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ENGN2226 Systems Engineering Analysis

# Analysis of an Electric Vehicle System

### Optimising the electrical vehicle system in order improve adoption rates among consumers

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## Abstract

Electric vehicles are a promising technology that can serve to increase energy security and reduce greenhouse gas emissions. However, their adoption rate has been slow due to consumer expectations relating to certain factors not being met. Optimising the electric vehicle system in order to overcome these limitations using systems analysis techniques will be the focus of the report with the Nissan Leaf used as an example. Recommendations include the substitution of high-strength steel used in the chassis with aluminium yielding a weight reduction of 147 kg, removing the differential and using individual motors connected to wheels yielding a 5% efficiency improvement, implementation of charging and battery swapping stations to reduce charge times and reduce range anxiety, utilisation of a proportional-integral derivative (PID) algorithm with feedforward controllers alongside the individual motors to improve vehicle stability system and performance. These recommendations when incorporated in the MATLAB range model yielded a 10% increase in range. The cost was compared with an equivalent conventional vehicle and a payback period of 13 years was determined. The reduction in upfront cost was found to be the main way to reduce this to an ideal payback period of 5 years. In order to reduce driver distraction in-vehicle information systems should reduce visual and physical interactionwith mean task duration of 10 seconds to allow for a 1.5 second reaction time in demanding traffic.

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# 1 Introduction

Electric vehicles (EVs) have existed as long as conventional vehicles but they are not equally as popular. In recent years, however, most modern economies have been seeking to address future energy requirements with achieving sustainable transportation emerging as a central goal. EVs are a promising pathway that can serve to increase energy security and reduce greenhouse gas emissions and other pollutants.

According to BP, there are 1,700.1 billion barrels of proven oil reserve left, sufficient to last 52.5 years at the current production rates (BP 2014b). Due to the increasing scarcity of the commodity, there will be significant price rises resulting in the use of oil and other fossil fuels to not be econimically viable An alternate fossil fuel from which oil can be produced is coal. However, oil produced in such a way is approximately 10% more expensive and generates greater carbon emissions (Larminie and Lowry 2012). Although coal reserves are able to meet 110 years of global production, an equal trend in price increase applies (BP 2014a).

Another issue directly related to the burning of fossil fuels, oil, coal and gas is global warming. These activities in addition to deforestation results in the release of carbon dioxide into the atmosphere in increasing amounts. The accumulation of carbon dioxide results in an increase in absorption of infrared radiation from the Earth's surface. Such an effect is known to increase the global average temperature and with the continuing expansion of the world's industry, there is likely to be a significant change. It is already predicted that there will be a rise by a third of a degree Celsius or more every ten years (Houghton 2009). Hence, it is imperative to curb the rise in the emission of carbon dioxide in order to prevent further global climate change.

Some of the benefits associated with electric vehicles include reduction in the dependence on oil and other fossile fuels, zero carbon emissions and contribution to pollution of the vehicle itself. Although there is ample interest among stakeholders including policymakers, businesses and consumers, the development of the market has been slow. Some of the factors that are contributing to the lack of adoption of EVs it their higher upfront cost relative to conventional vehicles; the lacks of charging infrastructure; restricted driving range compared with equivalent conventional vehicles; perceived distance needs of consumers as well as longer refuel times (Beltramello 2012).

## 1.1 Approach

The electric vehicle system will be analysed using a systems approach to engineering, specifically systems analysis. Systems analysis aims to evaluate a particular system or design from various perspectives. These perspectives are comprised of several sub-factors that can be analysed using specific techniques (Blanchard and Fabrycky 2011). Overall, the system approach enables a system to be considered from several aspects in order to improve its design or operation. In this report,recommendations on alterations or improvements on the EV system design are provided with the primary focus of ensuring that switching to EVs is feasible compared to conventional ICEs as well as meeting the expectations of the consumer. For the purpose of analysis, important factors including infrastructure, impact on the environment, adoption rates and cost will be considered from the perspective of the Canberra region.

### 1.1.1 Vehicle Range Model

The range of an electric vehicle is considered a primary drawback. In order to quantify the resultant benefits of the recommendations, their effect on the range of the vehicle will be considered. The MATLAB model simulates the range of a vehicle based on specific vehicle parameters and driving conditions. The specific equations used in the model are presented in Appendix A. Some key assumptions used to simplify the simulation include constant velocity, a level ground and still air. Although these asssumptions seem unrealistic, the outcomes of the simulation yield useful figures to compare changes in certain parameters on the range of the vehicle.

### 1.1.2 Nissan Leaf

At present there is ongoing development of electric vehicles. Many EVs have been made commercially available with more announced by various manufacturers. In this report the Nissan Leaf will be used for conducting the analysis; as it is the best-selling EV in the world based on the number of units sold (Helmes 2015). The specification of the Nissan Leaf will also be used for the vehicle parameters in the model. The Nissan Leaf is a commercial electric vehicle that uses a 24 kWh lithium battery and a permanent magnetic synchronous motor. It is capable of covering 160 km on a single charge with the battery able to be charged in 8 hours using a residential charging unit or in less than 30 minutes to 80% capacity using a rapid charger (Larminie and Lowry 2012).

## 2 Qualitative Analysis

In order to understand the problem of the slow adoption of electric vehicles, it is imperative to determine consumer preferences and expectations from electric vehicles. An approach is to utilise qualitative methods such as a survey to gain a better insight into the issue in terms of the customer, as it is ultimately their choice to adopt electric vehicles. The audience for the survey would be consumers who have recently purchased a vehicle, are in the market looking to purchase/lease a new vehicle or will be purchasing/leasing a vehicle in the near future. The survey was designed to minimise the errors outlined by the ABS and is presented in Appendix A (Australian Bureau of Statistics 2013b). As consumer preferences vary among different regions, a large sample size is required and such a survey requires extensive resources and cannot be conducted individually. Therefore, secondary research such as global studies and surveys on consumer transportation preferences and expectations of electric vehicles are required for the analysis (Rea and Parker 2014). Specifically, the comprehensive set of studies and surveys conducted by Deloitte with a similar aim are used, with one survey of 23,000 individuals over 19 countries and another with over 13,000 individuals over 17 countries. Although, these surveys are conducted over a range of countries, the results are fairly consistent. It is noted in these studies that individuals in Australia had similar responses to those in North America.

The initial survey explores the consumers' mobility choices and transportation decisions. The respondents represent a broad range of cross generation consumers. As 80% of Gen Y consumers plan to purchase or lease a vehicle within the next five years, they are the focus group of the survey due to their relatively large market potential (Deloitte 2014a). It was found that the top three reasons Gen Y would not buy a new vehicle is due to affordability, operational costs and if public transit is a plausible alternative. Another point of interest is that 59% of Gen Y consumers would prefer to be driving an alternative powertrain five years from now, however, of these only 7% prefer a battery-powered electric vehicle (Deloitte 2014a). Gen Y are also willing to pay upwards of US $2,000 for an alternative powertrain, however, reduction in operational cost is still the primary motivation rather than being environmentally friendly. Around 67% of the consumers prefer a range of engine options for each model as opposed to a specialized line of vehicles (Deloitte 2014a).

Another survey conducted by Deloitte focuses on determining consumer attitudes towards pure EVs. It specifically aims to reveal consumer expectations of electric vehicle capabilities in terms of several key considerations discussed below. For each, the expectation of the customers are compared with the current capabilities of electric vehicles.

### Range

Based on the survey, it was determined that 80% of drivers typically drive 80 km per day on average. However, 58% of the respondents expect the range of an EV to be at least 320 km before they consider purchasing (Deloitte 2014b). Currently, the average range of an electric vehicle is approximately 160 km (100 miles) as there are limits to the energy density of lithium ion batteries. It should be noted that lithium ion batteries offer the highest energy density among the commercial battery technologies available. Based on information available on electric vehicle models yet to be released, the range of EVs will not exceed customer expectations in the near future.

