Conventional, hybrid and electric vehicles for Australian driving conditions. Part 2: Life cycle CO₂-e emissions

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Abstract
This paper is the second 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 second study focuses on the life cycle greenhouse gas emissions. Two vehicle sizes are considered, Class-B and Class-E, which bracket the large majority of passenger vehicles on Australian roads.

Using vehicle simulation models developed in the first study, the trade-offs between the ability of increasingly electric powertrains in curtailing the tailpipe emissions and the corresponding rise in the embedded vehicle emissions have been evaluated. The sensitivity of the life cycle emissions to fuel, electricity and the change in the energy mix are all considered. In conjunction with the total cost of ownership calculated in the companion paper, this allows the cost of mitigating life cycle greenhouse gas emissions through electrification of passenger transport to be estimated under different scenarios. For Class-B vehicles, fully electric vehicles were found to have a higher total cost of ownership and higher life cycle emissions than an equivalent vehicle with an internal combustion engine. For Class-E vehicles, hybrids are found to be the most cost effective whilst also having lowest life cycle emissions under current conditions. Further, hybrid vehicles also exhibit little sensitivity in terms of greenhouse emissions and cost with large changes in system inputs.

1. Introduction
Reducing the level of greenhouse gas emissions attributable to the transportation sector is a major part of the environmental protection policies in many developed and developing economies. Road transportation is a significant component of global transportation emissions and in Australia it accounts for about 15% of CO₂-e pollution (Australian Government Department of Climate Change, 2011; Australian Government Department of Climate Change and Energy Efficiency, 2010).

Partial and full electrification of the vehicle powertrain leads to a reduction or elimination of tailpipe emissions. This has led to several Australian government departments running electric fleet trials, and the local development of prototype electric vehicles. However, tailpipe emissions represent only part of the life-cycle emissions, as embedded emissions arising from production also need to be included in a life cycle analysis. Existing approaches for analysing vehicle life cycle emissions are usually either engineering-based or economics-based. In engineering-based approaches, the embodied energy associated with the vehicle materials and vehicle assembly is evaluated by analysing individual production processes (Leduc et al., 2010; Röder, 2001; Weiss et al., 2000). The advantage of this approach is the accuracy of the outcomes, but data availability...
is often a limiting factor. An alternative approach is to use economic input–output models (Joshi, 1999; Maclean and Lave, 1998), which yield cost-based estimates of the vehicle's embedded emissions, although this approach provides an averaged output across the whole automotive sector and consequently does not distinguish between different powertrain configurations. These different life cycle analysis approaches may yield similar conclusions, with outcomes dependent on a number of factors including the chosen system boundary for the analysis, vehicle configuration, the energy mix used for vehicle production and the emissions intensity of vehicle operation.

The choice of the system boundary involves a trade-off between the necessary detail and the availability of reliable data (Suh et al., 2004). For a given boundary selection, the environmental benefits from vehicle electrification heavily rely on the drive-train configuration, the battery size and the energy mix (Weiss et al., 2000). The source of electricity is crucial in the outcome of the life cycle emissions analysis if the vehicle requires external charging of the on-board batteries. The energy mix also determines the energy-to-emissions conversion factors which are used to calculate vehicle embedded emissions.

A number of studies on life cycle emissions have already been conducted for different vehicle types. In Patterson et al. (2011), a comprehensive evaluation of the life cycle emissions corresponding to a mid-size passenger vehicle in its conventional (CV), hybrid electric (HEV) and full battery electric vehicle (BEV) configurations is presented for the UK energy mix and emission intensities. This study quantifies the displacement in the tailpipe emissions to those arising from the grid and more intensive production requirements. Similar conclusions have been drawn in Huo et al. (2010) which investigated the environmental implication of electric vehicles in China and found that both SO2 and NOx emissions could significantly increase if electric vehicles were charged using the existing Chinese energy mix. More recently, there has been also been increased attention paid towards estimating the up-front and life cycle impact of plug in hybrid vehicles (Samaras and Meisterling, 2008; Silva et al., 2009; Sioshani and Denholm, 2009; Stephan and Sullivan, 2008).

