APPLICATION OF MULTI-OBJECTIVE OPTIMISATION TO DETERMINE THE LIFE CYCLE COST, PETROLEUM USAGE AND GREENHOUSE GAS EMISSIONS OF PLUG-IN HYBRID VEHICLES IN AUSTRALIA

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Plug-in hybrid electric vehicles (PHEV) could provide a more cost effective and environmentally friendly alternative to hybrid electric vehicles (HEV) and conventional internal combustion engine (ICE) vehicles in the Australian new car market. This report will analyse the available vehicles on the market today for a new car buyer in Australia, daily driving trends in Australia, and the current methods and trends in power generation in Australia. This data will be analysed using multi-objective optimisation to provide an assessment of the most cost effective and environmentally friendly vehicles on the market in Australia today, as well as when PHEV are likely to become the leader in this field.
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</tr>
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1. Introduction

1.1 Motivation
Plug-in Hybrid Electric Vehicles (PHEV) are an emerging platform that could potentially provide Australian motorists with a more energy efficient as well as cost efficient means of travel. PHEVs differ from standard hybrid electric vehicles (HEV) in that they can be charged by mains power when not in use. This gives PHEVs the potential to reduce costs to the owner dependent on the cost of mains power. PHEVs also have the potential to reduce dependence on petroleum as a fuel source and reduce overall greenhouse gas (GHG) emissions per kilometre travelled.

1.2 Aims
The aim of this thesis is to investigate whether PHEV can potentially replace standard internal combustion engine vehicles (ICE) and/or HEV. The key factors as to whether PHEV can replace ICE and/or HEV is if they provide consumers with a cheaper means of travel, especially commuting to and from work, as well as a reduction in greenhouse gas emissions per kilometre driven.

This report will aim to quantify the data of Australian driving statistics, in particular daily kilometres driven. By quantifying the trends in Australian driving habits, it will allow recommendations to be made on what percentage of the Australian population will benefit from the availability of PHEVs on the Australian new car market.

This report will also provide a cost and GHG emission analysis per kilometre travelled in a single journey. This will seek to optimise the distance range for which each type of vehicle (PHEV, HEV, ICE) is most efficient in terms of cost and GHG emissions.
2. Background

2.1 Plug-In Hybrid Electric Vehicles

Plug-in hybrid electric vehicles (PHEV) provide a potentially more cost effective and environmentally friendly method of personal transportation. PHEV utilise mains power to charge the vehicle batteries when not in use. This power is then used to drive the vehicle via electric motors until the batteries are discharged to a target state of charge (SOC) in charge depleting (CD) mode. Once the batteries reach the target SOC the internal combustion engine (ICE), often called a range extender by automotive manufacturers, will start and commence charging the batteries. This is known as charge sustaining (CS) mode. Once in CS mode a PHEV operates in the same manner as a HEV.

When in CS mode the ICE produces power to charge the batteries. The batteries in turn power the electric motors that provide drive to the vehicle. The use of electric motors increases the efficiency of the drivetrain as the ICE is able to operate at its peak efficiency frequency at all times. As the ICE is not directly driving the vehicle, merely charging the batteries, it enables more a fuel efficient ICE to be selected as the torque and power output of the ICE at various loads does not influence the performance of the vehicle. The final advantage of an electric drivetrain is it enables a kinetic energy recovery system (KERS) to be utilised. This system recovers energy from braking to charge the batteries rather than a conventional braking system where this energy is dissipated as heat.

The key advantage of the PHEV over a conventional hybrid electric vehicle (HEV) is the ability to have additional charge utilised during CD mode. This energy is sourced from mains power rather than the onboard ICE. Mains power has the potential, depending on the location, to be more cost effective and more environmentally friendly than utilising petroleum to generate this power.

The Carnegie Mellon University completed a study to the applicability and cost effectiveness of PHEV in the United States. The study found that in the United States there was a saving to be made by people who travel less than 51 miles (82km) per day by purchasing a PHEV. Anyone who travels further than this will be better off purchasing a HEV.

The key factors limiting the market penetration of PHEV is high battery costs, low petrol prices and high electricity prices. In this case a HEV is more cost effective over a PHEV. The relative lowering of lithium battery prices resulting in lower initial vehicle costs since this study was published and differences in the petroleum and electricity markets in Australia may change the results of when a PHEV is more cost efficient than a HEV or ICE.

