

# Lifecycle Costs of Ultracapacitors in Electric Vehicle Applications

A. G. Simpson      G. R. Walker

School of Information Technology and Electrical Engineering  
The University of Queensland

*Abstract* – The pulse power characteristics of ultracapacitors appear well suited to electric vehicle applications, where they may supply the peak power more efficiently than the battery, and can prevent excessive over sizing of the battery pack due to peak power demands. Operation of ultracapacitors in battery electric vehicles is examined for possible improvements in system efficiency, vehicle driving range, battery pack lifetime, and potential reductions in system lifecycle cost.

The lifecycle operation of these ultracapacitors is simulated using custom-built, dynamic simulation code constructed in Matlab. Despite apparent gains in system efficiency and driving range, the results strongly suggest that the inclusion of ultracapacitors in the electric vehicle does not make sense from a lifecycle cost perspective.

Furthermore, a comparison with results from earlier work shows that this outcome is highly dependant upon the efficiency and cost of the battery under consideration. However, it is likely that the lifecycle cost benefits of ultracapacitors in these electric vehicles would be, at most, marginal and do not justify the additional capital costs and system complexity that would be incurred in the vehicle.

## I. INTRODUCTION

The pulse power characteristics of ultracapacitors appear well suited to electric vehicle applications, where they may supply the peak power more efficiently than the battery, and can prevent excessive over sizing of the battery pack due to peak power demands [1]. Despite these perceived technical benefits, the economic feasibility of including ultracapacitors in electric vehicles remains in question.

This paper outlines a study that examines the lifecycle costs of ultracapacitors in battery electric vehicle applications. The lifecycle operation of these ultracapacitors is simulated using custom-built, dynamic simulation code constructed in Matlab.

## II. ULTRACAPACITORS IN BATTERY ELECTRIC VEHICLES

Generally speaking, battery electric vehicles (BEVs) have seen limited acceptance in the marketplace [2]. This stems primarily from technical limitations in their power source – the electrochemical battery – with two of the greatest concerns being:

- The size and weight of the battery pack required for acceptable driving range and performance, due to the low specific energy and power density of batteries (when compared to other vehicle power sources).
- The high capital cost and relatively short lifetime (commonly 3 years) of electrochemical batteries, which leads to high system costs over the lifetime of the vehicle

In contrast with batteries, ultracapacitors offer several benefits that appear well suited to BEV applications:

- Higher power density
- Lower internal impedance
- Longer lifetime

With these benefits in mind, it seems technically sensible to couple ultracapacitors and batteries to improve the power source of a BEV. The higher power density of the ultracapacitor can reduce the size and weight of the power source, as determined by the vehicle performance (peak power) requirements. Also, the lower impedance ultracapacitor can supply peak powers more efficiently than the battery, leading to increased overall system efficiency and increased driving range. Previous studies [3], [4] have demonstrated the gains that may be achieved in these areas by including ultracapacitors in an electric vehicle.

In terms of lifecycle cost, however, the benefits of ultracapacitors in BEVs are unclear. A higher operating efficiency should reduce depth of discharge in the battery pack, resulting in extended battery life and a decrease in lifetime battery costs. Higher energy efficiency should also reduce the energy costs per kilometre of travel. These gains may not, however, be sufficiently large enough to offset the additional capital cost of the ultracapacitor bank and its associated power electronics.

In previous work [5], the authors examined the lifecycle costs of ultracapacitors in electric vehicles using custom Matlab-based simulation code. The study showed that despite improvements in system efficiency, driving range and battery lifetime, the improvements in lifecycle cost were quite marginal. Furthermore, these results were heavily dependant upon the assumed costs of components, the driving cycle used in the simulation and the power control strategy for the ultracapacitor bank. The purpose of this work is to improve the exploration of these trade-offs in lifecycle cost by using more realistic cost assumptions and driving cycles, and an optimised power control strategy for the ultracapacitors.