The life cycle emissions and ownership costs of different powertrains can be coupled to estimate the cost of avoided emissions for different powertrains. An economic and environmental evaluation of the Toyota Prius with its conventional equivalent (Lave and MacLean, 2002) highlighted the need for lower battery prices if the emissions reduction is to be considered economically viable. More recently, studies of plug-in hybrids (Kammen et al., 2008) and BEVs (Peterson et al., 2011) in the US have attempted to quantify the cost effectiveness of alternative powertrains in reducing emissions under different scenarios. Australia has on average a carbon intensive electricity network, characterised by an average emissions intensity almost double that of the UK. The Australian state of Tasmania is the exception to this, deriving most of its electricity from hydroelectric generators but accounting for only 2% of national average electricity consumption (ABARE, 2011). The national network is coupled with vehicle purchasing and driving characteristics that differ from either European or US conditions partially due to a propensity for locally produced larger cars and potentially influenced by lower relative traffic densities. Consequently, the outcomes of the earlier studies may not be directly transferrable in either economic or environmental terms.

The objective of this paper is therefore to analyze the benefits of vehicle electrification for Australian manufacturing and driving conditions. The studies have been performed for two vehicle size segments, Class-B and Class-E, to examine the effect of vehicle size on relative variations in the life cycle emissions between the conventional vehicle and its electric variants. In addition, the cost of emissions reduction has been assessed by comparing the life cycle emissions against the life cycle costs evaluated in a companion paper (Sharma et al., 2012) under different energy and pricing scenarios.

2. Modelling CO2-e emissions of different vehicles

This section describes the method used to evaluate the total CO2-e emissions during a ten-year life cycle of different powertrain configurations. An estimate of the vehicle embodied energy is obtained through a hybrid approach which involves the use of available process-based and input–output data (Treloar and Crawford, 2010; Crawford, 2011). The vehicle in-service emissions are determined by using the fuel and electricity consumption estimates obtained through the drive cycle implementation of the vehicle powertrain models (Sharma et al., 2012).

2.1. Vehicles under consideration

The base vehicles selected are commercially available Class-B and Class-E sedans with internal combustion engines. For the Class-E sedan, the 4-litre, 6-cylinder, 1800 kg Ford Falcon is selected. This class of vehicle represents 15–20% of passenger vehicles sold annually in Australia (Federal Chamber of Automotive Industries, 2011). Detailed experimental data over the legislative drive cycle was available to the authors which was used to validate the vehicle simulation modelling procedure. The base Class-B sedan chosen was the Ford Fiesta ECOnetic (1.6 litre, inline 4 cylinder, diesel), as this represents one of the most fuel efficient vehicles in Australia, and the car size accounts for 35–40% of Australian passenger vehicle sales (Federal Chamber of Automotive Industries, 2011). Together, these vehicles bracket the majority of vehicles presently on Australian roads.

In Sharma et al. (2012), the components of the Class-E conventional vehicle (CV) model were altered using the PSAT (Powertrain System Analysis Toolkit) simulation package to obtain Mild HEV, Parallel HEV, Series HEV, plug-in HEV and BEV configurations. The latter two vehicles were designed to have an electric range of 60 km and 160 km respectively. In addition, a BEV variant of the Class-B vehicle was also developed with a 160 km range requirement. To estimate the fuel consumption, electricity consumption and tailpipe emissions, simulation models of the vehicles were developed and tested over drive
cycles representative of real world driving. The estimates of fuel and electricity consumption and tailpipe emissions for different powertrains calculated over the Australian Urban Drive Cycle (AUDC) are presented in Table 1.

2.2. Boundary selection

In order to establish the relative life cycle emissions of the different vehicle configurations the selected system boundary is illustrated in Fig. 1. This choice has been commonly adopted for vehicle life cycle emissions analysis, e.g. see Patterson et al. (2011) and the references therein. The items which have been omitted from the system boundary include the minor goods and services associated with vehicle production, such as finance, insurance and research and development. As the only approach for quantifying these items is based on input–output analysis and the price of the vehicles, in was considered to unfairly disadvantage the hybrid and electric vehicles because of their current cost premium beyond that related to their energy demand in production. In addition, the embodied energy associated with vehicle on-road costs such as registration and insurance are likely to have a similar impact on all vehicle configurations and hence their exclusion should not influence the outcomes of this study.

