of the flywheel's maximum-rated revolutions per minute squared (rpm^2).

HYBRID-ELECTRIC VEHICLE (HEV) -- A road vehicle that can draw propulsion energy from both of the following on-vehicle sources of stored energy: 1) one consumable fuel and 2) one (or more) RESS that is recharged by an on-board electric generating system, or an off-board charging system, or recovered kinetic energy.

NET ENERGY CHANGE (NEC) -- The net change in energy level of an RESS expressed in Joules (watt-seconds), or as a percentage of the Total Cycle Energy.

PRIME MOVER – Power unit which provides the primary source of mechanical energy used to move the vehicle

PROPULSION ENERGY -- Energy that is derived from the vehicle's consumable fuel and/or rechargeable energy storage system to drive the wheels. If an energy source is supplying energy only to vehicle accessories (e.g., a 12-volt battery on a conventional vehicle), it is not acting as a source of propulsion energy.

PROPULSION SYSTEM -- A system that, when started, provides propulsion for the vehicle in an amount proportional to what the driver commands.

REGENERATIVE BRAKING -- Deceleration of the vehicle caused by operating an energy recovery system, thereby returning energy to the vehicle propulsion system and providing charge to the RESS or to operate on-board auxiliaries.

RECHARGEABLE ENERGY STORAGE SYSTEM (RESS) -- A component or system of components that stores energy and for which its supply of energy is rechargeable by an electric motor-generator system, an off-vehicle electric energy source, or recovered kinetic energy, or a combination of thereof. Examples of RESS for HEVs include batteries, capacitors, and electromechanical flywheels.

STATE OF CHARGE – see "Battery state of charge"

TOTAL CYCLE ENERGY -- The total energy expended by the vehicle in driving the test cycle. This is equal to the Total Fuel Energy minus the RESS Net Energy Change in Joules.

TOTAL FUEL ENERGY -- The total energy content of the fuel in MJ consumed during a test as determined by carbon balance or other acceptable method and calculated based on the lower heating value of the fuel.

3. State of Charge – Charge-Sustaining Hybrid Vehicles

When a conventional vehicle completes a chassis dynamometer test, the energy provided by the combustion engine is equal to the total energy necessary to complete the cycle, and this value is consistent from test run to test run. There is no energy storage on board the vehicle other than consumable fuel, and no need for state of charge (SOC) correction.

However, in a Hybrid Electric Vehicle (HEV), for example, a significant amount of motive energy is stored on board the vehicle within the RESS, and the vehicle may remove or add energy to this energy reservoir over short periods of time. In order to compare the emission results of an HEV to a conventional vehicle, the data from the HEV must be corrected so that the net change in RESS energy is essentially zero (i.e., all of the energy and emissions are essentially provided by the Prime Mover).

This procedure allows for some level of tolerance between the initial SOC and final SOC to avoid correcting the fuel economy and emission results unnecessarily. A net energy change of ±1% or less in stored energy, compared to total cycle energy, is considered negligible and does not require SOC correction calculations. If the percentage change is greater than ±1% but less than ±5%,a correction procedure can be applied, providing a clear relationship between NEC and emissions and fuel economy can be established. This procedure is outlined below in Section 3.4. If the vehicle has a NEC greater than 5%, the collected data may not be reliably corrected and the test should be considered invalid. If a vehicle repeatedly produces test results where the NEC is above 5% then it should be considered to be a charge depleting hybrid and tested according to the procedure in Annex A3.

3.1 SOC Terminology

The following terms are used to distinguish between the different values of SOC referred to in the test procedure.

$SOC_{initial}$:	SOC at the beginning of the test run (Ah, V^2 or rpm^2)
SOC_{final} :	SOC at the end of the test run (Ah, V^2 or rpm^2)
SOC_{delta}	Change in SOC measured during a test

NEC calculations are presented in Joules (watt-seconds).

3.2 Net Energy Change (NEC)

Provision should be made for recording the RESS SOC at the start and stop of each test run, although in practice this is not always achievable. It is therefore essential that second by second logging of energy flows in and out of the RESS be carried out for the duration of each test run. For each different vehicle and test cycle a minimum of three test runs must be performed to provide sufficient data for a SOC correction, if needed. It is also desirable that at least one test run have a net positive and another a net negative NEC value so that net SOC calculations are based on interpolation and not extrapolation. Since different types of RESS store energy differently, each type of RESS will use different equations to define NEC. The following section gives the NEC calculations for batteries, capacitors and electro-mechanical flywheels. The appropriate calculations for NEC where other types of RESS are fitted must be determined as necessary on a case by case basis.

BATTERIES

Equations 1(a) and 1(b) calculate the NEC for batteries.

$$\mathbf{NEC = [SOC_{final} – SOC_{initial}] * V_{system} * K_1} \qquad \textit{(Equation 1a)}$$

where:

V_{system} = Battery's DC nominal system voltage as specified by the manufacturer, in volts (V)

K_1 = Conversion factor = 3600 (seconds/hour) (not used if SOC_{final} and $SOC_{initial}$ values are in Ampere-seconds)

or,

$$\mathbf{NEC = [SOC_{delta}] * V_{system} * K_1} \qquad \textit{(Equation 1b)}$$

where:

V_{system} = Battery's DC nominal system voltage as specified by the manufacturer, in volts (V)

K_1 = Conversion factor = 3600 (seconds/hour) (not used if SOC_{final} and $SOC_{initial}$ values are in seconds)

CAPACITORS

Equation 2 calculates NEC for capacitors.

$$\mathbf{NEC = (C/2) * [SOC_{final} – SOC_{initial}]} \qquad \textit{(Equation 2)}$$

where:

C = Rated capacitance of the capacitor as specified by the manufacturer, in Farads (F)

ELECTROMECHANICAL FLYWHEELS

Equation 3 calculates NEC for electromechanical flywheels.

$$\mathbf{NEC = (1/2) * I * [SOC_{final} – SOC_{initial}] * K_2} \qquad \textit{(Equation 3)}$$

where:

I = Rated moment of inertia of the flywheel system, in kilogram-meter^2 (kg/m^2)

K_2 = Conversion factor = $4\pi^2/3600$ (rad^2/sec^2/rpm^2)

