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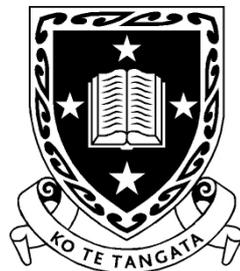
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# **Electric Vehicles in New Zealand – Policy, Regulation and Technical Standards for Emerging Vehicle Technology**

A thesis  
submitted in fulfilment  
of the requirements for the degree of  
Master of Engineering



THE UNIVERSITY OF  
**WAIKATO**  
*Te Whare Wānanga o Waikato*

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## **Abstract**

The need for a technical standard for the conversion of Internal Combustion Engine (ICE) to electric drive has been identified by government regulators in New Zealand (NZ). The aim of this project was to review the technical and inspection requirements that would allow Electric Vehicle (EV) conversions of passenger vehicles of gross weight < 3500 kg (Class MA), to be safely designed, built, sold, and operated in NZ. A detailed description of the spectrum of EV technology is given. A literature review of NZ and international transport regulations and technical standards has shown many requirements affecting EVs. A risk analysis showed that most EV technological risks related to electrical, battery and braking safety are controlled by implementing a reduction in risk event likelihood, rather than a reduction in risk event severity. This indicates that risk controls need to be reliable in order to be effective. A detailed review of EV electrical systems, Lithium Ion (Li-ion) battery systems and regenerative braking technology is also carried out. With the use of battery chemistries and designs which minimise the risk of failures, coupled with adequate safeguards in the form of redundant protection and well designed component management systems, EV converters can achieve safe and high performance conversions.

## **Statement**

I Mark Schafer declare that this thesis, submitted in fulfilment of the requirements of the award of Master of Engineering, in the School of Engineering, Faculty of Science and Engineering, University of Waikato, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other institution. All Photos, Figures and Tables are the work of the author unless otherwise stated. All units used in this thesis are from the International System of Units (SI) unless otherwise stated. All currencies are expressed in NZD unless otherwise stated.

*Mark Schafer*

Mark Schafer 28,01,2011

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## **Glossary**

ABS	Anti Skid Braking (Anti-lock Braking System)
ANCAP	Australian New Car Assessment Program
BEV	Battery Electric Vehicle
BMS	Battery Management System
CoG	Centre of Gravity
EBD	Electronic Brake-force Distribution (always coupled with ABS)
EBS	Electronic Braking System
EMB	Electromechanical Brake
EMC	Electromagnetic Compatibility
ESC	Electronic Stability Control
EV	Electric Vehicle
FMVSS	Federal Motor Vehicle Safety Standard (United States)
GVM	Gross Vehicle Mass
HEV	Hybrid Electric Vehicle
HV	High Voltage (by whatever definition)
ICE	Internal Combustion Engine
LA	Lead Acid Battery
LEV	Light Electric Vehicle
LVV	Low Volume Vehicle (a modified vehicle in New Zealand)
LVVTA	Low Volume Vehicle Technical Association
MED	NZ Ministry of Economic Development
MOT	NZ Ministry of Transport
NiMH	Nickel Metal Hydride (battery)
NZ	New Zealand
NZTA	The New Zealand Transport Agency
OEM	Original Equipment Manufacturer
OPEC	The Organisation of the Petroleum Exporting Countries
PHEV	Plug in Hybrid Electric Vehicle
RCD	Residual Current Device
RESS	Rechargeable Energy Storage System (Electrical)
REV	Range-extended Electric Vehicle
RUC	Road User Charges (New Zealand)

SLA	Sealed Lead Acid (battery)
SOC	State of Charge (battery)
SOH	State of Health – The remaining operating usefulness of the battery
SOP	State of Power (charge or discharge)
Tare	The empty or curb weight of the vehicle
TRAC	Traction control
UNECE	United Nations Economic Commission for Europe
V2G	Vehicle to Grid
VAC	Volts Alternating Current
VDC	Volts Direct Current
VSC	Vehicle Stability Control
WOF	Warrant of Fitness (NZ)

## **Chapter 1 - Introduction**

Electric Vehicles (EVs) are currently undergoing a resurgence of interest as the environmental and energy use benefits become increasingly important due to concerns about peak oil, energy security and climate change. New Zealand (NZ) is in a unique situation with regard to EVs as a high proportion of electricity generation is from renewable sources such as hydroelectric, geothermal and wind. Studies have also shown that by utilising off-peak charging a large number of EVs could be supported in NZ with relatively small increases in electricity production and new infrastructure cost (Dirr 2008; Erwan Hemery 2008).

In a national cost-benefit assessment of the early uptake of EVs in NZ, Hyder (2009) summated that “EVs are good for New Zealand”. Hyder’s modelling shows considerable private net benefit from purchasing of EVs once EV prices drop below Internal Combustion Engine (ICE) vehicle prices.

The EV can be seen as a new technology that presents unique challenges to regulators and the automotive industry as we learn about the different safety characteristics of this technology. The recent development of new interest in EV technology has highlighted the need for technical safety focused standards to govern the modification and scratch building of EVs in NZ. Vehicle maintenance, certification and emergency personnel also need different skills and training for working with these vehicles. All stakeholders in this technology system need an understanding of the implications of EV adoption in NZ.

In NZ vehicles and transport energy are supplied by an international market place. This thesis proposes that the conversion of an ICE vehicle to an EV could become commonplace if a sharp rise in the cost of petrol creates a demand that cannot be met by major international EV manufacturers. This thesis will explore the risks associated with emerging EV conversion technology and how these risks may impact on the development of technical safety standards specific to NZ.

A life cycle costing for several different EV configurations and future energy scenarios are analysed and discussed. A risk analysis is carried out to identify the major sources of technological risk in the EV system. The risks are discussed in detail and recommendations are proposed providing an input to the development of a new Low Volume Vehicle (LVV) standard for EVs. Assessment tools are also provided to aid transport policy decision making for both government and

industry groups. The consumer issues of environmental and energy use labelling are discussed briefly as these issues have implications for government regulation. This thesis aims to inform and encourage further debate between stakeholders which is an essential part of policy making. It is hoped that the recommendations put forward by this thesis can be used to develop a Low Volume Vehicle (LVV) Standard for the conversion and scratch building of EVs. Information collated in this thesis is also offered as a useful resource for not only policy makers, but also those who are involved in the development and construction of EVs in NZ. The design of EVs requires new engineering solutions in order to reduce the inherent safety risks of the technology. It is the assessment of these solutions that is the focus of this thesis.

## 1.1 Research Focus

The last 30 years of automotive development has seen the development of vehicles focus on emissions, safety and electronics. We now see low energy consumption and carbon dioxide emissions joining this list.

Discussion within this thesis has been limited to passenger vehicles of gross weight <3500 kg (Class MA), but does not include Light EVs (LEV) such as electric power-assisted cycles (<300 W), scooters, motorbikes, and heavy vehicles (>3500 kg) such as trucks and busses. The applicability of the information in this thesis is not confined to passenger vehicles as much of the general requirements will also apply to other vehicle classes.

During this project many issues concerning EVs were identified but were outside the scope of this research. These issues however, all warrant further research in helping to contribute to a broader understanding of EV implementation in NZ. These include;

- Lightweight low speed EVs (LEVs). These vehicles which are also sometimes referred to as ‘neighbourhood EVs’ or quadricycles, are not used in NZ due to current safety requirements (King 2007). However LEVs are included in international standards for pedal assisted cycles and scooters. Bossche (2003) identified that there is less risk with LEVs due to smaller batteries and lower voltages. Research investigating the risks of allowing ‘neighbourhood EVs’ into the NZ transport fleet is recommended.
- The environmental and resource use of EVs particularly with the manufacture and recycling of batteries (Lazar 2009). Supply constraint issues may also exist with the materials used for EV batteries and motors.
- Taxation and revenue collection issues. King (2007) identified particular issues identified for Plug-in Hybrid Electric Vehicles (PHEV). The full re-write of the Road User Charges (RUC) legislation investigates the merits of alternative methods of collecting revenue from diesel vehicles. The taxation of new energy vehicles requires further research.
- Government incentives for the mass- adoption of EVs, and
- Insurance implications for EVs.

The focus within this thesis has been restricted to the area of vehicle safety. The dominant aim was to review the technical and inspection requirements that would allow EV conversions to be safely designed, built, sold, and operated in NZ. This also includes the identification of some infrastructure issues such as energy labelling.

EV technology continues to develop at a great rate and many new documents on EV safety have been published in 2010. Although some of the information in this thesis may date quickly, a number of general design guidelines have been identified and discussed. It is acknowledged that some technical positions explored in this thesis may be controversial and not all parties may agree on the right stance to take on a particular issue. Rather than offer one solution to a complex discussion, this thesis proposes viable options concerning particular safety issues for EVs specific to NZ.

## **1.2 Research Methodology**

A variety of research methods were employed in this research such as an extensive literature review, interviews, calculations, vehicle testing the attendance at conferences such as the EECA Biofuels and Electric Vehicles Conference (2010).

A thorough literature review was completed of NZ and international transport regulations and technical standards. An important focus for this project was to review the international technical standards for EVs and assess the engineering requirements for the safe design of EVs in NZ.

A variety of testing and assessment exercises were also used throughout this thesis to explore different scenarios. For example, vehicle testing was completed involving vacuum and deceleration measurements on ICE vehicles. This information helped to fill in knowledge gaps about EV braking. An assessment of the economic performance of EVs was also undertaken where several fuel price scenarios were investigated by comparing the cost of EVs with ICEs. While a detailed risk assessment was developed to clarify what risks are associated with EVs and how to mitigate for these.

Over 25 informal face to face interviews were also completed. Although the interview process applied in this research was not fully consultative, opinions were sourced from across the EV sector. This included discussions with representatives from; NZTA, LVVTA, LVV certifiers, importers, designers (in NZ and internationally), EV modifiers (in NZ and Australia), and members of the public engaged in private EV conversions. A list of organisations is given in Appendix 1.

The methodology used during these interviews was based on informal face to face discussions, but also included ongoing dialogue with some participants by means of emails and telephone conversations. The objective was not to conduct a 'formal' interview with a prescribed set of questions, but rather to gain a broad insight into what EV policy, regulations and technical standards may look like in the future for NZ. These interviews also influenced some of the dominant perspectives put forward in the following chapters concerning electrical, brake and battery safety implications for EVs. Most interviews took place across New Zealand and some in Australia where fieldwork was undertaken in Melbourne, Sydney and Brisbane.

During this process it became clear that battery safety of specific battery chemistries is a major issue when discussing the safety of EVs. From this concern, it was decided to attend a major conference on the most promising battery technology, Lithium ion (Li-ion). The conference attended was the EV Li-ion Battery Forum 2010 in Beijing, China which was a 5 day event which focussed specifically on Li-ion Batteries for EVs. Information gained from this conference was invaluable in building a detailed understanding about the implications of Li-ion batteries for EVs. This has been summarised in Chapter 7.

## 1.3 Background

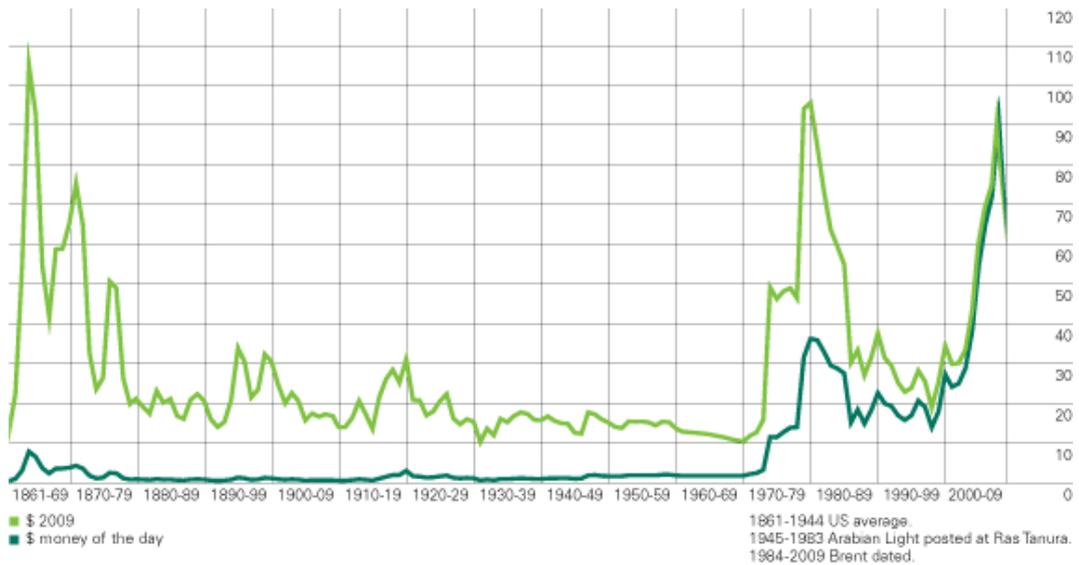
### 1.3.1 Brief Historical Context

The concept of practical EVs is not new. Over one hundred years ago, during the birth of the automobile age, EVs made up a high proportion of the vehicle fleet. EVs were a common sight in NZ with over 200 in operation in Christchurch in the 1920s as shown Figure 1.1 below.