## III. SIMULATION TO CALCULATE LIFECYCLE COSTS OF ELECTRIC VEHICLE POWER SOURCE

Operation of ultracapacitors in a battery electric vehicle power source was simulated to examine possible improvements in system efficiency, vehicle driving range, battery pack lifetime, and potential reductions in system lifecycle cost.

## A. Vehicle System Configuration



Figure 1: A 1/10th scale model of the UltraCommuter – currently under development at The University of Queensland

### 1. Vehicle Parameters

The simulated vehicle specifications (Table 1) were for the UltraCommuter (Fig. 1) – a low drag, energy efficient commuter vehicle being developed at The University of Queensland.

Vehicle Parameter	Symbol	Value
Vehicle Mass (not including batteries or ultracapacitors)	m	630kg
Coefficient of drag times frontal area	CdA	0.3m <sup>2</sup>
Coefficient of rolling resistance	Crr	0.0075
Motor efficiency	$\eta_{mot}$	90%
Motor controller efficiency	$\eta_{cont}$	92%

Table 1: UltraCommuter specifications

### 2. Power Source Architecture

The simulated vehicle power source consisted of a battery pack connected to the electrical power bus, in parallel with the ultracapacitor bank via a DC-DC converter (Figure 2).

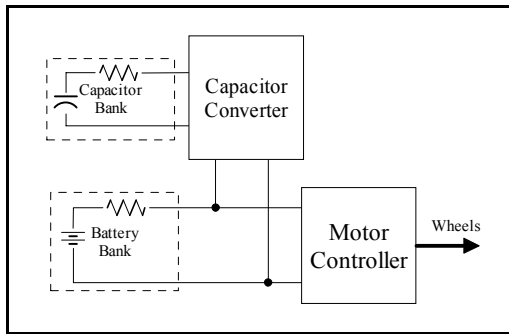


Figure 2: Electrical power source architecture for the simulated vehicle

### 3. Batteries

The batteries chosen for the simulated vehicle were Hawker Genesis 26Ah batteries (Table 2). The battery bank was sized to provide the vehicle with a driving range approximately double that required by the driving cycle

(Fig. 3), producing depths of discharge around 50%. This necessitated a pack of 20 Hawker 26Ah batteries, which also provided sufficient power capability for the vehicle.

Battery Parameters	Value
Capacity	26Ah
Internal resistance (fully charged)	5.0mOhm
Short circuit current (fully charged)	2400A
Mass	10.8kg
Cycle life (@ 100%DOD)	400
Coulombic efficiency	90%
Unit cost (per 12V battery)	US \$127

Table 2: Hawker Genesis 26Ah battery characteristics [6], [7] and [10]

### 4. Ultracapacitors

Ultracapacitors chosen for the simulated vehicle were the Maxwell Powercache PC2500 Ultracapacitor (Table 3). A string of 40 of these ultracapacitors (Table 4) was scaled to represent different 100V capacitor bank sizes, which were used to examine tradeoffs within the power source. Scaling laws were employed to ensure that parameters such as series resistance varied in a realistic manner.

Ultracapacitor Parameters	Value
Capacitance	2700F
Series resistance (DC)	1.0mOhm
Voltage	2.5V
Rated current	625A
Mass	725g
Volume	0.6L
Temperature	-40°C to 70°C
Unit cost (per cell)	US \$30

Table 3: Maxwell Powercache PC2500 ultracapacitor characteristics [8] and [12]

## B. Vehicle System Dynamics in Simulation

### 1. Driving Cycle

The chosen BEV configuration, supplemented with ultracapacitors, was modelled in operation over an intensified ( $\times 1.2$ ) combination of the Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET). This cycle (Fig. 3) represented a total distance of approximately 50km, which was deemed a reasonable daily driving distance for an electric commuter vehicle.

### 2. Vehicle Power Requirements

The driving cycle velocity profile was differentiated with respect to time to determine vehicle acceleration. Vehicle power requirements were then calculated using the standard road load equation [9]. For the intensified combined driving cycle, gradient =  $Z = 0$ .

$$P(v) = \frac{1}{2} \rho C_d A v^3 + C_{rr} m g v + m \frac{dv}{dt} v + m g Z v$$

Power flows through the motor and controller were subjected to their respective efficiencies (Table 1) in order to calculate the power demands at the electrical power bus (input to the controller).