3.3 Determining NEC Variance

TOTAL CYCLE ENERGY

This procedure uses total cycle energy to determine NEC tolerances, as opposed to total fuel energy, which can vary from test run to test run. To remain consistent with the calculations for NEC, either the total cycle energy must be reported in watt-seconds or the NEC must be converted to kWh.

$$\textbf{Total Cycle Energy} = \textbf{Total Fuel Energy} - \textbf{NEC} \qquad \textit{(Equation 4)}$$

Total fuel energy is the energy value of the fuel consumed by the internal combustion engine during the test and is calculated as shown in equation 5.

$$\textbf{Total Fuel Energy} = \mathbf{NHV_{fuel} * m_{fuel}} \qquad \textit{(Equation 5)}$$

where

NHV_{fuel} = Net heating value in Joules per kilogram (J/kg)
m_{fuel} = Total mass of fuel consumed over test, in kilograms (kg)

3.4 Determination Procedure

To determine if a test run has an acceptable NEC that does not require SOC correction, divide NEC, in Joules, by total cycle energy. If the absolute value of the calculation yields a number less than or equal to 1%, as shown in equation 6, then the NEC variance is within tolerance levels and the emissions and fuel economy values for that test run do not need to be corrected.

$$\left|\frac{\textbf{NEC}}{\textbf{total cycle energy}}\right| * 100\% \leq 1\% \qquad \textit{(Equation 6)}$$

If the absolute value of the calculation yields a number greater than 1%, but less than or equal to 5%, as shown in equation 7, then the emission and fuel economy values from the test run need to be corrected for SOC as described below. Test runs with NEC variance greater than ±5% are considered invalid, or, if the vehicle is consistently charge depleting, may have to be tested under the charge-depleting vehicle recommendations.

$$1\% < \left|\frac{\textbf{NEC}}{\textbf{total cycle energy}}\right| * 100\% \leq 5\% \qquad \textit{(Equation 7)}$$

3.5 SOC Correction Procedure

In order to calculate the state of charge correction for each emission species and for fuel economy, the emission and fuel economy values for each run must be plotted against the NEC for each run. A linear interpolation (in some cases extrapolation may be allowed) is then performed to establish the fuel economy or emissions at a NEC of zero.

3.6 SOC Correction Example

A worked example from a test on a diesel-electric series hybrid bus is provided in Appendix 2. This shows the correction factor applied due to NEC variation and calculates CO_2 emissions on a Well-to-Wheel basis.

ACCURACY COMBINED WITH SOC CORRECTION

On a hybrid vehicle, NEC values approaching 5% of the total cycle energy can result in emission data that varies significantly from the zero NEC case. This is because the vehicle was propelled by energy that is not accounted for. The only way to determine acceptable values is to correct the data using the SOC correction procedure. Because the SOC correction procedure effectively turns multiple test values into a single value, the coefficient of determination, R^2, of the linear best fit is used to determine whether the collected data is valid. For the purposes of this procedure the data is considered acceptable if the R^2, which compares the predicted and actual values of the linear regression, is equal to or greater than 0.80.

4. Test Preparations

4.1 Test Site

The ambient temperature levels encountered by the test vehicle shall be maintained at 18°C ± 2°C throughout the test

Ambient temperatures must be recorded at the beginning and end of the test period. Test conditions specified in 70/220/EEC and 77/88/EEC shall apply, where appropriate.

Adequate test site capabilities for safe venting and cooling of batteries, containment of flywheels, protection from exposure to high voltage, or any other necessary safety precaution shall be provided during testing.

One or more speed tracking fans shall direct cooling air to the vehicle in an attempt to maintain the engine operating temperature as specified by the manufacturer during testing. These fans shall only be operating when the vehicle is in operation and shall be switched off for all key off dwell periods. Fans for brake cooling can be utilized at all times. Additional fixed speed fans should be used if required and must be documented in the test report.

4.2 Pre-Test Data Collection

Prior to testing, detailed characteristics of the vehicle should be recorded. These requirements are specified in Appendix 4 of this Annex. The chassis test laboratory will be used to measure actual cycle distance during a test, as it is generally considered a more accurate method of calculation; as a result, an odometer on the vehicle is not required.

For all tests, a fuel sample shall be taken for potential analysis at a later date. The vehicle will be tested using the fuel with which it arrives at the test facility. Fuels should meet the requirements of EN590 and any exceptions to this should be advised by the vehicle manufacturer for reporting purposes.

4.3 Operation of the vehicle

If the vehicle is capable of several operating modes (e.g. delivery, electric-only, limp-home, normal, etc.), and these can be selected by the driver then it shall be operated in the most appropriate mode for the drive cycle. This mode shall be decided by the manufacturer and recorded in the test report.

If the vehicle is unable to be driven on the chassis dynamometer in a conventional operating mode then the reasons for this should be provided by the manufacturer in advance of the tests for reporting purposes. Any deviations from standard operation must be approved by the LowCVP prior to the issue of a LCEB certificate (where appropriate).

4.4 Condition of the Vehicle

Vehicle Stabilization -- Prior to testing, the vehicle shall be stabilized to a minimum distance of 3000km. This will be documented in the test report.

Vehicle Test Weight -- Buses shall be tested at kerb weight plus driver weight (75kg) and one quarter of the specified total passenger load using a weight of 63 kg per passenger. The curb weight of the vehicle shall be determined prior to test by the technical service carrying out the test. For buses which have previously been tested for Transport for London bus approval, this procedure can be followed retrospectively. In this case, the change in CO_2 emissions due to the difference between the LCEB test inertia and the TfL test inertia shall be calculated using the following equation.

$$\Delta CO_2 = 0.0637 * \Delta TI \qquad \text{(Equation 8)}$$

where:

ΔTI = Difference in test inertia, in kilograms (kg)

Tyres -- Manufacturer's recommended tyres shall be used and shall be the same size as would be used in service. This will be documented in the test report.

Tyre Pressure -- For dynamometer testing, tyre pressures should be set at the beginning of the test to manufacturer's recommended pressure. This will be documented in the test report.

Lubricants -- The vehicle lubricants normally specified by the manufacturer shall be used. This specification shall be supplied by the manufacturer in advance of the tests and recorded in the test report.