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3 ibid
This study was completed in 2010 and improvements in lithium batteries and increases in fuel prices may have changed this figure. The newest range of PHEV may rival and even exceed HEV in their fuel efficiency.

The foremost competitors for PHEV are HEV and small fuel efficient ICE. The vehicle models used to apply this model to the Australian market were the 2015 Toyota Prius (HEV), 2013 Holden Volt (PHEV), 2015 Toyota Corolla (petrol ICE), 2015 Volkswagen Golf (diesel ICE) and the 2015 BMW i3 (PHEV). The full details and data for each of these vehicles can be found at appendix XXX.

2.2 Mains Power Generation in Australia

Australia generates 242TWh of power per year. Of this 75% is generated by coal power, 15% liquid natural gas (LNG), 9% renewables and 1% oil. The proportion of each fuel source that contributes to power generation has remained largely consistent over the last 30 years. This is unlikely to change in the near future due to the significant natural resources that Australia has, in particular coal and LNG. Renewables are simply not economically viable alternatives to coal or LNG. Significant policy changes and incentives from the Australian Government would be required to make renewable energy sources such as wind, solar or geothermal economically viable.

Figure 1: Cost of production for Li-Ion batteries (Jarvinen et al, 2011)

Figure 2: Proportion of electricity by source (International Energy Agency, 2012)

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5 ibid
The National Electricity Market (NEM) consists of five electricity generation areas, NSW, QLD, SA, TAS and the Snowy Mountains Hydroelectric Area. The price of energy varies per state and is quite volatile, depending on demand, rate of economic growth, cost of fuel source amongst other factors. This makes providing a prediction for the price of power in the future very difficult. The predictions for the increase in power prices per state are shown below.\(^6\)

<table>
<thead>
<tr>
<th>Power Production Area</th>
<th>Predicted Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>New South Wales</td>
<td>Less than 2%</td>
</tr>
<tr>
<td>Queensland</td>
<td>2014/5 to 2021 – 2%, from 2021/2 onwards – less than 1%</td>
</tr>
<tr>
<td>South Australia</td>
<td>1.5%</td>
</tr>
<tr>
<td>Tasmania</td>
<td>3.3%</td>
</tr>
<tr>
<td>Victoria</td>
<td>Less than 1%</td>
</tr>
</tbody>
</table>

2.3 **Fuel Usage in Australia**

Australia has had a relatively limited market penetration of PHEV, HEV and EV vehicles. Sales of hybrid and electric vehicles are increasing, however the best selling hybrid in Australia (Toyota Prius) doesn’t even make the top ten of new vehicle sales in Australia.\(^7\) The Australian car market remains almost completely reliant on fossil fuels.

It is estimated there will be a 27% increase in fossil fuel prices in Australia over the next ten years.\(^8\) The price of petrol is almost solely dependent on the price of crude oil.\(^9\) The fact that Australia has limited crude oil reserves means it is especially vulnerable to fluctuations in crude oil prices. This increasing cost of petrol is likely to make a PHEV or HEV more cost effective in the future as mains generated power becomes a more cost effective power source than fossil fuels.

![Figure 3: Estimate of future Australian petrol prices (Pekol, 2010)](image)

There is also a political benefit to reducing fossil fuel usage. Reliance on foreign oil can cause considerable issues with foreign policy development and also makes economies overly reliant on factors outside of their

\(^9\) ibid
control, such as regional conflict and pricing pressures from cartel structures. The world’s oil reserves are predominantly located in some of the most unstable and volatile areas of the globe.\textsuperscript{10}

\subsection*{2.4 Population Trends in Australia}
89.4\% of the total population of Australia in 2015 is considered urbanised. There has been an annual increase of 1.47\% of the population becoming urbanised between 2010 and 2015.\textsuperscript{11} An urbanised population is much more likely to be benefitted by PHEV due to their shorter driving distances during a single trip. The key advantage of a PHEV over a HEV is the kilometres that are driven in CD mode using mains generated power stored in the battery before the ICE is required to generate power to recharge the batteries.