**Figure 1.1** More than 50 of Christchurch's electric vehicles on Bealey Ave, 1924. (Riley 1976).

After the 1920s the electric road vehicle receded into niche applications such as industrial vehicles, the concept only to be revived during the 1970s OPEC oil embargo (Bossche 2003). At present the increased interest in EVs is due to a combination of factors such as peak oil, energy security, local pollution and global climate change. To illustrate the link between EVs and oil prices a graph of historical oil prices is given below which shows a peak in the 1970s and today.



**Figure 1.2** Graph of oil prices from 1861–2009 from USD/barrel. from; <http://www.bp.com>

### 1.3.2 Sustainable Transport Technologies

NZ is in a strong position to support the development for EV technology due to several features:

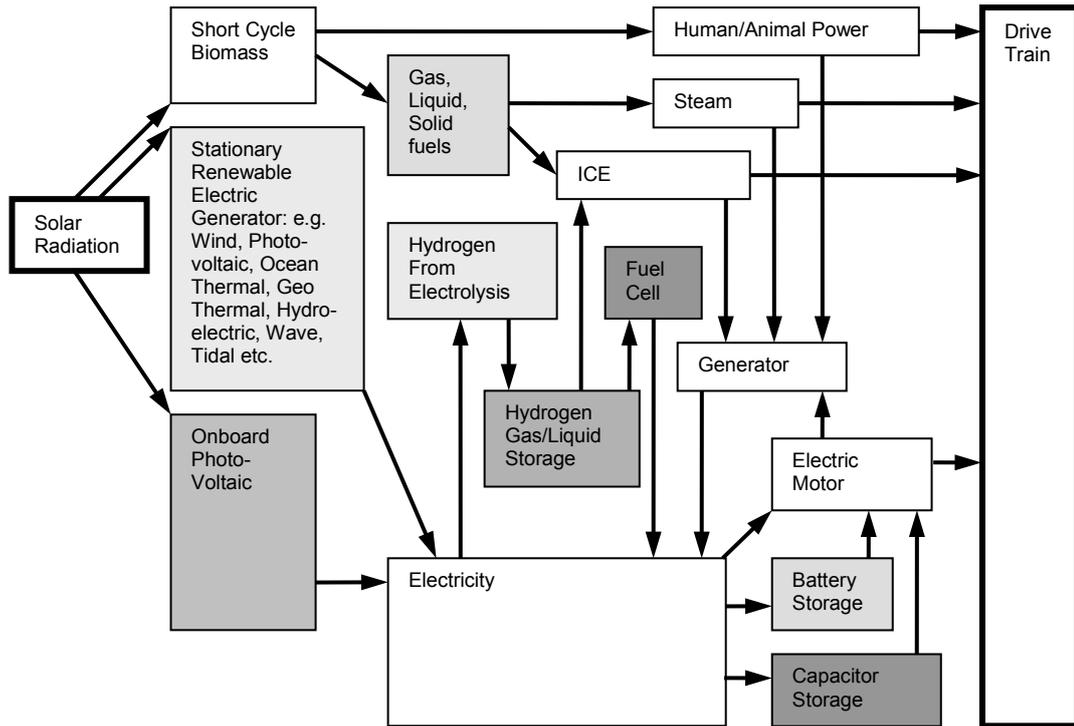
1. NZ has a 230 V domestic electrical system,
2. approximately 65-70% of electricity generation is from renewable sources and
3. the NZ public has a history of being enthusiastic early technology adopters.

All of the worlds energy comes from the sun. Sustainable energy is short cycle solar energy converted for use by various renewable technologies. Some energy pathways to sustainable transport are shown in Figure 1.3 below. The light coloured boxes represent technologies that are currently available or in use and would require minimal technological development for large scale implementation.

The darker coloured boxes represent technologies which require either;

- large capital investment in equipment,
- change in public perception or acceptance and/or
- investment in technological development.

The darkest boxes represent technologies which currently are difficult to implement and may never be practically or economically viable.



**Figure 1.3** Energy Pathways to Sustainable Land Transport.

The above Figure does not represent an exhaustive list; for example fringe technologies such as compressed air storage, stirling cycle engines and flywheel energy storage have been omitted for clarity. The sustainability of current nuclear power generation technology is also controversial and so has not been included. The aim of the above Figure is to show that EVs represent a viable pathway to sustainable land transport. Furthermore, the above ‘electricity box’ has the most arrows going to and from it and so it is likely that some form of electric drive-train will be a feature of vehicles in the future.

### **1.3.3 What is an Electric Vehicle (EV)?**

An EV or electrically driven vehicle uses and/or creates electricity on board. EVs cover a wide range of products from simple mobility scooters to large busses and trucks capable of moving thousands of kilograms. The definition of an EV covers a broad spectrum of vehicles that include hybrid traction systems which employ both electric motor and ICE. In Christchurch, locally manufactured LPG/battery electric hybrid busses are in use and an important part of the Wellington public transport system is the electric trolley buses that draw electricity from overhead wires. As stated previously, this project will focus on vehicles that utilise an onboard energy storage provided by a 'Rechargeable Energy Storage System' (RESS), typically in the form of a battery pack.

As a concept, the Battery Electric Vehicle (BEV) is the simplest type of EV. Charging of the battery requires an external power source connection so the BEV must be plugged into a power supply at its destination. Periodic refuelling at the petrol station however is no longer required. The range or distance a BEV can achieve before it requires recharging is a critical specification.

Hybrid Electric Vehicles (HEVs) use a mixture of electric and ICE or Fuel Cell (FC) to propel the vehicle. A pure HEV generates all its electrical energy on board, using a control system to employ the electric portion of the traction system as a load levelling device and power absorbing device (by regenerative braking) to achieve higher efficiencies in use of energy. The electric motor in a HEV is primarily a power assist device so the HEV battery is optimised for power delivery and absorption rather than energy storage. All the energy to drive the vehicle comes from petrol. The HEV can be described as a 'non-depleting hybrid' as the battery is never fully discharged during use and never charged from outside the vehicle (the battery is usually at approximately 50% State of Charge (SOC)). The Toyota Prius (Figure 1.4) has become the ubiquitous HEV during the last ten years however during 2010 other models entered the NZ market including the Honda Insight and the Australian manufactured Toyota Camry Hybrid.

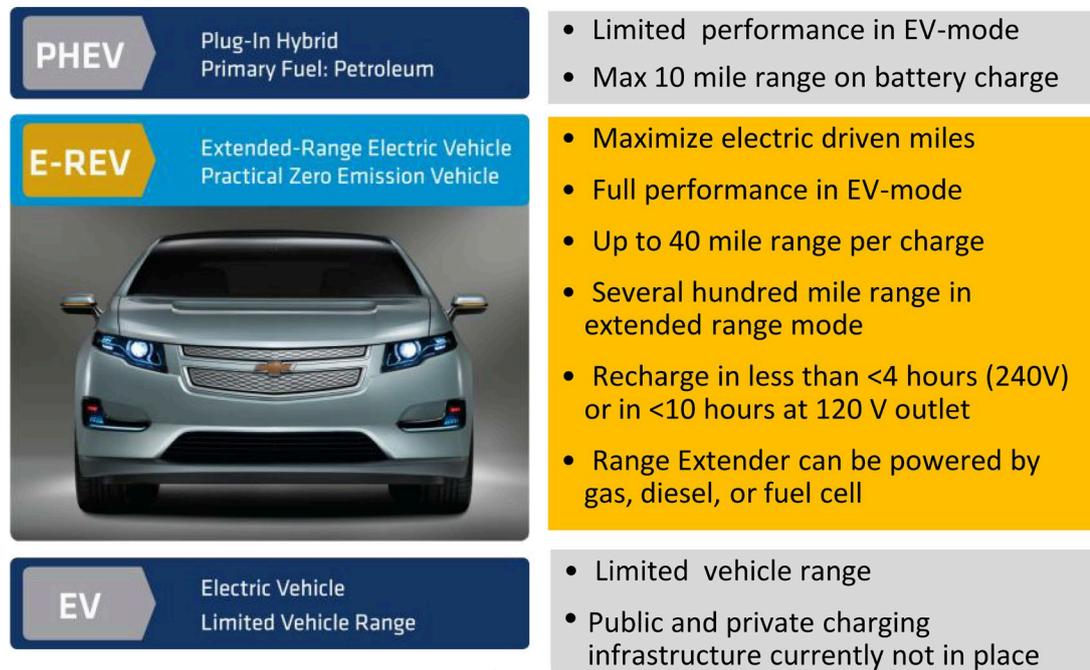


**Figure 1.4** 1999 Toyota Prius Hybrid Car.

The Plug-in Hybrid Electric Vehicle (PHEV) differs as the battery is able to be recharged from the grid. The performance of a PHEV depends on its motor configuration, battery size and control architecture as well as its operation. A PHEV that fully drains the battery in EV mode before it switches to the range-extending ICE is called a Range-Extended EV (REV). This is because its range performance is no longer constrained by battery pack energy storage capacity. This type of PHEV can be exclusively operated in EV mode (within its EV range), without using any petrol during its lifetime (it is beneficial to design the size the battery pack around the expected travel distance). As identified by Bossche (2003), there are two different operation modes for PHEVs which determines the energy use profile of the vehicle (petrol or grid electric);

1. EV with range extender used in city mode (EV mode) and for occasional long distance travel,
2. HEV with zero-emission capability for short trips. The EV mode is used only occasionally (Bossche 2003).

2010 has seen the launch of the Chevrolet Volt REV on the US market. As shown in Figure 1.5 the marketing used by GM separates this vehicle from other PHEVs.



**Figure 1.5** Creating a new propulsion category - GM Chevrolet Volt range extended electric vehicle (Cai 2010a).

The Chevrolet Volt can travel 40 miles (64 km) in EV mode then a range extender ICE provides power with no torque to the wheels from the electric motor. The electric motor has a 100kW power rating. The ICE range extender generator can also drive vehicle at 110 Mph continuous (Cai 2010a). The electricity producing Fuel Cell (FC) generator can also be used in a Fuel Cell Hybrid Vehicle (FCHV). A Fuel Cell Vehicle (FCV) could conceivably operate without a battery using a direct drive electrical transmission between the FC and motor.

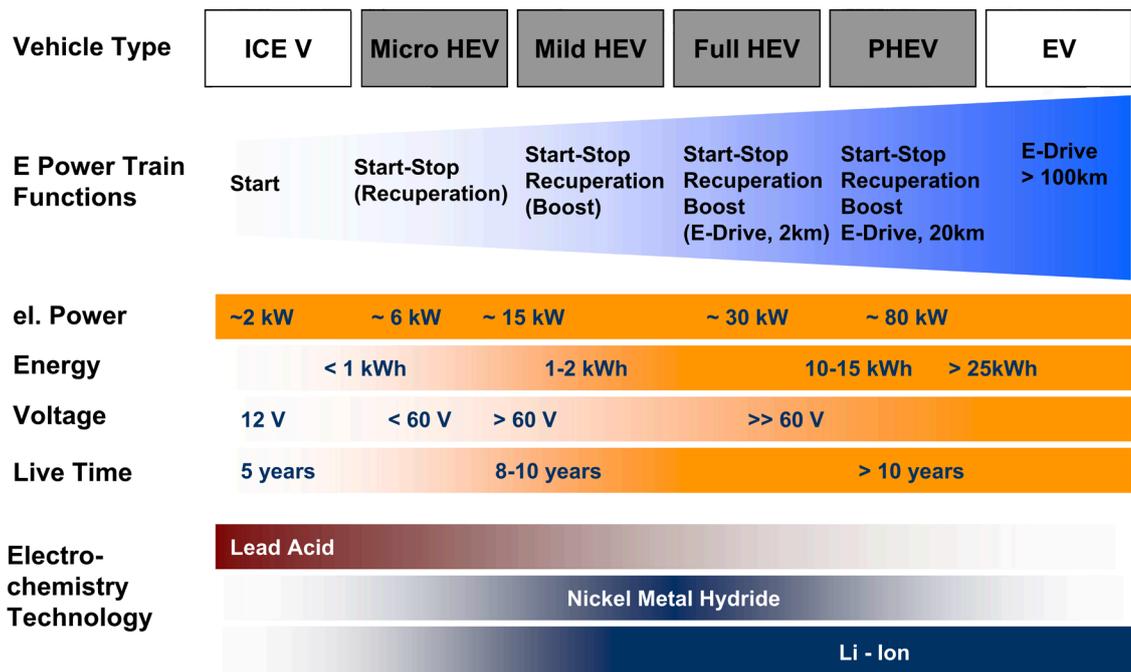
In a micro-hybrid the battery and electric motor do not provide any motive force to the vehicle but the ICE is turned off whenever the vehicle is stopped and would otherwise be idling. By keeping the combustion engine from idling, fuel is saved and the engine economy improved, typically in the range of 5–10% (Pistoia 2010).