Gear Shifting – The vehicle shall be driven with appropriate accelerator pedal movement to achieve the time versus speed relationship prescribed by the drive cycle. Both smoothing of speed variations and excessive acceleration pedal perturbations are to be avoided and may cause invalidation of the test run. In the case of test vehicles equipped with manual transmissions, the transmission shall be shifted in accordance with procedures that are representative of shift patterns that may reasonably be expected to be followed by vehicles in use.

Vehicle Preparation & Preconditioning **--** as a minimum, should include:

- The vehicle should be preconditioned using a complete run of the test cycle followed by the appropriate key off dwell period (see Appendix1)
- Initial SOC setting (if necessary)

4.5 Conditioning of Rechargeable Energy Storage System

RESS Failure -- In the event that the RESS is damaged or has an energy storage capability below the manufacturer's specified rating, the RESS shall be repaired or replaced and stabilized, and then the test procedure should be repeated. Data from tests with a faulty RESS shall be considered invalid.

The RESS must have undergone a minimum of 300km of vehicle operation prior to the test to allow for initial 'running-in' and shakedown.

4.6 Dynamometer Specifications

The evaluation of the emissions and fuel economy from a low carbon bus powered by hybrid powertrain should be performed using a laboratory that incorporates a chassis dynamometer, a full-scale dilution tunnel, and laboratory-grade exhaust gas analyzers as described in 70/220/EEC (Light-duty vehicles) and 88/77/EC (Heavy-duty engines). The chassis dynamometer should be capable of simulating the transient inertial load, aerodynamic drag and rolling resistance associated with normal operations of the vehicle. The transient inertial load should be simulated using appropriately sized flywheels and/or electronically controlled power absorbers. The aerodynamic drag and rolling resistance may be implemented by power absorbers with an appropriate computer control system. The drag and rolling resistance should be established as a function of vehicle speed. The actual vehicle weight for the on-road coast down should be the same as the anticipated vehicle testing weight as simulated on the dynamometer. The vehicle should be mounted on the chassis dynamometer so that it can be driven through a test cycle. The driver should be provided with a visual display of the desired and actual vehicle speed to allow the driver to operate the vehicle on the prescribed cycle.

4.7 Dynamometer Calibrations

The dynamometer laboratory should provide evidence of compliance with calibration procedures as recommended by the manufacturer.

4.8 Inertial Load

Inertial load must be simulated correctly from a complete stop (e.g., total energy used to accelerate the vehicle plus road and aerodynamic losses should equal theoretical calculations and actual coastdowns). For HEVs this may be determined by measuring the power delivered to the dynamometer at the drive motors.

4.9 Road Load

Road load and wind losses should be simulated by an energy device such as a power absorber. Road load should be verified by comparison to previously tested vehicles having similar characteristics or by coastdown analysis on the track.

4.10 Dynamometer Load Coefficient Determination

The dynamometer coefficients that simulate road-load forces shall be determined as specified in Directive 70/220/EEC, with the following provisions:

a) Vehicles equipped with regenerative braking systems that are actuated only by the brake pedal shall require no special actions for coastdown testing on both the test track and dynamometer.

b) Vehicles equipped with regenerative braking systems that are activated at least in part when the brake pedal is not depressed shall have regenerative braking disabled during the deceleration portion of coastdown testing on both the test track and dynamometer, preferably through temporary software changes in the vehicle’s control system. Mechanical changes to the vehicle to deactivate regenerative braking (such as completely removing the drive shaft) are discouraged. However, if this practice becomes necessary as a last resort, every safety precaution shall be taken during vehicle operation, and the same mechanical modifications shall occur on both the test track and dynamometer. Methods to accelerate a vehicle without a drive shaft on both the test track and the dynamometer shall be determined by the manufacturer. However, pushing the vehicle with another vehicle is not an option.

c) The vehicles shall be weighted to the correct dynamometer test weight when the on road coastdowns are performed.

4.11 Dynamometer Settings

The dynamometer's power absorption and inertia simulation shall be set as specified in 70/220/EEC. It is preferable to insure that the dynamometer system provides the appropriate retarding force at all speeds, rather than simply satisfying a coastdown time between two specified speeds. The remaining operating conditions of the vehicle should be set to the same operating mode during coastdowns on road and on the dynamometer (e.g., air conditioning off, etc).

4.12 Test Instrumentation

Equipment referenced in 70/220/EEC and 88/77/EC (including exhaust emissions sampling and analytical systems) is required for emissions measurements, where appropriate. All instrumentation shall be traceable. to national standards.

The following instruments are likely to be required for determination of change of SOC on an as-needed usage.

- DC wideband Ampere-hour meter: Any meter using an integration technique shall have an integration frequency of 10Hz or higher so that abrupt changes of current can be accommodated without introducing significant integration errors.
- An instrument to measure a capacitor's voltage
- An instrument to measure an electromechanical flywheel's rotational speed
- AC Watt-hour meter to measure AC Recharge Energy
- A voltmeter and ammeter for as-needed usage

5. Test Procedure

5.1 Vehicle Propulsion System Starting and Restarting

The vehicle's propulsion system – specifically, the unit that provides the primary motive energy, e.g., the internal combustion engine -- shall be started according to the manufacturer's recommended starting procedures in the owner's manual. Only equipment necessary to the primary propulsion of the vehicle during normal service shall be operated. The air conditioner and other auxiliary on-board equipment not generally used during normal service shall be disabled during testing.

5.2 Dynamometer Driving Procedure

The emission test sequence starts with a "hot" vehicle that can be utilized to warm the dynamometer to operating temperature and allow for vehicle rolling loss calibration.

5.3 Dynamometer Warm-up

The test vehicle is used to warm the dynamometer and operated to allow for proper laboratory and vehicle loss calibrations.

5.4 Practice and Warm Up Runs

The test vehicle will be operated through a preliminary run of the desired test cycle. During this preliminary cycle, the driver will become familiar with the vehicle operation, and the suitability of the selected operating range of gas analyzers will be verified. Additional preliminary runs will be made, if necessary, to assure that the vehicle, driver, and laboratory instrumentation are performing satisfactorily.