In addition, vehicle servicing, which includes occasional unplanned replacement of parts, repairs and maintenance, has also been excluded from the system boundary. Although it is possible that BEVs may require less maintenance than CVs and HEVs due to their fewer moving parts, there is insufficient data available to quantify the reduction in the life cycle emissions due to vehicle servicing with BEVs.

The vehicle disposal or end-of-life emissions have also been excluded for two reasons. First, their end-of-life emissions have been estimated to be around 2% of the conventional vehicle life cycle emissions (Patterson et al., 2011). Further, for hybrid and full battery electric vehicles there is little precedent to establish the end-of-life emissions associated with these vehicles.

2.3. Embedded emissions

This section estimates the emissions related to vehicle production and is decomposed into the emissions associated with the different materials used in vehicle manufacturing and the emissions associated with vehicle assembly.

2.3.1. Vehicle materials

A hybrid analysis utilising material energy coefficients (Crawford, 2011) has been used to evaluate the embedded emissions associated with the production of materials. As these coefficients have been compiled based on available process data and national input–output data, they include the energy associated with the main material production process as well as all processes upstream of this that are needed to support the production of the main materials (e.g., finance, insurance, R&D etc). This avoids the upstream truncation of the system boundary typically associated with similar studies. The software package GREET 2.7 (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation, Burnham et al., 2006) is used to estimate the composition of vehicle components. Consumables such as the fluids used in the vehicle (including engine oil, coolant, transmission oil and brake fluid), tyres and lead–acid batteries, undergo periodic replacements during the course of the vehicle use and are therefore included in Section 2.4.3 rather than classified as embedded emissions.

The components of each vehicle are classified into five groups: powertrain/engine; transmission system; glider; motor/generator; and batteries. The masses of each of these groups are estimated at the component level using PSAT and/or the component datasheets for the vehicle models developed by the authors in Sharma et al. (2012). The estimated masses of each component group are presented in Table 2.

These mass estimates are used with the estimated percentages of the materials from GREET 2.7 to infer the quantities of different materials used in each component group. For each of the groups, the energy coefficients corresponding to the manufacturing of the vehicle materials in Australia (Table 3) are multiplied by the quantity of the respective material to calculate the embodied energy on a component group basis. To obtain the embedded emissions from the estimated embodied energy a

<table>
<thead>
<tr>
<th>Class-E</th>
<th>Fuel consumption</th>
<th>Electricity consumption</th>
<th>Tailpipe emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>12.5</td>
<td>–</td>
<td>289</td>
</tr>
<tr>
<td>Mild</td>
<td>11.0</td>
<td>–</td>
<td>256</td>
</tr>
<tr>
<td>Parallel</td>
<td>7.2</td>
<td>–</td>
<td>168</td>
</tr>
<tr>
<td>Series</td>
<td>6.9</td>
<td>–</td>
<td>164</td>
</tr>
<tr>
<td>Plug-in</td>
<td>1.4</td>
<td>17.0</td>
<td>33</td>
</tr>
<tr>
<td>BEV</td>
<td>–</td>
<td>18.0</td>
<td>–</td>
</tr>
<tr>
<td>Class-B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV</td>
<td>4.5</td>
<td>–</td>
<td>121</td>
</tr>
<tr>
<td>BEV</td>
<td>–</td>
<td>12.0</td>
<td>–</td>
</tr>
</tbody>
</table>


Table 1
Estimated AUDC fuel consumption ($C_f$, litres/100 km), electricity consumption ($C_e$, kWh/100 km) and tailpipe emissions ($H_{tp}$, g CO$_2$-e/km) for various vehicle configurations.
conversion factor of 60 kg CO₂-e/GJ (Treloar, 2000) has been used. This figure is the average emission intensity for Australia based on the current fuel mix (predominately coal, oil and gas, Australian Government Bureau of Resources and Energy Economics, 2012). Using a fixed emissions factor for all embodied energy requirements may result in uncertainty for the emissions associated with any specific material or process. However, the use of a fixed emissions factor is considered appropriate in this study as the analysis covers not only the energy associated with material production processes but also the upstream non-material inputs required to support these production processes. As it is virtually impossible to determine the fuel mix used for every one of the millions of processes included in the analysis, an average emissions factor based on the national fuel mix is considered a practical and appropriate alternative.

