



Conventional, hybrid and electric vehicles for Australian driving conditions – Part 1: Technical and financial analysis

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ABSTRACT

This paper is the first of a two part study which quantifies the economic and greenhouse performance of conventional, hybrid and fully electric passenger vehicles operating in Australian driving conditions. This first study focuses on the total cost of vehicle ownership. Two vehicle sizes are considered, Class-E and Class-B, which bracket the large majority of passenger vehicles on Australian roads.

Simulation models of baseline production, conventional vehicles are first developed. These models are then systematically altered to obtain the fuel and/or electricity consumption of equivalent mild hybrid, parallel hybrid, plug-in hybrid and fully electric vehicles. The total operating cost of each vehicle is then calculated, and the vehicle production costs are estimated by decomposing the vehicles into their major constituent parts. This enables the total cost of vehicle ownership to be estimated, taking particular account of variations in fuel, electricity and battery prices.

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1. Introduction

Increasing the degree of passenger vehicle electrification has the potential to reduce greenhouse gas emissions, improve urban air quality and reduce consumption of liquid fuels simultaneously. However, partial or total vehicle electrification typically comes at a purchase price premium, with other considerations such as vehicle range and charging times for fully electric vehicles also potential purchase disincentives (Boulanger et al., 2011). Offsetting the higher purchase price, partially or fully electrified vehicles reduce running costs by reducing or eliminating the on-board consumption of liquid fuels. However, for consumers the choice is often not clear as to which vehicle configuration is the most economic over the duration of its ownership, thus necessitating a lifetime cost-analysis for the different vehicle configurations. Worldwide, there is recognition of the uncertainty in life cycle costs as reflected in studies performed for American (Brooker et al., 2010; O'Keefe et al., 2010; Simpson, 2006; Becker et al., 2009; Lee and Lovellette, 2011) and European driving conditions (Douglas and Stewart, 2011; van den Bulk and Hein, 2009). The combination of Australian energy production and driving characteristics mean outcomes of these studies may not be directly transferrable in either economic or environmental terms.

Recognition of this need has resulted in some studies being undertaken. The topics investigated include an estimation of the uptake of the different vehicle configurations in the Australian state of Victoria (Kinghorn and Kua, 2011) and assessment of the economic viability and potential greenhouse gas savings of plug-in hybrid electric vehicles in the Australian state of New South Wales (Feeney, 2009). However, these studies do not develop or utilize explicit vehicle powertrain simulation

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models. In addition, the vehicle configurations are not decomposed into constituent parts to enable high fidelity component-wise cost estimation.

The benefits of vehicle electrification can be examined in two related problems. On one hand, the cost of vehicle ownership is of importance to the consumer, while greenhouse gas emissions are relevant to the community. This paper addresses the former by estimating the total cost of ownership for different vehicle types under a range of possible scenarios, while a companion paper (Sharma et al., *in press*) addresses the latter. Together these two works attempt a systematic assessment of vehicles with increasingly electric powertrains for Australian driving conditions.

The total costs of ownership (TCO) are calculated by estimating the purchase price, lifetime running costs and the resale values, and is coupled with a net-present-value (NPV) analysis to account for depreciation. To conduct these studies, the base vehicles are selected to be commercially available Class-B and Class-E sedans with internal combustion engines. Class-E sedans constitute 15–20% of the new car sales in Australia (Federal Chamber of Automotive Industries, 2011), and are heavily represented by two makes with very similar specifications and pricing: the Ford Falcon and the Holden Commodore, representing around 33% and 47% of vehicle sales in this class over the past 3 years respectively. The 4-L, 6-cylinder, 1800 kg Ford Falcon is selected as the base vehicle in this study as detailed experimental data over the legislative drive cycle was available to the authors.

The base Class-B sedan chosen was the 1.6 L, turbocharged four-cylinder diesel, 1100 kg Ford Fiesta EConetic, as this represents one of the highest fuel economy vehicles in Australia, and this car size accounts for 35–40% of Australian passenger vehicle sales (Federal Chamber of Automotive Industries, 2011). These two vehicle classes bracket the large majority of vehicles on road, and so trends in their electrification can be used to infer similar trends in vehicles of intermediate size.

The total cost of ownership for different vehicle configurations is evaluated under scenarios which include possible variations in the fuel and electricity prices to establish the most cost effective vehicle type. Furthermore, since there is significant uncertainty in the price of the batteries, different costing scenarios which favour or penalise vehicle electrification are presented and analysed. A cost-equivalence analysis is also conducted to establish different combinations of the fuel, electricity and battery prices that result in cost parity of the conventional vehicle with its electric variants within the first 3–5 years of owning a particular electric or hybrid vehicle type.

2. Modelling energy usage

The objective of this section is to estimate the fuel and electricity usage for different vehicle types. This is accomplished in two steps. In the first step, commercially available conventional vehicles are chosen as the base vehicles and their simulation models are developed and validated using legislative drive cycles. These conventional vehicle simulation models are sequentially altered to obtain simulation models of the electric variants of the conventional vehicles with comparable performance.

The simulation models are developed using PSAT (Powertrain System Analysis Toolkit). Upon validation of the modelling procedure, the components of the Class-E internal combustion engine vehicle (the 'conventional vehicle', CV) model are altered to develop models with increasing levels of electrification to successively obtain mild, parallel, series and plug-in hybrid electric vehicles as well as a full battery electric vehicle (BEV). In addition, a BEV variant of the Class-B vehicle is also modelled.

