

A Study of Fuel Converter Requirements for an Extended-Range Electric Vehicle

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ABSTRACT

Current focus on techniques to reduce the tailpipe carbon dioxide (CO₂) emissions of road vehicles is increasing the interest in hybrid and electric vehicle technologies. Pure electric vehicles require bulky, heavy, and expensive battery packs to enable an acceptable driveable range to be achieved. Extended-range electric vehicles (E-REVs) partly overcome the limitations of current battery technology by having an onboard fuel converter that converts a liquid fuel, such as gasoline, into electrical energy whilst the vehicle is driving. Thus enabling the traction battery storage capacity to be reduced, whilst still maintaining an acceptable vehicle range.

This paper presents results from a drive style analysis toolset that enable US and EU fleet vehicle drive data to be categorised and compared. Key metrics, such as idle frequency, idle duration, vehicle speed, and vehicle acceleration are analysed. Vehicle usage patterns in the US and EU have been compared against each other and to relevant legislative drive cycles.

Based on results from examination of the fleet data, a drive-cycle is selected and used as the basis for analysis of the fuel converter requirements for a hypothetical E-REV based on a typical European C-class vehicle. The influence of drive-cycle and battery pack size on the fuel converter requirement is discussed. Finally, the influence of the fuel converter efficiency upon the new European Drive Cycle (NEDC) fuel consumption of the E-REV is assessed.

INTRODUCTION

Automotive manufacturers around the world are currently investigating a wide range of technologies that will reduce the drive-cycle CO₂ output of their vehicles, driven largely by legislative CO₂ targets. Tate and Savagian [1] observe that in

some markets a greater than a 30% CO₂ reduction, over a 10-year period, is proposed. The UK has set, in the 2008 Climate change Act [2], the target that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline. Currently, the transport sector accounts for almost 24% the UK national CO₂ emissions, of which cars and road haulage vehicles account for nearly 80% [3]. The CO₂ emissions of a given vehicle are directly proportional to the fuel consumption of the vehicle. The ratio of CO₂ emissions to fuel consumption is dependant of the carbon and oxygen content of the fuel. [Figure 2](#) shows the CO₂ emissions to fuel consumed ratio by mass for all the vehicles in the May 2009 UK VCA New Car Fuel Consumption database [4]. The ratio of CO₂ emissions to fuel consumed is roughly just under 3.15 to 3.2:1 for both gasoline and Diesel fuelled vehicles, as can be seen in [Figure 2](#).

<[figure 1](#) here>

The New Automotive Innovation and Growth Team (NAIGT) was formed in April 2008 to provide a collective strategic view of the UK automotive industry on the innovation and growth challenges it faces. NAIGT published a 20-year vision for the UK automotive industry and made recommendations as to how this should be realised [5]. The NAIGT report included a vision of the key innovations and technologies that would be required to achieve the CO₂ targets set for the automotive sector. This roadmap shows plug-in hybrid technology ramping up in the 2015-2020 time frame, enabled by a break-through in energy storage. The report presents mass-market electric vehicles (EVs) and hydrogen fuel cell powered vehicles as desirable 'end games' in terms of low fleet averaged CO₂ emissions.

The electric vehicle is viewed as desirable, as it does not generate pollutants as it passes through inhabited areas, and

can potentially rely on its energy being provided by a selection of renewable sources. Despite the continued developments in battery technology, the overall range of such a vehicle or its ability to sustain high output for a prolonged period is limited. Furthermore, once the battery is depleted relatively long recharging times are currently required before the vehicle is available for use again. Cost and range capability, possibly coupled with 'range anxiety of the driver', are still viewed as barriers to the widespread adoption of electric vehicles [6,7,8]. Pearson *et al.* [9] show a comparative plot of the net (including storage container) gravimetric energy and net volumetric energy of current battery technologies verses a variety of liquid and gaseous fuels. They estimate that a battery pack enabling a similar range to 50 litres (13.2 US gallons) of gasoline would weigh roughly 600-1000kg (1320-2200lbs), depending upon the battery technology and permissible depth of discharge. This yields a gravimetric energy density ratio of between 13 to 22:1 for gasoline verses current battery technologies.