### Charge Time

It was found that most consumers expect an electric vehicle battery to charge within two hours. Only 18% of respondents considered a charge time of eight hours - which is the typical recharge time of an electric vehicle battery using a level 2 charger - to be acceptable (Deloitte 2014b). Hence, it can be seen that there is a large deviation between customer expectations and the reality surrounding charge times of current technology.

### Price Premium

Around 61% of consumers surveyed expect to pay the same price or less for an electric vehicle compared to an equivalent petrol vehicle (Deloitte 2014b). It is known that batteries for around 50% of the cost of an EV contributing to its high retail price. An average cost of an electric vehicle battery is estimated at US$16,000. Although this cost is offset due to the removal of the internal combustion engine (ICE), it is still a significant increment relative to the cost of conventional vehicles (Deloitte 2014b).

### Purchase Price

Price expectations among consumers are quite low. Some 85% of respondents are not willing to pay more than US$30,000 for an electric vehicle. A significant proportion suggest that they would not even pay more than US$20,000 (Deloitte 2014b).

### Fuel Price

There is a significant correlation between the adoption rate of EVs and the price of oil. The operational costs of conventional ICE vehicles are significantly impacted by fuel prices; with these tending to increase. It was found that if the price of fuel increases to AUD$2.60 per litre, around 71% of consumers would opt for an EV (Deloitte 2014b). However, such an oil price shock is unlikely in the short based on trends.

### Fuel Efficiency

Conventional ICE vehicles have become very fuel efficient due to the development of various innovative technologies, and this trend is forecasted to continue in the future. Most new vehicles are attaining fuel efficiencies of around 50 mpg (5 L/100 km). Based on survey results, it appears that if ICE engines are able to achieve a fuel efficiency of 50 mpg (5 L/100 km), around 54% of the respondents would be less likely to consider an EV (Deloitte 2014b). Hence, as the fuel efficiency of ICEs improve, there would be a lower proportion of individuals opting for EVs.

### Key Outcomes

It is apparent from these survey results that consumers are interested in the future of electric vehicles and consider them as a possible option for a new vehicle. However, there are large differences between consumer expectations of electric vehicles and their actual capabilities. The main motivation behind the purchase of an EV is reduction in operational costs as opposed to the environmental benefits. Factors that have the largest impact on consumer interest include the range, charge time, purchase price and fuel price. These factors will be focused on when identifying and proposing improvements to the EV system.

# 3 Vehicle Weight Reduction

Electric vehicles depend on batteries for energy storage which have a very low energy density compared with liquid fuels (Scrosati et al. 2013). Hence, to obtain adequate range, EVs require larger battery modules, resulting in increased mass; which has a strong negative impact on the range and performance of the vehicle. Therefore, it is imperative to achieve substantial mass reductions to compensate for the additional mass of the battery. By reducing the mass of the vehicle, the tractive effort required to propel the vehicle forward is lowered, thus reducing the power consumption. As a result, the range of the vehicle is extended per one-time charge. There are several ways weight reduction can be achieved including material substitution, vehicle redesign and vehicle downsizing (Bandivadekar et al. 2008). For the material consideration, we will focus on lightweight material substitution as this method can also be adopted by all manufacturers of electric vehicles.

Vehicles are manufactured primarily from steel for most body and chassis components; as it is relatively cheap and provides the required strength and rigidity. Steel has a comparatively low strength-to-weight ratio therefore a relatively heavy structure is formed. Some possible alternative lightweight material include high-strength steel, aluminium, magnesium and polymer composites such as glass- and carbon-fibre. These could replace steel in both non-structural and structural components of the vehicle, subject to proper design (Cuenca, Gaines, and Vyas 1999). The comparative properties of these materials is presented in Table 1.

Table 1: Comparison of material properties (Larminie and Lowry 2012; Cheah 2010)

| Material | Density $\rho$ (kg m$^{-3}$) | Strenth to mass ($\sigma/\rho$) |
|---|---|---|
| Mild steel | 7850 | 0.059 |
| High-strength steel | 7855 | 0.125 |
| Aluminium alloy | 2810 | 0.178 |
| Magnesium alloy | 1780 | 0.104 |
| Carbon fibre (CFRP) | 1500 | 0.7 |
| Glass fibre (GRP) | 2000 | 0.62 |

High-strength steel by combining several alloy compositions and applying certain to yield a high strength compared to mild-steel (Bandivadekar et al. 2008). It is a common alternative to steel as it also allows utilisation of existing infrastructure. Currently, around 230 kg/vehicle of high-strength steel is used, predominantly in structural components (Cheah 2010). It has twice the strength-to-weight ratio of mild-steel, however, this is still relatively low compared with other light-weight materials available. It is indicated from several studies that parts made from high-strength steel can be expected to weigh 0 to 25% less than a conventional steel part, depending on the application (MacKenzie, Zoef, and Heywood 2012).

The manufacturing technology for aluminium vehicle bodies is well defined. A vehicle body composed from stamped aluminium sheet is very similar to the equivalent stamped steel sheet body. The main difference between the manufacturing methods is the joining process. Aluminium, due to its higher conductivity compared with steel, is difficult to spot-weld. Hence, a combination of welding and bonding or mechanical joining and bonding is often used (Cuenca, Gaines, and Vyas 1999). Aluminium accounts for approximately 140 kg/vehicle, mainly being utilised in cast parts (Cheah 2010). It has a strength-to-weight ratio around 1.5 times that of high-strength steel.

Magnesium is relatively easy to machine due to its lower latent heat. However, it has a lower strength-to-weight ratio than both high-strength steel and aluminium. Magnesium therefore represents a very small fraction of automotive materials usage, accounting for only 5 kg/vehicle (Cheah 2010). Its primary use is for constructing thin-walled cast parts.

Polymer composites have the greatest strength-to-weight ratios, however their use in vehicles is limited. The reason for this is the long production times, the cost of the fibres, limited design know-how and familiarity as well as not being able to be recycled easily at vehicles end of life. The common composite materials are carbon fibre reinforced polymer (CFRP) and glass-reinforced plastic (GRP). Technical issues of using CFRP is the lack of infrastructure available to deliver large quantities of materials.

Table 2: Alternative Weight Saving Versus Cost per kg (MacKenzie, Zoef, and Heywood 2012; Cheah 2010)

| Material | Steel:Material ratio (kg) | Weight Reduction (%) | Relative Cost |
|---|---|---|---|
| High-strength Steel | 1.3 | 23 | 1.5 |
| Aluminium | 1.8 | 45 | 2 |
| Magnesium | 2.5 | 60 | 2.5 |
| Polymer Composite | 2 | 50 | 10 |

## 3.1 Key Outcomes

Based on the analysis of the properties of alternative light-weight materials it appears that the most suitable option for electric vehicles is the use of aluminium to replace conventional steel for constructing the chassis/body. Aluminium is already extensively used in electric vehicles and the manufacturing process is well defined. Since it yields a significant reduction in weight of around 45%, there is likely to be a considerable increase in the range of vehicles, given manufacturers opt for this alternative material. However, there is need for the cost associated with the replacement to be analysed in order to determine if such a change is feasible and also determine the percentage improvement in range using the defined vehicle model. Furthermore, the end of life issues relating to the material decision will also be analysed. These would be conducted in later sections.

## 3.2 Material Audit

In order to determine the impact of using light weight material for the chassis/body on the range of a vehicle, the Nissan Leaf will be used as an example. Initially, a material audit will be conducted for the Nissan Leaf. This would allow for a decomposition of the materials utilised in the Nissan Leaf and where possible weight reductions can be made. As the vehicle is a complex system and there is limited information on the mass of various components, it is not feasible to provide a breakdown of all parts. Hence, we will use a information available to subtract known weights of major vehicle subsystems from the known curb weight in order to approximate the weight of the chassis/body.

