Determining a Suitable All Electric Range for a Light Weight Plug-in Hybrid Electric Vehicle

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***Abstract* — With the increasing awareness and adoption of eco-friendly vehicle technologies such as hybrid electric vehicles (HEVs); most if not all major worldwide vehicle manufacturers have released an eco-friendly vehicle or have announced a future release (e.g. concept demonstrator vehicles). Such vehicles can meet current legislative emissions standards (with comparatively lower CO_2 tailpipe emissions compared to conventional combustion engine vehicle equivalents), yet performance in the real world is often far worse than quoted test figures (e.g. fuel economy).**

In order to maintain and grow customer acceptance of such vehicle technologies it is important that real world usage is considered during the design and development processes. This paper describes the method of selecting a suitable all electric range (AER) to meet both legislative emissions and real world usage demands and demonstrates its use through a case study of a lightweight plug-in hybrid electric vehicle (PHEV).

Keywords- All Electric Range (AER); Electric Vehicle (EV); Hybrid Electric Vehicle (HEV); Plug-in Hybrid Electric Vehicle (PHEV); State-of-Charge (SoC); Well-to-Wheel (WTW) CO_2

I. INTRODUCTION

The growth of eco-friendly vehicle technologies such as pure electric (EV) and hybrid electric vehicles (HEVs) have presented new opportunities, including: reduced dependency on non-renewable energy resources, lowering of CO_2 emissions from transport and greater public awareness of leading a lower carbon lifestyle. Due to the more complex nature of such vehicle technologies, there are opportunities present to improve factors such as fuel economy through advanced control strategy development (e.g. development of a suitable EV range for a plug-in HEV).

The aim of the work covered in this report was to develop a method for choosing an appropriate EV range for a predominantly urban based vehicle (i.e. low speed, start/stop) yet still be able to be used for smaller periods of motorway driving (i.e. high speed/acceleration). Therefore, a case study of a lightweight inner-city vehicle was chosen (≈ 550kg kerb mass).

A base vehicle was created and results simulated using WARPSTAR (Warwick Powertrain Simulation Tool for Architectures); a flexible tool developed at the University of Warwick using the MATLAB/Simulink® environment. A number of individual studies were carried out to determine a suitable EV range; initially for a pure EV (section III) leading onto an EV range for a lightweight plug-in HEV (section VI). A selection of suitable standard legislative and real world drive cycles were chosen (e.g. NEDC and ARTEMIS) in each case and resulting component selections (e.g. battery mass) and CO_2 well-to-wheel (WTW) figures calculated.

This work leads onto the development of more complex HEV control strategy options (e.g. blended operation of the ICE and electric motor) which will be covered in a later report.

II. BACKGROUND TO STUDY

A. *Drive Cycle Selection*

Standard drive cycles such as the NEDC (figure 1) are used for emission certification of light and heavy duty vehicles. Yet, most of these drive cycles are not representative of actual vehicle usage. The figures quoted by manufacturers for fuel economy for example are very misleading and are often not achieved in the ‘real-world’. Therefore, when considering the development and testing of a new vehicle (e.g. HEV) it is important to consider the real-world usage to improve vehicle specification, selection of a suitable architecture and control strategy optimisation.

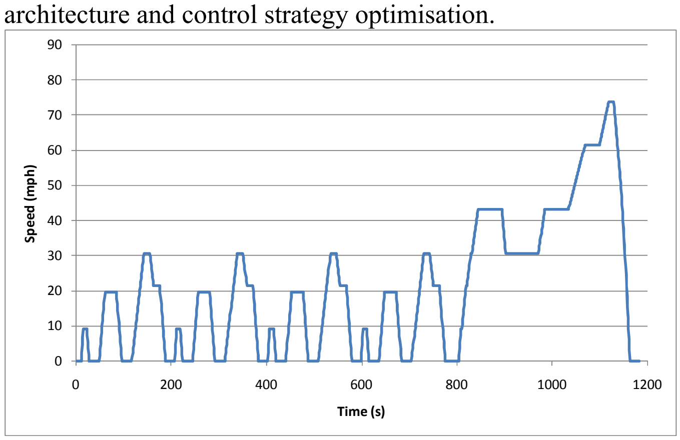

Figure 1. NEDC Drive Cycle

Previous work has been carried out to collect data from actual driving and used to create representative real-world drive cycles. The ARTEMIS drive cycles for example (ARTEMIS urban and motorway combined drive cycle shown in figure 2) were created using the data from a number of on road studies in Europe as discussed in the following paper [1]. Additional real world and standard drive cycles were chosen as discussed throughout.