People located in country areas will likely exceed this range during their normal driving due to the large distances between country population centres in Australia. If a PHEV is less efficient than an ICE when in CS mode, this may make an ICE more suitable to those people who live in country areas or require to frequently travel between urban centres.

\subsection*{2.5 Optimisation Code}
MATLAB was used to run an optimisation model to ascertain whether a PHEV was more cost efficient and environmentally friendly than a HEV or ICE. The key outputs were to identify the key points in terms of daily kilometres driven where a PHEV, HEV and ICE became the most cost effective and environmentally friendly option for an Australian in the market for a new vehicle.

The following parameters were used for the model.

\begin{table}[h]
\centering
\begin{tabular}{|l|l|l|l|}
\hline
\textbf{Parameter} & \textbf{Nomenclature} & \textbf{Value} & \textbf{Unit} \\
\hline
Nominal Discount Rate & r_N & 2.8 & \% \\
Inflation Rate & r_I & 1.5 & \% \\
Vehicle Life & s_LIFE & 266640 & km \\
Base Vehicle Cost & c_BASE & 32628.05 & \$AUD \\
Annual Electricity Price & c_E & 0.044 & \$AUD/kWh \\
Annual Gasoline Price & c_G & 1.288 & \$AUD/L \\
Lithium Battery Cost & c_B & 300 & \$USD/kWh \\
Electricity Production GHG Emissions & v_E & 0.8 & kg.CO2/kWh \\
Gasoline GHG Emissions & v_G & 3.34 & kg.CO2/gal \\
\hline
\end{tabular}
\caption{Parameters used in optimisation model}
\end{table}

\textsuperscript{10} ibid
\textsuperscript{11} https://www.cia.gov/library/publications/the-world-factbook/fields/2212.html accessed 06 Sep 15
3. Results

3.1 Optimal Solutions

The average distance driven by passenger vehicles in 2012 in Australia was 13,200km in a year. This equates to 36.2km per day. With this in mind an average daily driving distance of 25km, 50km, 75km and 100km was used to develop a series of optimised solutions for a PHEV.

![Figure 4](image1.png)  
Figure 4: Series of optimised solutions for 25km average daily driving distance

![Figure 5](image2.png)  
Figure 5: Series of optimised solutions for 50km average daily driving distance

![Figure 6](image3.png)  
Figure 6: Series of optimised solutions for 75km average daily driving distance

![Figure 7](image4.png)  
Figure 7: Series of optimised solutions for 100km average daily driving distance

As can be seen in the above figures, the range of optimal solutions is much greater at lower average daily driving distances. At 75km and particularly 100km the reduced percentage of driving in charge depleting mode reduces the beneficial effect of the PHEV.

3.2 Sensitivity Analysis

The importance of the price of petroleum and energy, as well as the emissions from lithium battery production were analysed through a sensitivity analysis. In order to determine the relative sensitivity of the optimal solutions on each of these factors, the model was run with a factor of 90% or 110% for each of these input parameters. The model was run at an average driving distance of 25km, 50km, 75km and 100km for all

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combinations resulting in 32 sets of data. Two optimal solution sets are shown below for all input parameters at 90% and 110% respectively at 25km average daily driving distance.

As can be seen in the above example there was limited change in the set of optimal solutions with input parameter changes in cost of electricity, petroleum or the GHG emissions from lithium battery production.

### 3.3 Future Energy Price Model

In order to determine how a PHEV may become more applicable in the future the model was run for a predicted annual increase of petroleum prices of 2.7% and 1.8% increase in energy prices.

As could be predicted from the sensitivity analysis there was limited difference between the optimal models as the prices of electricity and petroleum increase over time.
4. Discussion

4.1 Optimal Models
The range of optimal solutions at an average daily driving distance of 25km and 50km is vastly increased for the ability to pick an ideal combination of GHG emissions, fuel efficiency and equalised annual cost. As daily driving distance increases, reducing the distance driven in CD mode, the options are reduced. This is not an issue as Australia’s already urbanised population drives an average distance of 36.2km per day.

The sensitivity analysis showed there was no significant change in the optimal solutions as a result of 10% changes in either direction for the price of petroleum or electricity, or the GHG emissions from lithium battery production.