2.1. Modelling and validation of conventional vehicles

The PSAT library does not contain a component-based model of a 2010 internal combustion engine based Ford Falcon vehicle, and consequently one was created using the Ford Taurus as the base vehicle with only minor changes required to meet the Falcon specifications. These included modifying the component files corresponding to the engine (including the engine fuel consumption map and the physical characteristics of the Falcon engine) and the gearbox (the 2010 Falcon models use a ZF 6HP26 six speed automatic gearbox). Additional minor modifications are also required including electrical accessories load, exhaust after-treatment power and the equivalence ratio. All other components in the existing model were of minor difference to the Falcon vehicle for which transient dynamometer test results were available.

In Australia, the legislative fuel consumption and emissions requirements are tested by operating the vehicles over the New European Drive Cycle (NEDC). The Class-E CV model was simulated over the NEDC and the transient simulation responses are compared against the experimental data obtained from Ford of Australia, with both datasets presented in Fig. 1. The simulated responses for both engine torque and instantaneous fuel consumption exhibit some high frequency dynamics that are not present in the experimental data, possibly due to a combination of the gear change strategies or experimental sampling rate. The lower initial fuel consumption is due to the absence of a cold start model in the PSAT simulation. This leads to roughly 5% lower cumulative fuel consumption, however there is good general agreement between the experimental and simulated data. The simulated fuel consumption over the cycle is 9.4 L/100 km, which is close to the reported consumption of 9.9 L/100 km, and indicates the simulation model is sufficiently accurate for the financial analysis in this paper.

A similar approach was used to develop a Class-B CV model, whereby existing components close to the EConetic specifications are selected and modified slightly to meet the available power, fuel economy and emissions specifications. In particular, the Ford Focus PSAT model components apart from the engine are chosen and the parameters in their initialization

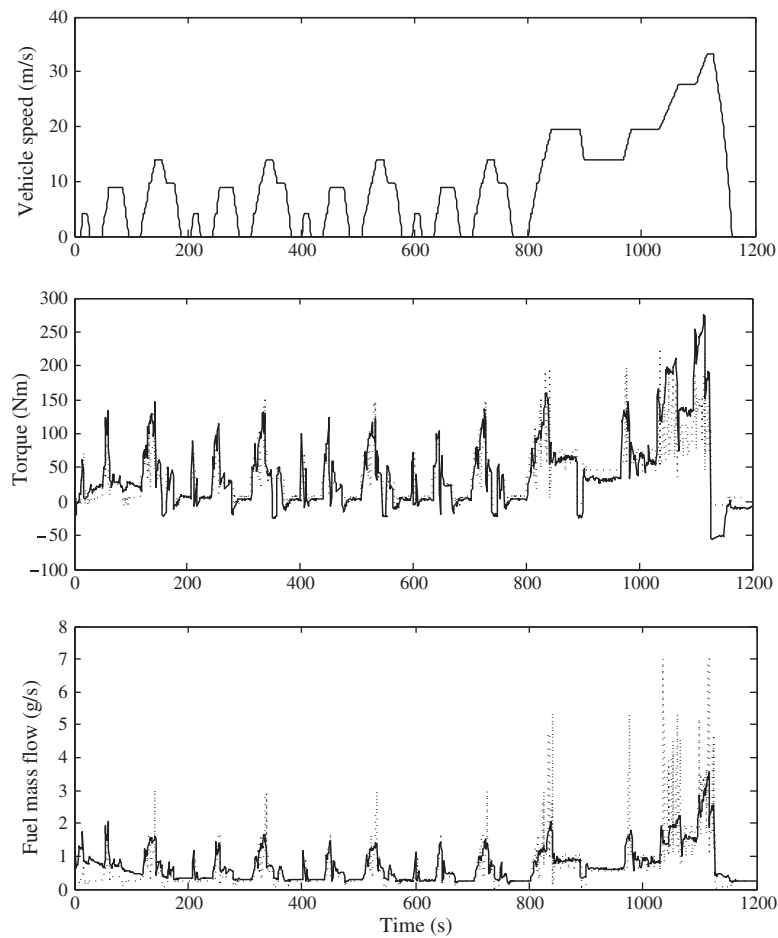


Fig. 1. (Dashed) PSAT model of Class-E conventional vehicle and (solid) transient experimental data for the NEDC.

files are modified as per the 1.6 L TDCi 2010 Fiesta ECONetic specifications. The engine component is chosen as the Volkswagen 1.9 L four cylinder turbocharged diesel and its initialization file is modified for engine specifications and fuel consumption map to match those of ECONetic. The modelled fuel economy and CO₂e emissions obtained are 3.69 L/100 km and 105 g-CO₂e/km which closely approximate Ford Australia's reported figures of 3.7 L/100 km and 98 g-CO₂e/km (Ford Australia, 2011).

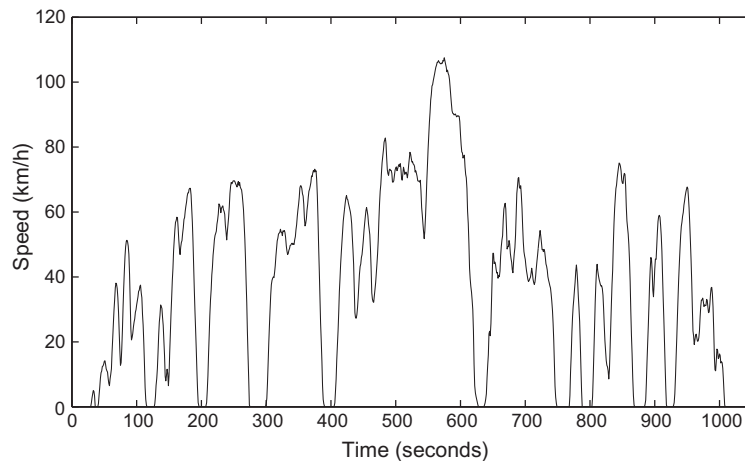


Fig. 2. Australian urban drive cycle.