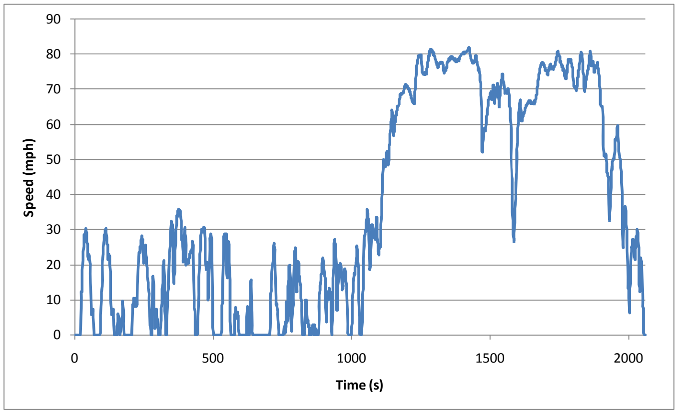

Figure 2. ARTEMIS Drive Cycle

In order to establish an all electric range (AER), the motor was assumed to be placed on the rear axle for simplicity. This meant that a reduction gear must be specified; this was established to be a 4:1 reduction, typical of many vehicle differential reduction ratios. This allowed the motor to be able to rotate below its maximum speed over the ARTEMIS drive cycle, even if the vehicle itself may not be able to meet this cycle under EV power alone.

B. WARPSTAR Simulation Tool

The simulation tool WARPSTAR (Warwick Powertrain Simulation Tool for Architectures) was used to create the required vehicle architectures and to generate simulated results (e.g. CO_2 emissions and potential AER) for this study (screenshot shown in figure 3). WARPSTAR is a flexible tool developed at the University of Warwick as part of the Premium Automotive R&D programme (PARD) using the MATLAB/Simulink® environment.

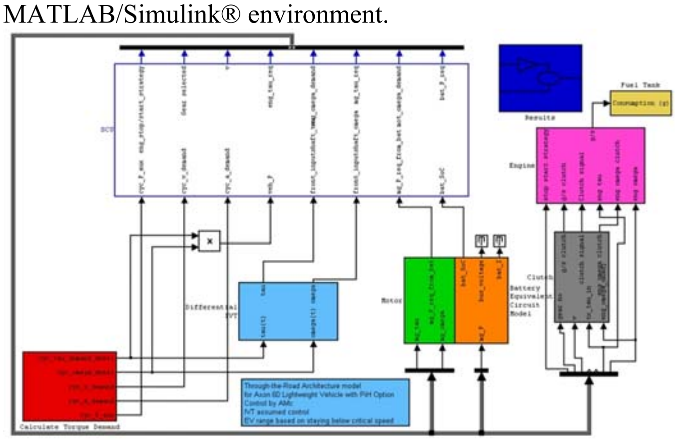

Figure 3. WARPSTAR Simulation model

Drive cycle data is loaded into the model from which torque, power, speed and acceleration demands are determined (highlighted by the red block). The demanded torque and angular velocity is fed into the differential block (highlighted light blue) from which the modified torque and angular velocity are determined. This information is then fed into the supervisory control unit (SCU – large white block with blue outline) along with further data such as vehicle power demand (kW) and battery state of charge (SoC) in which the control strategy is determined (e.g. EV only, ICE only or blended operation in the case of a HEV). The control strategy is addressed at every time step (i.e. every second) to choose the relevant operational conditions (i.e. component selection) for the current torque and speed demands. At each time step, the vehicle speed, selected gear and torque data is fed into the engine model (pink block) from which the fuel consumption is then determined. Additional continuous and absolute data is determined for other attributes including: CO_2 emissions (g/km), fuel economy (mpg), battery SoC change and total energy used by the engine and electric motor/generator (J). This tool offers the comprehensive functionality required by both manufacturers and customers for HEV modelling; discussed in more detail in the associate paper [2].

III. DETERMINING A 60 MILE ALL ELECTRIC RANGE (AER)

A. Purpose

Existing real world components were initially chosen for the purpose this study; these were a generation I Toyota Prius PM motor (30kW), Honda Insight PM motor (10kW) and a Prius NiMH battery pack. By using existing components; validation of real world usage and component operational limits were ensured.