5.5 Emission Tests

During the actual emission tests the test facility shall measure all emission data from the moment the vehicle is started, excluding the actual start event.

If the vehicle has not been operated for more than 30 minutes then it shall be started and warmed to operating temperature utilizing the same test cycle that will be used for emission characterization. Once the vehicle is at operating temperature it shall be turned off and will be restarted within 30 minutes. The test cycle shall then begin and emission measurements will be taken. At the end of the test cycle the vehicle shall be returned to the "key off" condition. Analysis will be carried out between test cycles

The number of tests runs performed must be sufficient to provide a minimum of three test runs with valid results i.e. NEC < $\pm$5% total cycle energy used. If the test sequence lapses in timing, another preliminary warm up run must be performed, after which the schedule can be resumed. Valid data gained prior to the breaking of the schedule may be preserved and reported. It is important to adhere to the time schedule and soak periods because engines and aftertreatment devices are sensitive to operating temperature.

5.6 Test Termination

The test shall terminate at the conclusion of the test run. However, sufficient idle time should be included at the end of a run, such that the analyzers are not missing emissions that are still in the sampling train.

5.7 Air Conditioning

Emissions from air conditioning systems are outside of the scope of this procedure. Air conditioning and conventional heating systems will therefore be switched off for the duration of the test

5.8 Data Recording

The emissions from the vehicle exhaust will be ducted to a full-scale dilution tunnel where the gaseous emissions of carbon monoxide, oxides of nitrogen (both nitric oxide and nitrogen dioxide) and carbon dioxide will be analysed as an integrated bag sample. Emissions of hydrocarbons, methane and nitrous oxide shall be measured on a continuous basis at a frequency of 5 Hz or greater. It is recommended that emissions of carbon monoxide, oxides of nitrogen and carbon dioxide are also measured on a continuous basis, and that these levels be compared to the integrated bag measurements as a quality assurance check. Particulate matter will be measured gravimetrically using fluorocarbon-coated glass fibre filters by weighing the filters before and after testing. Filters will be conditioned to temperature and humidity conditions as specified by 88/77/EEC

For each constituent, a background sample using the same sampling train as used during the actual testing must be measured before and after the emission test, and the background correction must be performed as specified by 70/220/EEC. In cases where some speciality fuels are examined by the test procedure, it may prove necessary to sample for additional species, including alcohols, aldehydes, ketones, or organic toxics if it is suspected that the levels of these additional species might be significantly higher than is normally found for diesel fuel. It is recommended that the tunnel inlet be filtered for PM with a HEPA filter to aid in lowering the detection limits.

Fuel consumed shall typically be determined by carbon balance from the gas analyzers, and the actual distance travelled by the dynamometer roll surface shall be used to provide the distance travelled during the driving cycles. Alternative methods for fuel consumption, such as direct mass measurement of the fuel tank, shall be considered if they are sufficiently accurate. This would require that the mass measurement system has an accuracy of greater than 1% of the fuel amount consumed during the test cycle. This method would be required for vehicles consuming hydrogen fuel. Mass measurement is preferred to volumetric measurement.

In the case where the vehicle is to be tested and operated on multiple fuels with different GHG pathways it is essential that the individual flows of each fuel can be resolved to an accuracy of 1% or better, either by measuring the flow of each fuel separately, or by introducing them at a fixed ratio into the engine. In this case the GHG analysis in Annex 5 shall be performed separately for each fuel and the final values combined.

5.9 State of Charge

The SOC of the RESS must be recorded at the beginning and the end of the test to an accuracy of $\pm$ 1% or better. If it is not possible to reliably measure SOC to this accuracy then the starting SOC shall be declared by the vehicle manufacturer and the real-time SOC data shall be calculated continuously from energy flow measurements (at a rate of 10Hz or greater) and recorded throughout the test.

Recorded data must then be time integrated against the emission data to provide a calculated end of test SOC. Provided the SOC is measured, OR declared, time sequenced and integrated according to the procedures listed earlier in this document, only the actual beginning and ending SOC values are necessary in the final test report.

It is recommended that both Ah and system voltage be recorded, where appropriate, during the test as outlined in the method for determining NEC.

5.10 Deviations from Standard Procedure

It is permissible to deviate from the prescribed procedure in cases where it can clearly be shown that this would result in a more realistic simulation of real-world vehicle operation.

For example:

> Where technology exists to enable the internal combustion engine to be switched off at bus stops, the MLTB cycle may be modified to include a series of simulated stops.
>
> In this case the stops are defined as all periods where the vehicle remains stationary for 15 seconds or more and this results in 19 simulated stops with a total duration of 411 seconds.
>
> During each 'stop' the bus may be operated in a manner which is consistent with normal operation, i.e. park or neutral transmission, park brake applied, doors opened.

Any deviations from the standard test procedure must be recorded in the test report and approved by the LowCVP prior to the issue of a LCEB certificate (where appropriate).

6. Test Validation

The value of the mass emission rates for each species will be averaged over the test distance (i.e. reported in g/km). There will be a minimum of three valid runs for each type of drive cycle. The coefficient of variance will be determined for each species. If the coefficient of variance is poor, additional runs should be performed until acceptable repeatability of emissions values are obtained. For hybrid vehicles the SOC correction is conducted first, and the R^2 of the linear best fit must be greater than 0.8. If a hybrid vehicle has three valid runs with less than the 1% NEC delta, then the data can be used without SOC correction. Under these circumstances, the R^2 of the best fit would be poor since all data points are essentially on the same axis (0% SOC correction). Any obvious error in the data should be identified and removed from the dataset; however, a minimum of three successful runs should be used in reporting the data.

At the end of each run, the total distance travelled by the vehicle over the test run will be noted from the dynamometer distance measurements. Adherence of the driver to the test cycle target speeds will be noted, and a regression will be performed to compare actual speeds with target speeds on a second-by-second basis. Target speed (x) and actual speed (y) should be charted in 1Hz increments and a trend line inserted with a zero intercept. If the resulting trend line has a slope that varies from unity by more than 10% or an R^2 of less than 0.8 the test run should be considered an invalid representation of that test cycle. The actual distance travelled by the dynamometer roller(s) should be used for the test cycle distance value.