2.3.2. Vehicle assembly

The emissions associated with material production in Section 2.3.1 does not consider the energy required for vehicle assembly. Process data for vehicle assembly in Australia is unavailable in the public domain, and so the direct energy requirement (DER) for vehicle assembly is estimated using an energy-based input–output model for Australia (Lenzen and Lundie, 2002) and the estimated cost of the vehicles. For Australia, the DER based on economic input–output data for passenger vehicles is 0.3603 GJ/$1000 (Lenzen and Lundie, 2002). Thus, the embodied energy attributed to vehicle assembly can be evaluated using the authors’ estimated purchase prices (Sharma et al., 2012) for each vehicle.

It is acknowledged that while this approach is a good approximation across various manufacturing sectors, for automotive assembly it may exhibit greater error as the economic value of the vehicles is not necessarily directly proportional to the energy spent in the vehicle assembly (for example, the energy associated with assembling a luxury sedan is unlikely to be significantly greater than for an equivalent sized standard vehicle). However, the contribution of vehicle assembly towards the embedded emissions is observed to be approximately 7% for the different vehicle types considered, which corresponds well with existing studies using process data – for example an 8% contribution was observed in Patterson et al. (2011). Furthermore, the contribution of the embodied energy and emissions due to vehicle assembly is found to be about 0.5% of the total life cycle emissions (Section 2.5).

2.3.3. Vehicle embedded emissions

Fig. 2 presents the grouped embedded emissions for each vehicle. For each vehicle class, the vehicle’s embedded emissions rises with the level of powertrain electrification. In the Class-E segment, the CV’s embedded emissions are found to be almost half of those of the equivalent BEV. This is mainly attributed to the Lithium-ion batteries used in the BEV. This
result is consistent with other studies that reported the main contributor to the environmental burden caused by the battery is the supply of copper and aluminium for the production of the anode and the cathode (Notter et al., 2010).

For both Class-B and Class-E, under the current battery technology, about 50% of the embedded emissions in the BEVs are attributed to the on-board batteries. On the other hand, in the Class-E configuration a switch to parallel or series configuration from CV only results in an increase in the embedded emissions of approximately 5%. This is because the rise in the embedded emissions due to the larger batteries (relative to the CV) is partially offset by a relative reduction in embedded emissions due to engine downsizing.

2.4. In-service emissions

The in-service emissions are classified as direct, indirect and replacement. Direct emissions are those from the vehicle tailpipe while indirect emissions are associated with the source of propulsion energy (i.e. the grid electricity or fuel production). The replacement emissions are those attributed to the periodic replacements of consumables. Consistent with Sharma et al. (2012), it is assumed that the vehicles travel a total distance of 15,000 km/year with a lifetime of 10 years. The estimates of the fuel and electricity consumption and tailpipe emissions were listed in Table 1.

2.4.1. Direct emissions

The direct emissions, \( E_d (\text{kg CO}_2\text{-e}) \) consist of the tailpipe emissions resulting from the combustion of the on-board fuel and may be computed using the tailpipe emission estimates in Table 1 and the total distance travelled by the vehicle during its lifetime, \( D \), i.e.:

\[
E_d = \frac{\Theta_{th} D}{1000}
\]  

2.4.2. Indirect emissions

The indirect emissions, \( E_i (\text{kg CO}_2\text{-e}) \) during the vehicle service comprise the emissions associated with generation, transmission and distribution of the electricity which in turn is used to charge the batteries of the PHEV and BEV, and the emissions due to the extraction, production and transportation of the fuel.
The indirect emissions have been calculated from the estimates of the total fuel and electricity consumption for each of the vehicle configurations during the vehicle life cycle, as calculated from Table 1 and D, along with the corresponding emission factors for Australia, which are taken to be $E_{\text{fuel}} = 5.3 \text{ kg CO}_2\text{-e/GJ}$ and $E_{\text{elec}} = 1.04 \text{ kg CO}_2\text{-e/kWh}$ (Australian Government Department of Climate Change and Energy Efficiency, 2011). This latter value represents the emission factor for consumption of purchased electricity by end user, and represents the emissions attributable to the fuel extraction and electricity production, transmission and distribution. This value is high by international standards and is primarily due to Australia’s strong reliance on electricity generation from coal, with natural gas and renewables playing a much smaller role.