The aim of the first study was to determine an AER range of 60 miles over a selection of standard emission and real-world drive cycles. By choosing a 60 mile range it was a way of selecting a suitable motor (related to upper power limits) of a maximum inner city commute (30 miles each way) combined with a smaller section of motorway driving that someone might realistically use.

B. Overview

- Study carried out for both 1 and 2 passengers (550kg kerb mass of vehicle plus 75kg for each passenger).
- 30kW (e.g. Toyota Prius) and 10kW (e.g. Honda Insight) electric motors used for each drive cycle (motor maps shown in figures 3 and 4).
- NiMH battery packs (Nominal pack voltage = 274V; where 6Ah = 70kg battery mass, including 17kg for inverter mass)
- Drive cycles used were the NEDC, ARTEMIS, 10-15 (Japanese test drive cycle; carried out on a dynamometer similar in nature to European NEDC drive cycle testing) and Real_World_Urban (a representative real-world urban drive cycle, as shown in figure 6).
- The battery capacity (Ah) was then chosen which would fulfill a range of 60 miles (97 km) with an effective ΔState-of-Charge (SoC) closest to/less than -0.7. Initial SoC = 0.7; a realistic fully usable capacity for NiMH batteries, as previous work has determined [3].

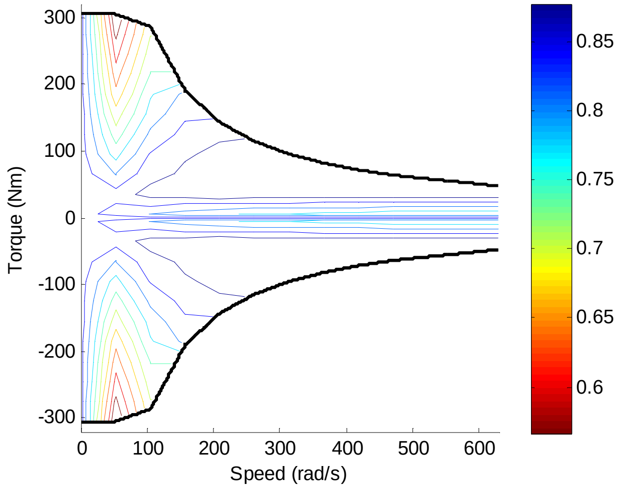

Figure 4. 30kW (e.g. Toyota Prius Gen I) Motor Map

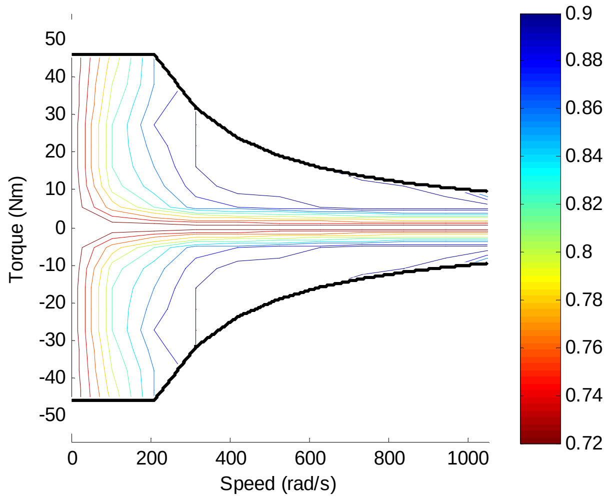

Figure 5. 10kW (e.g. Honda Insight) Motor Map

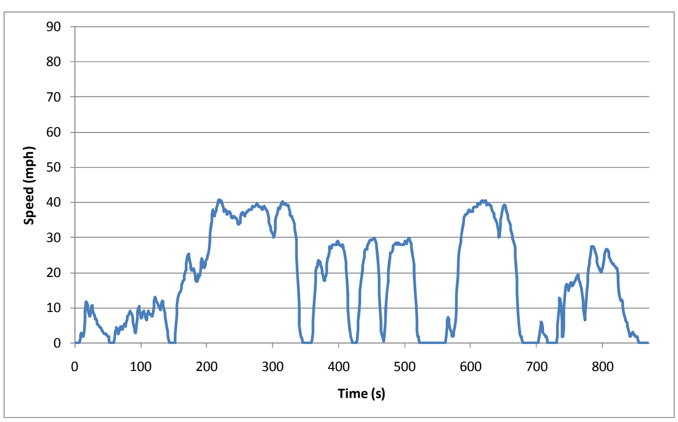

Figure 6. Real_World_Urban Drive Cycle

C. *Discussion*

Figure 5 shows the results for the potential AER (miles) obtained for each drive cycle in relation to the required battery capacity (Ah); assuming the operation of the electric motor was not exceeded for the 30kW case. The 60 mile AER could be fulfilled using a 30kW motor for the NEDC and 10-15 drive cycles (circled in orange on figure 7) using battery capacities of ≈ 50-70Ah. The other two drive cycles could not be met due to excessive motor torque (e.g. due to higher levels of acceleration - representative of real world usage). However, when considering the limits of the electric motor none of the four drive cycles could be met in full when using a 10kW motor.