Based on data, the vehicle mass distribution by subsystems is as follows: body (40%), chassis (24%), power train (16%), interior (15%) and electrical systems (5%) (Cheah 2010). It is known that the curb weight of the vehicle is 1521 kg (Larminie and Lowry 2012). The weight of the electric motor and inverter are 58 kg and 16.8 kg respectively (Yakushi 2012). Another key component is the battery pack which weighs 218 kg (Weissler 2010). The electric motor and inverter form part of the power train subsystem, however, the electric motor weighs comparatively less than a conventional ICE. Hence, the battery pack is assumed to be part of the power train to compensate for this. The combined weight of the electric motor, inverter and battery pack is 292.8 kg which is 19.2% of the total weight. This proportion seems consistent with 21% which is the proportion of the vehicle weight from the power train and electrical systems. It is also known that the Nissan Leaf has a unibody body/chassis made from corrosion-resistant ultra-high strength steel (SAE International 2011). For the purpose of analysis we will assume that 64% of the total weight is from the body/chassis equivalent to 974 kg with the following material composition: iron (8%), high-strength steel (53%), aluminium (15%) and other (24%) (Cheah 2010).

Table 3: Material Audit (Hammond and Jones 2011)

| Material | Quantity | Embodied Energy |
|---|---|---|
| Iron | 78 kg | 25 MJ/kg × 78 = 1,950 MJ |
| High-strength steel | 516 kg | 56.7 MJ/kg × 516 = 29,257 MJ |
| Aluminium | 146 kg | 159 MJ/kg × 146 = 23,214 MJ |
|  | Total | 54,421 MJ |

It can be seen that steel and aluminium have the largest embodied energy and form a significant part of the total energy of the Nissan Leaf. As determined in the the previous part, an alternative material to steel is aluminium for the construction of the body/chassis components. In this case, the body is already made predominantly from high strength steel. However, aluminium is still a better alternative to high-strength steel as further weight reduction can be achieved. It is known that each kg of high-strength steel is equivalent to 1.3 kg of conventional steel. Hence, 516 kg high-strength steel is the same as 671 kg of conventional steel. Each kg of aluminium can replace 1.8 kg of conventional steel. Therefore, the required amount of aluminium to replace 671 kg of conventional steel is 369 kg. This amounts to an overall weight reduction of 147 kg. However, since aluminium has a higher embodied energy than steel, the total embodied energy increases to 83,835 MJ.

## 4 Energy Flow and Efficiency

The energy efficiency of a vehicle is given as by the percentage of energy available at the tank that is utilised at the wheels in order to move the vehicle. In the case of conventional vehicle the energy is provided by petrol whereas for electric vehicles the energy is provided by the battery. The energy flows for both ICEs and EVs are given in Figures 1 and 2 respectively.

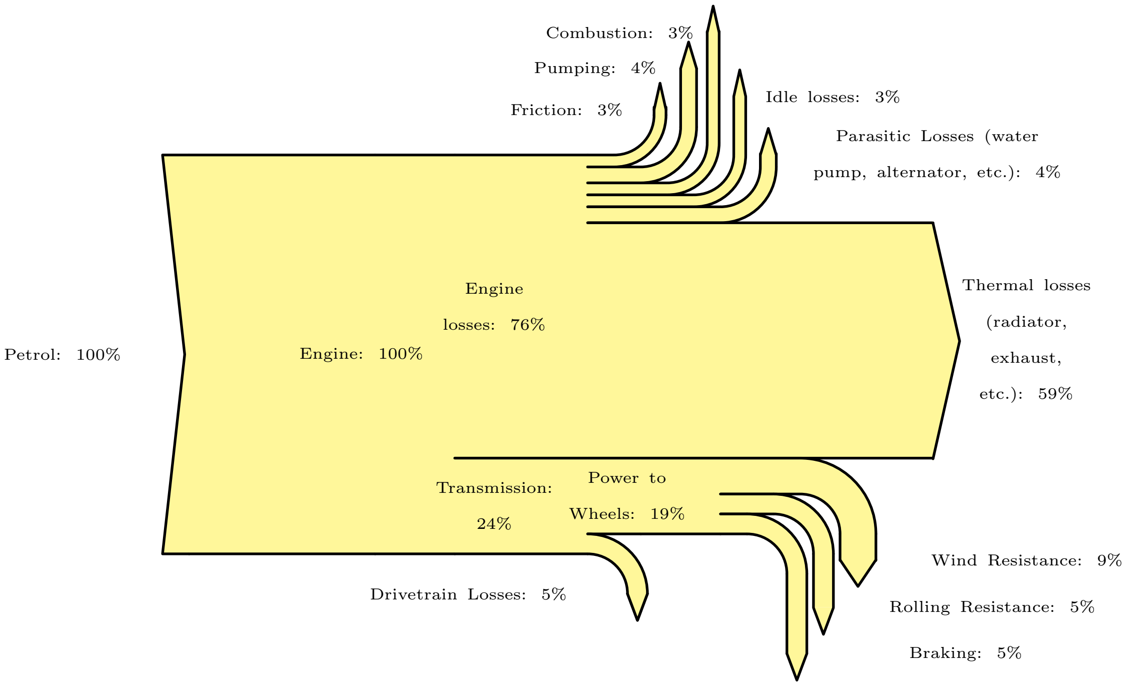

Figure 1: Energy losses in a conventional intenal combustion engine for combined City/Highway Driving (U.S. Department of Energy 2015).

The efficiency of a conventional vehicle is determined to be approximately 20%, as this is the percentage of total energy available at the wheels. For an electric vehicle, the efficiency is given by the product of the individual vehicle component efficiencies including the battery, motor and the drivetrain. The overall efficiency is therefore $\eta_b \times \eta_m \times \eta_d = 0.99 \times 0.85 \times 0.96 \approx 80\%$. Hence, electric vehicles are around four times more efficient compared with conventional vehicles. The least efficient

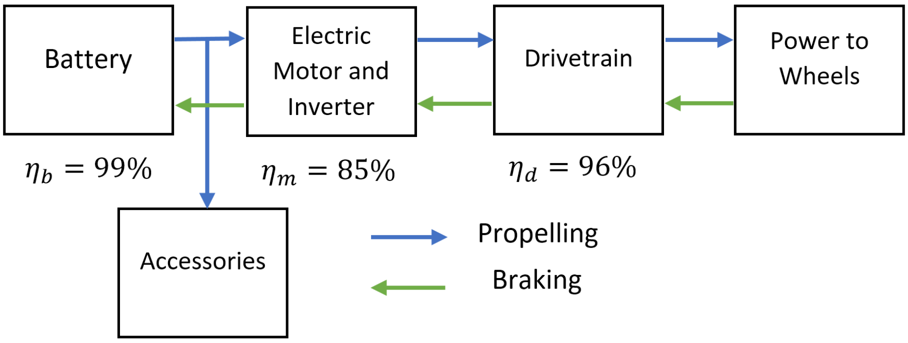

Figure 2: Propelling and braking energy flow for a battery-powered electric vehicle that incorporate regenerative braking. Note the motor efficiency is determined based on the EPA Urban Dynamometer Driving Schedule (UDDS) (Gantt 2011; Larminie and Lowry 2012).

component of an electric vehicle is the motor. However, it should be noted that the efficiency of the motor presented here is based on a specific drive cycle and may vary considerably based on driving patterns. Instead, we will focus on providing improvements to the drivetrain. The efficiency of a conventional vehicle is determined to be approximately 20% as this is the percentage of total energy available at the wheels. For an electric vehicle, the efficiency is given by the product of the individual vehicle component efficiencies including the battery, motor and the drivetrain. The overall efficiency is therefore $\eta_b \times \eta_m \times \eta_d = 0.99 \times 0.85 \times 0.96 \approx 80\%$. Hence, electric vehicles are around four times more efficient compared with conventional vehicles. The least efficient component of an electric vehicle is the motor. However, it should be noted that the efficiency of the motor presented here is based on a specific drive cycle and may vary considerably based on driving patterns. Instead, we will focus on providing improvements to the drivetrain.