The energy content $X_{\text{fuel}}$ for gasoline and diesel has been taken to be 0.034 GJ/l and 0.038 GJ/l respectively (Australian Government Department of Climate Change and Energy Efficiency, 2011). Thus, the indirect emissions for each vehicle configuration has been evaluated by:

$$E_i = \frac{C_e D E_{\text{elec}} + C_f D E_{\text{fuel}} X_{\text{fuel}}}{100}$$ (2)

2.4.3. Replacements

This section accounts for the emissions due to the replacement of the engine and brake fluids, lead-acid batteries (all vehicles are assumed to maintain a low voltage electrical system) and tyres. It is assumed that the quantities of the fluids required by all the HEV configurations is the same. The mass and number of replacements of the fluids, lead-acid batteries and tyres for the CV, HEV and BEV are presented in Table 4. The estimates of the fluids are based on Burnham et al. (2006). The tyres and lead-acid batteries are typically replaced every 45,000 km (RACV, 2011) and, consequently, are expected to undergo three replacements over the vehicle lifetime. The emissions due to the replacements have been calculated by following the same procedure as in the case of the vehicle materials given in Section 2.3.1.

2.4.4. Vehicle in-service emissions

The total in-service emissions are plotted in Fig. 3. As expected, the in-service emissions for the CV, mild, parallel and series configurations are mainly due to the onboard combustion of the fuel, while for plug-in and BEVs the emissions during the in-service phase are associated with the generation, transmission and distribution of electricity. In the Class-E segment, the parallel and series hybrids result in minimum in-service emissions as they reduce the fuel consumption and do not use external sources of electricity to charge the batteries. In the Class-B segment, there is the somewhat surprising result that the in-service BEV emissions are higher than those of the CV. This is due to a combination of the highly efficient internal combustion engine in this segment and the high emissions intensity of the electricity network.

It is therefore apparent that the carbon intensive power generation in Australia has a strong impact on the emissions generated by the grid-connected vehicles in both classes. A shift towards cleaner energy production or focussed use of renewable energy will significantly improve these emissions levels.

2.5. Total life cycle emissions

Combining the results from Sections 2.3.3 and 2.4.4, the total life cycle emissions in Fig. 4 shows a trade-off between the increase in the embedded emissions due to electrification and a resulting decrease in the in-service emissions. The ratio of the embedded to in-service emissions grows with increasingly electric powertrains, primarily due to the embedded emissions associated with the larger battery packs.

Overall, under the current conditions the parallel and series hybrids have the lowest life cycle emissions in the large car class, in conjunction with their lower relative cost of ownership (Sharma et al., 2012). Nevertheless, from the environmental impact point of view the Class-B segment vehicles are always significantly better than all the Class-E segment vehicles in terms of both cost and life cycle emissions. This indicates that downsizing the vehicle size may be the best option to reduce emissions associated with passenger vehicles.

Improvements in the power density of batteries (thereby reducing battery size) and manufacturing processes would lead to larger reductions in the embedded emissions in the BEV and PHEV vehicle options than for the other vehicle configurations.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Assumed mass and number of replacements of the fluids, Pb-acid battery and tyres.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (kg)</td>
</tr>
<tr>
<td></td>
<td>CV</td>
</tr>
<tr>
<td>Engine oil</td>
<td>3.8</td>
</tr>
<tr>
<td>Brake fluid</td>
<td>0.9</td>
</tr>
<tr>
<td>Transmission fluid</td>
<td>10.9</td>
</tr>
<tr>
<td>Coolant</td>
<td>10.4</td>
</tr>
<tr>
<td>Adhesives</td>
<td>13.6</td>
</tr>
<tr>
<td>Pb-Acid battery</td>
<td>14.5</td>
</tr>
<tr>
<td>Four tyres</td>
<td>36</td>
</tr>
</tbody>
</table>

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Conversely, improvements in all other vehicle technologies are likely to benefit the combustion engine driven configurations more, as the internal combustion engine has a lower average efficiency than an electric powertrain.