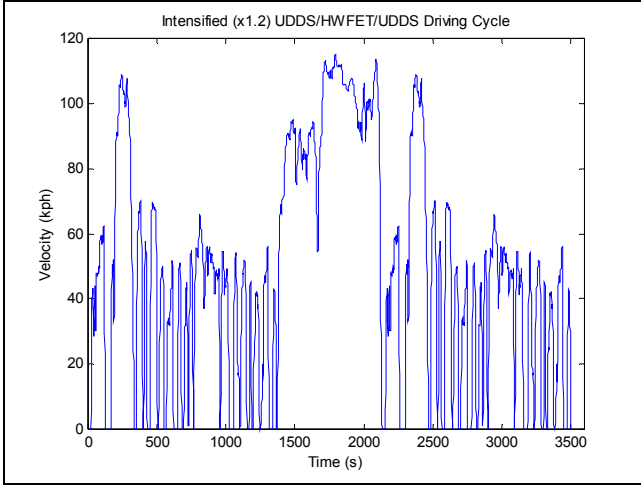


Figure 3: Intensified ( $\times 1.2$ ) UDDS/HWFET/UDDS driving cycle

### 3. Power Control Strategy

The power-split between the battery pack and ultracapacitor bank was determined via the power control strategy for the system. Stored energy in the ultracapacitor bank was controlled using the following voltage control strategy (Figure 6). For this study,  $v_{car}^{max}$  was set to 120kph:

$$\frac{V_{cap}}{V_{cap}^{max}} = \sqrt{1 - k \left( \frac{v_{car}}{v_{car}^{max}} \right)^2}$$

For this strategy, the factor  $k$  represents the fraction of total energy storage in the ultracapacitor bank which may be utilised by the vehicle during the driving cycle. A larger value of  $k$  will better utilise the ultracapacitor as a load-leveling device, but will also reduce the DC/DC converter efficiency through the reduced ultracapacitor voltage.

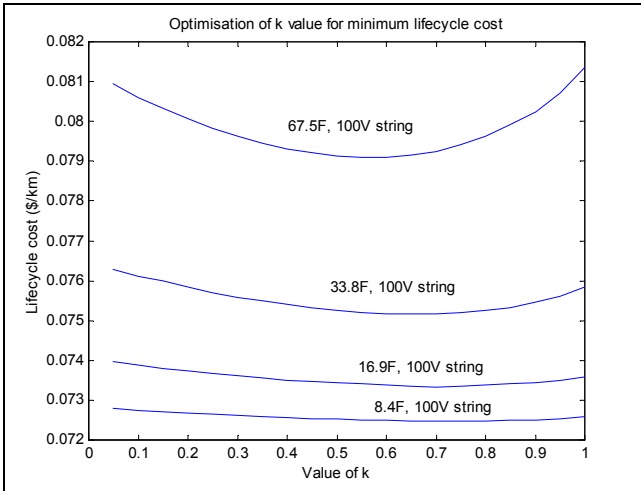


Figure 4: Optimisation of  $k$  for minimum lifecycle cost

Because of this trade-off, the factor  $k$  was optimised across a range of capacitor bank sizes to achieve minimum

system lifecycle cost. Although there was a slight variation in the optimal value of  $k$  for different ultracapacitor sizes (Figure 4), a value of  $k=0.65$  was deemed to be sufficiently near optimal for use in all cases.

Energy stored in the ultracapacitor was differentiated with respect to time to determine power flow from the capacitor bank. Power requirements from the battery were determined as the difference between power demanded at the electrical bus and the power provided by the ultracapacitor.

### 4. Capacitor/DC-DC Converter Model

Losses in the capacitor were modelled via a DC series resistance (Figure 2). Losses in the DC-DC boost converter were modelled as a series resistance in the inductor and constant voltage drops across the IGBTs in the half-bridge converter. The series resistance of the inductor was set equal to the series resistance of the capacitor string, and an IGBT voltage drop of 2.3V was assumed. Losses in the output filter capacitance of the converter were assumed to be negligible. Calculation of these losses allowed the available capacitor power at the electrical bus to be determined.