There is increasing interest in combining the desirable features of the electric vehicle with the range freedom of a conventionally fuelled vehicle, leading to the investigation of the extended-range electric vehicle (E-REV), most conspicuously with the GM Volt [10]. The E-REV is defined succinctly, by Tate *et al.* [11], as "A vehicle that functions as a full-performance battery electric vehicle when energy is available from an onboard rechargeable energy storage system (RESS) and having an auxiliary energy supply that is only engaged when the RESS energy is not available".

The addition of an auxiliary energy supply, which for the purposes of the analysis presented in this paper will be limited to a liquid fuelled combustion engine linked to an electric generator (range-extender), has the benefit of enabling the ultimate range of the vehicle to be limited only by the combined capacity of the battery and liquid fuel tank. For long journeys, when the battery and fuel tank are both depleted, the driver can simply refuel the liquid tank in a matter of minutes, in the same way that current vehicles are refuelled. However, it is desirable that for the majority of time the vehicle will operate in a purely electric only mode from the RESS, and that the user recharges the vehicle when it is not in use, e.g. over-night. Thus, the battery should be sized to cope with the majority of daily usage that the vehicle will encounter, and only rely on the range extender for infrequent, longer, journeys.

This study is intended to investigate the range extender requirements of a hypothetical E-REV based on a typical European C-class vehicle. Based on results from examination of vehicle fleet data, a drive-cycle is selected and used as the basis for analysis of the range extender requirements. The E-REV has been modeled using the GT-Drive software package from Gamma Technologies [12]. GT-Drive enables the complete vehicle, battery, motor, generator, and range

extender system to be modelled, permitting component size optimisation. The key aim for this study was to determine the power output requirement of the range extender unit. This is desirable to be minimised as far as practicable, in order to minimise likely cost, size and weight of the device.

In order to control the operation of the range extender within the GT-Drive simulation a simplistic control strategy has been implemented such that when the battery state of charge (SOC) drops below a predetermined lower threshold, the range extender engine is started and it will continue to operate until the battery reaches a second, upper, predetermined threshold. The upper threshold is still significantly below the fully charged state of the battery, as it is desirable that the user would predominantly be able to charge the battery from an off-vehicle supply. During periods when the range extender is running, the energy from the range extender is fed directly to the drive motor, any surplus being used to recharge the battery.

FLEET USAGE ANALYSIS

MAHLE Powertrain has developed a drive style analysis toolset that defines key metrics, which enable fleet vehicle drive data to be categorised and compared [13]. The toolset objectively quantifies driving behaviour through an 'aggressivity' algorithm designed to detect subtleties in vehicle performance. The development of this toolset also includes detailed metrics to compare drive data using cumulative fraction plots. Key metrics include idle frequency, idle duration, vehicle speed and vehicle acceleration. These definitions were formulated using a range of production passenger vehicles with power-to weight ratios varying from 100 to 230hp/tonne (approximately 0.07 to 0.17kW/kg).

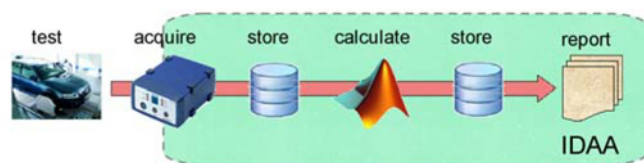


Figure 2. ProLogiq IDAA's coverage of the fleet vehicle data analysis path.

The aim was to define, or identify, a suitable drive cycle that could be used for the E-REV performance simulations and be representative of 'real world' vehicle usage patterns. The approach adopted was to utilise MAHLE Powertrain's extensive database of fleet vehicle drive data and take a sample of vehicles from this database and compare the usage of these samples against legislative and other well known cycles (NEDC, FTP, Artemis etc.) using the Drive Style Analysis Toolset. The prescribed vehicle speed histories for the drive-cycles analysed are shown in [Figures A1.1 and A1.2](#) in [Appendix 1](#).

All results presented here are calculated from samples taken from fleet drive data for a range of different sizes of vehicle. The vehicles used in this study are based in the UK, all controlled by MAHLE Powertrain and are based at one location. 20+ engineers regularly drive these vehicles. Fleet data is also available for vehicles based in the US, under OEM control, at 7 locations with fleets managed from technical centres, where the OEM's employees and customers drive the vehicles. The drive data is representative of customer use (vehicles used during normal weekday commuting and weekends). Every vehicle drive is logged using ETAS 715/730 loggers configured to automatically switch on/off with ignition and all data is transferred to servers based in Northampton. ProLogiq IDAA is used to process and manage the data and produce analysis reports, as depicted in [Figure 2](#). The current database of drive data has been accumulated over the past 6+ years and contains 50,000+ recorded drives, which equates to 1+ Terabyte of data. Over 100 different vehicles have been logged and in some cases there is over 80,000km data for a single vehicle alone. The sample set used for the analysis presented in this paper is summarised in [Table 1](#).