If at any point during the test, vehicle propulsion is not possible or the driver is warned by the vehicle to discontinue driving because the RESS energy supply is too low, the test is considered invalid. The RESS should be recharged and the testing procedure restarted from the beginning of the interrupted test run.

7. Reporting

The final test report shall include all measured parameters including vehicle configuration, vehicle statistics, test cycle, measured parameters and calculated test results. See Appendix 5.

The following information will be included in the report:

Exhaust Emissions and Fuel Economy - The exhaust emissions and fuel economy of the vehicle shall be measured during each test. The measurements shall be reported in grams per kilometre and litres per 100 kilometre, respectively. Total fuel energy shall be reported in MJ.

Actual Distance Travelled - The actual distance that the dynamometer roll surface travelled shall be measured during each test phase.

SOC Difference and NEC - The state of charge difference of the RESS shall be measured during the test and reported along with the RESS NEC.

Tank-to Wheel emissions - Values for TTW emissions will be presented for CO, HC, NOx, PM, CO_2, N_2O and CH_4

Well-to-Tank GHG emissions - Values for WTT GHG emissions will be presented as appropriate to the fuel in-use

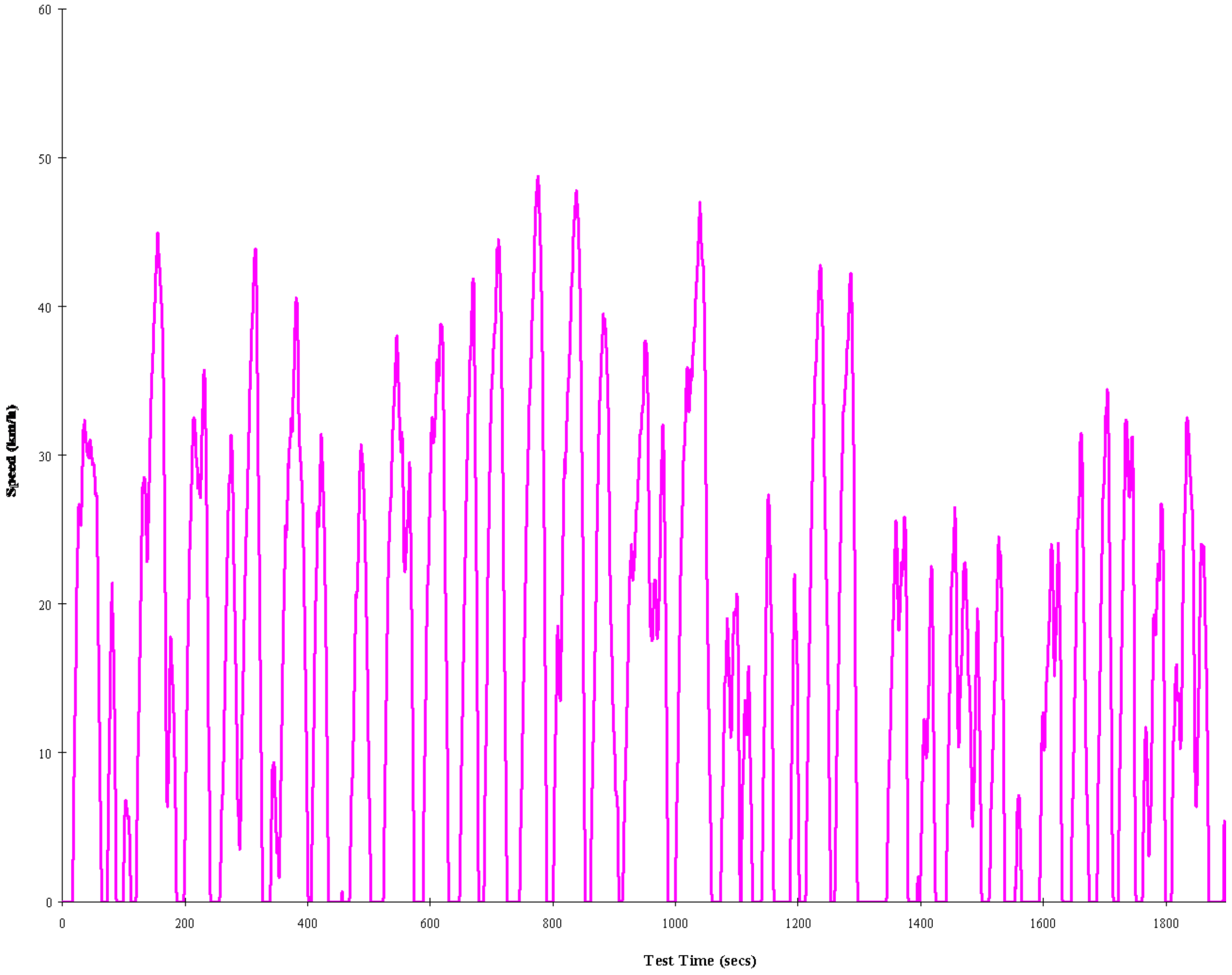
Well-to-Wheel GHG emissions - Values for WTW GHG emissions will be presented as appropriate to the fuel in-use

Appendix 1: MILLBROOK LONDON TRANSPORT BUS (MLTB) DRIVE-CYCLE (Also known as Route 159 Drive Cycle)

This test cycle was specifically developed for use with buses and was derived from data logged from a bus in service within inner London.
The drive cycle consists of two phases, a medium speed ‘Outer London’ phase simulating a journey from Brixton Station to Trafalgar Square and a low speed ‘Inner London’ phase simulating a journey from Trafalgar Square to the end of Oxford Street.

The cycle is composed of two phases:

(1) Outer London Phase, nominal distance 6.45 km, 1,380 seconds in duration
(2) Inner London Phase, nominal distance 2.47 km, 901 seconds duration



General information
The overall length of the test is 2,281 seconds and the nominal distance covered is 8.92 km.
Test cell ambient temperature for duration of test = 18°C ± 2°C

Appendix 2 : Well-to-Wheel Calculations

Worked Examples from a test on a charge sustaining hybrid single deck bus

Base Vehicle Data: 36 seated passengers, 17 standees, total 53 Passengers.