### 5. Battery Model

The battery model included losses due to series resistance (Figure 2) and round trip (charge-discharge) Coulombic efficiency (Table 2). Data for the battery model was obtained from the validated ADVISOR vehicle modelling software [10]. The state-of-charge (SOC) of the battery pack was integrated over the driving cycle to adjust open circuit voltage and series resistance of the battery.

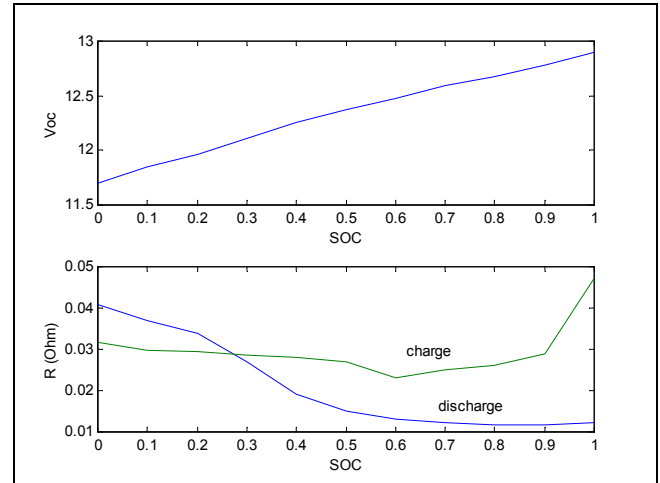


Figure 5: Open circuit voltage and series resistance of Hawker 26Ah battery [10]

### C. Lifecycle Cost Calculations

#### 1. Battery Lifetime

The cumulative depth-of-discharge (DOD) of the battery pack over the driving cycle was used to determine the cycle life of the battery pack, using the following expression [11]:

$$\text{Cyclelife} = 400\text{cycles} / \text{DOD}(\%)$$

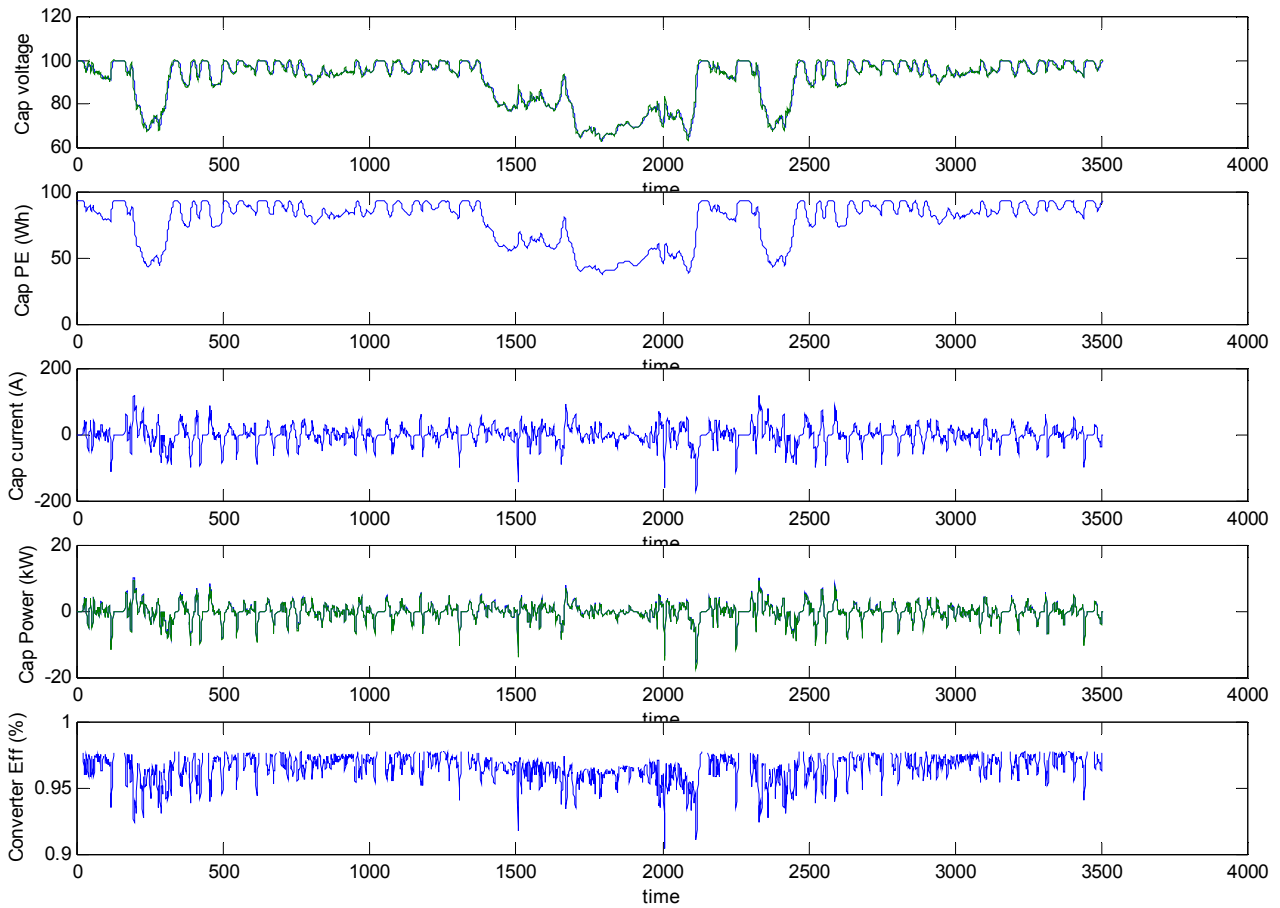


Figure 6: Simulation traces for an ultracapacitor bank (67.5F) over the driving cycle

As stated by the battery manufacturer [11], this relationship was valid for DOD greater than 25% and simulated DOD was always within this range.

The lifetime distance travelled by the battery pack was calculated by multiplying the cycle life (no. of cycles) of the battery pack by the distance travelled per cycle.

## 2. Component Costs

The installed cost of the battery pack was calculated using the size of the battery pack (in kWh) and a calculated specific cost for the batteries of US\$407/kWh. This cost calculation was based upon pricing obtained through the House of Batteries online catalogue [7].

Ultracapacitor string parameter	Value
No. of cells in series	40
Total capacitance	67.5F
Voltage	100V
DC-DC converter input current rating	200A
DC-DC converter output voltage rating	300V
Cost of ultracapacitor string	US \$1200
Cost of DC-DC converter	US \$1200
Total cost	US \$2400

Table 4: Scaleable ultracapacitor reference case

The installed cost of the ultracapacitor pack was calculated by scaling the total cost of the reference string of 40 ultracapacitors (Table 4). A constant specific cost (dollars per farad) relationship was assumed, with capacitor pricing based upon a long term estimate of US\$30 per unit quoted in a Maxwell press release [12].

The cost of the DC-DC converter was assumed equal to the cost of the scaled ultracapacitor string. This is a generous assumption for this converter (which for the reference case in Table 4 would be rated for approx. 200A input, 300V output), but represents the level of cost that might be required for an automotive application. The criticality of this assumption was also tested (Fig. 9).

Costs of the motor, controller, and rest-of-vehicle were assumed identical for the various scenarios examined and therefore were not included. Maintenance costs (other than battery replacement) over the lifetime of the vehicle were not considered.

## 3. Energy Costs

Energy costs for recharging the battery pack were calculated by simulated charging from the attained DOD back to 0%DOD (100%SOC). Simulated charging was performed at the 5-hour rate, according to manufacturer's specifications [11], and an electricity cost of US\$0.05/kWh was assumed.

Energy costs over the lifetime of the battery were then calculated by multiplying the energy cost per cycle by the cycle life.