<[table 1](#) here>

Similar vehicle types were sampled for the large capacity gasoline and mid capacity diesel engine groups. The vehicle types for the small capacity gasoline engines were similar to a C-class vehicle. The drive style analysis toolset is used to categorise drives into type (Town, Country, Motorway) and style (Gentle, Normal, Aggressive). Drive type represents road conditions and is calculated using vehicle speed. Drive style represents how the user is driving the vehicles. To allow large data sets to be compared (UK sample vs drive cycles) key metrics have been defined:

- Vehicle Speed (time and distance) - dependent on road conditions / speed limits
- Vehicle Acceleration and Deceleration
- Vehicle Aggressivity - measure of vehicle kinetic energy
- Pedal Aggressivity - measure of driver demand
- Idle Duration
- Idle Frequency

The vehicle aggressivity, is derived from an industrial classification, first described by Nam *et al.* [14], who classified vehicle aggressivity ([Eqn 1](#)), using the root mean square of the power factor ([Eqn 2](#)).

$$\text{Vehicle Aggressivity} = \sqrt{\frac{1}{N} \sum_i^N pf_i^2} \quad (1)$$

Where

N - total number of positive vehicle acceleration profiles;
 i - individual vehicle acceleration profile.

The power factor (Pf_i) is given by

$$Pf_i = 2va \quad (2)$$

Where:

v - average vehicle speed for the current;
 a - individual profile vehicle acceleration.

FLEET USAGE ANALYSIS RESULTS

In this section, the results of the comparison of the UK vehicle fleet data with various legislative drive-cycles for various metrics are presented. [Figure 3](#) shows the cumulative fraction plot based on time in each vehicle speed bin. A large separation between the drive-cycles is observed, and it can be seen that the FTP72(75) and NEDC (MVEG) are biased towards lower speeds, representing town driving) and the US06 and HWFET are biased towards higher vehicle speeds. The Artemis cycle [15, 16], which was developed to replicate European 'real world' driving conditions, has an even speed distribution based on time residency and is an extremely close match to the cumulative fraction speed data for the UK fleet.

<[figure 3](#) here>

From [Figures 4a](#) and [4b](#), which show the deceleration rate and acceleration rate cumulative profiles distributions respectively, it can be seen that the Artemis cycle has the closest match to the UK fleet deceleration data, and the UDC shows the best match to the UK fleet acceleration data, in this case the Artemis cycle acceleration rate distribution is lower than those measured for the UK fleet. The Acceleration rate is clearly an important metric in this assessment, as it will have direct effect upon the load on the traction motor, and hence battery load, during these events. Additionally, for vehicles that feature some regenerative capability, such as the E-REV considered in this study, deceleration rate is also a significant metric, as it determines the regeneration power requirement to capture energy during the deceleration event.

<[figure 4](#) here>

The vehicle aggressivity distributions are shown in [Figure 5](#). The UK fleet data has higher levels of vehicle aggressivity than most legislative cycles. There is good agreement between the Artemis and UDC cycles and the UK fleet data at lower levels of aggressivity.

<[figure 5](#) here>

Figure 6 shows comparisons of idle duration and frequency distribution for UK based vehicle fleet data and several legislative drive-cycles. It can be seen from Figure 6a that the Artemis cycle has a similar idle duration profile to the UK fleet data. The idle durations in the Artemis cycle range from 0 to 60 seconds. The longest idle duration on the other legislative cycles is 35 seconds, which is considerably lower than the UK fleet data sample spread. From Figure 6b it can be seen that the UDC shows the closest match to the UK fleet data sample in terms of idle event frequency. The majority of legislative cycles have a very defined idle frequency profile, giving rise to a ‘stepped’ idle distribution profile.

Figure 7 shows analysis of the daily usage, based on the averages for one UK based vehicle and comprises data taken over 729 individual drives over 208 days, covering 15,000km and 275 hours. It can be seen from Figures 7a,7b,7c,7d,7e,7f, that the Artemis cycle compares well with the metrics presented for the daily usage of this vehicle, in typical daily drive duration, distance, idle count, total idle duration, number of accelerations and no of decelerations. Figure 7g shows the cumulative distribution of the daily distance driven. The 70th and 80th percentile values, which are 100km and 80km respectively, are also shown in the Figure.