The HEV represents a range of technology from a microhybrid or start–stop hybrid to a mild hybrid, full hybrid and then plug in hybrid. The typical technology employed in each type of vehicle is summarised as follows;

Vehicle category	Battery voltage [V]	Electric motor power range [kW] <sup>1</sup>	Battery energy content [kWh]	Typical battery chemistry (Optimisation)
LEV	12, 24, 36, 48	1	1 - 2	LA, Ni (Energy)
Industrial	12, 24, 36, 48	1 - 100	5 - 50	LA (Energy)
BEV	200 - 500	100 - 200	25 - 75	Ni, Li (Energy)
FCV	300 - 400	100 - 200	1 - 5	Ni (Power)
HEV - Micro	12	2	0.5	LA (Power)
HEV - Mild	42 - 200	15	1	Ni, Li (Power)
HEV - Full	300 - 500	30	2 - 5	Ni, Li (Power)
PHEV	300 - 500	30 - 100	5 - 20	Li, Ni (Energy)

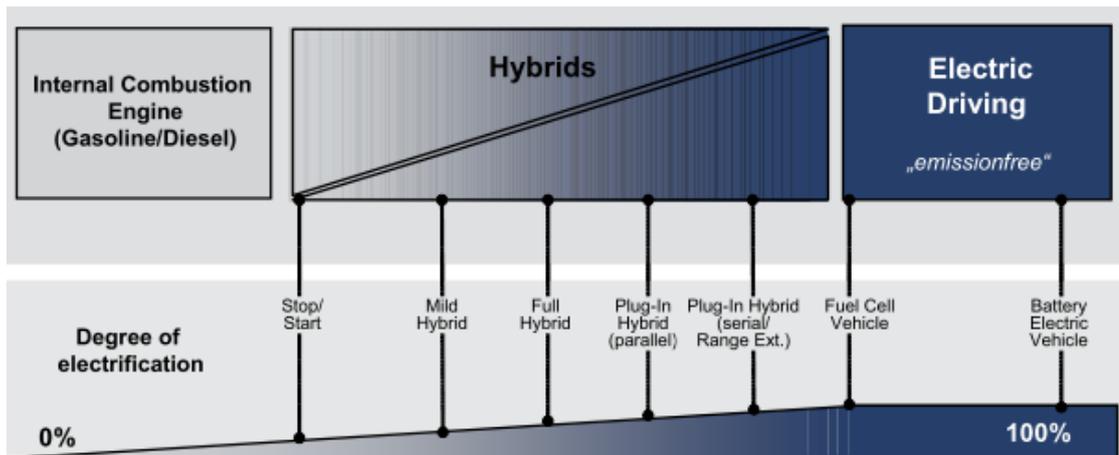
**Table 1.1** Summary of EV characteristics. Adapted from (Pistoia 2010) (p. 499).

<sup>1</sup>Added by author.



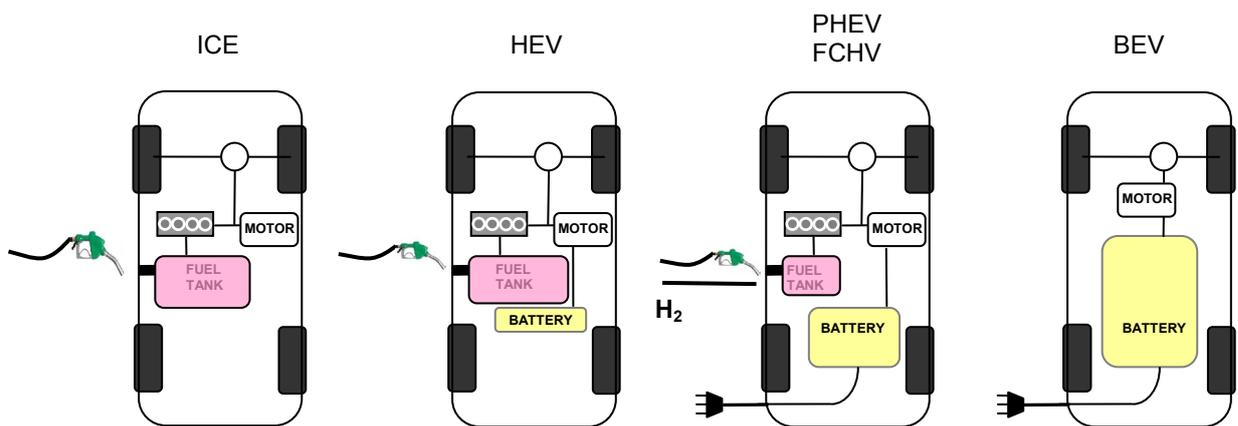
**Figure 1.6** Energy Storage: Requirements and Technology. Volkswagen Research Lab China (Giebel 2010).

Figure 1.7 below from the European Council for Automotive R&D (EUCAR) illustrates the electrification of the vehicle power-train through the application of a range of vehicle technology.



**Figure 1.7** Electrification of the power-train from (EUCAR 2009)

These vehicle technologies are also described in the typical vehicle component schematics below;



**Figure 1.8** Electrification of the power train - a spectrum of technology.

In summary, ‘EV’ refers to a spectrum of technology which this thesis uses as a general term meaning ‘electrically propelled vehicle’. Unless stated otherwise the term EV encompasses BEVs, HEVs, PHEVs, REV and FCVs.

## **Chapter 2 - Cost Aspects of EV Conversions**

### **2.1 Introduction**

The financial cost of products is a major determinant of consumer behaviour and as such economic factors will be a significant driver in the large scale adoption of EVs in NZ. This section will present a simple cost comparison between EVs (that are entering the market) and currently available petrol and ICE hybrid vehicles to determine what cost factors are the most important in influencing consumer behaviour. Many cost/benefit studies that take into account the wider economic, social and environmental characteristics of EVs have been identified such as in the recent report by Hyder (2009); National Cost-benefit Assessment of the Early Uptake of Electric Vehicles in New Zealand. This section however will focus on the direct financial cost to the vehicle user, to help determine what factors may influence consumer behaviour in the future. Environment, air pollution and other external costs are identified as important features below, but are not included in the cost analysis.

#### **2.1.1 Factors for the Adoption of EVs**

A vehicle that can transport 5 passengers and luggage in comfort, travel at 100 km/h for 1000 km without refuelling has been immensely beneficial to society. As such the ICE vehicle has been one of the leading tools used in the advancement of first world society over the last one hundred years. The negative impacts of the widespread use of ICE vehicles, such as energy use and environmental pollution are widely recognised and different technologies are being assessed as alternatives, including EVs. The drivers and barriers for the introduction of EVs have been identified as follows;

<b>Drivers</b>	<b>Barriers</b>
Running cost	Purchase cost and electricity cost
Environmental credibility; Individuals and companies are buying EVs to associate themselves with environmental causes.	General taste preference for ICE vehicle.
Local pollution; Air quality, reduced noise BEVs have zero tailpipe emissions.	Vehicle performance; Range anxiety. Recharge time.
Climate change; Reduced CO <sub>2</sub> emissions.	Lack of charging infrastructure
Peak oil; Energy security, Fuel cost	

**Table 2.1** EV drivers.

Which of these factors results in a major uptake of EVs remains to be seen? Although different customers will have different requirements cost will always remain a dominant factor in influencing the wide scale adoption of EVs.

## 2.2 Comparative Cost Analysis

### 2.2.1 Model Assumptions

The costs of ICE vehicles, whilst being uncertain for most vehicle owners (due to unforeseen maintenance or replacement) are well understood. EVs however have a unique cost profile over the life cycle of the vehicle. Hyder (2009) outlines the model assumptions used in the study National Cost-benefit Assessment of the Early Uptake of Electric Vehicles in New Zealand and identifies the most important assumptions as:

- USD/NZD exchange rate
- EV battery price
- new and used vehicle purchase prices
- price of carbon
- price of oil
- petrol and diesel costs
- fuel consumption
- price of electricity
- vehicle kilometres travelled

Hyder (2009) notes that;

“...many of the model assumptions are highly uncertain. Changes to the assumptions impact not only on the estimates of EV demand, but ultimately the cost-benefit assessment and the results of the study” (Hyder 2009).

The cost model developed and presented in this section assumes a use profile for all vehicles assessed as being driven 14000 km/year (the NZ average of 38.3 km/day) during the first years of ownership. The vehicles chosen are well known and representative of their class. High profile EVs such as the Tesla Roadster are high performance luxury sports cars and are not included in this analysis. The purchase cost of the Nissan Leaf is taken as the reported price for the first EV models to be released in 2011. The price of this vehicle is expected to drop in subsequent years. Hyder (2009) gives the initial purchase cost of mass produced EVs as between \$52,000 – 65,000 NZD<sup>1</sup>. Davis (2010) however, reports that the newly launched Mitsubishi iMiEV will cost \$84,500 NZD.

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<sup>1</sup> For more information see: Hyder (2009), Table 4-1, p.10

The period studied is the first 100,000 km which represents 7 years and 51 days of vehicle use. 100,000 km represents a reasonably long period over which costs might be recovered. Converted EV vehicles have a battery life exceeding 100,000 km (3000 cycles assumed for a Li-ion battery), so it is assumed that battery replacement is not required (The exception is the LA battery which has an assumed cycle life of 600 cycles). The analysis takes values from the AA 2010 Car Running Costs Folder which provides a breakdown of costs and uses information from the NZTA Heavy Vehicle Selection Guide (NZTA 2005; NZ AA 2010).

The cost of vehicle energy is currently assumed as 0.24 \$/kWh for electricity including domestic lines charges and 0.195 \$/kWh<sup>2</sup> for petrol. The data for ICE petrol consumption is published from vehicle drive cycle tests. The values for ICE fuel consumption shown in Table 2.2 below were taken from the website <http://www.fuelsaver.govt.nz/>. The indirect (external) costs identified by NZTA (2005) such as safety, environment, maximising load, driver retention and brand/image are not considered in this analysis as these are considered secondary commercial considerations. The assumed vehicle cost data has been summarised in Table 2.2 below. Maintenance and insurance are assumed to be equal for the vehicles studies, however in reality there will be differences. No assumptions have been made of whether government policy will provide economic incentives for 'clean vehicles', however the exemption of EVs from Road User Charges (RUC) as is currently the case until 2013 is included in the cost analysis. Incentives for EVs are discussed by King (2007) and a summary of national incentives is given by BERR. (2008, p. 57).

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<sup>2</sup> This is calculated from an assumed cost of petrol of \$1.90 litre which is representative of 2010 prices and a lower heating value of 35 MJ/l. Petrol energy per litre,  $35/(3.6) = 9.722$  kWh → Petrol cost,  $1.90/9.722 = 0.195$  \$/kWh.

	Toyota Corolla	Toyota Prius	New Nissan Leaf	Blade Electron	Converted EV/ Li-ion	Converted EV/ LA <sup>2</sup>
<b>Nominal Purchase Cost<sup>1</sup> [NZD]</b>	30000	50000	70000	62200	26000	12000
<b>Fuel Use [l/100km]</b>	8	4.5	NA	NA	NA	NA
<b>Battery Size [kWh] (Range) [km]</b>	NA	NA	24 (160)	16 (100) <sup>3</sup>	16 (100)	26.6 (80)
<b>Energy Use [kWh/km]</b>	0.78	0.44	0.11	0.12	0.12	0.29
<b>Energy Cost<sup>4</sup> [\$/km]</b>	0.152	0.0855	0.04	0.035	0.035	0.035
<b>Fixed Cost<sup>5</sup> [\$/day]</b>	6.39	6.39	6.39	6.39	6.39	6.39
<b>Running Cost<sup>6</sup> [\$ /km]</b>	0.067	0.067	0.067	0.067	0.067	0.067
<b>Total Cost<sup>7</sup> [\$/km]</b>	0.39	0.32	0.26	0.26	0.26	0.30
<b>Total Cost<sup>7</sup> [\$/day]</b>	14.79	12.24	9.95	10.02	10.02	11.61

**Table 2.2** Assumed vehicle cost data.

<sup>1</sup> [http://www.companyvehicle.co.nz/webfiles/Adrenalin/files/Company\\_Vehicle\\_Nov\\_2010\\_1.pdf](http://www.companyvehicle.co.nz/webfiles/Adrenalin/files/Company_Vehicle_Nov_2010_1.pdf)

<sup>2</sup> 24 Trojan 6V T-105 Flooded LA (185Ah and 600 cycles assumed) (Rekker 2009). Pack replacement cost at 48000 km assumed \$7200 NZD.