As predicted by the sensitivity analysis there is limited change in the future as prices of electricity and petroleum increase. The relative difference predicted in Australia for electricity and petroleum prices is 0.9%, and not significant enough to have a marked difference on the optimal solutions.

4.2 The Future Outlook for PHEV Market Penetration
The drive of pressures to decarbonise the vehicle fleet, rising fossil fuel prices, improving operating efficiencies and the falling prices of Lithium ion batteries all indicates that EVs are likely to significantly increase their market penetration in the new car market.13

The Australian government is yet to legislate a target number of electric vehicles for the future.14 Many other countries of similar culture, geography and socioeconomic status have set EV targets and this can be used to educate an estimate of potential market penetration of EVs in Australia. Most European countries to set targets have aimed for between two and six percent by 2020. Australia is likely to be at the low end of this scale due to the increased population density in European countries compared to Australia. This would equate to roughly 250000 vehicles. Considering the limited market penetration of EV, HEV and PHEV it is difficult to see the EV market increasing in Australia in such a significant volume in such a short space of time.

The driving habits of the Australian population are crucial as to whether or not a PHEV is a cost effective or environmentally beneficial alternative to a conventional ICE vehicle. Urban driving is particularly suited to PHEVs due to their relatively short range. This makes the urbanisation and daily driving trends of the Australian population particularly pertinent. The increasing amount of people living in urban centres driving short distances each day indicates that PHEV will become more effectual in the future.

Energy prices, both power and petrol, directly affect the cost benefits of owning a PHEV. The significant cost savings are made by using power from the grid, which is cheaper per kilometre driven than petrol or diesel. Current predictions have shown that power prices are likely to increase in the region of 1-2% per annum15.

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whereas petrol prices are predicted to increase at approximately 2.5-3% per annum.\textsuperscript{16} This will see mains power becoming more cost effective and therefore making PHEV the most cost efficient means of personal transport.

Greenhouse gas emissions are also a factor as to why a new car buyer may select a PHEV. The huge reliance of coal generated power in Australia means that our mains power has relatively high GHG emissions and the use of PHEVs in Australia may not be as environmentally beneficial as overseas. European nations, which have seen much higher PHEV sales, have higher proportions of power generated by renewables leading to significant reductions in GHG emissions per kilometre driven.

As it currently stands there is limited advantage to our switching from petrol or diesel to electrical power in terms of GHG emissions. However, there is significant pressure on policy makers to decarbonise our power generation and increase our use of renewable power sources. The Australian Government has set a renewable energy target (RET) of 33000GWh by 2020. The original target set in 2001 was 41000GWh, however such a target is not economically viable due to the inability of renewables to compete with coal and LNG power.\textsuperscript{17} An increase in the proportion of renewable power generation would see a potential GHG emission benefit in owning a PHEV as opposed to a HEV or ICE.

5. Summary

Plug-in hybrid electric vehicles could provide a more cost effective and environmentally friendly alternative to conventional internal combustion vehicles. The cost of fuel and power will directly influence whether or not PHEVs are currently more cost effective than a conventional ICE. If PHEV vehicles are not currently cost effective the decreasing price of lithium ion batteries, increased use of renewables for power generation and increasing crude oil prices are likely to mean that PHEVs will become viable in the near future.

6. Acknowledgements

I would like to thank Dr. Hemant Kumar Singh for his assistance as my advisor in completing this project. I would also like to thank Dr. Tapabrata Ray for his input and expertise on the conduct of the project. Finally, I would like to thank Kalyan Shankar Bhattacharjee for compiling the MATLAB code and providing vital help in running the optimisation code.