The Artemis cycle has shown the best match, to the UK sample data analysed, for vehicle speed, acceleration, deceleration and aggressivity. Repeated Artemis cycles will give a reasonable representation of the likely ‘real world’ usage of the E-REV. A range of 100km will cover 80% of daily driving, based on the sample analysed. Likewise a range of 80km will cover 70% of daily driving.

<figure 6 here>

<figure 7 here>

VEHICLE MODELLING

Analyses of the range extender power requirements, for a hypothetical E-REV, are described in this section, and the results of this analysis are presented. Initially a model of a typical gasoline fuelled European C-class vehicle was constructed in GT-Drive. This model was then modified to represent an E-REV. The electrical components (battery pack and drive motor) were sized to enable a number of performance targets for the E-REV to be met. The battery state of charge (SOC) of the model E-REV, and the operation of the range extender unit, were then analysed during steady-state cruise and using a number of repeated drive-cycles.

BASELINE VEHICLE MODEL

The vehicle modelling work that is reported in this paper has all been performed using GT-Drive, which enables the user to build a virtual vehicle driveline and test it over a drive-cycle.

GT-Drive is able to link directly to the MATLAB/Simulink[®] software environment enabling users to construct vehicle control systems within that environment. The driveline is constructed using a toolkit of elements for modelling devices such as wheels, clutches, gears, electric motors and batteries.

Table 2. Comparison of baseline model acceleration, Vmax, and NEDC fuel consumption over the NEDC with manufacturer's published data for a similar specification European C-class vehicle.

	Model	Published data for Similar vehicle
0-100km/h (s)	11.26	11.3
Vmax (km/h)	187.9	188

NEDC Fuel Consumption	Model	Published data for Similar vehicle
Urban (l/100km)	9.60	9.7
Extra Urban (l/100km)	5.66	5.6
Combined (l/100km)	7.11	7.1
Combined CO2 (g)	169.3	166

A model of a typical gasoline fuelled European C-class vehicle, with a manual transmission, was constructed in GT-Drive. The salient vehicle data required by GT-Drive, for the baseline vehicle, is summarised in Table A2.1 in Appendix 2. A measured BSFC map for a contemporary 1.6 litre gasoline engine was used in the analysis of the baseline vehicle fuel consumption analysis. The 0-100km/h acceleration time and maximum speed (Vmax) of the baseline model were computed as being 11.3 seconds and 188 km/h respectively, which compare well with manufacturer's published data for a similar specification European C-class vehicle, as shown in Table 2. Table 2 also shows a comparison of the NEDC fuel consumption of the baseline vehicle model with manufacturer's published data. The total fuel consumed over the cycle, as well the fuel consumption split between the urban and extra-urban phases of the cycle, compares well with the published data.

The fuel economy of the baseline vehicle was calculated for several drive-cycles calculated, and the results of this analysis is summarised in Table A2.2 in Appendix 2. The results presented in Table A2.2 correspond to the vehicle driving a single cycle and are all based on a cold start. The average brake power output of the engine during each of these cycles is also shown in Table A2.2. It can be seen that the lowest average fuel consumption is achieved on the HWFET cycle, which also has the lowest average acceleration rate and the highest fuel consumption is observed for the US06 cycle, which has the highest average acceleration rate.

E-REV MODEL DEVELOPMENT

Performance targets were set for the E-REV vehicle to enable the drive motor and battery pack specification to be determined. The E-REV performance targets selected for this study are:

- Desirable that acceleration performance, grade-ability and maximum speed are not degraded too significantly from baseline
 - Ideally as good as, or superior to, baseline
- Electric only range desired to cover 70% of typical daily driving
 - 80 km target selected, based on UK fleet data presented in the previous section
- Charge-sustaining cruising speed capability at a reasonable speed to give acceptable motorway performance
 - Target set at 120 km/h

Traction motor selection

The traction motor of the E-REV was selected to be capable of delivering a 0-100km/h acceleration time that was superior to the baseline vehicle. The acceleration performance of the vehicle was assessed based on the published peak torque ratings of the motors considered, whilst the Vmax performance was analysed based on the published continuous torque ratings of the motors. Several motors were considered, based on published specifications from the motor manufacturers. It was also decided that, for simplicity, the motor should directly drive the wheels without a transmission. For the purposes of this analysis, torque and efficiency data for a commercially available ‘off the shelf’, liquid cooled, permanent magnet motor was used. This motor has a peak power rating of 100kW, a continuous power rating of 55kW and a combined motor and controller peak efficiency of over 93%. The motor and control unit have a combined mass in excess of 100kg.