#### 4. Total Lifecycle Costs

Total lifecycle costs were calculated in terms of dollars per kilometre (US\$/km). Battery and total energy costs were amortized over the life of the battery pack (in km). Ultracapacitor and DC-DC converter costs were amortized over the life of the vehicle (in km), due to the extraordinarily large lifetime expected of the ultracapacitors [13]. A vehicle lifetime of 300 000km was assumed [14]. Amortized costs were then added to determine the total lifecycle cost for the vehicle power source.

### IV. LIFECYCLE COST RESULTS

To establish a base case for comparison, simulations were performed for various numbers of batteries in the battery pack, ranging from the lower pack size limit of 20 batteries up to 25 batteries. No ultracapacitors were included in this simulation set. The lifecycle cost results for these simulations are presented in Figure 7, which plots battery lifetime (km) vs. lifecycle cost (\$/km), overlaid on constant total lifetime cost contours.

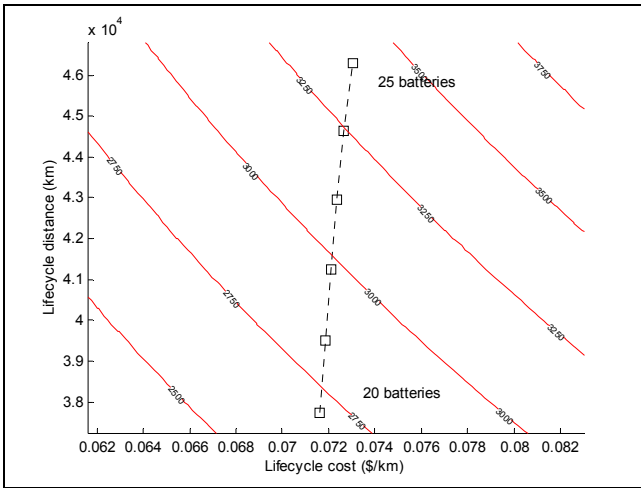


Figure 7: Lifecycle costs for 20-25 batteries

As expected, the inclusion of more batteries in the battery pack increased battery pack lifetime (and driving range), but also increased the system lifecycle cost marginally (through larger battery costs and increased energy consumption due to increased vehicle mass).

Number of batteries	Ultra-capacitor size (F)	Energy consumption (Wh/km)	Range (km)	Battery lifetime (km)	Lifecycle cost (c/km)	Installed cost (\$)
20	0	75.8	84.6	37 731	7.16	2 544
20	1.7	75.8	84.6	37 748	7.18	2 604
20	8.4	75.8	84.5	37 813	7.25	2 844
20	16.9	75.8	84.5	37 881	7.34	3 144
20	33.8	75.4	85.1	37 976	7.52	3 744
20	50.6	75.4	85.1	38 011	7.71	4 344
20	67.5	75.4	85.1	37 985	7.92	4 944
25	0	78.2	102.5	46 301	7.30	3 180

Table 5: Lifecycle cost results for various power source configurations.

Lifecycle cost simulations were performed for differing sizes of ultracapacitor bank in the powertrain (Table 4). Figure 8 presents simulation results for an ultracapacitor bank size ranging between 0 - 67.5F.

The results from the comparison of different capacitor bank sizes (Table 5) are quite clear. Despite achieving marginal gains in battery lifetime and driving range, the gains in system efficiency are not sufficient to overcome the cost penalties of including the ultracapacitor bank in the system. Furthermore, the inclusion of more batteries in the vehicle (Fig. 7) seems to be the more economical way of improving driving range and battery lifetime. Based upon these results, the inclusion of ultracapacitors in the electric vehicle power source cannot be justified.