To some extent, this is evident in the Class-B vehicle size where, due to the higher efficiency of the downsized engine, the total life cycle emissions of the CV are lower than that of the BEV. This is principally due to the Class-B CV’s small engine, which on average is significantly more efficient over the drive cycle than that in the Class-E CV. As a result, the Class-B vehicle’s fuel consumption is 64% of the Class-E, despite it weighing only 38% less than the Class-E vehicle (from Table 3 in Sharma et al. (2012)).

3. Analysis under different energy and technology scenarios

The life cycle emissions estimated above are based on current energy intensity and vehicle technology scenarios. With technology improvements for all vehicle types and lower carbon energy generation, the sensitivity of estimated life cycle emissions will be investigated in three alternative scenarios, as follows:

- **Low carbon scenario.** This represents a change in the electricity grid to capture greater incorporation of renewable generation. The Australian state of Tasmania, which utilises a large percentage of hydroelectric generation, is used to set the emissions factor at $E_{\text{elec}} = 0.33 \text{ kg CO}_2\text{-e/kWh}$ (Australian Government Department of Climate Change and Energy Efficiency, 2011), and the embodied energy to embedded emissions conversion factor is halved from the benchmark case to 30 kg CO$_2$-e/GJ.

- **Improved technology scenario.** Under this scenario, the electricity grid remains unchanged from the benchmark case but the vehicle technology improves to reduce in-service energy consumption and tailpipe emissions by 20%, in keeping with recent proposals for passenger vehicle fuel economy standards over the next decade such as US National Highway Traffic Safety Administration and Environmental Protection Agency (2011). Such improvements are likely to come from many
sources, including vehicle mass reduction, optimised engine operation, better aerodynamics and lower rolling resistance tyres. The emissions factors in this scenario assume the grid remains unchanged from the benchmark case at $E_{\text{elec}} = 1.04$ kg CO2-e/kWh, and the embodied energy to embedded emissions conversion factor remains at 60 kg CO2-e/GJ.

- **Low carbon and improved technology scenario.** This scenario combines the emissions advantages of the previous two scenarios, with a 20% improvement in energy efficiency, along with the improved emissions factors of $E_{\text{elec}} = 0.33$ kg CO2-e/kWh and the lower embodied energy to embedded emissions conversion factor of 30 kg CO2-e/GJ.

Table 5 shows the estimated vehicle life cycle emissions for the different vehicle classes and configurations under these scenarios. As expected, a switch to a low carbon energy mix aids all vehicle configurations in limiting their life cycle emissions. Unsurprisingly, the low carbon scenario has the most impact on the more-electrified powertrains, as they have greater emissions associated with manufacture. The inclusion of technology improvements that increase the operating efficiency with the cleaner grid only leads to relatively minor further improvement.

The opposite situation is observed for the internal combustion engine based powertrains, whereby the relatively high proportion of in-service emissions means that technology improvements have greater impact relative to the benchmark case. The combination of the two scenarios also leads to cumulative improvements.

While the Class-E CV has the maximum life cycle carbon emissions under all four scenarios, for the Class-B vehicles it requires a low carbon scenario for the BEV to become the better option. However, in all situations considered, the worst performing Class-B vehicle has comparable or better life cycle emissions than the best performing Class-E, again reinforcing that downsizing may be the most effective method of emissions mitigation.

### 4. Cost of emissions mitigation

Combining the results of the previous section with the authors’ life cycle financial analysis (Sharma et al., 2012), it is possible to calculate the cost of emissions mitigation. This represents the price premium per tonne of CO2 avoided.