Using the bag mass emissions generated from the tests carried out and using the current data supplied from the data logging system, it was possible to derive the NEC corrections required from the chassis dynamometer tests in order to interpolate the level of CO_2 emitted from the test vehicle at zero energy change.

NEC = [SOC_{delta}] * V_{system}

SOC = state of charge

V = nominal system voltage volts

From the recorded fuel consumption figures it was possible to calculate the fuel energy consumed across each test

Test number	Fuel consumption litres/100km	Fuel used over cycle litres	Net heating energy MJ/litre	Total fuel energy MJ
2006121	25.22	2.2916153	35.67485429	81.75304193
2006123	26.62	2.4005916	35.67485429	85.64075555
2006124	25.7	2.304519	35.67485429	82.21337954
2006125	24.86	2.2217382	35.67485429	79.26018656
2006126	24.5	2.19422	35.67485429	78.27847879

It was then possible to derive the NEC variance across each test and determine suitability of the test for interpolation

Test Number	NEC (kW hr)	NEC - Mega Joules (Mwatt seconds)	Total Cycle Energy (MJ)	NEC Variance (%)
2006121	-0.49764	-1.79149	83.5445	-2.14%
2006123	1.09048	3.92571	81.7151	4.80%
2006124	1.93729	6.97423	75.2391	9.27%
2006125	-1.05876	-3.81155	83.0717	-4.59%
2006126	-0.11043	-0.39754	78.6760	-0.51%

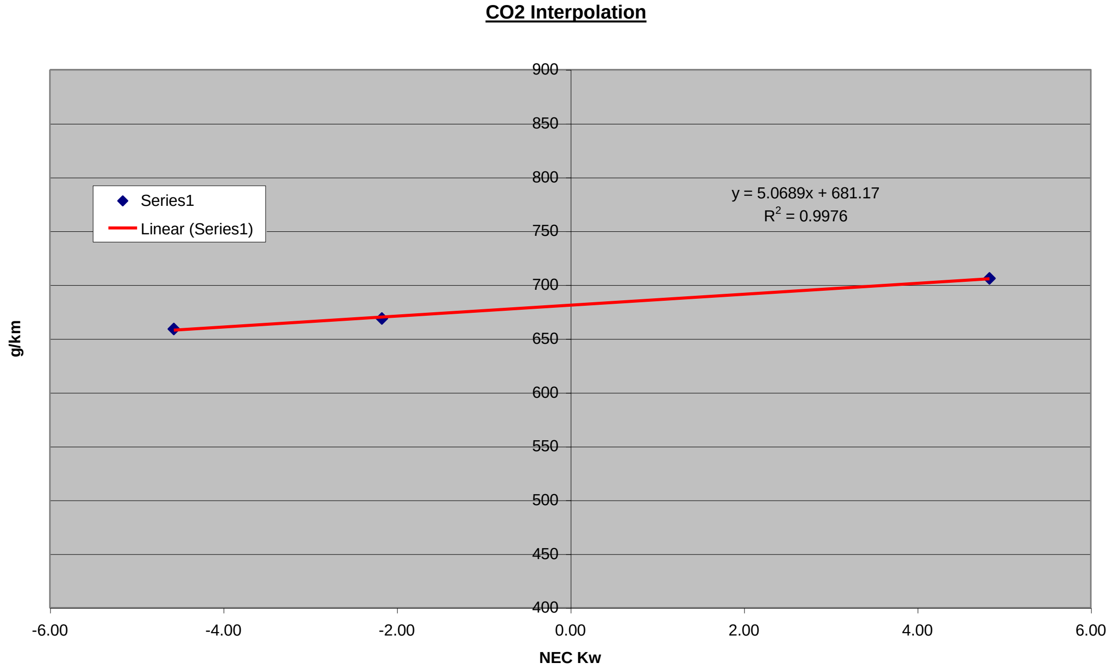
The procedure requires that test results can be used without correction if the NEC is less than 1% of total energy used over the drive cycle. If the NEC is between 1 and 5% of total cycle energy, the test results can be corrected by using a linear interpolation method.

Test runs 2006121, 2006123 and 2006125 were used for interpolation

The chassis dynamometer results are shown in the table below:

Test No.	CO_2
2006121	668.8
2006123	706.0
2006125	659.8

By plotting the test data and interpolating the data points it is possible to determine the CO2 levels from the vehicle at zero NEC:



Similar interpolations are used to give values for the other important greenhouse gases, methane and nitrous oxide, to allow calculation of the total TTW GHG emissions:

	CO_2 Emissions (g/km)	CH_4 Emissions (g/km)	CO_2 Equivalent (g/km)	N_2O Emissions (g/km)	CO_2 Equivalent (g/km)	Calculated GHG Emissions (TTW) (CO_2 Equivalent g/km)
Zero NEC	681.2	0.000	0.0	0.006	1.9	683.0

Finally, an interpolation is used to give the fuel consumed at zero NEC to allow calculation of the TTW GHG contribution for the fuel pathway:

	Fuel Used Over Cycle (Litres)	Net Heating Energy (MJ/Litre)	Total Fuel Energy (MJ)	WTT GHG Equivalence Factor * (CO_2 Equivalent g/MJ)	Calculated WTT GHG Emissions (CO_2 Equivalent g/km)	Calculated WTW GHG Emissions (CO_2 Equivalent g/km)
Zero NEC	2.274	35.67	81.11	14.2	129.1	812.2

Note, this calculation must be carried out separately for each fuel if more than one has been used during the test.

The bus was found to have a CO_2 output, when corrected for zero NEC, of 681.2 g/km.

This was equivalent to a TTW GHG output of 683.0 g/km

This would result in a WTW (well to wheel) GHG level of 812.2 g/km.