For a conventional vehicle, the internal combustion engine transmits power via the clutch to the gearbox which is connected to a propeller shaft that delivers power to the differential gears. The differential then drives the wheels. All these components have certain inefficiencies that contribute to energy loss in the system. An electric vehicles powertrain is relatively simply as it does not require a clutch and uses a single-ratio gear. Most powertrain arrangements for electric vehicles drive the wheels through a differential as such a design is well-tested, reliable and easily produced in large quantities. However, the use of differentials contributes to power loss, increases the mass of the vehicles and reduces space that can be usefully utilised.

An alternative drivetrain arrangement eliminates the differential by attaching a motor to each wheel using a single gear. The use of such a system reduces the power consumption as the vehicles mass is lowered and the drivetrains efficiency is increased. As there is less space taken up by the drivetrain, the design of the vehicle can be modified to further improve the aerodynamics and enlarge passenger and luggage space. However, such a system requires the implementation of a complicated electronic controller and is more expensive due to multiple small electric motors. It is fair to assume that the energy loss between the connection of an electric motor and a single gear is negligible. Hence, the drivetrain efficiency is approximately 100%.The efficiency of the vehicle then becomes $\eta_b \times \eta_m \times \eta_d = 0.99 \times 0.85 \times 1 \approx 85\%$. Due to the use of individual motors in combination with an electronic controller to supply torque on demand, the motor efficiency is likely to be improved. However, it is difficult to quantify without performing tests.

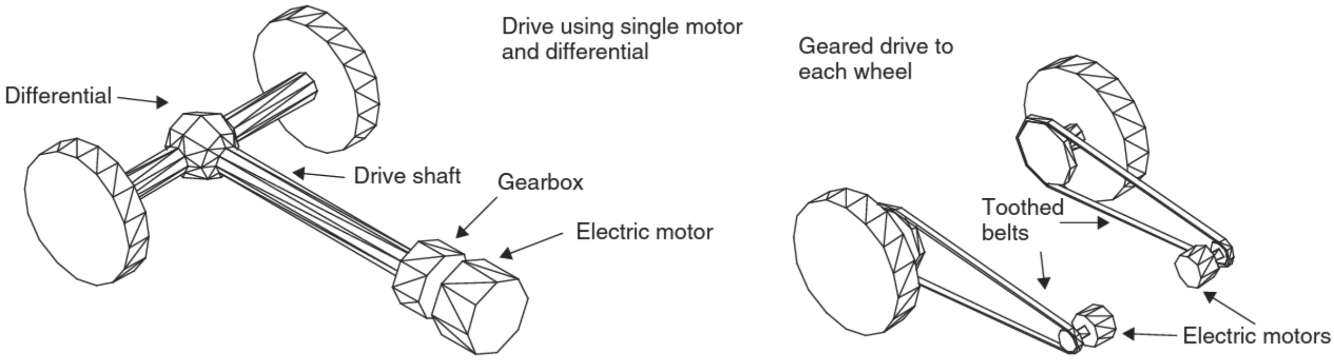

Figure 3: Conventional (left) and alternative (right) transmission arrangement for electric vehicles (Larminie and Lowry 2012).

Although electric vehicles are more efficient than conventional vehicles, this does not translate into higher driving ranges due to the low density of current battery technology compared with liquid fuels such as petrol. However, it should be noted that lithium batteries offer the highest energy density among the commercially available battery technologies at 140 Wh/kg (Larminie and Lowry 2012). Now, comparing this to the energy density of fuel of 12,000 Wh/kg, gives a clear indication of why ICEs have a higher range even after signficant energy losses due to inefficiencies (Scrosati et al. 2013). Therefore, to improve the range of the electric vehicle, batteries with higher energy density are needed, but this cannot be achieved by simply improving current lithium ion batteries.

Metal-air batteries are a promising new technology that represent an entirely different approach to energy storage. In order to recharge typical lithium ion batteries, the current is reversed. However, in the case of metal-air batteries the spent electrodes are required to be replaced or reprocessed (Larminie and Lowry 2012). In a sense, the metal electrodes are a kind of fuel which have the advantage of being able to be reprocessed and turned into new fuel. Such an energy storage concept is similar to that of a conventional vehicle that is required to be refueled periodically. As such it would appeal to consumers that are slow to adapt to change. A specific battery of this type is the zinc-air battery which has an energy density of capacity of 230 Wh/kg (Pei, Wang, and Ma 2014, Larminie and Lowry 2012). It should also be noted that it takes approximately 10 min to replace the electrolyte and spent electrodes (Larminie and Lowry 2012). Using the Nissan Leaf as an example, which has a 24 kWh battery with a specific density of 140 Wh/kg, the theoretical weight of the battery is 24,000/140 = 141 kg. Now, for the same overall power, using a zinc-air battery would require a battery mass of 104 kg, a reduction of 37 kg. Hence, manufacturers would be able to provide greater capacity using batteries with a lower overall weight. However, currently lithium ion batteries are the most stable and reliable and the adoption of new battery technologies requires a few years of further testing before they are able to be used in commercial vehicles.

## 5 Time Factors

An important consideration when purchasing a vehicle is its reliability over time. There are many variables that determine the reliability of a vehicle such as the frequency with which a problem occurs that requires repair. For conventional vehicles, there are various components that require replacement on a periodic basis due to their short serviceable life. However for the case of electric vehicles such as the Leaf, the number of components requiring regular replacement is limited. Hence, it can be inferred that most components in the EV are designed to have a long life. Furthermore, it can be assumed that there is a lower likelihood that a serious malfunction would occur with the EV compared with a conventional vehicle. However, as the EV utilises a battery which is known to lose its capacity over time, the performance of the vehicle will depreciate. The rate at which this happens is dependent on various factors with user driving and charging patterns being the most important.

In this analysis, we will determine the rate at which a battery loses capacity and the effect this has on the range of the vehicle. For the example we will consider a typical Canberra motorist. Now, the average number of kilometeres that a vehicle travels in Canberra is approximately 14,300 km annually (Australian Bureau of Statistics 2013a). This is equivalent to 275 km per week and 55 km per day assuming the car is driven primarily on working days. It is known that the power consumption of the Nissan Leaf is 120 Wh/km (Green Car Congress 2012). Hence, the power consumed to travel 55 km is 6600 Wh. It is assumed that motorists, charge their car when the battery warning light turns on at around 18% SoC and proceed to completely charge the battery. As the capacity of the battery is given to be 24 kWh, at 18% SoC it has 4320 Wh remaining (Larminie and Lowry 2012). Therefore, the battery completes a cycle every $19680/6600 \approx 3$ days. A typical lithium ion battery can last 1000 cycles before reaching 80% of its initial capacity. At this point it is required to be replaced. Based on these calculations, we can determine the capacity of the battery (as percentage of initial) and the corresponding range over time (Figure 4).