\textsuperscript{16} Pekol, \textit{The Price of Petrol – Past and Future}, Australasian Transport Research Forum, 2010
\textsuperscript{17} Clean Energy Council, \textit{A Bipartisan Renewable Energy Target: The Huge Opportunities for Australia}, 2015
## 7. Appendix

### 7.1 Appendix A – Vehicle Parameters

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<th>Vehicle</th>
<th>Initial Cost</th>
<th>Engine</th>
<th>Power (kW)</th>
<th>Torque (Nm)</th>
<th>Fuel Consumption (L/100km)</th>
<th>Fuel Capacity (L)</th>
<th>Range (km)</th>
<th>Range (battery stored)</th>
<th>GHG Emissions (CO2 g/km)</th>
<th>Weight (kg)</th>
<th>Power to Weight Ratio (kW/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 Toyota Prius18</td>
<td>36500</td>
<td>1.798cc Petrol</td>
<td>100</td>
<td>142</td>
<td>3.9</td>
<td>45</td>
<td>519.2</td>
<td>N/A</td>
<td>89</td>
<td>1379</td>
<td>72.5</td>
</tr>
<tr>
<td>2013 Holden Volt19 20</td>
<td>59990</td>
<td>1.398cc Petrol</td>
<td>111</td>
<td>N/A</td>
<td>1.2</td>
<td>35.2</td>
<td>550.4</td>
<td>61.2 km (17.1k Wh)</td>
<td>27</td>
<td>1721</td>
<td>64.5</td>
</tr>
<tr>
<td>2015 Toyota Corolla (CVT Auto Hatch)21</td>
<td>26500</td>
<td>1.800cc Petrol</td>
<td>103</td>
<td>173</td>
<td>6.1</td>
<td>50</td>
<td>819.7</td>
<td>N/A</td>
<td>153</td>
<td>1275</td>
<td>80.8</td>
</tr>
<tr>
<td>2015 Volkswagen Golf 110TDI22</td>
<td>38490</td>
<td>1.968cc Diesel</td>
<td>110</td>
<td>320</td>
<td>4.9</td>
<td>50</td>
<td>1020.4</td>
<td>N/A</td>
<td>124</td>
<td>1326</td>
<td>83.0</td>
</tr>
<tr>
<td>2015 Nissan Leaf23</td>
<td>56535</td>
<td>Permanent Magnet Electric</td>
<td>80</td>
<td>280</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>120</td>
<td>N/A</td>
<td>1795</td>
<td>N/A</td>
</tr>
<tr>
<td>2015 BMW i324</td>
<td>76351</td>
<td>647cc Petrol to charge batteries</td>
<td>125</td>
<td>250</td>
<td>0.6</td>
<td>9</td>
<td>1500</td>
<td>169.2 km (0.13k Wh/km)</td>
<td>13</td>
<td>1315</td>
<td>95.1</td>
</tr>
</tbody>
</table>

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20 [https://www.fueleconomy.gov/feg/Find.do?action=sbs&id=32655&id=33900&id=35246](https://www.fueleconomy.gov/feg/Find.do?action=sbs&id=32655&id=33900&id=35246) accessed 05 Sep 15
21 Toyota Corolla Specifications Brochure, 2015
22 Volkswagen Golf Specifications Brochure, 2015
23 [http://www.carsales.com.au/newcars/details.aspx?R=701558&Vertical=Car&__Qpb=1&Cr=0&__Ns=p_HasPhotos_Int32%7C1%7C%7Cp_IsSpecialOffer_Int32%7C1%7C%7Cp_Year_String%7C1%7C%7Cp_ReleaseMonth_Int32%7C1%7C%7Cp_Make_String%7C0%7C%7Cp_Family_String%7C0&spotid=393592&__N=2994+3296+4294947575+4294105566&Silos=1304&scot=1&__Nne=15&src=sr-landing-search&csn_tn=true&treec=1&__sid=14AFFCA4A2FD&sdmve=1](http://www.carsales.com.au/newcars/details.aspx?R=701558&Vertical=Car&__Qpb=1&Cr=0&__Ns=p_HasPhotos_Int32%7C1%7C%7Cp_IsSpecialOffer_Int32%7C1%7C%7Cp_Year_String%7C1%7C%7Cp_ReleaseMonth_Int32%7C1%7C%7Cp_Make_String%7C0%7C%7Cp_Family_String%7C0&spotid=393592&__N=2994+3296+4294947575+4294105566&Silos=1304&scot=1&__Nne=15&src=sr-landing-search&csn_tn=true&treec=1&__sid=14AFFCA4A2FD&sdmve=1) accessed 05 Sep 15
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Toyota Corolla Specifications Brochure, 2015

Volkswagen Golf Specifications Brochure, 2015