<sup>3</sup> <http://bev.com.au/about/specifications/>

<sup>4</sup> Calculated from petrol fuel consumption (ICE) or from energy to charge 80% battery capacity at an efficiency of 0.9 divided by the range on one charge (BEV).

<sup>5</sup> Vehicle licencing, warrant of fitness, interest on outlay, Insurance 35 year old male, comprehensive policy including glass cover (NZ AA 2010).

<sup>6</sup> Oil, tyres, repairs and maintenance excluding petrol and electricity energy costs.

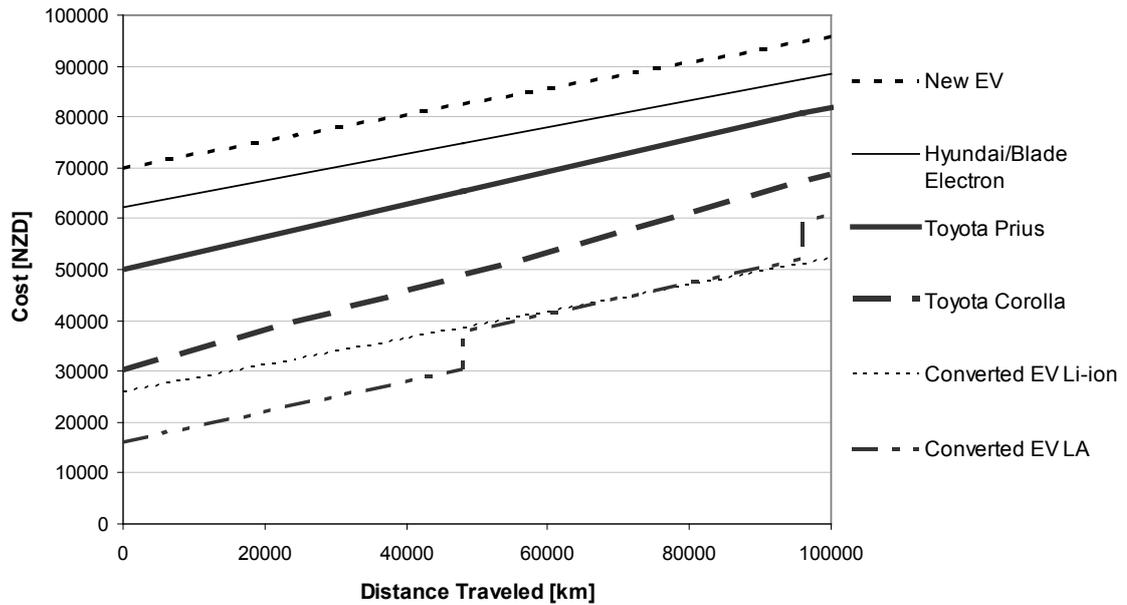
<sup>7</sup> Excluding capital outlay



**Figure 2.1** The Hyundai Blade Electron.

### **2.2.2 Analysis**

The ICE vehicle operating costs are dependent on petrol prices. As BEVs rely only on electricity for energy, BEV operating costs are dependent on electricity prices. On the other hand operating costs for PHEVs (not considered here as drive cycles need to be considered) are a function of both petrol and electricity costs. An analysis of the values in Table 2.2 gives the life time costs of the vehicles which are presented in Figure 2.2 below.



**Figure 2.2** Plotted vehicle cost profile. Petrol 1.90 \$/litre (0.195 \$/kWh), Electricity 0.24 \$/kWh. Petrol/Electricity price ratio = 0.81.

A baseline (control) cost is represented by the Toyota Corolla ICE vehicle which is shown by the dashed bold line. The upper two lines represent the approximate costs of currently available EVs whilst the lower two line represent the costs of EV conversions for the home builder. Home conversion costs represent the cost of materials only and would not generally include the labour required to convert the EV. The kinks in the Converted EV LA line represent the replacement costs of the LA battery (assumed as \$7200 every 48000 km).

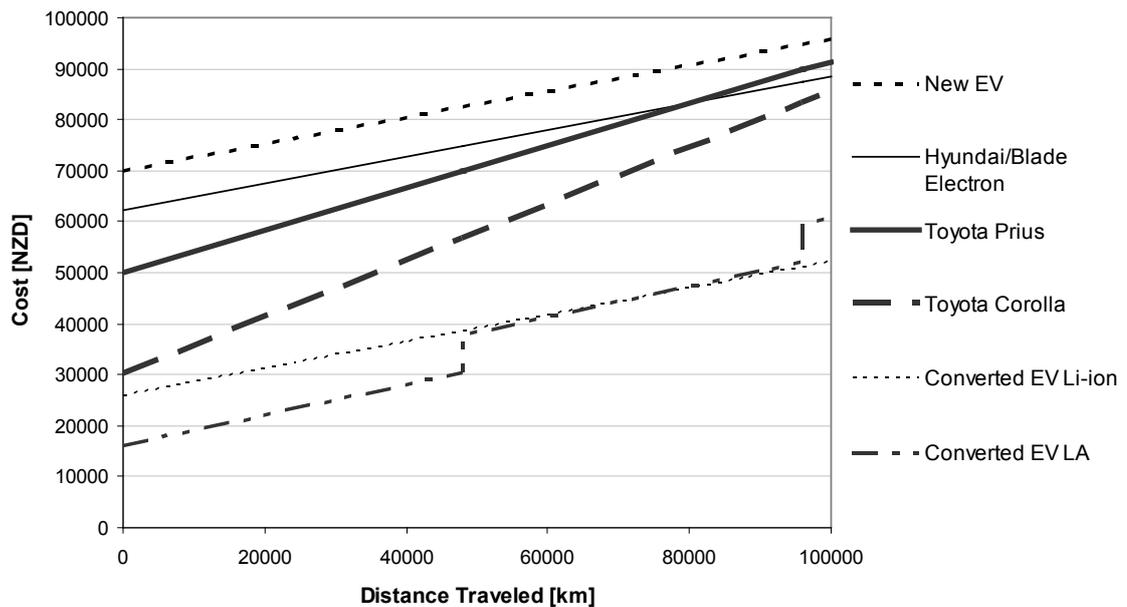
This analysis shows that the purchase price of the EV has a large effect on the overall life cycle cost of the vehicle and that new OEM EVs would need to be priced a similar level to ICE vehicles to be competitive. This is confirmed in the report by (Association 2010) which states;

“Many factors affect the vehicle running cost, but contrary to popular belief, although fuel cost is one of those components, the biggest factors are depreciation and interest rates” (p. 5).

Therefore, a decline in the purchase price of EVs has a greater effect on the overall ownership costs than the same proportional increase in the price of petrol would. This situation is also born out by the fact that most New Zealanders buy second hand cars, where significant depreciation has already taken place. Simpson (2006) discusses the economics of PHEVs and concludes “...that it will be

quite a challenge to justify the PHEV capital cost premium on the basis of reduced lifetime energy costs alone” (Simpson 2006, p. 13).

It is useful to investigate what happens in this model when petrol prices increase. Below is a representation of a scenario that involves a more than doubling of the petrol price to 4.0 \$/litre. It is assumed that the electricity price remains constant so the petrol/electricity price ratio goes to 1.71.



**Figure 2.3** Plotted vehicle cost profile. Petrol 4.00 \$/litre (0.195 \$/kWh), Electricity 0.24 \$/kWh. Petrol/Electricity price ratio = 1.71.

This Figure shows that with high petrol prices, the EV becomes economically attractive and if EV purchase costs were at parity with ICE vehicle costs, EVs would have a strong economic advantage. The Hyundai/Blade Electron pays back its capital cost at around 80,000 km compared with a Toyota Prius Hybrid. This analysis is simplistic as it does not take into account any increase in electricity prices as petrol prices increase. As Donovan et al. (2008) explains;

“High oil prices also have the potential to directly affect the costs of other energy forms. Oil is the major pillar of an increasingly interlinked global energy market. These linkages mean that the price of oil closely influences the price of other fuels, such as natural gas. Thus when the price of oil increases the price of natural gas tends to follow. This has potential implications for electricity generation, which contributed approximately

17% of electrical energy generated in 2005 (MED, 2006). Should domestic gas supplies dwindle and be replaced by imported gas then New Zealand's electricity consumers may become increasingly exposed to international gas prices and, by default, global oil prices" (p. 18).

It has been shown that vehicle purchase price is currently the most important factor in EV cost. EV prices will need to reduce to be comparable with ICE vehicle prices before a large number of consumers will make the shift. This is especially pertinent considering the reduced performance of range and refilling time the customer is accepting when purchasing an EV. The BEV will first be purchased by commercial users as half of all new vehicles are purchased by businesses and as explained by AECOM (2009);

"...owners of larger vehicles and vehicles that travel large distances tend to purchase a higher proportion of EVs. This is due to the fact that operating costs are more important for these vehicle owners" (p. i).

This is evidenced by the fact that the Toyota Prius has become a popular vehicle for taxi service. During research for this thesis, one Taxi operator reported to the author savings of 1000 \$/month when compared to a V6 Holden driven 12,000 km/month, and he commented on the increased reliability of the Toyota (personal communication).

Another factor in favour of the ICE status quo is the high elasticity of demand of petrol. This results in people tending to pay higher prices before reducing consumption or moving to alternatives.

### **2.3 The Case for Converted EVs**

In this section a scenario is presented to show how a global EV supply constraint could trigger demand for locally converted EVs. Parker (2008) discusses the economics of the introduction of new technology;

“Peak oil could be another ‘millennium bug’ event. Peak oil arguments ignore rationing function of market and their power to induce innovation ...we know that the arrival of alternative fuels or substitutes is not necessarily slow. There are always part-developed or dormant technologies that have been biding their time, waiting for oil prices to rise. These can be activated relatively quickly” (p. 16).

The EV conversion represents one of these technologies. Parker (2008) goes on further, to say;

“The transition to a reduced dependence on oil is likely to involve a myriad of technologies until, by a process of iteration, a new paradigm is developed” (p. 16).

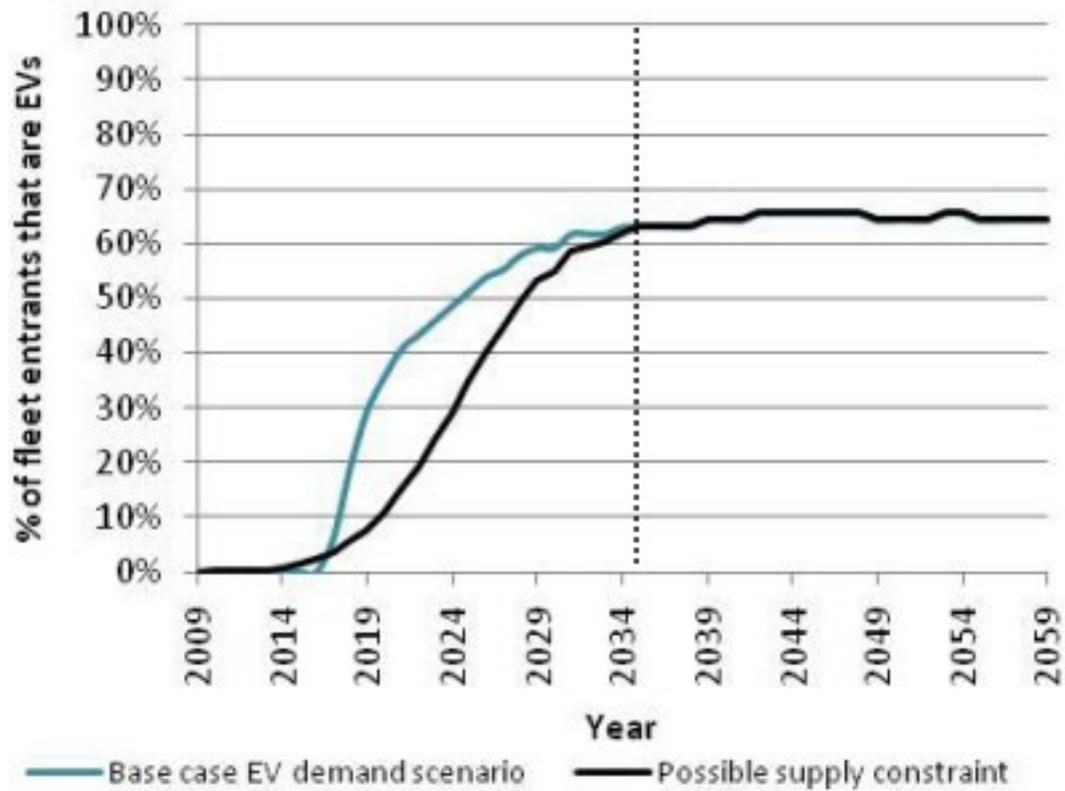
It has been shown in the previous Section that the cost of imported OEM EVs is too high to recover by reduced fuel consumption. EV purchase prices could remain high if the global demand for EVs increases but the supply of EVs is constrained as the capacity to manufacture these vehicles catches up.