While legislative drive cycles have been used to predict operational costs in other studies, these typically under-represent real world fuel consumption in urban settings. This has led to the development of other drive cycles which typically have higher fuel consumption. Examples of drive cycles that better represent real world driving behaviour include the US Federal Test Procedure (FTP-75), the Australian Urban Drive Cycle (AUDC) (Milkins and Watson, 1983) and Common ARTEMIS Drive Cycle (CADC) (Andre, 2004). Since this analysis is focussed on Australian driving conditions, the AUDC pictured in Fig. 2 will be used. The AUDC, which was derived from real world data in Australian driving conditions, features harder accelerations than exhibited in the other two cycles and typically exhibits higher fuel use than the other cycles.

2.2. Modelling hybrid and electric vehicles

Partial and full electric variants equivalent to the conventional vehicles modelled in the previous section do not yet exist in the marketplace, so it is necessary to develop realistic models that do not unduly penalise or advantage a specific technology. The approach used in this study is to set operational assumptions and constraints on the vehicle configuration as listed in Table 1, iteratively select the hardware (e.g. motor and engine sizing) and then minimise an economic cost metric to find the battery sizing.

In estimating the economic cost over the vehicle lifetime, there are several general operating assumptions that need to be made (Table 1). The vehicle ownership duration is set to be 10 years based on the average age of passenger vehicles in Australia (Australian Bureau of Statistics, 2011b). While the vehicle driving behaviour is described by the AUDC, the annual distance travelled is 15,000 km over each year of ownership, which is close to the Australian average (Australian Bureau of Statistics, 2011a). The baseline fuel (gasoline and diesel) and off-peak electricity prices were assumed to be the average over the 10-year horizon. There is also large uncertainty in the mass production vehicle battery pricing with ranges from $\$260 \text{ (kWh)}^{-1}$ to $\$1800 \text{ (kWh)}^{-1}$ (see e.g. the summary in Table 13 of (Kinghorn and Kua, 2011)), consequently a baseline value was taken to be $\$800 \text{ (kWh)}^{-1}$ in keeping with (Brooker et al., 2010).

The details of the model development for each vehicle type are now given in the following paragraphs, starting from the fully electric vehicle configurations.

- **Class-B and Class-E BEVs:** The main requirements in developing the BEV models are to choose the battery size and motor to meet range and drivability requirements respectively. The choice of the electric motor is governed by the torque and power rating to resemble the driving performance specifications of the base CVs, and consequently the PSAT simulations showed 145 kW/400 Nm and 75 kW/240 Nm motors are required to match drivability with the Class-E and Class-B CVs respectively.

In choosing the battery size, it is necessary to set a range requirement. More than 90% of the vehicles in Australian cities cover less than 160 km during their daily commuting (Taylor et al., 2010), which is equivalent to the 100 mile range often quoted as necessary for the US market. Consequently, the battery is to be sized to achieve a range of 160 km with an 80% depth of discharge by iteratively running the PSAT BEV models repeatedly over the AUDC until the range and discharge criteria are met. No electrical auxiliary loads such as lights or air-conditioner are considered during these tests. The resulting battery capacities for the two vehicle classes are 21 kWh and 34 kWh.

Table 1
Assumptions used in developing vehicle models.

General	(1) Vehicle lifetime km travelled: $D = 150,000$ on AUDC (2) Base battery price: $P_B = \$800 \text{ (kWh)}^{-1}$ storage capacity (3) Base fuel price: $P_{fuel} = \$1.4 \text{ L}^{-1}$ (4) Base electricity price: $P_{elec} = \$0.175 \text{ (kWh)}^{-1}$ (5) All vehicles match CV drivability
Electric vehicle	(1) Battery technology: Li-ion (2) Minimum state of charge (SOC): 20% (3) Range: 160 km
Plug-in hybrid	(1) Battery technology: Li-ion (2) All Electric Range (AER): 60 km (3) Controller strategy: Thermostat (engine on-off) (4) Min SOC: 25%, Max SOC in hybrid mode: 30%
Series hybrid	(1) Battery technology: Li-ion (2) Controller strategy: Thermostat (engine on-off) (3) Min SOC: 60%, Max SOC: 70%
Parallel hybrid	(1) Battery technology: Li-ion (2) SOC target: 65% (3) Engine and motor power equivalent
Mild hybrid	(1) Battery technology: NiMH (2) SOC target: 65% (3) Maximum motor power: 20 kW

- **Class-E plug-in and series HEVs:** The plug-in and series hybrid models are both assumed to have a similar powertrain configuration, whereby the electric motor is used to propel the vehicle and the engine is only used as an onboard generator. Since the electric motor is solely responsible for propulsion, the drivability conditions ensure that the electric motor for both plug-in and series vehicles must be the same size as in the Class-E BEV, i.e. 145 kW.

For the plug-in hybrid, the engine is controlled using a switched approach (denoted as a thermostat control strategy), in which the vehicle operates in a charge depletion mode until the battery state of charge meets some minimum limit. Once the minimum limit is reached the vehicle enters and remains in a charge sustaining mode, where the generator switches on and remains at maximum efficiency until an upper state of charge level is reached, at which point the engine switches off. For the series hybrid, there is no initial charge depletion strategy available, and the vehicle starts in a hybrid control mode.

The battery pack sizes differ based on the constraints developed for each of the configurations. The plug-in hybrid is allowed to run in a charge depletion mode to cover its all electric range which is specified to be 60 km based on the daily distances travelled in Sydney by 80% of commuters (Taylor et al., 2010). This can be used to specify a minimum battery requirement, although it may be advantageous to have greater all electric range. To ascertain the optimal battery capacity, N_B , for the plug-in hybrid several quantities must be estimated. Firstly, the utility factor, u , (which represents the fraction of time spent in charge depletion mode according to SAE J1711 standard) is estimated at 0.79, by extrapolating from (Taylor et al., 2010) using an annual distance travelled of 15,000 km. Further, the electricity consumption, C_e in kWh/km during charge depletion mode is estimated by running the vehicle through a drive cycle with an initial state of charge at 100%. Lastly, to estimate the fuel consumption, C_f , in litres/km during charge sustaining or hybrid mode the simulation is repeated with an initial state of charge equal to the minimum limit. Both of these energy consumptions are functions of the battery capacity, N_B .