WTW GHG target for a bus with a total passenger capacity of 53 passengers is 834.8 g/km

Overall Well-to-Wheel is 812.2 g/km.
Low Carbon Status: PASS

* Equivalence factor from JRC-CONCAWE-EUCAR WTW Report Version 2, 3rd November 2008

Appendix 3: Passenger Capacity vs. Greenhouse Gas Emissions (CO_2 equivalent)

LCEB 30% WTW GHG Emission Reduction Target in g/km vs. Maximum Passenger Capacity					
Passengers	g/km	Passengers	g/km	Passengers	g/km
22	640.2	61	885.1	100	1130.0
23	646.4	62	891.4	101	1136.3
24	652.7	63	897.6	102	1142.6
25	659.0	64	903.9	103	1148.8
26	665.3	65	910.2	104	1155.1
27	671.6	66	916.5	105	1161.4
28	677.8	67	922.8	106	1167.7
29	684.1	68	929.0	107	1174.0
30	690.4	69	935.3	108	1180.2
31	696.7	70	941.6	109	1186.5
32	703.0	71	947.9	110	1192.8
33	709.2	72	954.2	111	1199.1
34	715.5	73	960.4	112	1205.4
35	721.8	74	966.7	113	1211.6
36	728.1	75	973.0	114	1217.9
37	734.4	76	979.3	115	1224.2
38	740.6	77	985.6	116	1230.5
39	746.9	78	991.8	117	1236.8
40	753.2	79	998.1	118	1243.0
41	759.5	80	1004.4	119	1249.3
42	765.8	81	1010.7	120	1255.6
43	772.0	82	1017.0	121	1261.9
44	778.3	83	1023.2	122	1268.2
45	784.6	84	1029.5	123	1274.4
46	790.9	85	1035.8	124	1280.7
47	797.2	86	1042.1	125	1287.0
48	803.4	87	1048.4	126	1293.3
49	809.7	88	1054.6	127	1299.6
50	816.0	89	1060.9	128	1305.8
51	822.3	90	1067.2	129	1312.1
52	828.6	91	1073.5	130	1318.4
53	834.8	92	1079.8	131	1324.7
54	841.1	93	1086.0	132	1331.0
55	847.4	94	1092.3	133	1337.2
56	853.7	95	1098.6	134	1343.5
57	860.0	96	1104.9	135	1349.8
58	866.2	97	1111.2	136	1356.1
59	872.5	98	1117.4	137	1362.4
60	878.8	99	1123.7	138	1368.6

Valid for:

- MLTB test cycle only.
- Vehicles tested at: Mass of vehicle in running order (including 75kg driver), plus 25% of total passenger load.
- Passengers assumed to weigh 63kg each.
- "Maximum passenger capacity" = Manufacturer stated capacity, OR (GVW – Mass of vehicle in running order)/63, whichever is the lower.

Appendix 4: Essential Characteristics of the Vehicle powered by a Charge Sustaining Hybrid Electric Powertrain

The following information, when applicable, shall be supplied.

If there are drawings, they shall be to an appropriate scale and show sufficient detail. They shall be presented in A4 format or folded to that format. In the case of microprocessor controlled functions, appropriate operating information shall be supplied.

1. GENERAL
1.1. Make (name of manufacturer): ....
1.2. Type and commercial description (mention any variants): ....
1.3. Means of identification of type, if marked on the vehicle: ....
1.3.1. Location of that mark: ....
1.4. Name and address of manufacturer: ....
1.5. Name and address of manufacturer's authorized representative where appropriate:
1.6. Vehicle stabilization distance: ....

2. GENERAL CONSTRUCTION CHARACTERISTICS OF THE VEHICLE
2.1. Photographs and/or drawings of a representative vehicle: ....
2.2. Powered axles (number, position, interconnection): ....

3. MASSES (kilograms) (refer to drawing where applicable)
3.1. Mass of the vehicle with bodywork in running order (including coolant, oils, fuel, tools, spare wheel and driver): ....
3.2. Technically permissible maximum laden mass as stated by the manufacturer: ....
3.3. Vehicle test mass: ....
3.4. Theoretical maximum passenger capacity (3.2. – 3.1.)/63: ....

4. DESCRIPTION OF POWER TRAIN AND POWER TRAIN COMPONENTS
4.1. **Description of the hybrid electric vehicle**
4.1.1. Category of Hybrid Electric vehicle: Off Vehicle Charging/Not Off Vehicle charging 1/
4.1.2. Operating mode switch : with/without 1/
4.1.2.1. Selectable modes:
4.1.2.1.1. Pure electric : yes/no 1/
4.1.2.1.2. Pure fuel consuming : yes/no 1/
4.1.2.1.3. Hybrid modes : yes/no 1/ (if yes, short description)
4.1.3. General description of Hybrid Electric power train
4.1.3.1. Drawing of the hybrid powertrain system layout (engine/ motor/ transmission combination 1/): ....
4.1.3.2. Description of the general hybrid powertrain working principle: ....
4.1.4. Manufacturer's recommendation for preconditioning: ....

4.2. **Internal combustion engine**
4.2.1. Engine manufacturer:
4.2.2. Manufacturer's engine code (as marked on the engine, or other means of identification):
4.2.2.1. Working principle: positive-ignition/compression-ignition, four-stroke/two-stroke 1/
4.2.2.2. Number and arrangement of cylinders: ....
4.2.2.3. Engine capacity: 2/ ....cm^3

4.2.2.4. Maximum net power: …………. kW at ……………… min^{-1}
4.2.2.5. Maximum net torque:…………...Nm at ………………..min-1
4.2.3. Fuel type: …………..
4.2.4. Intake system:
4.2.4.1. Pressure charger: yes/no 1/
4.2.4.2 Charge-air cooler: yes/no 1/
4.2.5. Exhaust system
4.2.5.1. Description and drawings of the exhaust system:..
4.2.6. Lubricant used:
4.2.6.1. Make:..
4.2.6.2. Type:...