The scenario presented here suggests that the conversion industry would be quick to take advantage of this market opening, as it is unconstrained by the industrial momentum of the major automakers. Low cost producers of converted EVs would quickly enter the market. During research for this thesis it was noted that NZ has a base of EV enthusiasts and engineers with the knowledge and capability to produce EV conversions to a reasonable standard and performance. This situation may be further advanced by a good supply of EV batteries as battery manufacturers have been positioning themselves for a growing market (Deng 2010).

The current situation in NZ is that EV enthusiasts build their own vehicle, absorbing the labour costs themselves. As economic factors become favourable these people can quickly take advantage of this market opportunity. Several professional EV converters including Blade Electric Vehicles are currently operating in Australia. Reports indicate that a low technology conversion can take

as little as three days to a week to compete. With sophisticated conversions taking a large number of hours.

An example of an EV supply constraint scenario used by Hyder (2009) is shown in Figure 2.4 below;



**Figure 2.4** Example of an assumed supply constraint scenario showing a 17 year gap (Hyder 2009).

## 2.4 Battery Costs

The battery pack is the most expensive component of a BEV. Although a detailed assessment of future petrol and electricity price scenarios is outside the scope of this thesis, it is worth noting that the cost of EV batteries will play a significant role in the future costs of EVs. The cost of EV batteries is likely to reduce as the market develops. (Deng 2010) describes the situation for Li-ion batteries as “...not so rapid market development” indicating the EV battery market is not ready. As such manufacturers are currently producing batteries and investing in new production facilities for market positioning, not profit. The market for Li-ion batteries is currently being lead by the Chinese E-bikes market. The use of E-bikes in China has grown from 0-80 M in the last 10 years (Deng 2010). Current

production of E-bikes is 20 M/year, however most are equipped with Lead Acid (LA) batteries with Li-ion batteries currently representing around 1% of the market.

A reduction in battery cost is likely as the production of cells for EV applications enters the mainstream. Although future costs of EV batteries remains highly uncertain it is useful to give current and future price estimations for the most promising EV battery, Li-ion.

Source	Current	Future ~ 2020
(Yang 2010)	>1056 <sup>1</sup> <528 <sup>2</sup>	
(Cheng 2010)	924 - 1188	330 <sup>3</sup> - 396
(Nakamura 2010)	1580 - 3160	316
<a href="http://bev.com.au">http://bev.com.au</a>	545 <sup>4</sup>	
Generic LA	~ 200	

**Table 2.3** Li ion battery costs, current and future predictions/target [NZD/kWh]

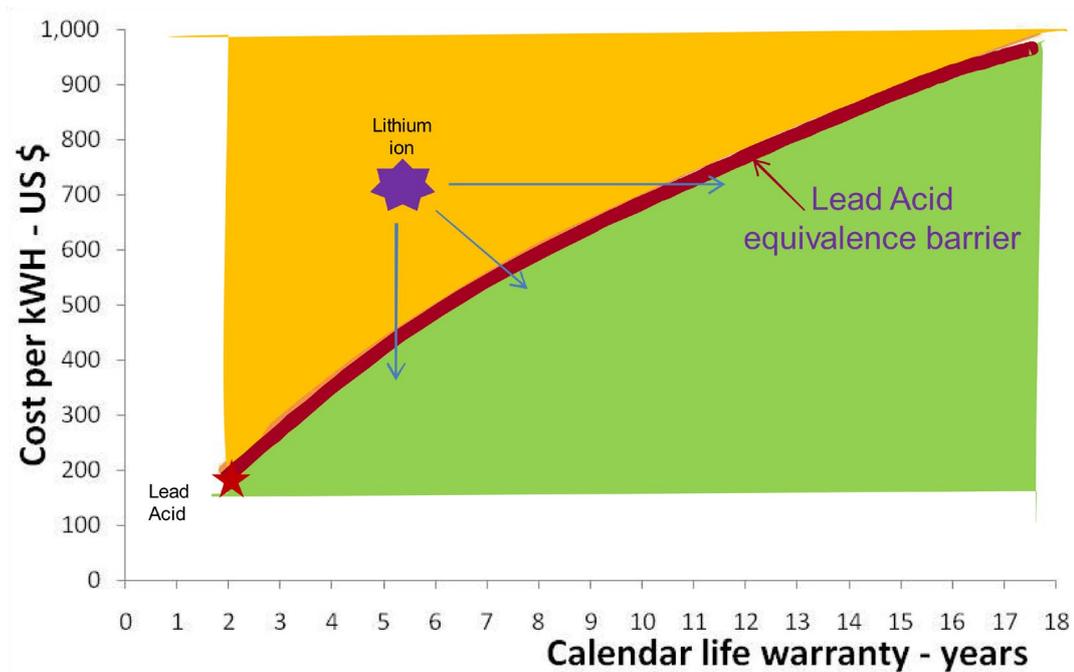
<sup>1</sup> Large format prismatic cell

<sup>2</sup> 18650 format cylindrical cell

<sup>3</sup> Pistoia (2010) suggests this a lowest probable specific cost for batteries in BEV

<sup>4</sup> Thundersky TS-LFP100AHA large format prismatic at 3.6V nominal

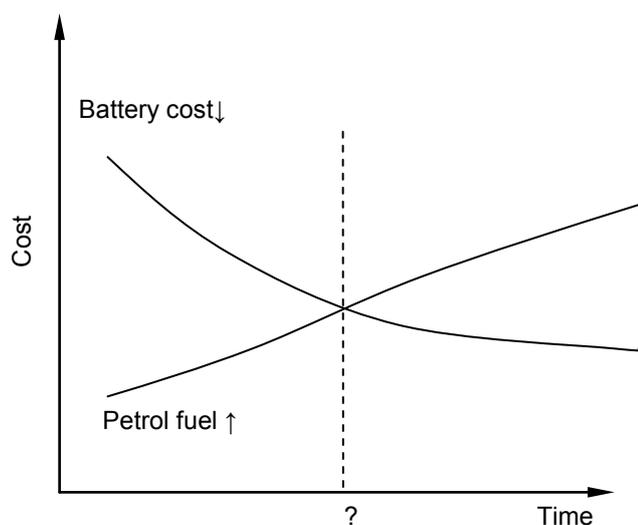
This Table shows why Thundersky is the most popular Li-ion battery for EV converters in NZ. It should also be noted it is not only the cost of the Li-ion battery that is an issue, but the Battery Management System (BMS) is also a significant cost, where Li-ion unavoidably has a greater cost than other chemistries due to increased system complexity. Prakash (2010) gives the ambition of Reva Electric Vehicle for battery cost and life performance of Li-ion cells in Figure 2.5;



**Figure 2.5** (Prakash 2010) Reva, Li-ion costs.

This shows that battery life is as equally important as cost and that this should be taken into account when choosing a battery. Figure 2.2 given above also suggests that the price performance of LA and Li-ion should be carefully compared by taking into account the cycle life and replacement cost of each battery type.

The drivers for EV introduction will include both the cost of petrol (energy cost) and battery cost (the cost of the alternative). This scenario is given by both Jen (2010) and Willums (2010) and is presented in Figure 2.6 below. The interaction of these two factors will influence the economic viability of EVs in the future.



**Figure 2.6** EV cost scenario adapted from (Jen 2010; Willums 2010)

An EV battery will also have a residual value after it is no longer fit for EV use. The EV battery is currently regarded as nominally spent after it reaches 80% of its original energy capacity. These batteries can be reused in stationary Uninterrupted Power Supply (UPS) applications, grid stabilisation facilities or even low performance or industrial EV applications. This residual value of the spent battery should be taken into account when a detailed cost analysis is undertaken. Jen (2010) suggests the use of the new LA battery price for the residual value of a used Li-ion battery. The prediction and measurement of battery end of life or failure mode holds many technical challenges but is important for vehicle costs, insurance and warranty claims.

## **2.5 New EV Business Models**

New business models will emerge to attempt to negate the upfront cost of the EV. Several organisations are exploring alternative cost models such as car share schemes, battery leasing, battery switch. The main objective of these enterprises is to change battery investment into an operating cost (change CAPEX to OPEX) and to manage the technology and market risk (Willums 2010).

Organisations involved in these types of operations must have a thorough understanding of the battery degradation over time and use in real-life, to determine the residual value of the battery. Wolkin (2010) presenting on behalf of company Betterplace gives the cost advantages of battery switch as;

- making EVs cost competitive with petrol-powered vehicles and,
- optimal charging in controlled conditions to prolong battery life and maximize residual value.

Betterplace has ordered and will operate over 100,000 AESC Li-ion batteries in Renault built vehicles over the next five years (Wolkin 2010).

## **2.6 EV Costs Summary**

This analysis has shown that the economics of EVs are a major determinant in the market uptake of EV technology. It has been found that two factors are important;

1. the purchase cost of the EV (influenced by battery cost) and less importantly,

2. the ratio of petrol to electricity cost.

A reduction in the purchase price of an EV has a greater effect on the overall ownership costs than the same proportional increase in the price of petrol would. EV battery costs are predicted to decrease as manufacturing increases, resulting in a reduction in EV price. New business models, based on car sharing or battery leasing are also developing to contend with the current high cost of EVs.

“Once EV prices drop below ICV prices, Hyder’s modelling shows considerable private net benefit from purchasing EVs... Most of the net benefit (91%) is accrued by the vehicle purchaser in terms of a lower long-run purchase price (inclusive of battery replacement costs), and lower fuel, electricity and maintenance costs” (Hyder 2009, p. 118).

EV conversions represent a good option for EV growth in NZ. Low cost producers of converted EVs can quickly enter the market and take advantage of international EV supply shortages as economic and market factors become favourable.

## Chapter 3 - NZ Regulations and Standards

### 3.1 Introduction - Why have Regulation for EVs in NZ?

The EV represents a new product paradigm. The additional risk posed by the introduction of new technologies is unknown. The question is, what is the risk to society with the introduction of new technology? The road environment is a place where all people from all societal and socioeconomic groups interact with one another, whether it be as pedestrians, cyclists, car drivers or bus operators. EVs and EV conversions will be involved in accidents (Figure 3.1) and they need to perform in at least a similar safety manner as ICE vehicles.



**Figure 3.1** A crash in Denmark between a Tesla Roadster (BEV) a Toyota Prius (HEV) and a VW Touareg (ICE) (Scardino 2009).

One hundred years of ICE car development has resulted in huge advancements in technology. The EV will have a different development route as we now have a high expectation of safety.

One way to assess the effect of a new technology is to look at the way it might be used. Hybrid electric vehicles are designed as direct substitutions for ICE vehicles

which currently dominate the vehicle fleet. Their operating characteristics allow them to be used for long distance travel on rural roads as well as in an urban setting. If all the current fleet were to be substituted by hybrid vehicle technology which had an equal inherent safety then you would not expect any change in road casualties. BEVs however, are likely to have a limited range and so are more likely to be operated for shorter trips in an urban setting.

Is regulation justified regulation for EV conversions? The current numbers of EV conversions are insignificant (less than 10 per year). So the risk to society is small. However it has been shown that the number of EV conversions could increase rapidly and it is important to have standards in place before they are really needed. EVs already fall into various aspects of law but EVs are not an exact fit and there is confusion about some areas as. Other important questions are; where should regulation be targeted? Who should pay the costs?

High volume production OEM vehicles need to go through stringent testing and certification to international standards in order to become part of the NZ vehicle fleet. The risk of these vehicles being unsafe is low as these vehicles will be purpose designed and rigorously tested. With these vehicles it is thus possible to adopt the international standards (discussed below) for EVs and allow importation and entry certification to be controlled by these standards.

With converted EVs however the technical risks are high, the risks of non compliance are high and the risks to OEM EV industry from bad publicity are also high. The MED have seen fit to regulate 230 V installations in campervans because the installation of solid core domestic wiring is not designed specifically for vehicles so the risks are higher. A 4 yearly Electrical Warrant of Fitness (EWOFF) is thus justified.