For a given lifetime distance travelled, D , and battery, P_B , electricity, P_{elec} , and fuel, P_{fuel} , prices respectively, the total cost J_B associated with N_B battery capacity is:

$$J_B = P_B N_B + D[(1 - u)P_{fuel}C_f(N_B) + uP_{elec}C_e(N_B)] \quad (1)$$

Eq. (1) is minimised by solving iteratively for N_B using the parameter estimates in Table 1. Following this procedure the optimal battery size for the plug-in hybrid is slightly larger than that required for the 60 km electric range at 17.1 kWh. Note that while the utility factor will depend on several factors, including battery capacity, that are not captured by assuming a constant u , the optimisation results were found to be relatively insensitive to this assumption and consequently neglected.

For the series hybrid, the same approach as (1) is used to identify the battery size. However there is no all electric range requirement and so the utility factor $u = 0$ as the vehicle cannot run in charge depletion mode. This results in a much smaller battery capacity of 2.6 kWh.

- **Class-E parallel HEV:** For the parallel HEV, the drivability constraint of the CV can be met by a combination of power sources as the electric motor and engine are both mechanically coupled to the transmission. It has previously been shown that best fuel economy can be achieved if the motor and engine are approximately equivalent in size (Manzie et al., 2007), and so this was set as an initial constraint for the optimisation. Along with the constraint that the original CV driveability must be maintained, the smallest engine and motor power combination was then found from the library of available components leading to a 99 kW engine and 100 kW motor being used.

The desired state of charge (SOC) setpoint for the parallel HEV controller was set to 65% in accordance with most parallel hybrids in production, and the battery capacity was determined using the same procedure for the series hybrid above, resulting in a 2.1 kWh pack being used.

- **Class-E mild HEV:** The constraint on the mild HEV was that the electric motor was capped at 20 kW, and its hybrid control strategy could principally enable stop-start behaviour and small power assist, as with most mild hybrid production vehicles. Consequently the same engine as for the CV was utilised, while the motor was chosen to closely emulate the power to weight ratios present in existing mild hybrids. In determining the battery capacity, Eq. (1) was again utilised in the same procedure as for the parallel and series hybrids, leading to a battery capacity of 0.5 kWh.

The resulting vehicle powertrain configurations developed using this procedure for each of the electrified variants are summarised in Table 2. It is worth noting that there are two competing considerations affecting the vehicle mass for the electrified variants described in this table. The reduction in engine capacity leads to a lower mass, while the inclusion of larger battery packs and electric motors increases the overall mass. This has previously been reported in other studies including (Samaras and Meisterling, 2008).

2.3. Estimation of the fuel and electricity consumption

For each of the vehicle configurations developed in the previous section the fuel and grid electricity consumption can now be calculated. Given the focus of this study is on Australian driving conditions, the AUDC is the cycle most representative of real world driving. For comparison, the energy consumption over two other legislative cycles, the ECE-EUDC and US-FTP, was

Table 2

Summary of key vehicle specifications following model development.

	Engine	Motor (kW/Nm)	Battery (kWh)	Mass (kg)
Class-E CV	I6, 4 L, 195 kW	–	–	1774
Class-E Mild	I6, 4 L, 195 kW	20/180	0.5	1787
Class-E Parallel	I4, 2.3 L, 99 kW	100/400	2.1	1762
Class-E Series	I4, 1.6 L, 85 kW	145/400	2.6	1723
Class-E Plug-in	I4, 1.6 L, 85 kW	145/400	17.1	1969
Class-E BEV	–	145/400	34.2	2029
Class-B CV	I4, 1.6 L, 66 kW	–	–	1107
Class-B BEV	–	75/240	21.0	1182

Table 3

Fuel (L/100 km) and electricity (kWh/km) consumption of the modelled vehicles.

Vehicle	AUDC		ECE-EUDC		US-FTP	
	Fuel	Electricity	Fuel	Electricity	Fuel	Electricity
CV (Class-E)	12.5	–	9.4	–	9.9	–
Mild (Class-E)	11.0	–	8.3	–	8.4	–
Parallel (Class-E)	7.2	–	5.7	–	5.6	–
Series (Class-E)	6.9	–	4.8	–	5.6	–
PHEV (Class-E)	1.4	0.17	1.1	0.14	1.0	0.12
BEV (Class-E)	–	0.18	–	0.16	–	0.15
CV (Class-B)	4.5	–	3.7	–	3.7	–
BEV (Class-B)	–	0.12	–	0.11	–	0.10

also calculated and the results are summarised in Table 3. As expected, increasing levels of electrification results in lower fuel use over each of the drive cycles. The fuel economy improvements through different configurations appear reasonable, with roughly 10% improvement for mild hybrids and 30–40% improvement for full hybrid configurations relative to conventional vehicles.

For the Class-E sedan, it is also observed that there are substantial differences in fuel economy between the different drive cycles, with the AUDC having markedly higher fuel consumption as a result of the frequent harder acceleration and deceleration present compared to the legislative cycles. This highlights the importance of considering real world driving in the analysis. The difference between cycles is not as pronounced for the electric powertrains as the efficiency contours are much flatter than in internal combustion engines.

Finally when comparing the Class-E and Class-B BEVs, the difference in electricity use equates to the mass difference in the two vehicle classes, with an offset due to the constant accessory loads. Again this is as expected as the technology used is consistent between the two vehicles. However, when the Class-E and Class-B CVs are compared the improvement in fuel economy is greater than might be expected from mass difference alone. The Class-B CV utilises a downsized and turbo-charged engine while the Class-E uses a naturally aspirated inline six-cylinder engine. This highlights the potential improvement in internal combustion engine technology.