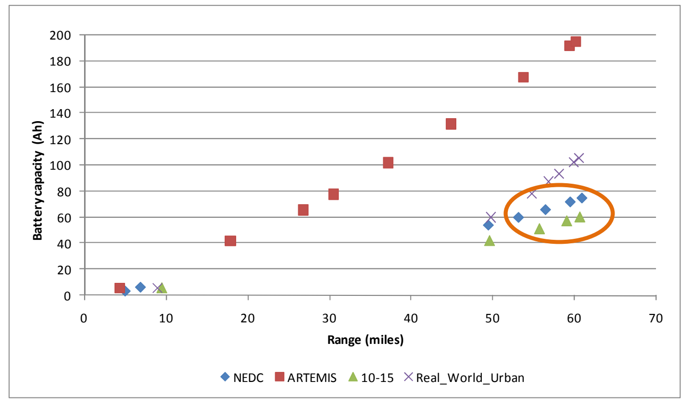

Figure 7. Battery capacity required for a seleciton of AERs. *(30 kW motor)*

When comparing the 10kW and 30kW motors at the same battery capacity (in this case 42Ah) over the 10-15 drive cycle the following results were obtained:

- Vehicle mass = 1146kg (30kW motor), 1102kg (10kW motor)
- Battery mass = 390kg (same for both)
- Tank-to-wheel (TTW) CO_2 emissions = 44.7g/km (30kW motor), 37.6g/km (10kW motor)
- Potential range = 49.6 miles (30kW motor), (62.0 yet N/A) miles (10kW motor); yet motor could not power vehicle over the full drive cycle as peak torque exceeded in places.

Even though the potential range was greater for the 10kW motor the actual limits were exceeded. Therefore as a pure EV it was not possible to achieve the required range. Figure 8 shows the battery capacities required for each drive cycle (for the 10kW and 30kW motors) to fulfill the 60 mile AER; irrespective of whether the drive cycle could be met or not due to the limitations of the motors. The only two that could be met (using the 30kW motor) as mentioned were the NEDC and 10-15 drive cycles, which required battery capacities of 75Ah and 60Ah respectively.

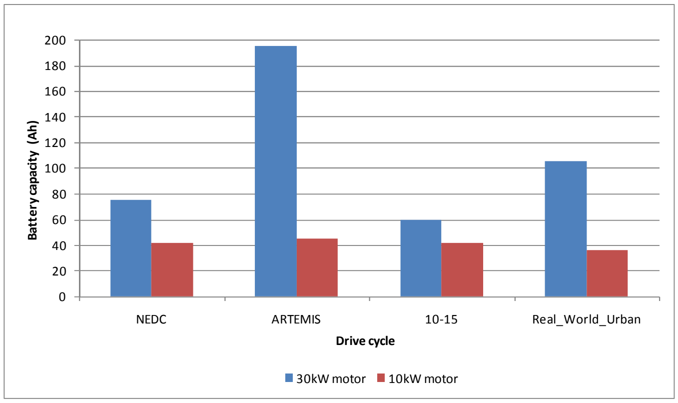

Figure 8. Battery capacity required to achieve 60 mile range for each drive cycle. *(30 kW and 10 kW motors)*

Figure 9 shows the overall mass of the vehicle selections which met the 60 mile range using the 30kW motor for each of the 4 drive cycles. The split of the weight is given as follows:

- Vehicle base mass = 550kg (in each case)
- Passenger mass = 150kg (2 passengers – 75kg each)
- Motor mass = 30kW motor, 56kg (in each case)
- Battery mass = 53kg for each 6Ah of battery capacity (+ 17kg for inverter)

The overall vehicle mass and percentage contribution of the battery for each of the four drive cycles was:

- NEDC
  - Overall vehicle mass = 1440kg
  - Battery mass as a percentage of the overall mass = 47%
- ARTEMIS
  - Overall vehicle mass = 2505kg
  - Battery mass split = 70%
- 10-15
  - Overall vehicle mass = 1306kg
  - Battery mass split = 42%
- Real_World_Urban
  - Overall vehicle mass = 1706kg
  - Battery mass split = 56%

In the two cases where the drive cycle could be met (NEDC and 10-15) the battery mass accounted for just under 50% of the overall mass of the vehicle. Therefore, even for these cases the storage of such a large battery supply would be unfeasible, especially within a small, lightweight vehicle. Despite meeting the 60 mile AER there would be poor performance as a result due to the excess weight and storage.