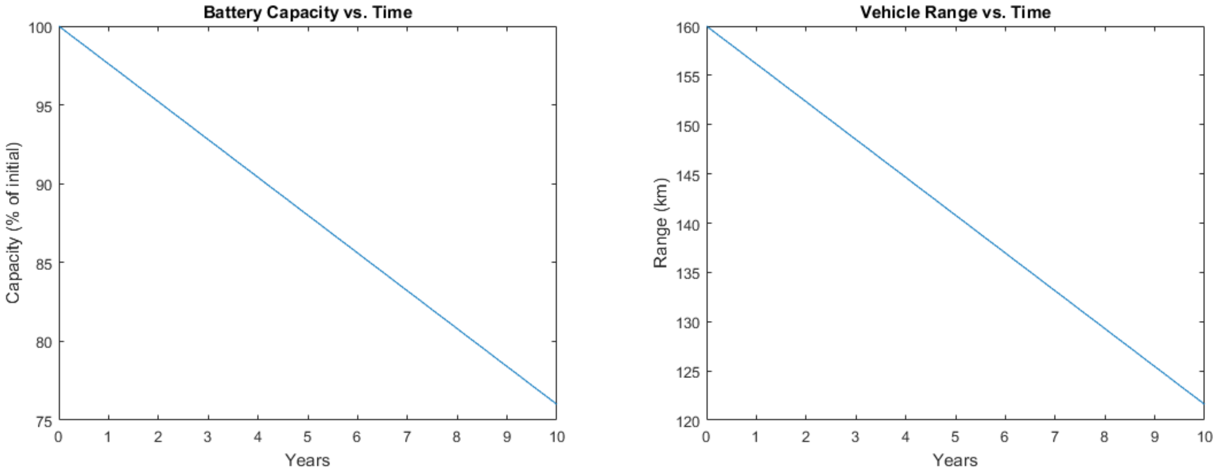

Figure 4: Battery capacity and range over time

It can be seen from the graphs that the useful life of the battery is approximately 8 years with the range of the vehicle decreasing by around 40 km over this period. These graphs present one particular scenario for comparison. The actual life of the battery and the observed range may be very different based on the driving patterns of the user as well as the charging habits. Furthermore, the trend will likely not be linear. The required replacement of the battery and reduction in range by approximately 25% will greatly influence the purchasing decision of the consumer; especially since the cost of the battery is around 50% of the value of the vehicle. Another reason is that the resale value of the vehicle is likely to diminish quite quickly.

Charge time of an electric vehicle battery also has a major influence on the purchasing decision of a consumer. Due to the prevalence of ICEs, individuals have become accustomed to the long range they provide as well as the convenience and speed of refuelling at a service station in a matter of minutes. In order to charge an electric vehicle, specific electric vehicle supply equipment (EVSE) is required with charge time in the order of hours. The shorter range of EVs also means more frequent charges are needed making the problem worse.

EVSE is classified into three standard categories. Charging level 1 and 2 both provide alternating current (AC) to the vehicle, with the on-board equipment converting AC to direct current (DC) required to charge the batteries (U.S. Department of Energy 2012). Specifically, charging level 1 refers to a single-phase AC system with up to 2 kW charging power, whereas charging level 2 uses 3-phase AC with up to 24 kW charging power (Payam, Abbas, and Hosein 2014). Charging level 3 provides DC electricity directly to the vehicles battery, bypassing the on-board charger (U.S. Department of Energy 2012). The specifications of the different types of chargers are presented in Table 4.

Table 4: EVSE Specifications (Deloitte 2014b; Brooker and Qin 2015; Payam, Abbas, and Hosein 2014)

| | Normal chargers | | Rapid chargers |
|---|---|---|---|
| | Level 1 | Level 2 | Level 3 |
| Voltage | 110 - 120 | 208 - 240 | 480 |
| Amperage | 15 | 13 - 80 | - |
| Charge power (kW) | 1 - 2 | 3 - 24 | 30 - 250 |
| Range per hour of charge | 2-5 miles (3 - 8 km) | 10 - 60 miles (16 - 97 km) | 150 miles (240 km) |
| Estimated charge time | 10-20 hours | 3-8 hours | < 30 minutes |
| Estimated price | US$1,000 | US$500-3,000 | US$17,500-50,000 |

Based on the information regarding the different specification for charging equipment, it is apparent that level 2 chargers seem to be the most feasible option as they optimize the charge time and cost for use in residential locations as well as external facilities. Currently, there is limited charging station in the Canberra region, due to the lack of electric vehicle users. In order to attract more consumers and reduce the range anxiety associated with owning a vehicle, the increase in the number of charging stations in the region is mandatory. According to the Australian Bureau of Statistics (2014), the ACT has one of the highest number of passenger vehicles per 1,000 population at 603 with around 83% of people using these to get to work. Hence, initially, charging stations should be located at office buildings.

Another potential concept that may be utilised is battery swapping stations. The business model associated with this was developed by a company called Better Place (BP), that currently operates in Canberra (Mak, Rong, and Shen 2013). The main idea is that along with being able to recharge batteries at homes, workplaces and other public locations, EVs may opt to exchange their depleted batteries with recharged ones. BP develops the necessary infrastructure required and provides the service. Furthermore, the batteries of the EVs are not owned by the user but leased to them on a service contract which charges based on usage (Mak, Rong, and Shen 2013). Such an approach has many benefits such as the decoupling of the battery and the EV which have different life cycles as well as allowing the user to take advantage of future improvements to the battery technology. Furthermore, the upfront cost to purchase an EV is greatly reduced as well as charge times reduced to approximately 5 minutes (Deloitte 2014b). Another implication of this is that battery replacement and the performance of the vehicles does not depreciate over time.

# 6 Dynamics and Control

For the case of electric and hybrid vehicles as well as conventional cars, many of the systems are automated and incorporate varying levels of feedback and control. A major system that utilizes the control and feedback theory and is specific to electric vehicles is the use of individually controlled powertrains as mentioned in section 4. These allow improvements in energy management, packaging and vehicle architecture as well as the dynamics of the vehicle (De Novellis et al. 2014). Due to the responsive torque control of individual electric motors, an improvement in the handling characteristics is obtained. The application of varying amounts of torque to each wheel known as Torque vectoring (TV) is more effective through the use of individual motor controls as opposed to active differentials found on conventional cars (De Novellis et al. 2014). The differentials are limited due to their response, torque transfer, efficiency and flexibility in terms of directions due to speed differences between gears.

By exploiting the benefits of TV controls provided by individual electric motors, and implementing more advanced controllers to determine torque requirements when turning, a better vehicle stability control system can be obtained. Current systems are not designed for smoothness especially during significant braking and acceleration, but rather designed to maximize friction brake actuation in case of an emergency (Tommaso Goggia et al. 2015). In this case, the implementation of improved control structures for electric vehicles would result in greater comfort and also safety while driving.

In modern passenger cars, vehicle stability control is based on feedback yaw rate controllers. These controllers monitor the deviation between a reference value (i.e. steering-wheel angle, vehicle velocity and estimated coefficient of friction) and a threshold, which when exceeded results in corrective action by supplying torque to wheels according to the specific scenario (De Novellis et al. 2014). These control structures are based on a proportional-integral-derivative (PID) controller and are rarely active (Tommaso Goggia et al. 2015). Hence, they result in abrupt safety interventions. With electric vehicles there is a possibility to further improve safety functionalities through the generation of continuous yaw moments. However, in order to continuously track a reference yaw rate through TV, the PID (feedback contribution) will need to be coupled with a feedforward component (FF). The feedforward component would ensure that the required understeer characterisitics of the vehicle in static conditions are provided (e.g. very slow steering inputs or acceleration and deceleration in a straight line) (Tommaso Goggia et al. 2015). The static contribution of the FF is set based on the reference vehicle behaviour with the PID intervening to correct vehicle response during transients or unmodelled dynamics. The drawback to this method is that it is not robust if vehicle characteristics deviate due to the use of different tyres, or their wear or the variation in vehicle payload (Tommaso Goggia et al. 2015). The structure of the yaw rate controller is given in the figure below.