<figure 8 here>

Figure 8 shows a normalised cascade diagram for the baseline vehicle, together with the peak and continuous normalised tractive wheel torque available from the motor. The final drive ratio for the E-REV, of 3.25:1, was selected to give compromise between maximum speed and grade ability. The E-REV has a computed Vmax of 170km/h at a motor speed of 4900 rev/min, based on continuous motor power rating, and a computed 0-100km/h acceleration performance, based on motor peak torque rating, of 8.4 seconds.

Battery Pack Selection

A battery pack was configured for the E-REV based on published data for individual cells from battery

manufacturer's specification sheets. It was decided to configure a battery pack from discrete cells, rather than select a complete battery pack unit available as an off-the-shelf item, as this would give most flexibility in defining a pack specification that was best suited to this application and vehicle targets. The cells selected for the basis of this study are lithium ion A123 ANR26650 mLA cells [17], as they are believed to have a good life expectancy and high discharge capabilities. The battery pack was sized to enable the target vehicle range with electric only operation. The energy requirement for this was based using the average brake power output of the baseline vehicle model data from Table A1.2. From this it can be calculated that the average power consumption is between 0.43 and 0.68 MJ/km, depending upon the cycle. The NEDC cycle requires ~0.46MJ/km, so for an 80km range over this cycle we would require ~37MJ of energy storage capacity within the battery pack.

The battery pack configuration is based on 2000 A123 ANR26650 mLA cells (20 parallel sets of 100 cells in series), giving a nominal voltage of 330V. The nominal pack capacity is 46Ah (15.18kWh or 54.6MJ). The model is operated between SOC limits of 0.95 and 0.25 (giving a useable pack capacity of only 32.2Ah, which is 10.6kWh or 38.2MJ). The maximum continuous discharge capability is 462kW, which is well beyond the peak traction motor power absorption capability. Purely based on the weight and dimensions of the cells alone, the pack would occupy 120 litres and have a mass of 140kg. It is estimated that the pack weight including enclosure, cooling and battery management would be approximately 200kg. The estimated pack total internal resistance used in the E-REV vehicle model is 0.075 Ω.

Table 3. Estimated component masses for E-REV and resulting E-REV mass estimate.

Description	Mass (kg)
<i>Vehicle</i>	
Baseline vehicle mass (1.6 litre gasoline, manual)	1157
1.6 litre gasoline engine	-118
5-speed manual transmission	-34
<i>Motor + Generator</i>	
100kW liquid cooled traction motor	86
Liquid cooled generator	40
2 x motor controllers	32
<i>Battery Pack</i>	
2000 x A123 ANR 26650mLA cells	140
Enclosure, cooling and battery management	60
<i>Range Extender Engine</i>	
~20 kW engine (HKS 700E 680cc 4-stroke twin)	50
Total	1413
+ Driver + Fuel	~1500

E-REV Vehicle Mass Estimate

An estimate of the mass of the hypothetical E-REV mass was made based on ballpark masses of the major components removed from the baseline vehicle and approximate masses of the major components that are required to be added for the E-REV, including the traction motor and battery pack described in the previous sections. Additionally, initial mass estimates for the range extender engine based on a HKS 700cc, 4-stroke, two-cylinder engine [18] and a commercially available, liquid cooled, generator unit have been included in the model. For the purposes of the simulation, the generator unit is assumed to have a fixed efficiency of 90%. No amendment to the mass of the vehicle to allow for the masses of the cooling system, exhaust or fuel system have been made; it has been implicitly assumed that those of the baseline vehicle are close, in mass, to the corresponding items required for the E-REV. Likewise, no adjustments have been made to the vehicle mass to allow for E-PAS, E-HVAC or a brake-vacuum pump, as again it has been assumed that those of the baseline vehicle are close, in mass, to the corresponding items required for the E-REV. The resulting ‘add and delete’ list of components, showing the mass adjustment allocated for each item, is shown in Table 3. The resulting estimated mass increase for the E-REV over the baseline vehicle is 257kg. The simulations for the E-REV were performed with a vehicle test mass of 1500kg.