3. Vehicle lifetime economic analysis

To estimate the cost to the consumer of different vehicle configurations, a net present value (NPV) analysis is used with a discount rate of 6% per annum (Partnerships Victoria, 2011). This rate is indicative of government discount rates and subsequently low in comparison to other consumer discount studies, but was chosen to avoid any unfair penalty towards vehicles with low running costs. While the battery, fuel and electricity price estimate remain as in the previous section, the vehicle distance travelled is refined from the previous approach to an annual distance in order to facilitate the NPV analysis.

Additional information in developing a cost breakdown is also required, with the engine and motor pricing developed as function of respective power ratings, kW_{eng} and kW_{motor} , in (Brooker et al., 2010). Similarly the transmission costing is formulated as a function of total power in (Cleary et al., 2010). The retail markup factor of 1.71 for the Australian automotive sector was obtained from (Australian Bureau of Statistics, 2011b), and is essentially the same used in (Brooker et al., 2010) for the US market. Given the uncertainty in battery pricing and their significant cost, a retail markup was applied to all components except the battery pack (the sensitivity of the results to battery price will be investigated subsequently). The glider price estimates were assumed constant for each vehicle class, and determined from the retail price of the CVs. The on-road costs (defined as the costs above production costs that enable the vehicle to be driven on public roads, including stamp duty, vehicle registration and insurance) were averaged across Australian states for conventional vehicles. Although different states offer small rebates for hybrid and electric vehicles, these were excluded in this analysis as they do not represent a real cost. The full set of assumptions leading to the costs are summarised in Tables 1 and 4.

Table 4
Additional assumptions used in developing cost of ownership.

Vehicle ownership duration	10 years
Distance travelled per annum	15,000 km
Depreciation rate	6% per annum
Transmission cost	\$ (12.5(kW _{eng} + kW _{motor}))
Motor and generator cost	\$ (425 + 21.7 kW _{motor})
Engine cost	\$ (531 + 14.5 kW _{eng})
Retail markup	1.71
Class-E glider cost	\$17,314
Class-B glider cost	\$12,274
Class-E on-road costs	\$4304
Class-B on-road costs	\$3313

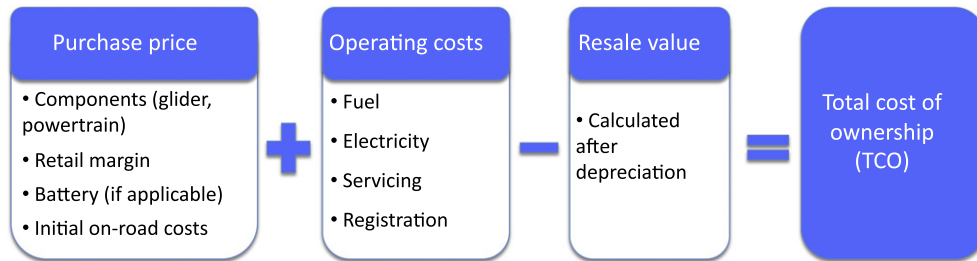


Fig. 3. Total cost of ownership calculation.

Table 5
Purchase price and decomposition for each of the vehicles considered under present pricing assumptions.

Component	Class-E						Class-B	
	CV	Mild	Parallel	Series	PHEV	BEV	CV	BEV
Glider	17,314	17,314	17,765	17,314	17,314	17,314	12,274	12,274
Engine	3359	3359	1967	1764	1764	–	1488	–
Motor/generator	–	859	2595	3572	3572	3572	–	2053
Transmission	2438	2688	2488	2875	2875	1813	825	938
Total powertrain	5796	6905	7049	8210	8210	5384	2313	2990
Glider + powertrain	23,110	24,219	24,363	25,524	25,524	22,698	14,587	15,264
Initial on-roads	4303	4303	4303	4303	4303	4303	3313	3313
Retail markup	16,482	17,273	17,376	18,204	18,204	16,188	10,357	10,837
Battery pack	–	374	1665	2102	13,666	27,331	–	16,800
Total purchase price	43,895	46,169	47,706	50,133	61,696	70,520	28,256	46,214

Fig. 3 shows the breakdown of factors which contribute to the total costs over the vehicle ownership duration. The purchase cost for each vehicle type can be calculated from the vehicle configurations developed in Section 2 and using the pricing estimates of Tables 1 and 4, with the retail markup applied to the powertrain and glider only. The resulting purchase prices of the different vehicle variants are given in Table 5.

The running costs are calculated from (1) the fuel and electricity consumption from Table 3 scaled to meet the annual estimated mileage and (2) the vehicle annual servicing and average Australian registration costs (Royal Automotive Club of Victoria, 2011), and converted to present values using the depreciation rate listed in Table 4.

Finally the resale values are based on the depreciation in value of the base CV over a 10-year period. Without production electric variants to compare to, the depreciation ratio is considered constant across the prices of all vehicle configurations without batteries. While there is some possibility for end-of-service applications for batteries (Neubauer and Pesaran, 2011), there is significant uncertainty in any value at this stage, particularly since it appears that no automotive battery supplier will offer warranties longer than a 10 year duration. In any event, the sensitivity to battery price will be investigated in Section 4.