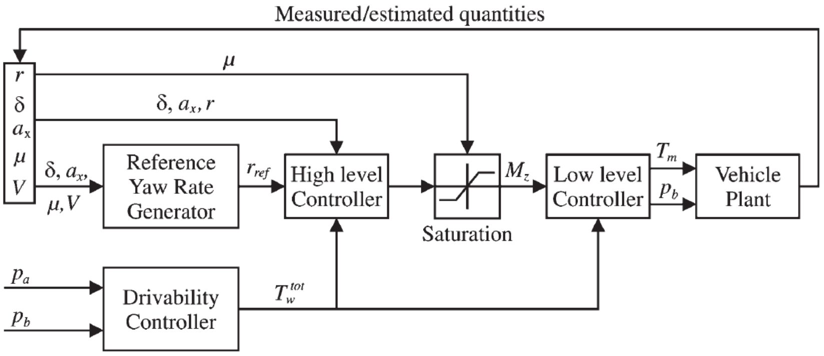

Figure 5: Feedback structure of yaw rate controller for TV (De Novellis et al. 2014)

There are many benefits of utilising individual electronic motors in an electric vehicle as they remove the drivetrain efficiencies associated with differentials as discussed in section 4; and also provide better acceleration, handling and safety for the user via the implementation of sophisticated electronic controllers. The introduction of such controllers also allow for the option of giving drivers different modes of driving such as normal, sport or eco that they can select based on their preferences (Tommaso Goggia et al. 2015). Furthermore, the incorporation of these controller will improve the overall efficiency and thus the range of the vehicle while providing increased performance. These characteristics of an EV are likely to attract normal consumers as well as motoring enthusiasts.

## 7 Cost Factors

Cost is one of the major factors that influences a consumers decision of purchasing any product. This is especially true for vehicles in general due to their relatively high upfront and ongoing operating costs. Furthermore, vehicles are typically considered as long term goods, hence it is imperative to ascertain the cost associated with them over their life cycle. In determining the feasibility of electric vehicles, it is important to compare both the upfront and ongoing costs compared with an equivalent conventional ICE vehicle. For the cost consideration we will compare the costs of the Nissan Leaf with the Nissan Pulsar.

It can been seen from the graph in Figure 6 that over the typical life cycle of a vehicle, the cumulative cost of owning an electrical vehicle remains greater than the cost of owning a conventional petrol vehicle assuming that the cost of petrol and electricity remain the same. Although, the costs seem to converge, the replacement cost of the battery at the assumed useful life of 8 years (see Section 5),

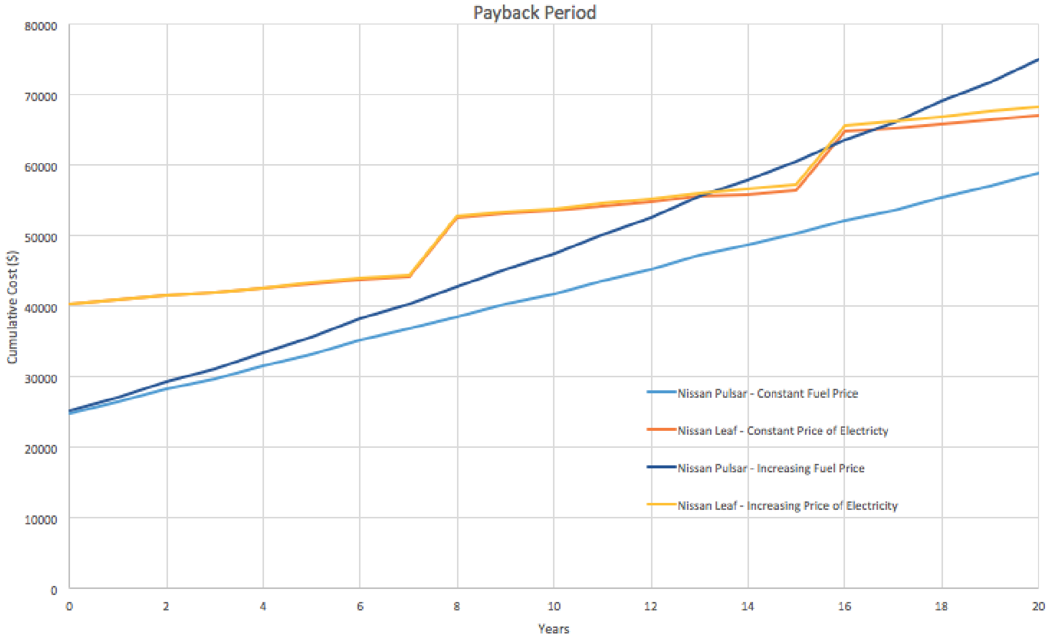

Figure 6: Cumulative cost over time for the Nissan Leaf and Nissan Pulsar.

results in the electrical vehicle having a higher cost. Based on previous average fuel price data, a linear regression can be used to extrapolate the increase in the cost of fuel over the next few years. In this case the average fuel price used to perform the projection was from the period 2002 - 2014 (Australian Institute of Petroleum 2015). The cost of electricity was determined based on the figures given by ActewAGL, with an expected increase by 6c every year (Australian Energy Market Comission 2015). It can be seen that when the increasing trend of the price of fuel is incorporated in the cost, the electrical vehicle becomes a viable option over the long term. However, the payback period is still quite long at 13 years, with 15 years considered the useful life of the vehicle (Ramoni and Zhang 2013). However, the term for evaluating the depreciation and payback period for vehicles is typically assumed to be over a range of 4 - 8 years (Australian Taxation Office 2014). Hence, it is ideal for the payback period to be around 5 years. Currently, the only feasible way of this occuring without having to incur further costs is if the price of the electric vehicles decreasing. Using a What-If analysis in Excel, the value of the up-front cost of the vehicle is required to be AUD$32338 in order to achieve a payback period of 5 years (Figure 7).

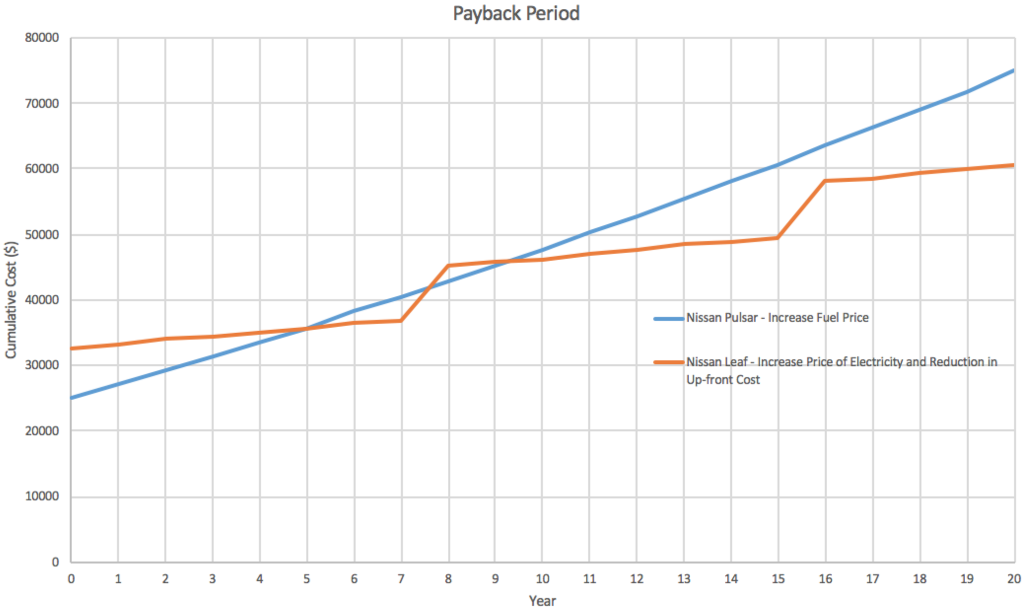

Figure 7: Payback period if the upfront cost of the Nissan Leaf is reduced.