Simplistic E-REV Control Strategy

A simplistic, SOC based, control strategy was implemented within the GT-Drive model of the E-REV to control the operation of the range extender. The resulting battery SOC and range extender operation is shown schematically in Figure 9. The E-REV operates purely as an EV when battery SOC is above the lower threshold value. Once the battery SOC falls to this lower threshold the range extender engine is started and kept running until the higher threshold value, at which point the range extender is switched off. The power output of the range extender engine was limited such that the battery pack was only charged at a rate of 1C (for the pack used in the model a 1C charge rate corresponds to an electrical charging power of 15.18kW into the battery). Thus, the range extender unit was only allowed to deliver a higher power than this when the traction motor was demanding power. The lower SOC threshold value used in this study was 0.25 and the upper SOC threshold values used was 0.40. The initial SOC used in the simulations was 0.95. The rationale for not having a higher upper threshold value is that it would not be desirable for the vehicle to return home with a battery that had been highly recharged by the range extender engine, as this would limit the amount of energy that could be utilised from an off-vehicle supply, thus potentially reducing the real EV operation of the E-REV. Relatively simple improvements could be made to this control strategy, for example operating the range extender during periods of high power demand from the traction motor; however, this was beyond the scope

of the present study. Regenerative braking is performed at all vehicle speeds, up to absorption powers equal to the 1C charge rate limit imposed for the battery pack.

<figure 9 here>

SIMULATION RESULTS FOR THE E-REV

The calculated electric only range, and corresponding electric only operation duration, of the E-REV for a variety of steady speed cruises and repeated drive-cycles, are shown in Figure 10. In all simulations a constant load of 300W has been added to the battery to account for the requirement of ancillary electrical systems likely to be present in the E-REV, such as lights, control systems, E-PAS and E-HVAC. The electric only ranges and times presented in Figure 10 are based simply on the values between simulation start and the first moment the range extender is switched on. The electric only range of vehicle (based on 70% SOC change, from 0.95 to 0.25 SOC) shows large variation with the drive-cycle; high-speed cycles having a shorter range. At a constant cruise speed of 140km/h the E-REV has an electric only duration of only 15 minutes and a range of 35km, whereas during the LA92 test cycle the electric only duration is 4 hours and 40minutes, with a corresponding range of 116km. The electric only range achieved for the NEDC is 90km and the electric only range for the Artemis cycle is 66km.

<figure 10 here>

The computed range extender fuel converter mechanical power requirements to maintain a constant battery SOC during steady speed cruises are shown in Figure 11. Cruising at 80km/h requires roughly 10.9kW, 120km/h requires roughly 27.5kW and 140km/h requires roughly 41.5kW. The power requirement is dominated by aerodynamic drag at higher speeds and the power requirement roughly increases as a function of the cube of cruising velocity. Table 4 shows how the cruising power requirement of the range extender fuel converter vary with varying vehicle mass.

Table 4. Effect of E-REV mass and cruise speed on range extender fuel converter mechanical power output to maintain battery SOC.

Speed (km/h)	1300 kg (kW)	1500 kg (kW)	1700 kg (kW)
80	10.3	10.9	11.6
120	26.3	27.5	28.6
140	39.9	41.5	43.1