Fig. 4 shows the running costs and resale for all the vehicle configurations considered in this study in present value terms. The total cost of ownership over the 10-year lifetime is then presented in Fig. 5, where it is clear that although vehicle electrification entails an increase in the initial price, it is accompanied with a reduction in the running costs. It is apparent that under the pricing estimates used in the analysis, the parallel HEV has the lowest net present value amongst the Class-E se-

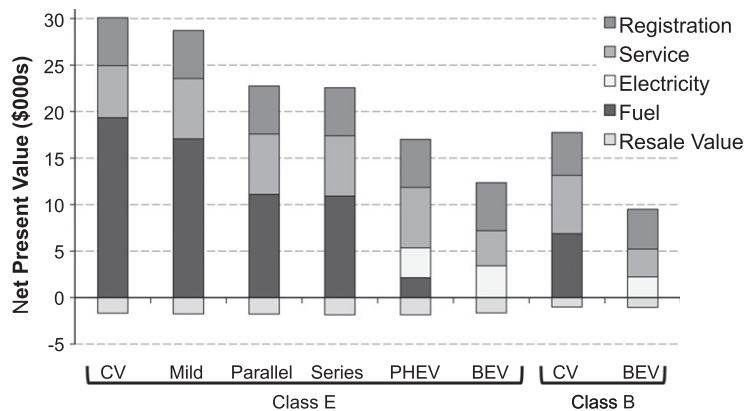


Fig. 4. NPV of accumulated running costs and resale under present pricing assumptions.

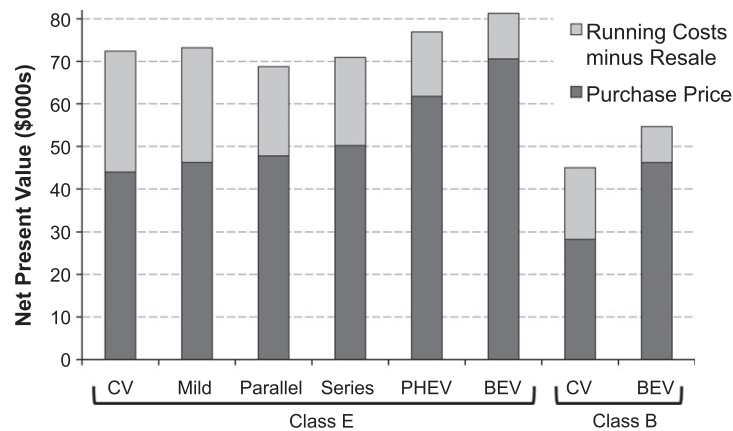


Fig. 5. Total lifetime cost of ownership for different vehicles under present pricing assumptions.

dans. Although not shown in the figure, it takes 5 years before the parallel HEV is a more cost effective solution than the CV, with the final margin made up in the reduced operational costs over years 5–10.

For both vehicle classes considered, the CV maintains a price advantage over the BEV as the additional up-front cost associated with the batteries is not overcome by the reduced running costs. This difference is most significant for the Class-B vehicle, as the more efficient engine and lower vehicle mass both contribute towards lower running costs.

4. Sensitivity analysis

This section investigates the sensitivity of the analysis to price variations. Annual mileage variation is captured by a representative change in the energy pricing. For example, if the annual distance travelled is doubled, this can be represented by a simultaneous doubling of the fuel and electricity prices. To conduct the sensitivity analysis, surface plots demonstrating the most fuel efficient Class-E vehicle configuration will be produced in the proceeding sections. As this alone does not indicate the 'flatness' of the total cost, an analysis will also be conducted to indicate when the various electrified configurations become cheaper relative to a conventional vehicle. Note that while the vehicle configurations developed in Section 2 were optimal in some sense for a given scenario, they are considered representative enough of the likely production variants that re-optimisation for the domain of scenarios being investigated in this section will not be undertaken.

4.1. Sensitivity to fuel and electricity prices

The relative importance of fuel and electricity prices can be demonstrated by plotting surfaces of the total cost of ownership in NPV terms against these two parameters. Fig. 6 shows this by Class-E vehicle with the lowest TCO, with all other costs fixed as per Sections 2 and 3 and the ownership duration set to 10 years. The results are plotted in Fig. 6, along with the base scenario used in Section 3 consisting of a fuel price of $\$1.4 \text{ L}^{-1}$, an electricity price of $\$0.175 (\text{kWh})^{-1}$ and projected retail

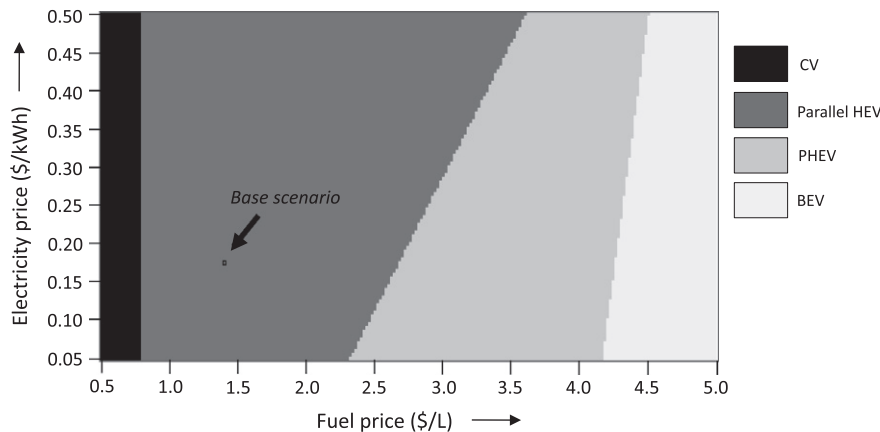


Fig. 6. Most economical vehicle configuration (lowest TCO) for varying fuel and electricity prices and a fixed battery price of $\$800 \text{ (kWh)}^{-1}$.

battery price of battery $\$800 \text{ (kWh)}^{-1}$. The results indicate that neither the mild or series hybrids are ever the most cost effective vehicle over the 10-year ownership duration considered.