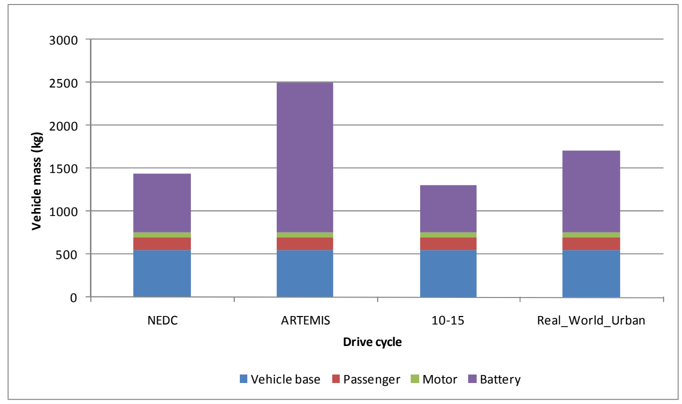

Figure 9. Split of vehicle mass to achieve 60 mile AER. *(30 kW motor)*

This study was repeated again for 1 passenger (75kg) and the results were very similar. The same two drive cycles could only be met using a 30kW motor as before. The impact of the battery mass in relation to the overall vehicle mass was far greater than that of the passenger mass in this case.

D. Conclusion of Study

- 10kW motor is too small.
- 60 mile AER is possible for low acceleration/urban based drive cycles but may not be feasible due to the excessive battery size/mass (compromising performance to achieve range).
- It was only possible to meet urban drive cycles with a 30kW motor.
- Little difference when considering 1 or 2 passengers as battery mass >> passenger mass.

IV. WTW CO_2 Comparision Study

A. Purpose

The majority of CO_2 emissions from transport occur during the 'in-use' phase, regardless of the vehicle technology [4]. Typically CO_2 emissions from transport are quoted as a TTW figure (e.g. as measured in vehicle certification tests). When considering TTW emissions of EVs for example, this is often considered to be zero; yet generated emissions from the electrical sector would be discarded in this case. A fairer way for differing vehicle technologies (e.g. conventional ICE vs. HEV vs. EV) would suggest well-to-wheels (WTW) CO_2 emissions comparison. WTW figures include the fuel generation and combustion phases. For this work a constant UK average figure of 480gCO_2/kWh was chosen [5].

The aim of this study was to see the difference in WTW CO_2 emissions over a range of AERs for a selection of drive cycles, when compared to a conventional ICE vehicle equivalent.

B. Overview

- NEDC, ARTEMIS and ECE-15 drive cycles reviewed (ECE-15 is the urban section of the NEDC drive cycle and was chosen as a purely urban based comparison).
- TTW CO_2 figures obtained for conventional ICE vehicles through simulation.
- 30kW electric motor used.
- WTW CO_2 (g/km) vs. AER plotted for NEDC, ARTEMIS and ECE-15 drive cycles. Equivalent ICE comparison also shown on the same plot (at 0 mile AER).
- WTW CO_2 (g/km) vs. maximum AER plotted for 13 drive cycles observed.

C. Discussion

The TTW CO_2 figures were obtained for each drive cycle for a conventional ICE vehicle, which were:

- NEDC
  - 61.4 TTW CO_2 g/km
- ARTEMIS
  - 86.9 TTW CO_2 g/km
- ECE-15
  - 59.8 TTW CO_2 g/km

The WTW figures were (shown at 0 mile EV range in figure 10):