<figure 11 here>

E-REV Analysis for Repeated Artemis Cycle Operation

In this section the performance of the E-REV is analysed by driving the model over 10 consecutive Artemis cycles, for various range extender fuel converter power output limits, for a 1500kg test mass, a 46Ah battery pack, and a 1C battery charge rate limit. Seven range extender fuel converter mechanical power output limits have been considered: 10kW, 15kW, 20kW, 25kW, 30kW, 40kW and 50kW. When on, the instantaneous range extender output is limited by the 1C charge rate limit imposed for battery charging, thus when the vehicle is stationary (traction motor is demanding no power) the maximum range extender fuel converter mechanical output is limited to 17.2kW (15.18kW charge to battery, 0.30kW continuous electrical load of vehicle systems and 1.72kW lost to generator inefficiency). [Figure 12](#) shows the battery SOC histories for the E-REV with differing fuel converter mechanical power output limits. It can be seen that the SOC for all cases follow the same path until the range extender is started, roughly halfway through the 2nd cycle. After this point the SOC histories diverge, the SOC corresponding to the highest power fuel converter attaining the upper threshold (SOC=0.4) soonest. At the other extreme, the SOC of the 10kW fuel converter continues to decrease even after the range extender is started. The 10kW range extender is not sufficiently powerful to maintain a cyclically sustainable SOC, and that during the 3rd cycle the battery SOC reaches a value less than 0 (i.e. a non-physical condition). The SOC histories for all cases reach a cyclically repeatable condition after only a few cycles, and certainly by cycle 5 a repeated sequence is established (except for the fuel converter with the 10kW power limit). The expanded view of cycles 5, 6 and 7 reveals that even the 25kW fuel converter is unable to maintain SOC control such that the battery does not fall below an SOC of 0.25. However, all fuel maximum converter power outputs of 15kW and above are capable of maintaining a cyclically sustainable SOC.

<[figure 12 here](#)>

The fuel converter mechanical outputs, during repeated Artemis cycles, for various range extender fuel converter power output limits, are shown in [Figure 13](#) for cycles 5, 6 and 7. Output of larger fuel converters is limited during low speed sections of the drive-cycle. The 50kW fuel converter only attains its maximum power output for brief periods, whereas the 10kW fuel converter is switched on during the 2nd cycle and remains on, at maximum power, thereafter. The average mechanical output powers of the fuel converters, whilst they are operating, are shown in [Figure 14](#). It can be seen from [Figure 14](#) that, due to the battery charge rate limit, the smaller fuel converters operate, on average, closer to their maximum power than the larger fuel converters. Thus, a larger fuel converter would be required to operate across a

broader range of output powers, which may add to the cost, complexity and reduce the average operating efficiency of the device.

<[figure 13 here](#)>

<[figure 14 here](#)>

[Figure 15](#) shows a series of plots relating to the average time that the range extender is on during each cycle (for cycles 3 to 10, i.e. ignoring the initial period where the cyclical sequence is being established). The number of range extender starts per cycle is shown in [Figure 15a](#). The 10kW fuel converter shows no starts per cycle for the period considered, as the range extender was started during the 2nd cycle and never switched off again. The 15, 20, 25 and 30kW fuel converters show one start per cycle, whereas the 40 and 50kW fuel converters start twice per cycle, thus a larger fuel converter power capability increases the number of range extender starts that occur. But the time on per start falls with increasing fuel converter output power, as shown in [Figure 15b](#), due to a shorter charging time being required to raise the SOC between the lower and upper charging thresholds. The time shown for the 10kW fuel converter is 52 minutes, which corresponds to the duration of the Artemis cycle, as this remains fully on after the 2nd cycle. [Figure 15c](#) shows the range extender on time per cycle, this is simply the product of [Figures 15a](#) and [15b](#), where it can be seen that increasing the fuel converter maximum power output leads to shorter on duration per cycle, again due to a shorter charging time between the SOC thresholds. However, the influence of the fuel converter maximum power on range extender on time per cycle can be seen to be diminishing at higher power outputs, as the effect begins to become negated due to the battery charge rate limit. [Figure 15d](#) shows the range extender duty cycle for the various fuel converter power outputs. The duty cycle, as plotted in [Figure 15d](#) is simply the range extender on time per cycle divided by the duration of one cycle (52 minutes). The 10kW fuel converter is on for full cycle and hence shows a 100%. Increasing fuel converter power capacity leads to lower duty cycle; the trend is identical to [Figure 15c](#).

<[figure 15 here](#)>

E-REV Analysis for Repeated Operation Over Various Cycles

The range extender duty cycle variation with fuel converter maximum power output, for several drive-cycles, is shown in [Figure 16](#). As for the Artemis cycle case discussed in the previous section, the duty cycle decreases with increasing fuel converter maximum power output for all cycles shown in [Figure 16](#). 100% duty cycle indicates that the fuel converter mechanical power output is insufficient to enable a sustained battery SOC to be achieved. Additionally, too high a duty

cycle may have implications for the fuel converter durability. It can be seen from [Figure 16](#) that a fuel converter with a 10kW maximum power output is unable to sustain the battery SOC during the Artemis, HWFET, US06 cycles and the 120 and 140 km/h cruises. To sustain battery SOC over repeated US06 cycles requires a fuel converter with a maximum power output of at least 20kW, the 120km/h cruise requires at least a 30kW fuel converter and the 140km/h cruise only achieves a sustained SOC with the 50kW fuel converter.