There will be shorter ownership durations under which the optimal choice changes. For example, at high fuel prices the operational savings of the mild hybrid relative to the conventional vehicle will result in the differences in purchase prices being overcome, however after the full 10 years the further reduced operational costs of the vehicles with greater degrees of electrification further outweigh the mild hybrid benefits. Shorter ownership horizons will be considered in equivalent cost analyses in Section 4.3.

Finally, Fig. 6 indicates that under existing Australian off-peak retail electricity pricing (around $\$0.175 \text{ (kWh)}^{-1}$), the price of fuel would have to increase by almost a factor of three for a Class-E BEV to be the cheapest option over its lifetime. While the use of solely off-peak electricity might be viewed as optimistic, there is relatively little sensitivity to this factor, since a doubling of the retail electricity price has only marginal effect on the transitions between the optimal configurations. This is perhaps expected, as the efficiency of the electric powertrain is higher, and there is a greater fraction of the cost in electric vehicles associated with production than operation.

4.2. Sensitivity to battery price

Given the impact battery price has on the vehicle production cost, and the considerable uncertainty in projecting future Li-ion battery price in mass adoption scenarios, it is of considerable interest to consider the relative impact of fuel and battery pricing scenarios on the optimal configuration from a NPV standpoint.

In completing this analysis, two cases for the electricity price were considered. In the first, the electricity price was fixed to the present off-peak rate resulting in Fig. 7. From this figure, it is clear that if fuel price remains constant at $\$1.40 \text{ L}^{-1}$, the battery price would need to drop below $\$410 \text{ (kWh)}^{-1}$ for BEVs to be the cheapest option. This is towards the lower end of battery price projections reported in the literature. However as the fuel price (or conversely the mileage) increases by a factor of two, the prospects of plug-in HEVs and BEVs become markedly better. This means that high mileage customers, such as fleet owners, may be justified in pursuing EVs or partially electrified vehicles as an option on a cost basis.

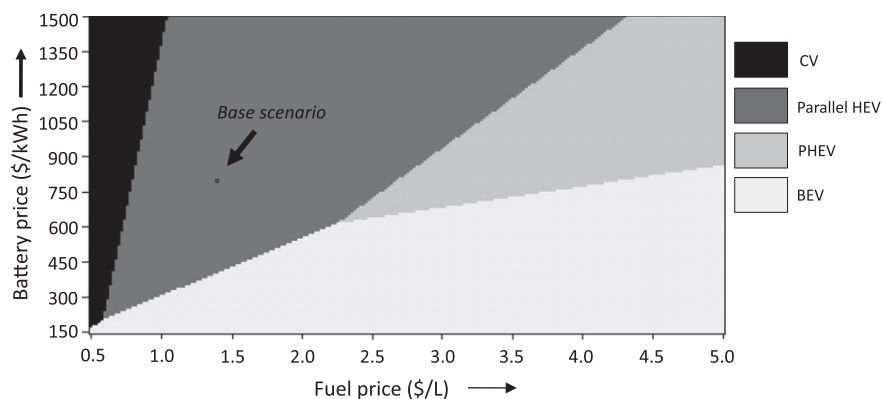


Fig. 7. Most economical vehicle configuration for varying fuel and battery prices. Electricity price = $\$0.175 \text{ (kWh)}^{-1}$.

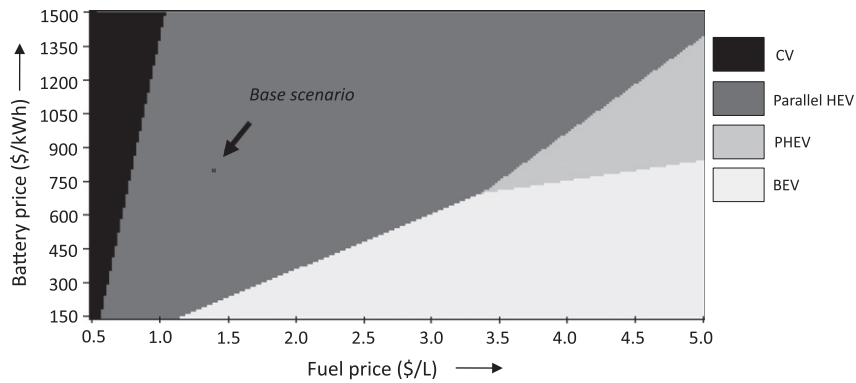


Fig. 8. Most economical vehicle configuration for varying fuel and battery prices. Electricity price = $\$0.5 \text{ (kWh)}^{-1}$.

By way of comparison, this relative fuel-battery price analysis was repeated for a higher electricity price. Given that much of the environmental benefit of BEV technology arises only if the electricity is created from renewable sources, this scenario is worth considering. Using an electricity price of $\$0.5 \text{ (kWh)}^{-1}$ leads to the result shown in Fig. 8, where the parallel HEV becomes the more economically viable option over a larger range of the price domain.

From both Figs. 7 and 8 it is clear that the battery price must be well below $\$800 \text{ (kWh)}^{-1}$ for pure EVs to become viable in the Class-E market segment on purely cost of ownership grounds. Although not shown, the price requirement is even stricter for the smaller, Class-B vehicles. However, the contours of total cost of ownerships for the vehicle configurations are not presented in Figs. 6–8, and consequently the margins by which one vehicle is preferable are not clear.

4.3. Sensitivity to ownership duration

Whilst variable, buyers generally consider a shorter ownership duration than 10 years.

Assuming that cost parity is expected within 3–5 year of the purchase, this section examines the conditions under which the total cost of ownership for the various vehicle configurations will be equivalent or better than that of the CV. Fig. 9 shows the situation for each of the nominated vehicles under the base pricing scenario (battery price $\$800 \text{ (kWh)}^{-1}$, electricity price $\$0.175 \text{ (kWh)}^{-1}$).