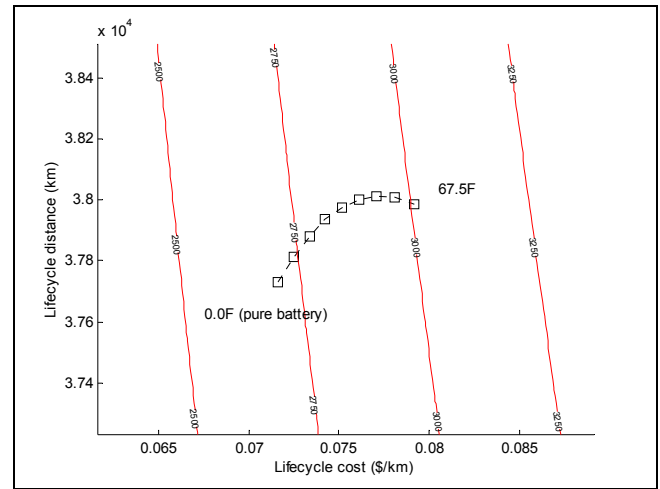


Figure 8: Lifecycle costs of differing ultracapacitor bank sizes (0-67.5F)

Lastly, the criticality of the assumption relating to DC-DC converter cost was tested. Figure 9 presents results for ultracapacitor bank size ranging between 0 – 67.5F, but with an assumed converter cost of zero. Even in this ideal case, the efficiency benefits provided by the ultracapacitors fail to achieve benefits in lifecycle cost.

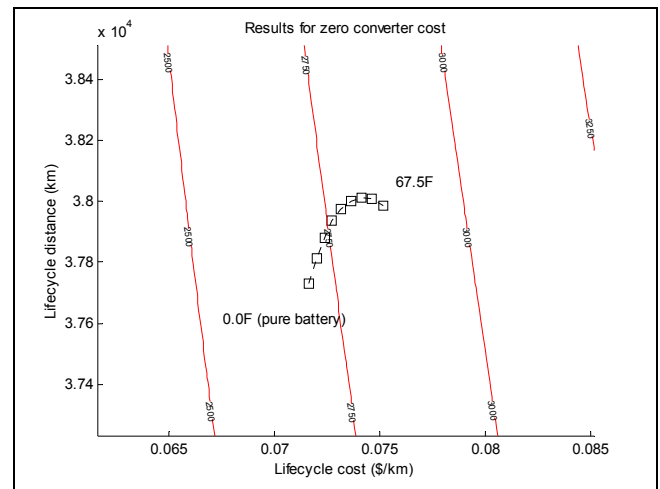


Figure 9: Lifecycle costs of differing ultracapacitor bank sizes (0-67.5F), with zero converter cost assumed

These outcomes contrast greatly with the results achieved in earlier work [5]. In [5], a pack of 30 Hawker

Genesis 16Ah batteries was used to power the same vehicle over a series of five consecutive UDDS driving cycles. Despite the fact that this cycle was less demanding and the vehicle operated with a non-optimised control strategy, the inclusion of ultracapacitors in the system still achieved marginal gains in lifecycle cost. The key difference here is the battery in the vehicle - this result can be attributed to the lower efficiency of the Hawker 16Ah battery, when compared to the 26Ah battery used in this study.

## V. CONCLUSION

The simulation results confirm that addition of ultracapacitors to the power source of a battery electric vehicle (BEV) can improve overall system efficiency, driving range and battery lifetime, although these gains were quite marginal in this study. However, the results strongly suggest that the inclusion of ultracapacitors in the electric vehicle does not make sense from a lifecycle cost perspective.

Furthermore, a comparison with results from earlier work shows that this outcome is highly dependant upon the efficiency and cost of the battery under consideration. It is likely, however, that the lifecycle cost benefits of ultracapacitors in these electric vehicles are, at most, marginal and do not justify the additional capital costs and system complexity that would be incurred in the vehicle.

It would be interesting to examine this problem for a high performance and efficient, yet expensive battery technology such as Li-Ion. Unfortunately, sufficient life cycle data for such advanced battery types is not available in the literature to facilitate this comparison.

Finally, the battery cycle life model used for this simulation only considers the effects of bulk discharge/charge, and does not include the detrimental effects of higher frequency cycling e.g. acceleration/deceleration events. In reality, the observed battery lifetimes would probably be significantly lower.

Proper testing of battery/ultracapacitor hybrid power sources in functioning vehicle platforms over extended periods of time is needed to explore these issues fully.

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