- NEDC
  - 68.8 WTW CO_2 g/km

ARTEMIS
  - 97.3 WTW CO_2 g/km
- ECE-15
  - 67.0 WTW CO_2 g/km

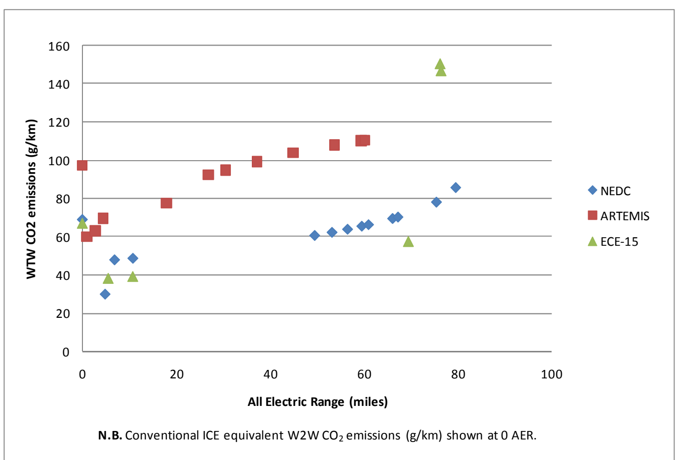

Figure 10. All Electric Range (AER) vs. WTW CO_2. *(30 kW motor)*

For the NEDC drive cycle the WTW figure for the conventional ICE equivalent was 68.8, which falls between an AER of 60 - 66 miles when comparing it to an EV equivalent. For the ARTEMIS drive cycle (97.3 WTW CO_2) this was between an AER of 30 - 39 miles and for the ECE-15 drive cycle (66.9 WTW CO_2) this was between an EV range of 69 - 76 miles. This shows that there is clear benefit in having an AER of less than or equal to 30 miles for all drive cycles in comparison to an ICE vehicle based upon WTW CO_2 emissions.

The plot for WTW CO_2 (g/km) vs. maximum AER is shown in figure 11.

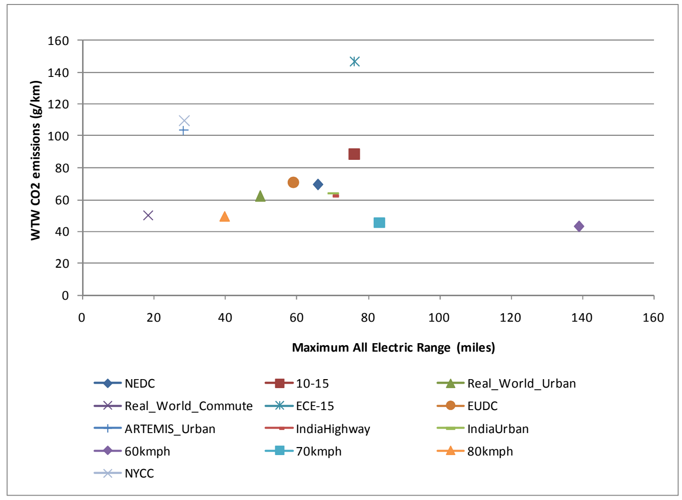

Figure 11. Maximum AER vs. WTW CO_2 for each Drive Cycle. *(30 kW motor)*

D. Conclusion of Study

An AER of >=60 miles for an EV or PHEV is unfeasible irrespective of the cost and size of the required battery as the WTW CO_2 comparison with an ICE equivalent is exceeded in this case, even for primarily urban based rive cycles. An AER is feasible for <=30 miles; for all drive cycles studied, the WTW CO_2 figure was lower for an EV compared to an ICE vehicle option. When considering the cost and size of a battery to achieve a 30 mile range previous studies have shown that this would not be feasible, leading more towards <= 10 miles as an AER. This supports the case for smaller AER for a PHEV option.

V. Determining a 5 Mile All Electric Range (AER)

A. Purpose

According to a DfT study in 2008, 55% of journeys were of less than 5 miles in length, with 22% of these being less than 2 miles in length [6]. Clearly a vehicle with an AER of 5 miles would be able to undertake a significant fraction of the journeys. Up to now it has been assumed that all of the drive cycle will be in AER mode, irrespective of speed on the drive cycle. The ECE-15 has a maximum speed of 31mph, whilst the Artemis_Urban and Real_World_Urban are ~ 40mph limit.

This is considered reasonable for a real-world commute of 5 miles in urban areas.

Table 1 illustrates the breakdown of vehicle usage in the UK, from [6]. Table 1 shows the trip length distribution for journeys of less than 5 miles in 2008.

TABLE I. PERCENTAGES OF JOURNEYS UNDERTAKEN OF SPECIFIED LENGTHS

Upper Limit Trip Length (m)	Percentage Journeys
1	6
2	16
5	33
Total < 5 m	55

This supports the reason for choosing an AER range of 5 miles for a light weight PHEV option.