The average mechanical output powers of the fuel converters whilst they are on, are shown in [Figure 17](#), where it can be seen that, due to the battery charge rate limit, the smaller fuel converters operate, on average, closer to their maximum power whilst they are running than the larger fuel converters. For the lower speeds cycles, the LA92, NEDC, UDDS and the JCO8, the average power output of the fuel converter, when running, does not rise significantly above 20kW.

<[figure 16](#) here>

<[figure 17](#) here>

Effect of Battery Pack Capacity on Fuel Converter Power Requirement

The effect of reducing the battery pack capacity, upon the range extender fuel converter maximum power requirement, was investigated over the Artemis cycle, both with and without a 1C charging rate limit imposed for the battery pack. Three sizes of battery pack have been analysed, 46Ah (as used in all previous E-REV results presented), 23Ah and 11.5Ah. The vehicle test mass was reduced to 1400kg and 1350kg for the 23Ah and 11.5Ah battery pack simulations respectively. Reducing battery pack capacity reduces the charging power when the 1C limit is imposed, which in turn reduces average range extender fuel converter mechanical power output during cycle and increases the range extender duty cycle in all cases. The power demand from the traction motor also reduces slightly with the reduced vehicle mass, in turn slightly reducing mechanical power required from the fuel converter. With the 1C charging rate limit in place, the battery SOC was not sustained over the Artemis cycle for the following combinations:

- 46Ah battery with the 10kW fuel converter;
- 23Ah battery, with a fuel converter power less than 20kW;
- 11.5Ah battery, with a fuel converter power less than 30kW.

The range extender duty cycle with the 1C charge rate limit in place, for the various fuel converter maximum power output and battery pack capacity combinations are shown in [Figure 19a](#). It is found that, with the charge rate limit in place, as the battery pack capacity reduces, the required fuel converter power output increases, as the load-levelling capability of battery pack is reduced and the E-REV

operation becomes more analogous to that of a series hybrid. However, without the 1C charge rate limitation, a reduced battery pack size has much less impact upon the range extender duty cycle, as shown in [Figure 19b](#). Although the frequency of switching on and off of the range extender increases proportionally with battery pack capacity, due to the change in energy required to move between the upper and lower SOC thresholds used to control the range extender. Reducing battery pack size also reduces the benefits that are hoped to be accruable from off-vehicle charging, as the electric only range of the vehicle will be proportionally reduced.

<[figure 19](#) here>

Effect of Fuel Converter Efficiency Upon NEDC CO₂ Emissions

The influence of the fuel efficiency of the fuel converter upon the CO₂ emissions of the E-REV was analysed over the NEDC, based on the cycle averaged fuel converter energy requirement to achieve a cyclically sustained battery SOC. Fuel converter brake specific fuel consumption rates of between 340 and 200 g/kWh were analysed. For comparison, a gasoline engine operating at its minimum BSFC point will achieve a fuel consumption of approximately 240g/kWh, which, assuming a fuel lower heating value of 44 MJ/kg equates to a maximum thermal efficiency of roughly 34% [19, 20]. Recent claims for rotary engine fuel consumptions are 260g/kWh [21] and published efficiency data for a micro-turbine of the required power output are roughly equivalent to a gasoline fuel consumption rate of about 300g/kWh [22].

UN/ECE regulation No 83 Rev 3, Amend 2, Annex 14 [23] gives a weighting factor for emissions of zero emission vehicle (ZEV) capable vehicles. The weighting factor reduces the mass of emissions as the electric operation only range of the vehicle increases. The influence of this weighting factor is shown in [Figure 20](#). Un-weighted results correspond to an electric only range of 0 km. As the electric only range of the vehicle increases, the weighting factor effectively reduces the significance of the fuel converter efficiency on the declared CO₂ figure for the E-REV.

<[figure 20](#) here>

CONCLUSIONS

Vehicle usage patterns for a fleet of vehicles based in the UK have been compared against several relevant legislative drive cycles. Based on results from examination of the fleet data, the Artemis drive-cycle has been selected and used as the basis for analysis of the fuel converter requirements for a hypothetical E-REV for a typical European C-class vehicle. The influence of drive-cycle and battery pack size on the fuel converter requirement has been investigated.