The safety engineering of new technologies is not always certain. This can be seen from a number of examples both in an out of the transport industry.

An example of unforeseen consequences in the large scale implementation of a new but simple technology occurred recently in Australia with the installation of aluminium foil in the ceilings of residential buildings. Poor installation practices led to major electrical safety issues causing fatalities. It was reported that; “The government relied on (insulation installation) guidelines partly formed by Standards Australia when it first introduced the scheme, but has since toughened the program's rules following the deaths of four workers ” [age.com.au](http://age.com.au) ,

17/02/2010). The Australian government is now in the position of auditing 48,000 homes which may have 'live' ceilings caused by an existing electrical fault or poor foil installation practice.

There is also a risk to the EV industry if EVs were seen to be dangerous as shown by the following example. This example is given to show that the introduction of new technology can cause confusion.

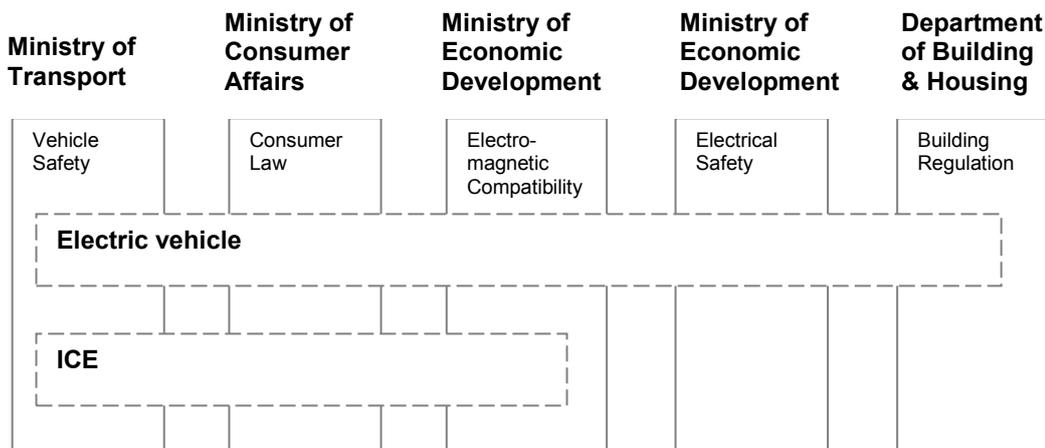
On 1 January 1996, New Zealand began to institute a completely unleaded petrol market by the introduction of premium unleaded fuel to replace the existing leaded 96-octane petrol. At the time there was great concern that the new fuel was the cause of vehicle fires as a result of rubber sealing components degrading. Garrett (1998) however, states;

“For most people a vehicle fire will be a once-in-a-lifetime experience. Therefore, given the widespread publicity linking vehicle fires and unleaded petrol during March-April 1996, it would be reasonable for anyone who changed from leaded to unleaded petrol and experienced a car fire around that time to infer a causal relationship ... On balance, it is unlikely that there was any increase in car fires related to the introduction of premium unleaded petrol into New Zealand in early 1996. Certainly there was nothing like the problem suggested by news media publicity at the time” (p. 328).

It is hoped that by implementing sensible regulation that a similar situation occurring with EVs would be avoided.

### 3.2 The Current NZ Regulatory Situation

The EV does not fit into the same regulatory framework as the ICE. EVs can be viewed as a completely new technology, or a mix of existing technologies. The EV can be interpreted as both an electrical appliance and a road vehicle as its operation is not confined to on road use. The ICE vehicle is essentially not operating when it is parked, a plug-in EV however is connected to the electricity grid and performs charging and other functions whilst it is parked. From this you can see that the EV will fit into a different regulatory framework and have a different safety profile from the ICE vehicle due to its use of different technology. EVs are also unique in the way they handle energy. Peter Morfee (2010) of the NZ Ministry of Economic Development (MED) Energy Safety Service explains: “...They (EVs) can move energy in both space and time. No other storage system can do this” (personal correspondence). Figure 3.2 below illustrates the regulatory silos that the EV and ICE belong to.



**Figure 3.2** Regulation silos.

This Figure shows that government regulators need to collaborate across many different areas to regulate for EVs. A government group comprising of Meridian Energy, Contact Energy, MOT, NZTA, EECA and MED (Energy Safety Service) representatives has already held informal meetings about EV safety.

### **3.3 Current Legislation**

EV safety is covered by two main areas of NZ legislation;

The first is vehicle safety standards which are covered by the Land Transport Rules administered by the New Zealand Transport Agency (NZTA). Under the Land Transport Rules, NZ accepts all vehicles made to European, Japanese, Australian or United States standards. The Land Transport Rules have number of additional clauses which affect EVs these are listed in Appendix 2. The second are the NZ electricity regulations the main regulation here being the Electricity (Safety) Regulations 2010. These regulations apply both when the vehicle is moving and stationary.

### **3.4 The Low Volume Vehicle (LVV) System in NZ**

The NZ Low Volume Vehicle (LVV) approval system is based on the European model of Individual Vehicle Approval (IVA). For a history of the development of the NZ LVV approval system see Johnson (2007). Under the European vehicle regulations each country within the European Union is permitted to have its own national IVA scheme to approve individually modified or scratch built vehicles. IVA approvals are only valid for the country in which they are issued.

The NZ LVV approval scheme is administered by the Low Volume Vehicle Technical Association (LVVTA) and is legally binding due to it being incorporated by reference in the Land Transport Rules (Johnson 2007). The concept of low volume vehicles and certification for such vehicles was not initiated until after 1991. Under the NZ LVV code up to 200 vehicles can be produced by a manufacturer in any one year<sup>3</sup>.

The process for approval involves certification of the vehicle by way of a survey of the vehicle to the relevant LVV Standard by a LVV Certifier appointed by the NZTA. Standards are jointly drafted by the LVVTA and the NZTA and are written using three different methods of certification; prescription based, performance based, and compliance. Compliance can also be shown via verification methods in some cases.

No LVV Standard for EV conversions currently exist however LVV certifiers have been using an unofficial document to certify vehicles which was developed

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<sup>3</sup> For more detail see: LVVTA (2004) Low Volume Vehicle Code- Issue 4. Terms and Definitions. p.22.

over 10 years ago. LVV EV certifiers as thus do not currently have the tools to do their jobs.

### **3.5 The EV - An Appliance or Connectable Installation?**

During the literature review and discussions with various people across the EV sector it became clear that confusion surrounds the status of EVs with regard to the issuing of an Electrical Warrant of Fitness (EWOFF) for EVs and EV conversions. The issuing of an EWOFF is well established for motorhomes and caravans that have a standard low voltage (230 V) connection under section 76 of the Electricity (Safety) Regulations 2010 (MED 2010). These EWOFF are issued for a period of four years after which they must be renewed. The standard AS/NZS3001:2008 Electrical Installations – Transportable Structures and Vehicles Including their Site Supplies is cited by MED (2010) as the applicable standard for EWOFF certification.

Although EVs converters have also been obtaining 4 yearly EWOFF for their completed conversions, it is unclear whether EVs are ‘connectable installations’ or ‘electrical appliances’. This is because the scope of AS/NZS3001:2008 (Standards NZ 2008), does not specifically state that the standard is applicable to EVs, and instead focuses on vehicles with accommodation or other commercial purposes that requires a 230 V electricity supply.

This area requires clarification by the authorities concerned. If EVs are found to be ‘connectable installations’ and as such do need a EWOFF every four years, this would also apply to imported OEM EVs as the Electrical Safety Regulation (MED 2010) makes no distinction whether the vehicle or electrical system is homebuilt, professionally built or imported (or a LVV for that matter). Furthermore as cited by the regulation, the standard requires that;

“...a person must not hire or lease out, or offer to hire or lease out, a vehicle, relocatable building, or pleasure vessel that contains a connectable installation unless the connectable installation has a current warrant of electrical fitness” (Med 2010, p. 55. Section 77(1))

The Passenger Service Vehicles (PSV) Rule Section 6.5 also has requirements for ‘electrical equipment’ fitted to PSVs and here it is clear high voltage traction system is included as it makes mention of ‘Trolley-booms and heads’ which are traction components of trolley busses.

The Electrical Safety Regulation thus would require vehicle rental and taxi companies to obtain an EWOFF for vehicles that charge from the grid. A situation could arise whereby two OEM HEVs from the same manufacturer, one of which is a PHEV the other a non-depleting HEV, have different electrical certification requirements whilst having a very similar risk profile. It seems from this research that the requirement for a EWOFF for EV conversions has been adopted by the certification community without it being an actual legal requirement. One LVV certifier told the author that he requires a copy of the EWOFF before the LVV (mechanical) certification is issued however a Warrant of Fitness (WOF) testing station does not require or check for an EWOFF before issuing a WOF or Certificate of Fitness (COF) to a motor home or caravan.

One option is to continue to require EWOFF for converted EVs (home or professionally built) but not for OEM EVs. These areas however, need urgent clarification in both electrical and transportation law as to the intent of the regulations to avoid further confusion. Further research is required to ascertain how this issue has been resolved internationally.

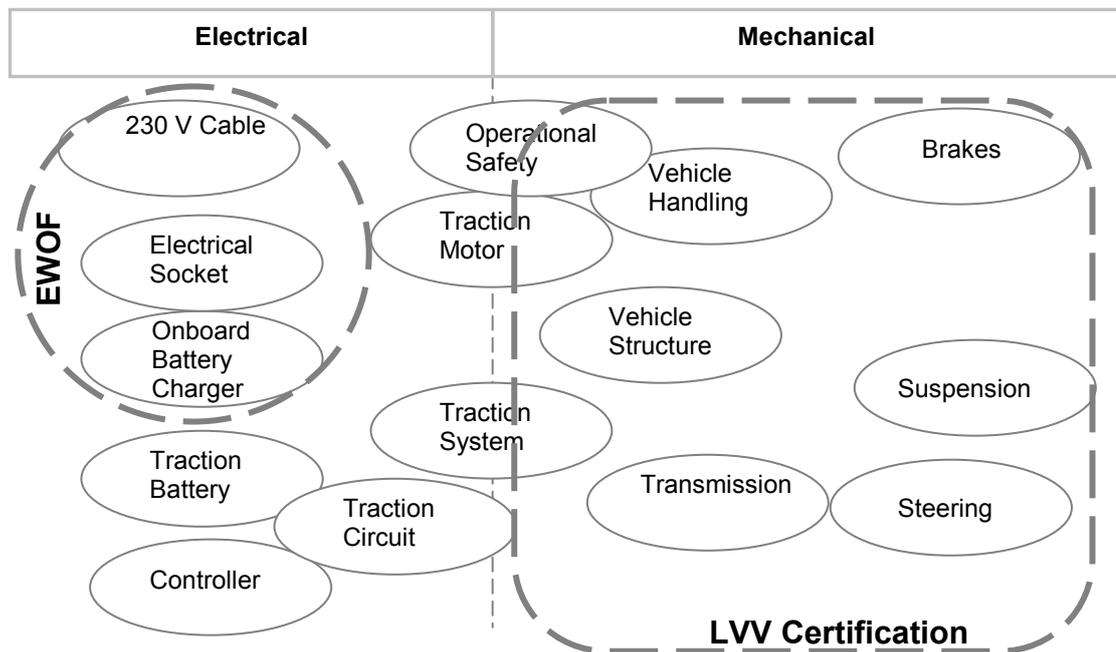
The Electrical Safety Regulation has defined the building and maintenance of EVs to be not 'prescribed electrical work' requiring an electrical registration. Working on homebuilt EVs thus does not come under the jurisdiction of the Electrical Workers Registration Board (EWRB) even though the traction systems in these vehicles may have voltages in excess of 600 V (MED 2010).

### **3.6 Mechanical and Electrical Certification of Low Volume Vehicles (LVVs)**

The LVVTA provides training, technical support and all necessary LVV documentation to the LVV certifiers. LVV certifiers for EVs must be appointed as a Category 4 (Electric Vehicles) certifier. It can take a number of years for an automotive trade certificate holder to achieve this.

There is currently no published LVV standard for EVs in NZ. Converted EVs however are being certified to the LVV code using an unpublished document the; Code of Construction & Inspection Forms for Electric Vehicles, released March 1997 by the NZ Hot Rod Association (Inc).

The LVV certification of EV conversions involves assessing the properties of a number of technological systems which are shown in Figure 3.3 over the page.