B. Overview

- Study carried out for 2 passengers (550kg kerb weight of vehicle plus 75kg for each passenger).
- 30kW (e.g. Toyota Prius) and 10kW (e.g. Honda Insight) electric motors used for each drive cycle.
- Drive cycles used were predominantly urban in nature (as with the previous studies).
- The battery capacity (Ah) was then chosen as with the 60 AER study, in this case fulfilling a AER of 5 miles (8 km).

C. Discussion

The previous studies carried out have shown that working towards gaining a 60 mile and/or maximum range for a lightweight EV or PHEV resulted in significantly large battery masses in relation to the overall vehicle mass. A more realistic AER has shown to be 5 miles. The vehicle selections with a 10kW motor before were unable to meet any of the drive cycles due to the limits of the motor torque and/or power being exceeded. This could be compensated now through the use of an engine in the case of a PHEV.

Using the 30kW motor it was possible to meet all of the drive cycles for a 5 mile (or greater) range with a battery capacity of 6Ah (battery mass = 70kg including inverter mass) as shown in figure 12. The average range achieved across the 11 drive cycles was 7.9 miles (greater than the target of 5 miles).

The battery mass now accounted for 9% of the overall vehicle mass which would be a feasible option for a PHEV, whereas before this was in excess of 50%. Therefore, the best case for overall vehicle mass to achieve a range of at least 5 miles would be 799.7kg. For such a case the mass of the passengers becomes a greater issue than that of the battery pack as passenger mass >> battery mass.

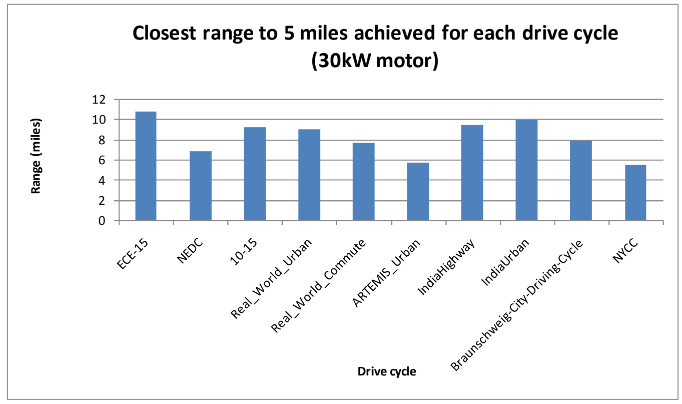

Figure 12. Closest range to 5 miles achieved for each drive cycle. *(30 kW motor and 6Ah battery pack)*

D. Conclusion of Study

- 10kW motor still slightly too small for all drive cycles.
- 5 mile range is realistic and feasible.
- A 30kW motor would meet all of the urban drive cycles chosen.
- Mass of 2 passengers (150kg) is now greater than the mass of the battery pack (70kg).

E. Summary of AER Studies

- A feasible lightweight EV solution could be made for predominantly urban usage, with limited EV range.
- A 10kW motor is too small for a lightweight EV, but maybe suitable for a PHEV with very limited EV capability.
- A 60 mile AER is not feasible and a 5 mile range is more realistic and feasible.
- A 30kW motor will meet most/all urban driving conditions with range ~ 5 miles.

VI. DETERMINING A SUITABLE ALL ELECTRIC RANGE FOR A LIGHT WEIGHT PHEV

A. Purpose

Building upon the learning from the previous studies, the option of a PHEV with an AER seemed liked the most sensible of choice based upon a WTW CO_2 emissions benefit. The supervisory control unit (SCU) was modified for varying AERs over a selection of drive cycles. The aim of this study was to determine a suitable AER for a PHEV as a better alternative to a pure EV, HEV or conventional ICE light-weight vehicle.

B. Overview

- NEDC, ARTEMIS, 10-15 and Real_World_Commute (a representative real world urban/motorway drive cycle as shown in figure 13) drive cycles reviewed.

- AERs were modified in each case by increasing the increment of the upper electric only speed limit (up to full EV operation).