# 8 Human Factors

Human factors are an important consideration when designing road vehicles. Stringent standards are required to be met in order to provide minimum road safety for both vehicles drivers and occupants and other road users. Now, it is futile to discuss ways to improve the safety and comfort of a vehicle, as it is one of the major factors that is considered in the design by manufacturers. Furthermore, there are too many parameter constraints that would need to be considered and recommendations would not be suited to every design. Instead we will focus on the issue of range anxiety that is required to be addressed by manufacturers. Range anxiety is a phenomenon whereby electric vehicle users suffer range related stress, and feel the need to reserve substantial amount of range as a safety buffer (Franke et al. 2014). It is one of the main reason behind the adoption rate of electric vehicles remaining low, as consumers expect greater range than they typically need.

The method that manufacturers are adopting in order to counteract the effects of such perceptions is by providing greater real-time information about the vehicles power consumption, battery capacity and the expected range. These variable take into consideration many present and forecasted parameters in order to provide very accurate estimates. Furthermore, sophisticated trip planners are also being incorporated in order to plan routes based on the proximity of charging stations, so the vehicle does not move out of range. However, at the present moment such trip planners are not of much use in the Canberra region and Australia as a whole due to the limited number of charging stations available (ChargePoint 2015). In any case the incorporation and display of such information - via in-vehicle information systems (IVIS) - to the driver of the vehicle in terms of potential risks is required to be analysed.

The introduction of additional information displays and secondary tasks in a vehicle have a number of implications, the main one being driver distraction. Driver distraction in this particular case occurs when a driver is delayed in the recognition of information in order to safely perform the task of driving due to in-vehicle information systems shifting their attention (ITU-T Technology 2010). These may be in the form of visual, auditory, physical or cognitive distractions. In a recent study. an experiment was performed using the Peripheral Detection Task (PDT) as a method to measure driver workload (Victor, Lee, and Regan 2013). The PDT is a standard method used to assess workload from the use of IVIS (Jahn et al. 2005). It was found that in high demanding driving situations the reaction time is 1.5 seconds with visual distraction being the major cause of the delay (Victor, Lee, and Regan 2013). Based on the Society of Automotive Engineers (SAE) International Practice J2364, the acceptable mean task duration is 15 seconds, with most experts limiting this to 10 seconds (ITU-T Technology 2010). Using the results from this study and the given standards, it appears that manufacturers of vehicles and IVIS should ensure minimum interaction between the driver and the technology is required during driving. Most of the communication should be aural and hands-free as opposed to an increasing proportion requiring visual and physical interaction.

# 9 Influence of Recommendations on Range

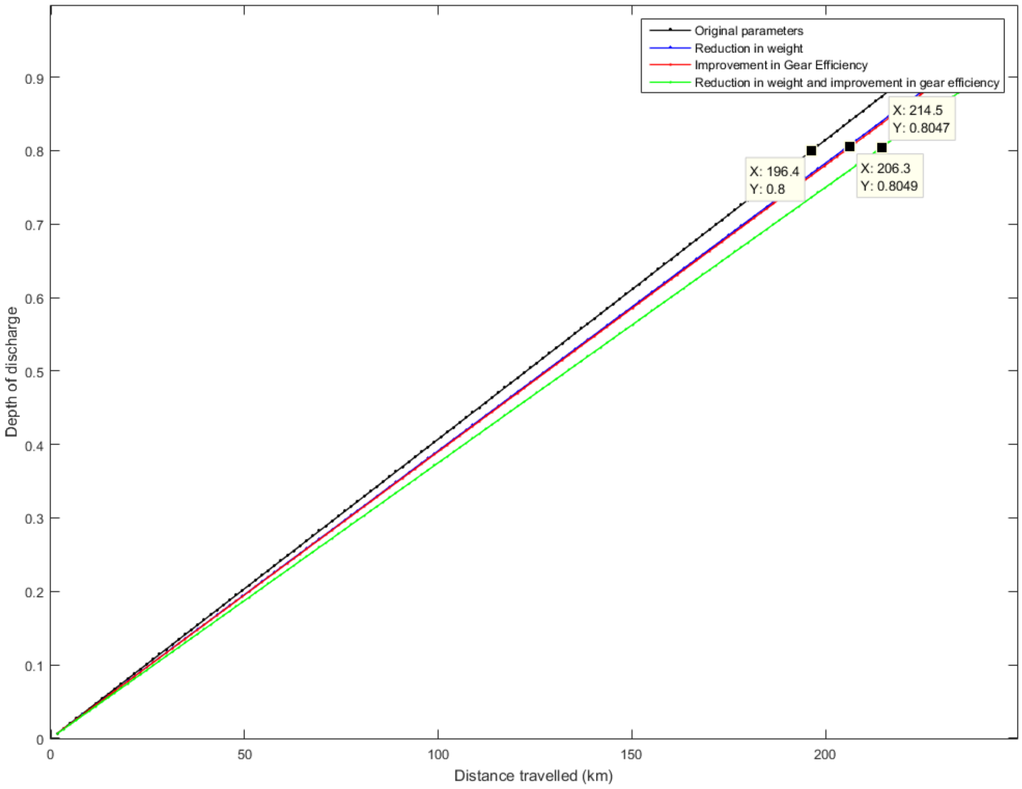

Figure 8: Range of the Nissan Leaf as parameters are changed.

It can be seen that if the Nissan Leaf is assumed to be travelling at a constant velocity, the range of the vehicle at 80% depth of discharge is 196 km. This is consistent with the value given by Nissan for the constant velocity assumption (Nissan 2015c). Incorporatng the reduction in weight and improvement in gear efficiency individually yields a range of around 206 km. However, incorporating both the reduction in weight and improvement in gear efficiency together results in a range of 215 km. Now this is equivalent to a 10% improvement in range. However, if an actual drive cycle with varying velocities is used, there would be an increase in the use of regenerative braking, and greater range would be realised due to the proposed weight reduction and improvement in gear efficiencies. The reason for this is that the mass has a greater impact when the car is accelerating and decelerating as opposed to maintaining constant speeds.

# 10 Summary

The electric vehicle system is required to be optimised in order to meet the expectation of consumers to ultimately improve the adoption rates. Weight reduction of the vehicle can be achieved by using aluminium instead of high-strength steel to contruct the chassis/body. Based on the mass distribution of subsystems in a vehicle it was found that the unibody chassis of the Nissan Leaf is composed of approximately 516 kg of high-strength steel. Substituting this with aluminium yields a 147 kg reduction in overall weight which amounts to 9.5% of the original weight. Hence, a recommendation is for manufacturers to opt for such material substitution to reduce weight and improve the range of electric vehicles. In order to further improve the efficiency of the drivetrain, it is recommended that manufacturers should attach motors to each wheel as opposed to using a differential which has many inherent inefficiencies. The implementation of individual motors requires the use of a sophisticated electronic controller. The use of a PID algorithm coupled with a feedforward controller that generates continuous yaw moments is preferred for such a controller. Implementing such a contoller would further improve the vehicle stability control whilst improving the efficiency and performance of the vehicle. Further to improvements to the vehicle, charging infrastructure is also required to support the user. Initially charging stations should be implemented at the workplace, as 83% of users drive to work. The implementation of battery swapping stations would further reduce the charge time whilst reducing the upfront cost. In terms of costs, electrical vehicles have a payback period of 13 years when compared with an equivalent conventional vehicle. In order for electric vehicle to have an ideal payback period of 5 years, the cost of the vehicle would need to be reduced. For the Nissan Leaf, the retail price is required to be reduced by AUD$7,652. It was also determined that the mean task duration should be less than 10 seconds to allow for the 1.5 second reaction time in demanding traffic.