**Figure 3.3** Some inspection criteria for EV conversions and the respective NZ certification systems

During interviews with EV converters and certifiers it became clear that parts of the vehicle were not being inspected by either the electrical or LVV inspector. The dashed cells show the certification areas covered by the two different EV conversion certifications currently in use. EWO inspections tended to cover only the entry of 230 V cable into the vehicle and its wiring to the onboard charger. Not the battery or traction circuit. This is a potential safety issue as neither the LVV (mechanical) or the EWO (electrical) certifier have the training to inspect these particular areas and due to the small numbers of EVs being currently certified, there is not much chance to learn.

It is unclear who is certifying what. The new LVV standard for EV conversions must thus clarify the roles and demarcations of the certifiers involved in complying the vehicle. Many of the mechanical areas of an EV conversion are covered by existing LVV standards and thus should not be repeated. One option is to bring the electrical areas into the LVV specialist certification – making it part of the vehicles standards (transport) legislation rather than electrical (as with the

Passenger Service Vehicle (PSV) Rule). Training can then be provided specific to EV electrical systems.

During interviews it was discovered that the EV conversion community are extremely nervous about new regulation regarding EV LVV certification. Lengthy discussions are summarised by the fact that EV home builders do not want any regulation that increases the cost of building an EV, complying an EV or running an EV. It is strongly advised that the EV community form a national advocacy group so as to be involved in any standards formation process.

### **3.7 The Motor Vehicle Register**

The purpose of the NZ motor vehicle register is manifold; it enables vehicles to be taxed and statistics on the vehicle fleet to be gathered. Using these statistics it should be possible for lessons to be learned from field failures and accidents which can be utilized and incorporated into test protocols so that their effects can be understood and mitigated in the future. During this research it was discovered that there is currently no way of identifying EVs in the NZ vehicle fleet King (2007) also identifies this). It is possible to search model name however this might obscure the main energy source of the vehicle. Future research in the area of EV safety will depend on data being available on the accident rates of EVs. Changes must be made to the motive power classifications in the motor vehicle register these should include classifications for ICE, BEV, HEV, and PHEV. Future taxation schemes for EVs in NZ will also need this information as discussed by King (2007).

## **Chapter 4 - International EV Regulations and Standards**

### **4.1 Introduction**

As a guide when discussing standards for EV conversions it is useful to have knowledge of the international safety requirements for EVs. Currently there are many standards published for EVs and EV components internationally. Bossche (2003) gives a detailed discussion of the development of EV standards between the late 1800s to 2003. The standards relating to EV safety are published by leading standards organisations such as UNECE, ISO, IEC and SAE. The main vehicle standards from the leading standards organisations are reviewed in this section. Standards for EVs are subdivided into the following groups;

- Vehicle
- Battery
- Electric supply - recharging devices
- EV components
- Electromagnetic Compatibility (EMC)

The standards are generally focussed on either;

- design requirements or
- testing protocols

The standards discussed here are EV vehicle standards rather than battery standards. EV battery standards are discussed in more detail in Chapter 7. The design of electrical components have there own traditions which might not be adhered to in the new paradigm of EVs and so a number of international EV component standards have also been published.

### **4.2 UNECE Regulations**

NZ already recognises an international regulation relating to EVs as NZ is a Contracting Party to the UNECE agreement on the harmonisation of vehicle regulations, Geneva 1958. Over one hundred UNECE vehicle regulations are in force including seven UNECE regulations with specific requirements for EVs as identified by Bossche (2003). UNECE Regulation 13, Uniform Provisions Concerning the Approval of Vehicles of Categories M, N and O with Regard to Braking is discussed further in Chapter 8 on braking issues. The UNECE

regulation specifically concerning EV safety is Regulation No. 100, Battery Electric Vehicles Safety. The regulation addresses three areas;

1. *Traction battery safety*. This section gives requirements for ventilation, electrical fusing, insulation resistance and a detailed hydrogen emissions test.
2. *Functional safety*. ECE 100 specifies a number of requirements, all of which can be found in the EV safety standards (ISO 6469 and EN 1987) which are discussed below. The concordance between the regulation and the standards is very good and any vehicle which complies with the standards will also comply with the regulation (Bossche 2003). The regulation gives requirements for protection against direct contact and bonding of conductive components.
3. *Protection against electric hazards*. For voltages below 60 VDC or 25 VAC, no specific protection is needed. Unlike the standards discussed below, ECE R.100 has a number of charger interlock and safety requirements

There is a strong argument that UNECE R.100 should become familiar to EV converters as this regulation is available free of charge.

#### **4.3 ISO 6469:2009 Electrically Propelled Road Vehicles – Safety Specifications**

ISO 6469 is a vehicle based standards that, like UNECE R100, comes in three parts.

*Part 1; On-board Rechargeable Energy Storage System (RESS).*

Part 1 gives requirements for battery systems up to 1000 VAC, the marking of hazardous voltages, insulation resistance and battery ventilation requirements.

*Part 2; Vehicle operational safety means and protection against failures.*

Part 2 specifies requirements for functional safety means and protection against failures related to the specific hazard of the electric propulsion system of battery-electric passenger cars and light commercial vehicles. Various switching is controlled to prevent unintentional behaviour of the vehicle including the requirement for two distinct control actions for power-on and reversing.

*Part 3; Protection of persons against electric hazards.*

Part 3 requires that protection against direct contact shall be provided either by basic insulation of live parts, by barriers/enclosures, or both. The standard gives requirements for enclosures as well as stating requirements and testing for protection against water effects (Bossche 2003).

#### **4.4 IEC Standards**

The International Electrotechnical Commission (IEC) is the international standards and conformity assessment body for all fields of electro-technology. The IEC has published some EV vehicle standards as well as many component based standards addressing areas such as wiring and connections, instrumentation, motors, controllers as well as battery and charging standards (Bossche 2003).

#### **4.5 FMVSS 305 (US) Electric Powered Vehicles**

##### **Electrolyte Spillage and Electrical Shock Protection**

This standard specifies requirements for limitation of electrolyte spillage, retention of propulsion batteries during a crash test, and electrical isolation of the chassis from the high voltage system. This regulation gives good post crash measurement procedures (FMVSS 2009).

#### **4.6 Society of Automotive Engineers (SAE)**

The SAE is an industry association which has published a large number of automotive standards and design guidelines including over 20 standards relevant to EVs with many others in active development. The standards include;

- EV and HEV performance standards
- EV safety
- Battery - Hydrogen emissions, battery crash testing, battery modules, battery performance, lifecycle testing, pack functional guidelines, vibration, and abuse testing.
- Electrical - HV cables, HV wiring assemblies and HV connectors.
- Charging infrastructure – conductive charging, Inductive charging, energy transfer system.
- Electromagnetic Compatibility (EMC)

SAE J2344: Guidelines for Electric Vehicle Safety is reviewed in relevant sections of this thesis. (Bossche 2003) gives a summary as follows. The SAE 'standards' are more stringent than the UN regulations however the SAE are

guidelines not standards. International OEM manufacturers generally comply with the more stringent SAE guidelines.

#### **4.7 UL Underwriters Laboratories**

Underwriters Laboratories Inc. (UL) is an independent, not-for-profit product safety testing and certification organisation. (Bossche 2003) and (Tabaddor 2010) give an overview of the UL standards relevant to EVs. It seems likely that UL 2580 - Batteries for use in Electric Vehicles will become an important battery safety standard for EV manufacturers when it is published in 2011.

#### **4.8 Japanese Electric Vehicle Association (JEVA)**

The JEVA has published over 20 standards, some of them only available in Japanese. (Bossche 2003) gives a brief description of these.

#### **4.9 NCOP 14 National Guidelines for the Installation of Electric Drives in Motor Vehicles (Australia)**

No Australian Design Rules (ADRs) for type certification of EVs exists in Australia. The Australian individual vehicle approval scheme is based on the documents of the National Code of Practice for Light Vehicle Construction and Modification (NCOP). The code of practice relevant for EV conversions is NCOP 14 - National Guidelines for the Installation of Electric Drives in Motor Vehicles (NCOP14 2011). Newly published, this is the most up-to-date and local document available. The standards covers – Electrical technical and safety requirements, mechanical technical and safety requirements and other requirements such as pedestrian safety. The standard covers much of the ground of the international EV standards as well as a clause on the battery management requirements of lithium chemistries. This standard provides a good model for NZ.

#### **4.10 UK Single Vehicle Approval (SVA)**

The UK SVA manual covers the requirements for modifying vehicles in the UK. It does not have any requirements for EV conversions.

#### **4.11 The Work of Standards Australia**

Standards Australia is actively addressing EV standardisation. The preliminary work undertaken is described in Standards Australia scoping study (Lazar 2009). In discussions with the author, whilst any published standard is some time away, it seems likely that a standard for EV conversions is high on the agenda and it is recommended that Standards NZ and the LVVTA become active in this process. This process could result in a standard that could be adopted as a LVV standard in NZ.

## **Chapter 5 - EV Technology Safety Risk Assessment**

### **5.1 Introduction**

The purpose of this section is to use a formal method of risk assessment to identify the most important aspects of EV safety in the context of the converted or modified vehicle. The formal risk management process which will be used is outlined in AS/NZS ISO 31000:2009 Risk Management – Principles and Guidelines (Standards NZ 2009). This risk management process establishes systematic practices for risk management, including application to specific projects. Guidance from (Ashtiani 2007) was used as he gives a procedure for risk analysis, assigning a Hazard Risk Number (HRN) to quantify identified risks and applying hazard controls to reduce risk. Morfee (2010) has also been referred to in regard to applying a risk assessment model to design a regulatory system for electrical products in NZ.

### **5.2 Definitions**

This section will look at the risk of new EV conversion technology entering the NZ market. Risk here is defined as a negative deviation from the expected objective of ‘safe EV use in NZ’. Risk assessment concerns include ‘risk’ that directly effects the general public including safety concerns, but not ‘organisational risk’ to potential EV governing agencies such as the MOT, NZTA and other government departments.

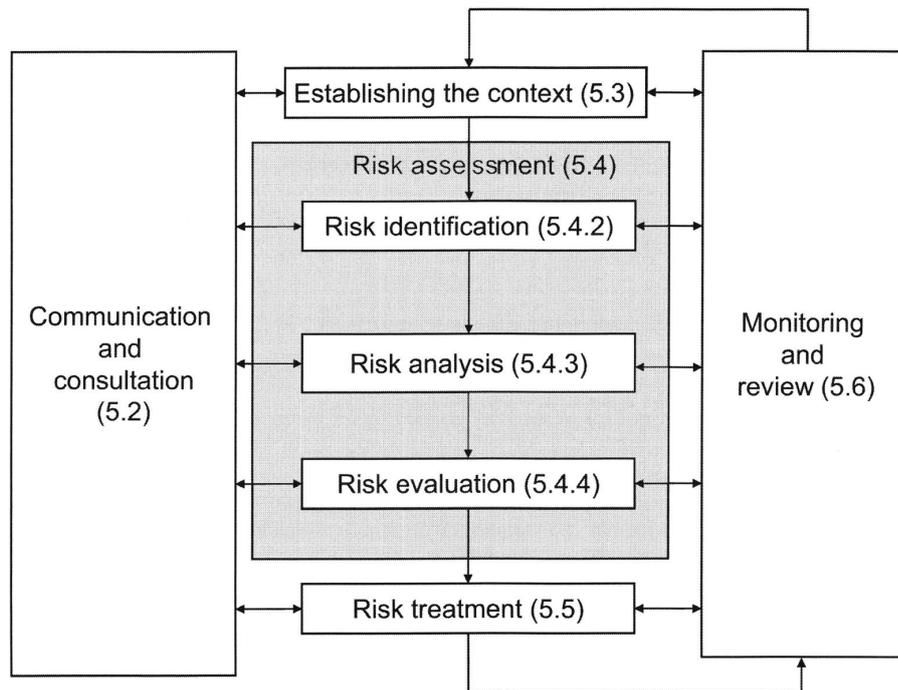
### **5.3 Assumptions**

In the context of adopting a new technology such as converted EVs, this assessment is confined to the ‘current point in time’, as technology is moving fast in this area. There is a need to keep the risk profile up to date as new information becomes available. Risk management is an iterative process which includes monitoring review and continual improvement of the framework. With this project it is not possible to achieve an iterative approach as given in AS/NZS ISO 31000 due to research constraints. In order to achieve a fair assessment of the likelihood of a risk event therefore, it is assumed that large numbers of converted vehicles (>10,000) will be in use on NZ roads. This is necessary as the number of converted EVs in NZ is currently so small that risk event likelihoods are negligible.

As information on the risk profile of new products is not freely available due to commercial confidentiality of test data, the following risk assessment provides an educated guess of the risk of EV technology. This assessment will change once the product is used publicly and risk data is collected and analysed.