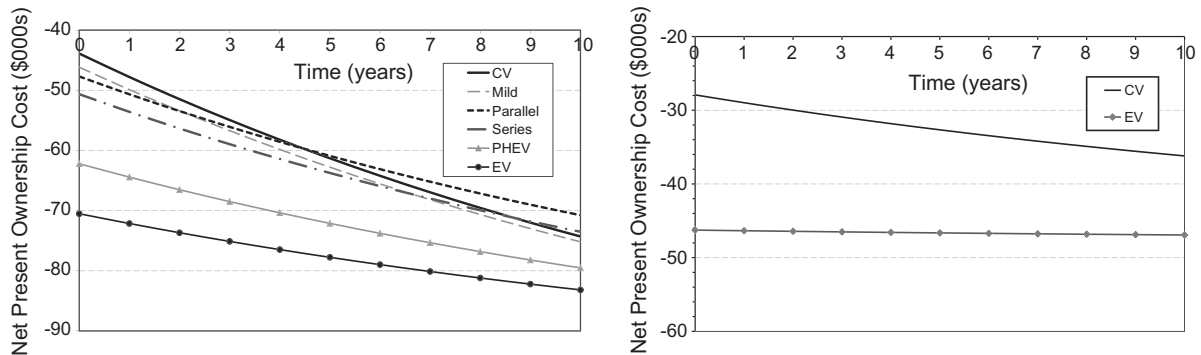


Fig. 9. Evolution of total cost of ownership under base pricing scenario with fuel at $\$1.40 \text{ L}$ for Class-E (left) and Class-B (right) vehicles.

Table 6

Fuel prices for CV-equivalent cost of ownership under different electric scenarios.

Duration	Scenario	Class-E			Class-B		
		Mild	Parallel	Series	PHEV	BEV	BEV
3 years	Electrically fav.	\$ 4.1	\$ 1.6	\$ 2.8	\$ 3.0	\$ 2.7	\$ 8.0
	Base	\$ 4.4	\$ 2.0	\$ 3.3	\$ 4.5	\$ 5.5	\$ 14.9
	Electrically unfav.	\$ 4.8	\$ 2.4	\$ 3.8	\$ 6.5	\$ 8.7	\$ 22.6
5 years	Electrically fav.	\$ 2.8	\$ 1.1	\$ 1.9	\$ 2.0	\$ 1.8	\$ 4.2
	Base	\$ 3.0	\$ 1.3	\$ 2.2	\$ 3.0	\$ 3.5	\$ 7.8
	Electrically unfav.	\$ 3.2	\$ 1.6	\$ 2.5	\$ 4.4	\$ 5.7	\$ 12.3

Along with the base scenario, the 3 and 5 years fuel prices required for TCO-equivalence with the conventional vehicle under two additional scenarios will be investigated. In the first *electrification favourable* scenario, the current off-peak electricity price is maintained but the battery price is halved to \$400 per kWh, representing a battery price of \$233 (kWh)⁻¹ with retail markup of 1.71. In the second, *electrification unfavourable* scenario, the price of electricity is assumed to rise to \$0.50 (kWh)⁻¹, while the battery price is increased 50%–\$1200 (kWh)⁻¹. The results for both vehicle classes under each scenario are listed in Table 6.

Table 6 highlights that a minimum 50% increase in fuel price must occur before anything but the parallel hybrid or conventional vehicle is the most cost effective Class-E vehicle over a 3 year horizon, even within an electrically favourable scenario of low battery and electricity prices. The gap is exacerbated in the smaller vehicle class as the low fuel consumption of the CV ensures the fuel price for an equivalent total cost small EV is very high. In the electrically unfavourable scenario of higher electricity and battery prices, the short term naturally favours the CV as the reduced up-front cost relative to the electric variants is difficult to overcome.

If the ownership duration is extended to 5 years, the parallel HEV is the most economic choice for Class-E. In this vehicle size, the BEV, series and plug in HEVs become economically feasible in an electrification favourable scenario, but in the smaller Class-B range the production price difference is still too great to be overcome.

Despite the apparently favourable situation for parallel hybrids depicted in Table 6 and Figs. 4–8, it is also worth observing that the total hybrid vehicles in Australia account for approximately 2% of overall passenger vehicle sales. This suggests that there are more factors at play than simply technology and economics alone.

5. Conclusions

This paper presented an integrated technical and financial analysis of conventional and equivalent hybrid and fully electric vehicles for the Australian market. The effect of price uncertainty, resulting particularly from variations in future battery, fuel and electricity prices, was accounted for by considering different pricing scenarios, with the base scenario estimated to be roughly current pricing. Two passenger vehicles were chosen of Class-E and Class-B, such that they bracket almost all vehicle sizes on Australian roads. The following results are of note.

- Using the base pricing scenario for fuel, electricity and the battery, the parallel hybrid vehicle is found to be the most cost effective vehicle type for the Australian market. This result is not reflected by the composition of the current road fleet, which is thought to demonstrate the importance of other factors not considered in the study.
- The optimal choice of vehicle in terms of its net present value is only weakly dependent on the price of electricity, and more strongly dependant on the fuel and battery prices.
- The Class-E parallel hybrid has the most insensitive total cost of ownership to variations in the prices of fuel, electricity and the battery.
- An increase of greater than 200% in fuel price relative to current appears required for plugin or fully electric vehicles of any class to have the lowest cost of ownership.
- All hybrid and electric vehicle types have a total cost of ownership that is lower than the conventional vehicle in the electrification favorable scenario. However, under all scenarios considered it takes a minimum of 3 years before the total cost of ownership of any Class-E electrified powertrains are economically superior to the conventional vehicle.
- In the smaller vehicle class, the lower operational energy requirements place a greater emphasis on production cost in determining the vehicle with the lowest lifetime cost. This makes their electrification significantly less economically attractive.

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