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# 11 Appendices

## A

### Electric Vehicle Modelling

The force required at the wheels to propel the vehicle forward is referred to as the tractive effort. It is given by the equation

$$F_{te} = F_{rr} + F_{ad} + F_{hc} + F_{la} + F_{\omega a}$$

where

$F_{rr}$ - rolling resistance force
$F_{ad}$ - aerodynamic drag
$F_{hc}$ - hill climbing force
$F_{la}$ - acceleration force
$F_{\omega a}$ - angular acceleration

### Rolling Resistance Force

$$F_{rr} = \mu_{rr} mg$$

where

$\mu_{rr}$ - coefficient of rolling resistance
$m$ - mass of the vehicle
$g$ - acceleration due to gravity

### Aerodynamic Drag

$$F_{ad} = \frac{1}{2}\rho A C_d v^2$$

where

$\rho$ - density of the air
$A$ - frontal area
$C_d$ - drag coefficient
$v$ - velocity

### Hill Climbing Force

$$F_{hc} = mg\sin\theta$$

where

$\theta$ - angle of inclination

### Acceleration Force

$$F_{la} = ma$$

where

$a$ - acceleration

### Angular Acceleration Force

$$F_{\omega a} = I\frac{G^2}{\eta_g r^2}a$$

where

$I$ - moment of inertia of the rotor of the motor
$G$ - gear ration
$r$ - radius of the tyre

# B

### Survey

The following questions can be used to ascertain consumer preferences and choices.

1. When do you expect to purchase or lease a new vehicle?

   (a) Within a year (b) Within 3 years (c) Within 5 years

2. Would you consider purchasing a vehicle with an alternative powertrain in the next five years? If so, which particular powertrain option do you prefer?

   (a) Hybrid electric
   (b) Plug-in hybrid
   (c) Compressed natural gas
   (d) Battery-powered electric
   (e) Diesel
   (f) Fuel cell

3. Will you be willing to pay AUD$3,000 or more for an alternative powertrain compared with a conventional vehicle?

   (a) Yes (b) No

4. Should there be range of powertrain options for a given vehicle model as opposed to a specialised line of vehicles that only have alternative powertrains?

   (a) Agree (b) Neutral (c) Disagree

5. What is the minimum range that an electric vehicle needs for you to consider purchasing or leasing it?

   (a) 80 km (b) 160 km (c) 320 km (d) 480 km (e) 640 km

6. On average, how many kilometers do you drive each working week?

   (a) 80 km or less (b) 160 km or less (c) 320 km or less (d) 480 km or less
   (e) 640 km or less

7. What is the longest time to fully recharge an electric vehicle battery that you consider acceptable when considering purchasing an electric vehicle?

   (a) 8 hours or less (b) 4 hours or less (c) 2 hours or less (d) 1 hour or less
   (e) 30 minutes or less

8. How much more are you willing to pay for an electric vehicle compared to an equivalent conventional vehicle?

   (a) Same price or less (b) AUD$250 more (c) AUD$500 more (d) AUD$1000 more
   (e) AUD$2000 more

9. Which of the following price ranges would you consider buying or leasing an electric vehicle?

   (a) Less than AUD$30,000 (b) Less than AUD$40,000

10. At which fuel price would you be more likely to consider an electric vehicle over vehicles wiht a petrol engine?

    (a) AUD$1.75 (b) AUD$2.00 (c) AUD$2.50 (d) AUD$3.00 (e) AUD$3.50
    (f) More than AUD$3.50

11. At what fuel efficiency of vehicles with a petrol engine would you be less likely to purchase an electric vehicle?

    (a) 8 L/100 km (b) 7 L/100 km (c) 5 L/100 km (d) 4 L/100 km

# C

## Vehicle Range Model in MATLAB

The following code is derived from the MATLAB examples given by Larminie et. al. (2012).

### constant.m

```
V = linspace(16.67, 16.67, 100); %vector of velocities
N = length(V); %length of the vector
```

### one_cycle.m

```
constant;

for C = 2:N
    %acceleration
accel = V(C) - V(C-1);

%aerodynamic drag equation
Fad = 0.5 * 1.25 * area * Cd * V(C)^2;

%assume no slop
Fhc = 0;

%mass increased by 5% to compensate for excluded moment of intertia information
    Fla = 1.05 * mass * accel;

    %tractive effort equation
    Pte = (Frr + Fad + Fhc + Fla)*V(C);

%angular acceleration
```

```
omega = Gratio *V(C);



if omega == 0
        Pte = 0;
        Torque = 0;
%motor efficiency nominal value when stationary
        eff_motor = 0.5;
    elseif omega > 0
            if Pte < 0
                Pte = regen_braking_ratio * Pte;
            end;
            if Pte >=0
                motor_power_output = Pte/eff_gear;
            elseif Pte <0
                motor_power_output = Pte*eff_gear;
            end;
            Torque = motor_power_output/omega;
            if Torque > 0
                %constant motor efficiency
eff_motor = 0.6;
            elseif Torque<0
                eff_motor = 0.6;
            end;
            if motor_power_output >=0
                motor_power_input = motor_power_output/eff_motor;
            elseif motor_power_output <0
                motor_power_input = motor_power_output*eff_motor;
            end;
    end;

    battery_power = motor_power_output+ Pac;

%open cell voltage function derived based on regression of
%observed cell voltage vs. depth of discharge


E = NoCells*(-0.0058*DoD(C-1)+4.1407);
    if batter_power >0

%current solved using quadrtic

I = (E-((E*E)-(4*Rin*battery_power))^0.5)/(2*Rin);
        %remaining charge
CR(C) = CR(C-1)+ ((I^k)/3600);

elseif battery_power == 0;
        I =0;
    elseif battery_power < 0
        battery_power = -1*battery_power;
        I = (-E-((E*E)-(4*Rin*Pbat))^0.5)/(2*Rin);
```

```
CR(C) = CR(C-1)-(I/3600);
    end;

    DoD(C) = CR(C)/PeukertCapacity;

    if DoD(C)>1
        DoD(C) = 1;
    end;
```

### vehicle_parameters

```
%load velocity vector
constant;
N = length(V);

%parameter information for the Nissan Leaf can be easily found online
%in this case multiple sources were used

%vehicle mass + two 70kg passengers
mass = 1521 + 2*70;
%frontal area
area = 2.27; %frontal area in square metres
%drag coefficient
Cd = 0.29;
%final gear ratio
Gratio = 7.94;
%gear efficiency
eff_gear = 1;
%regenerative braking does not apply but kept in the script in case
%a velocity vector for a drive cycle is used
regen_braking_ratio = 0.4;
%number of cells assuming 4.2 volt per cell
NoCells = 96;
% Capacity in Ah
Capacity = 66.2;
%peukert coefficient approximation for lithium ion battery
k = 1.10;
%power for accessories
Pac = 250;
%typical value of 0.005 is used for coefficient of rolling resistance of tyre
Frr = 0.005 * mass * 9.8;
%internal resistance
Rin = (0.006/Capacity)*NoCells;
%addition to internal resistance to account of higher resistance wires
Rin = Rin + 0.05;

%peukert capacity
PeukertCapacity = ((Capacity/10)^k)*10;

%vector to store depth of discharge at end of cycle
DoD_end = zeros(1,100);

%vector to store charge remainining at end of cycle
```

```
CR_end = zeros(1,100);
%vector to store distance travelled at end of cycle
D_end = zeros(1,100);

%vectors to store depth of discharge and charge remaining at end of one cycle
DoD = zeros(1,N);
CR = zeros(1,N);
D =  zeros(1,N);

%variable to
number_of_cycle =1;

%initial depth of discharge
DD = 0;

%loop to iterate between cycles until depth of discharge becomes 90%
while DD < 0.9
    one_cycle;
    DoD_end(CY) = DoD(N);
    CR_end(CY) = CR(N);
    D_end(CY) = D(N);
    DoD(1) = DoD(N); CR(1) = CR(N); D(1)=D(N);
    DD = DoD_end(CY);
    CY = CY+1;
end;

%plot the depth of discharge and distance travelled at end of simulation
plot(D_end, DoD_end, 'k+');
ylabel('Depth of discharge');
xlabel('Distance travelled (km)');
```