In Sharma et al. (2012) the baseline prices of the battery, fuel and electricity are assumed to be $800/kWh, $1.4/litre and $0.175/kWh. Two other pricing scenarios were also considered:

- **Electrification favourable scenario: In this scenario the battery cost is half of its base value ($400/kWh), fuel is priced at 150% of its base ($2.1/l) and the electricity price remains unchanged at the current off-peak rate of $0.175 per kWh.**
- **Electrification unfavourable scenario: In the electrification unfavourable pricing scenario, the battery is 150% of the base price ($1200/kWh), fuel price remains at the base value and the electricity price rises to $0.5/kWh.**

For the consumer, the additional up-front investment in purchasing a hybrid or electric vehicle relative to a CV should be achievable within the vehicle’s lifetime if the purchase is to be financially rational. In contrast, the accumulated life cycle emissions are most important from an environmental perspective. To reflect the different importance of time in evaluating both the cost and emissions of a given vehicle configuration, the following figure of merit is therefore introduced:

$$ \Delta q_N = \frac{\text{Ownership cost premium over the CV after } N \text{ years (dollars)}}{\text{Total life cycle CO2-e saved relative to the CV (tonnes)}} \quad (3) $$

Note that $\Delta q_N$ is a useful metric only if the cost of ownership after $N$ years is larger than that of the CV and the life cycle emissions are less than that of the CV, in which case it indicates the premium paid over that of a CV to mitigate one tonne of equivalent greenhouse gas emissions. If $\Delta q$ is negative, the technology is beneficial relative to the conventional vehicle in terms of both cost and emissions (with the exception of the Class-B BEV for which the life cycle emissions are greater than the Class-B CV).

Table 6 shows the cost of emissions mitigation relative to the CV with $N$ set to 3, 5 and 10 years. Each of the Class-E vehicle configurations is considered for the different pricing scenarios with the current Australian energy mix. The Class-B electric vehicle is not considered as it does not result in lower life cycle emissions relative to the CV under these conditions.

While it was determined in Section 2.5 that the parallel and series hybrids had the lowest life cycle emissions under the benchmark energy scenario, Table 6 indicates the parallel hybrid is most favourable under the base pricing scenario as the
The consumer is only paying $57 per tonne mitigated after three years ownership, compared to $202 per tonne mitigated for the series hybrid. After five years ownership the parallel hybrid has a lower total cost of ownership relative to the CV and also lower emissions, so consumer and environmental benefits are aligned in this case. Under the base pricing scenario, the plug-in and electric variants have mitigation costs that are significantly higher than the cost of greenhouse gas emissions in the Australian Federal Governments Emissions Trading Scheme (Australian Government Department of Climate Change and Energy Efficiency, 2011) regardless of duration. This obviously becomes more skewed under the electrification unfavourable pricing scenario, with only the parallel hybrid being competitive on cost of mitigation after five years.

If the electrification favourable scenario is adopted, all vehicle configurations are better than the CV in terms of both cost and emissions, although the parallel hybrid is again the fastest to reach cost parity.

The cost analysis was repeated for low carbon energy, with the results provided in Table 7. Once again under the base pricing scenario the parallel hybrid appears to be the most effective alternative with benefits for both the consumer and the environment relative to the CV in less than 5 years. The parallel hybrid also remains a reasonable choice under the electrification unfavourable scenario. Under the electrification favourable scenario, the reduced battery price makes the parallel financially superior in terms of cost of ownership within a very short time period, while after 5 years all the powertrain options are better than the Class-E CV.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Base pricing</th>
<th>Electrification favourable</th>
<th>Electrification unfavourable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N = 3</td>
<td>N = 5</td>
<td>N = 10</td>
</tr>
<tr>
<td>Class-E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild</td>
<td>341</td>
<td>282</td>
<td>163</td>
</tr>
<tr>
<td>Parallel</td>
<td>57</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Series</td>
<td>202</td>
<td>119</td>
<td>-</td>
</tr>
<tr>
<td>Plug-in</td>
<td>1383</td>
<td>1099</td>
<td>520</td>
</tr>
<tr>
<td>BEV</td>
<td>1822</td>
<td>1487</td>
<td>803</td>
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<tr>
<td>Class-B</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>BEV</td>
<td>1566</td>
<td>1385</td>
<td>1015</td>
</tr>
</tbody>
</table>

Table 6
The cost of mitigating life cycle emissions $\Delta q$ (tonne) for the base energy mix. ‘*’ indicates there is a cost saving relative to CV, i.e. $\Delta q \leq 0$.

Table 7
The cost of mitigating life cycle emissions $\Delta q$ (tonne) for the low carbon energy mix. ‘*’ indicates there is a cost saving relative to CV, i.e. $\Delta q \leq 0$.