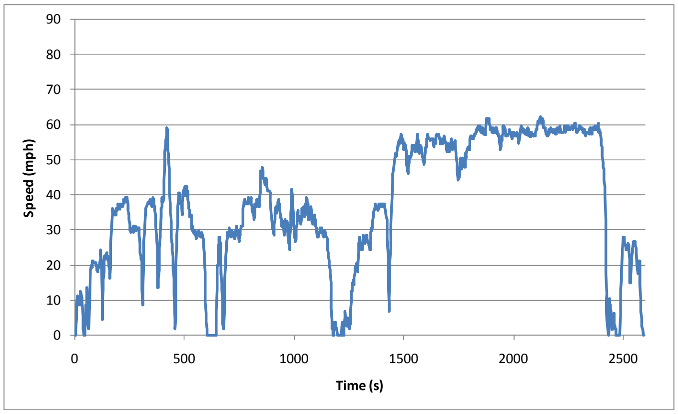

Figure 13. Real_World_Commute Drive Cycle

C. *Discussion*

For each drive cycle an AER was set for increasing increments of 5mph (2.24 m/s) up to the maximum speed of the drive cycle (representing pure EV operation over the full drive cycle). An example of this is shown in figure 14 for the NEDC drive cycle.

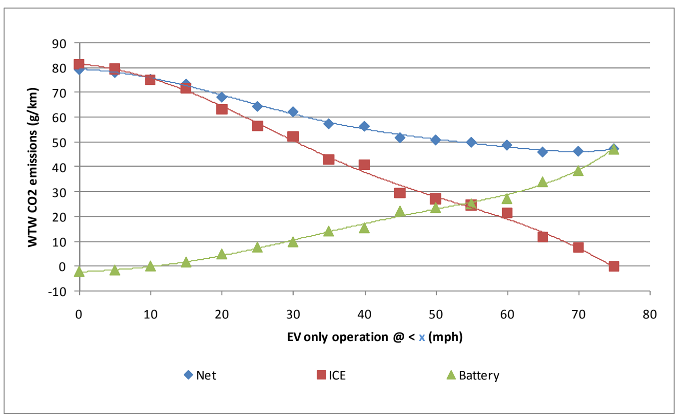

Figure 14. EV Only Operation vs. WTW CO_2 over NEDC. *(30 kW motor)*

The comparison of the WTW CO_2 figures for the NEDC, ARTEMIS, 10-15 and Real_World_Commute drive cycles can be seen in figure 15. The two points highlighted red on the ARTEMIS and Real_World_Commute drive cycles is where the ΔSoC would have been >= -0.7 (greater than full discharge, initial SoC = 0.7). In order to extend the possible AER over these drive cycles the PHEV option is confirmed to be the most feasible option. For the 10-15 drive cycle the EV only operation limit to offer 57.5g/km would be at less than ~ 22 mph.

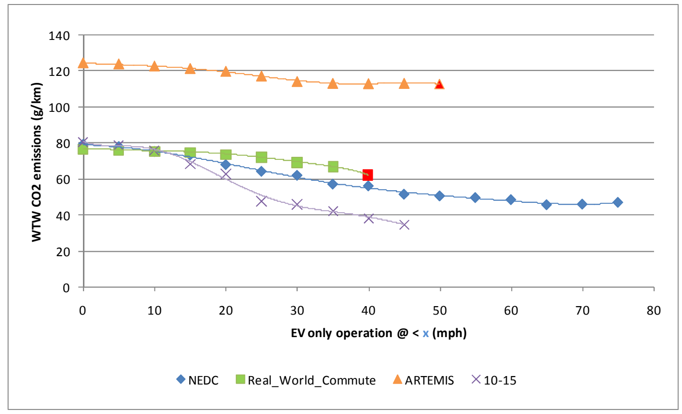

Figure 15. EV Only Operation vs. WTW CO_2. *(30 kW motor)*

This work has been expanded to consider blending of electric motor and ICE in addition to other more complex control strategy options in order to further optimise the selection of a HEV and will be reported at a later date.

D. *Conclusion of Study*

- EV only operation to be less than ~ 35 mph to achieve NEDC figures of < 50 g/km CO_2.
- EV operation needs to be proportional to power demand.
- More complex HEV control strategy options need to be explored (e.g. blending of ICE and electric motor) to ensure ICE is used optimally.

VII. Conclusion from Studies

- A 5 mile range for an EV is realistic and feasible.
- WTW CO_2 figures allow for fair comparison between selections of vehicle technology options (e.g. as EVs have 0g/km TTW CO_2).
- The proposed vehicle could have a limited EV range.
- Most sensible option is for a HEV with limited EV range.
- Vehicle is most likely to be tested over the NEDC drive cycle.
- EV only operation to be less than ~ 35 mph to achieve NEDC figures.
- EV operation needs to be proportional to power demand.
- This work leads onto more complex HEV control strategy options to be developed/explored (e.g. blending of ICE and electric motor).

Acknowledgments

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