4.3. **Measures taken against air pollution**
4.3.1. Additional pollution control devices (if any, and if not covered by another heading:
4.3.1.1. Catalytic converter: yes/no 1/
4.3.1.1.1. Number of catalytic converters and elements:...
4.3.1.1.2. Dimensions and shape of the catalytic converter(s) (volume,...):.....................
4.3.1.1.3. Type of catalytic action:...
4.3.1.1.4. Regeneration systems/method of exhaust after-treatment systems, description:
4.3.1.1.5. The number of MLTB operating cycles, or equivalent engine test bench cycles, between two cycles where regenerative phases occur under the conditions equivalent to MLTB test. ....
4.3.1.1.6. Parameters to determine the level of loading required before regeneration occurs (i.e. temperature, pressure etc.):..
4.3.1.1.7. Description of method used to load system during the test: ....
4.3.1.2. Oxygen sensor: yes/no 1/
4.3.1.3. Air injection: yes/no 1/
4.3.1.3.1. Type (pulse air, air pump,...): ....
4.3.1.4. Exhaust gas recirculation (EGR): yes/no 1/
4.3.1.5. Evaporative emission control system: yes/no 1/
4.3.1.6. Particulate trap: yes/no 1/
4.3.1.6.1. Dimensions and shape of the particulate trap (capacity): ....
4.3.1.6.2. Type of particulate trap and design: ....
4.3.1.6.3. Location of the particulate trap (reference distances in the exhaust system):..
4.3.1.6.4. Regeneration system/method. Description and drawing:................................
4.3.1.6.5. The number of MLTB operating cycles, or equivalent engine test bench cycle, between two cycles where regeneration phases occur under the conditions equivalent to MLTB test:...
4.3.1.6.6. Parameters to determine the level of loading required before regeneration occurs (i.e. temperature, pressure, etc.):...
4.3.1.6.7. Description of method used to load system during the test: ....

4.4. **Traction battery / Energy storage device**
4.4.1. Description of the energy storage device: (battery, capacitor, flywheel/generator/etc…)
4.4.1.1. Make: ....
4.4.1.2. Type: ....
4.4.1.3. Identification number: ....
4.4.1.4. Energy: ....(for battery: voltage and capacity Ah in 2 h, for capacitor: J,...)
4.4.1.5. Charger: on board/ external/ without 1/
4.4.1.6 Stabilization distance: ....

4.5. **Electric machines (describe each type of electric machine separately)**
4.5.1. Make: ....
4.5.2. Type: ....

4.5.3. Primary use: traction motor / generator 1/
4.5.4. Maximum power: .... kW

4.6. **Internal combustion engine control unit**
4.6.1. Manufacturer: ....
4.6.2. Type: ....
4.6.3. Software Identification number: ....
4.6.4 Calibration identification number: ....

4.7. **Hybrid system control unit**
4.7.1. Manufacturer: ....
4.7.2. Type: ....
4.7.3. Software Identification number: ....
4.7.4 Calibration identification number: ....

4.8. **Transmission (if fitted)**
4.8.1. Clutch (type): ....
4.8.1.1. Maximum torque conversion: ....
4.8.2. Gearbox:
4.8.2.1. Type:...
4.8.2.2. Location relative to the engine: ....
4.8.3. Control Unit:..
4.8.3.1. Type: ....
4.8.3.2. Software Identification number: ....
4.8.3.3. Calibration identification number: ....

5. SUSPENSION

5.1. Tyres and wheels
5.1.1. Tyre/wheel combination(s) (for tyres indicate size designation, minimum load-capacity index, minimum speed category symbol; for wheels, indicate rim size(s) and off-set(s):
5.1.1.1. Axle 1:...
5.1.1.2. Axle 2:...
5.1.1.3. Axle 3:...
5.1.1.4. Axle 4: etc. ....
5.1.2. Tyre pressure(s) as recommended by the manufacturer: .... kPa

6. BODYWORK

6.1. Seats:
6.1.1. Number of seats:
6.1.2. Number of standing passengers permitted

1/ Strike out what does not apply.
2/ This value must be calculated with π = 3.1416 and rounded to the nearest cm^3.

Appendix 5: Test Report and Approval

Note, only results from valid tests should be presented for approval

[Vehicle description and serial number] was submitted for accreditation as a Low Carbon Emission Bus on [date/month/year] by [supplier name and address]

The vehicle was tested to Low Carbon Emission Bus test protocol Annex A2: Test Procedure for Measuring Fuel Economy and Emissions of Low Carbon Emission Buses powered by Charge Sustaining Hybrid Powertrains at [technical service carrying out test]

The vehicle was tested using [name of operating mode] operating mode

The bus was inspected by [name of inspector] of [name of accreditation organization]

The Essential Characteristics of the Vehicle are recorded in Appendix 4 of this document.

The test was witnessed by [name of inspector] of [name of accreditation organization]

Emissions results

Test Number	CO (g/km)	HC (g/km)	NOx (g/km)	PM (g/km)	CO_2 (g/km)	CH_4 (g/km)	N_2O (g/km)

Fuel energy consumed over tests

Test Number	Fuel consumption litres/100km	Fuel used over cycle litres	Net heating energy MJ/litre	Total fuel energy MJ

Net Energy Change over tests

Test Number	NEC - kW	NEC – Mega joules (M watt-seconds)	Total cycle energy	NEC variance %

Interpolated emissions results at zero NEC (graphical representation to be attached)

CO (g/km)	HC (g/km)	NOx (g/km)	PM (g/km)	CO_2 (g/km)	CH_4 (g/km)	N_2O (g/km)	Fuel consumption (Litres)

Total Tank-to-Wheel GHG – CO_2 equivalence

CO_2 (g/km)	CH_4 (g/km ×21)	N_2O (g/km ×310)	Total TTW GHG (g/km)

Total Well-to-Tank GHG – CO_2 equivalence

Fuel Used Over Cycle (Litres)	Net Heating Energy (MJ/Litre)	Total Fuel Energy (MJ)	WTT GHG Equivalence Factor * (CO_2 Equivalent g/MJ)	Calculated WTT GHG Emissions (CO_2 Equivalent g/km)

Well-to- Wheel calculations

Total Tank-to-Wheel GHG (g/km)	
Fuel Energy Consumption (MJ)	
Fuel type	
Fuel Well-to-Tank pathway value (g/MJ)	
Fuel Well-to-Tank GHG (g/km)	
Total Well-to-Wheel GHG (g/km)	
Target WTW for [passenger capacity of bus] Passengers (g/km)	
Approved as Low Carbon Bus	Yes/No

Approval

Low Carbon Vehicle Partnership approves the following vehicle(s) as a Low Carbon Emission Bus for [number of passengers] and above

Manufacturer
Vehicle Type

Limitations

All vehicle characteristics to be as defined in Appendix 4 of this document