Fig. 5. Life cycle emissions mitigated vs. price premium (both relative to CV) in three years of Class-E vehicle ownership.
In the Class-B size, the low fuel consumption of the CV makes the BEV option an expensive mitigation choice, with the cost typically much greater than the anticipated carbon price, unless the electrification favourable scenario is considered over a duration close to ten years.

The relative cost of emissions mitigation presented in Tables 6 and 7 demonstrates one perspective on the potentially competing demands of cost of ownership and emissions. However the trade-off between consumer (who may desire a shorter than lifetime cost benefit) and environment may be captured in Fig. 5, where the premium paid over the CV over three years is plotted against the total CO2-e saved relative to the CV.

In this figure, the electrification favourable and electrification unfavourable financial scenarios have been coupled with the current emission factors for Australia and the low carbon scenario. These four scenarios are represented as rectangles in Fig. 5. The area covered by each rectangle is indicative of the sensitivity of the corresponding vehicle configuration to the variations in the emission factors and the prices of the fuel, electricity and batteries. Note that all of these influences are external to the use of the vehicle.

Irrespective of the scenario, the mild hybrid is close to the conventional in terms of costs and will save approximately five tonnes of CO2-e after 10 years. While the best overall emissions mitigation is possible through the BEV technology with up to 34 tonnes of CO2-e potentially saved over the lifetime, the financial and environmental performance of the BEV and plug-in HEV technologies are most sensitive in the pricing and energy scenario. Conversely, the parallel and series hybrids are much more robust to these variations, and offer significant environmental benefits at relatively low, or no, additional cost. This is because the embedded emissions of the parallel and series hybrids roughly track those of the equivalent conventional vehicle, whilst retaining their fuel consumption advantage.

5. Conclusions

This paper is the second of a two part study, and presented an analysis of the life cycle emissions of conventional and equivalent hybrid and fully electric vehicles for Australian driving conditions. Two vehicle sizes were considered, Class-B and Class-E, which bracketed the large majority of passenger vehicles on Australian roads.

The greenhouse gas emissions of both the manufacture and use of each vehicle was estimated using established life cycle emissions techniques. Uncertainty in key system inputs was accounted for using a scenario based approach, with the baseline scenario estimated to be current. Combined with the financial analysis conducted in the first part of this study (Sharma et al., 2012), the cost of life cycle greenhouse gas mitigation relative to an equivalent conventional vehicle was then calculated for both vehicle classes.

The following results are of note:

- For the Class-E vehicles in the baseline scenario, the parallel and series hybrid configurations were found to have the lowest life cycle greenhouse gas emissions. This was due to a combination of their superior fuel economy relative to the equivalent conventional vehicle and their smaller batteries (and hence lower embedded emissions) than the equivalent, purely electric vehicle.
- The Class-B electric vehicle has higher life cycle emissions than its equivalent conventional vehicle if the electricity used in its manufacture and for propulsion has the current, average Australian greenhouse intensity. This is due to its large battery and in-service electricity consumption.
- Simultaneously low battery prices, high fuel prices and a dramatic reduction in the greenhouse intensity of the electricity used for both vehicle manufacture and propulsion are required for the plug-in hybrid and fully electric Class-E vehicles to be cost effective forms of emissions mitigation. With these same inputs, the Class-B electric vehicle remains an expensive form of mitigation.
- The series and parallel hybrid Class-E vehicles both demonstrated significant life cycle emissions mitigation which was almost invariant with the greenhouse intensity of the energy used in their manufacture. This was because their embedded emissions roughly tracked those of the equivalent conventional vehicle, whilst retaining their fuel consumption advantage. In both cases, their total cost of ownership was similar to, or less than, the conventional vehicle and also relatively insensitive to component prices. In contrast, the plug-in hybrid and fully electric vehicles featured greenhouse and cost of ownership outcomes that were strongly reliant on the scenario.

Given these results, hybridisation of Class-E vehicles appears to be a more robust (i.e. tolerant to uncertainty) and cost effective means of achieving significant emissions mitigation for vehicles in this class. For Class-B vehicles, it is likely that conventional powertrains will retain a low cost of ownership for vehicles in this class, whilst achieving low life cycle greenhouse gas emissions.

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References