### 5.4 Methodology

Figure 5.1 shows the risk management process. This project will limit the scope to the highlighted area, risk assessment (5.4).



**Figure 5.1** The risk management process. From AS/NZS ISO 31000:2009 Risk Management.

Firstly, safety risks of EVs will be identified. It is important to be exhaustive with this step as any risks not identified at this stage will not be able to be included in the risk analysis. In the following analysis values expressing the results of an engineering assessment of risk are far from firm. By analysing and calculating the risks in this manner however, they can at least be better understood and focus attention on the most important matters. Ashtiani (2007) defines the hazard risk of an event as follows:

$$HRN = L \cdot S$$

Where *HRN* is the Hazard Risk Number, *S* is the Severity or consequences and, *L* is the Likelihood of occurrence of a risk event. The severity and likelihood levels used are chosen from the Tables 5.1 and 5.2 below:

<b>S</b>	<b>Description</b>	<b>Criteria for Severity Classification and Effects</b>
0	No effect	No effect, No loss of functionality
1	Reversible Loss of Function	No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Temporary loss of battery or vehicle functionality. Resetting of protective device needed.
2	Irreversible Defect/Damage	No leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Vehicle or battery irreversibly damaged. Repair needed. No injury.
3	Leakage $\Delta$ mass < 50%	No venting, fire, or flame; no rupture; no explosion. Weight loss <50% of electrolyte weight. Light smoke (electrolyte = solvent + salt).
4	Leakage $\Delta$ mass $\geq$ 50%	Venting; No fire or flame; no rupture; no explosion. Weight loss $\geq$ 50% of electrolyte weight. Heavy smoke (electrolyte = solvent + salt).
5	Fire or Flame	No rupture; no explosion (i.e., no flying parts). Risk of injury or severe injury.
6	Rupture Severe failure	No explosion. RESS could disintegrate but slowly without flying parts of high thermal or kinetic energy. Risk of severe injury or death
7	Explosion Catastrophic failure	Explosion (i.e., disintegration of the RESS with externally damaging thermal & kinetic forces). Exposure to toxic substances in excess of OSHA limits. Likelihood of death

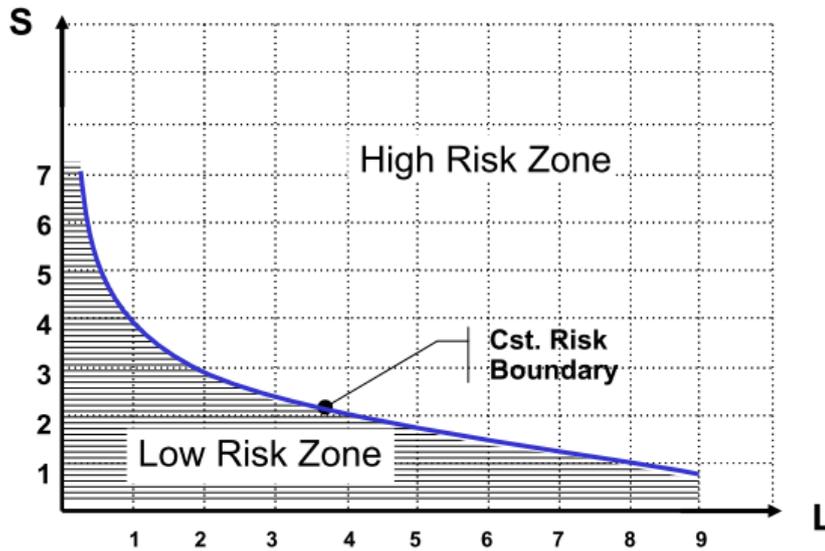
**Table 5.1** Severity levels, adopted and modified from Ashtiani (2007)

<b>L</b>	<b>Rate of occurrence Ppm (%)</b>	<b>Description</b>
10	100,000 (10%)	Extremely High
9	50,000 (5%)	Very High
8	20,000 (2%)	High
7	10,000 (1%)	Above Average
6	5000 (0.5%)	Average
5	2000 (0.2%)	Below Average
4	1000 (0.1%)	High Low
3	500 (0.05%)	Average Low
2	100 (0.01%)	Low
1	10 (0.001%)	Very Low

**Table 5.2** Likelihood levels adopted from Ashtiani (2007)

Once the risks are characterised by the Hazard Risk Number (*HRN*) and identified in the risk space (a plot of *L* vs *S* shown in Figure 5.2) unacceptable risks can be detected and decisions made on how to control the risks. Severity and likelihood cut-offs can be defined as threshold limiting values to control unacceptably high

severity events (consequences) and unacceptably high likelihood events (unreliability).



**Figure 5.2** The risk space (Ashtiani 2007).

Risk controls are assessed by putting forward a control measure and evaluating the impact of that control by representing it with a number in the range of [0 1] called the Hazard Control Number (*HCN*). The risk reduction is then represented by a modification of the *HRN* as follows:

$$HRN_c = L S (HCN)$$

*HCN* values suggested by Ashtiani (2007) are given in Table 5.3 below:

<b>HCN</b>	<b>Description</b>
0.9	Modest Risk Reduction
0.8	
0.7	
0.6	Above Average Risk Reduction
0.5	
0.4	Notable Risk Reduction
0.3	
0.2	
0.1	Significant Risk Reduction
0.0	Prevention

**Table 5.3** Hazard Control Numbers

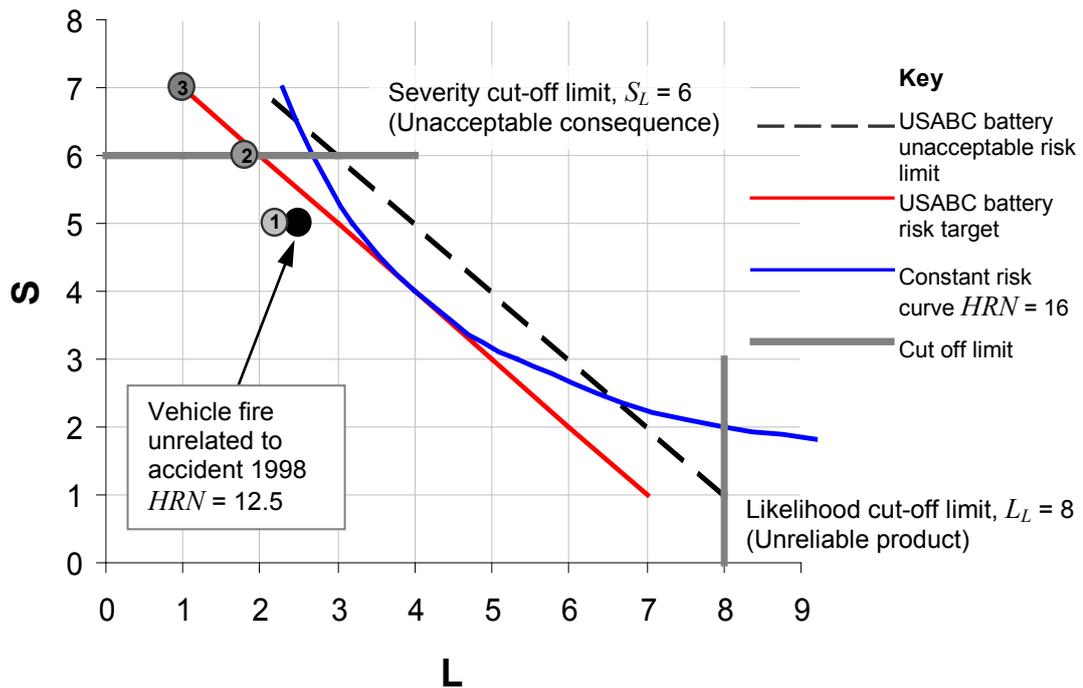
## 5.5 Evaluating the Risk Space

In risk management it is important to begin with what is known as there is currently minimal data on EV accidents. For this reason, it was decided to review some ICE risks which have similar failure modes to the failure modes possible with the EV. The objective is then to compare the possible severity and likelihood of the EV risk event against that of the known risk data for the ICE vehicles and then arrive at an assessment of the *HRN*.

Although a major objective is to eliminate all risk associated with vehicle use, some level of risk has to be accepted with the current use of petrol in vehicles. As a method of assessing the current risk of the use of petrol in vehicles I have used the vehicle fire as a risk event due to the availability of statistical data and the fact that during this research, similar safety issues have been identified for EV batteries. The risk of vehicle fire unrelated to vehicle accident is thought to be a function of fuel use risk and system reliability (older vehicles are over-represented in vehicle fires) (Garrett 1998). The likelihood of vehicle fire in NZ can be evaluated by using the data collected by Garrett (1998) which suggests that in NZ each year, there are about 900 vehicle fires unrelated to accidents or theft. Using a value of 2.7 million licensed vehicles in New Zealand in 1998 the likelihood of a vehicle fire is 333 ppm giving an *L* value of approximately 2.5. The severity of such a fire was assessed as  $S = 5$  giving an *HRN* calculated to be  $HRN = S L = 12.5$ . This is plotted in Figure 5.3.

Data from the Pedestrian Crash Fact Sheet (MOT 2009) and the NZ Vehicle Fleet Data Spreadsheet (MOT 2010) was also used to calculate the risks of pedestrian injury and fatality on a per vehicle basis (see Appendix 3). The results are also plotted in Figure 5.3 below.

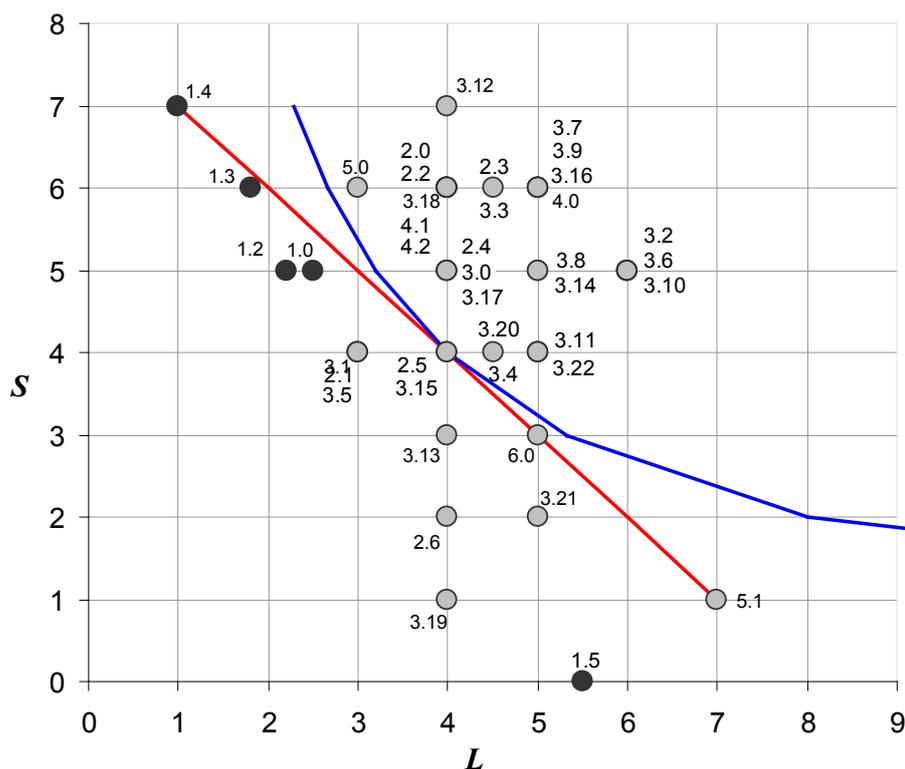
Furthermore, in July 2007 the United States Advanced Battery Consortium (USABC) published tables in its safety gap analysis to help EV battery manufacturers to better design and develop batteries for automotive propulsion applications. The safety requirements provide targets (limits) in terms of *HRN* as a minimum safety requirement for batteries (Ashtiani 2007). These limits have been also plotted in Figure 5.3 along with a hyperbolic curve representing a constant-risk contour is defined by the hyperbola:  $S L = 16$ . Later these *HRN* values will inform the assessment of *HRN* values for EV risk events.



**Figure 5.3** The risk space for vehicle risk events in NZ. 1. Pedestrian minor injury ( $HRN = 11$ ), 2. pedestrian serious injury ( $HRN = 10.8$ ) and 3. pedestrian fatal injury ( $HRN = 7$ ) - 2008.

### 5.6 Risk Analysis

The specific risk events and controls described in the Figures that follow will be discussed throughout this thesis. The risk assessment is a summary of findings and an attempt to justify specific risk levels and control measures in the absence of hard data. The risk analysis was carried out using a risk control matrix which is presented in Appendix 3. The risks of various events in Appendix 3 was estimated and plotted in the risk space in Figure 5.4 below.



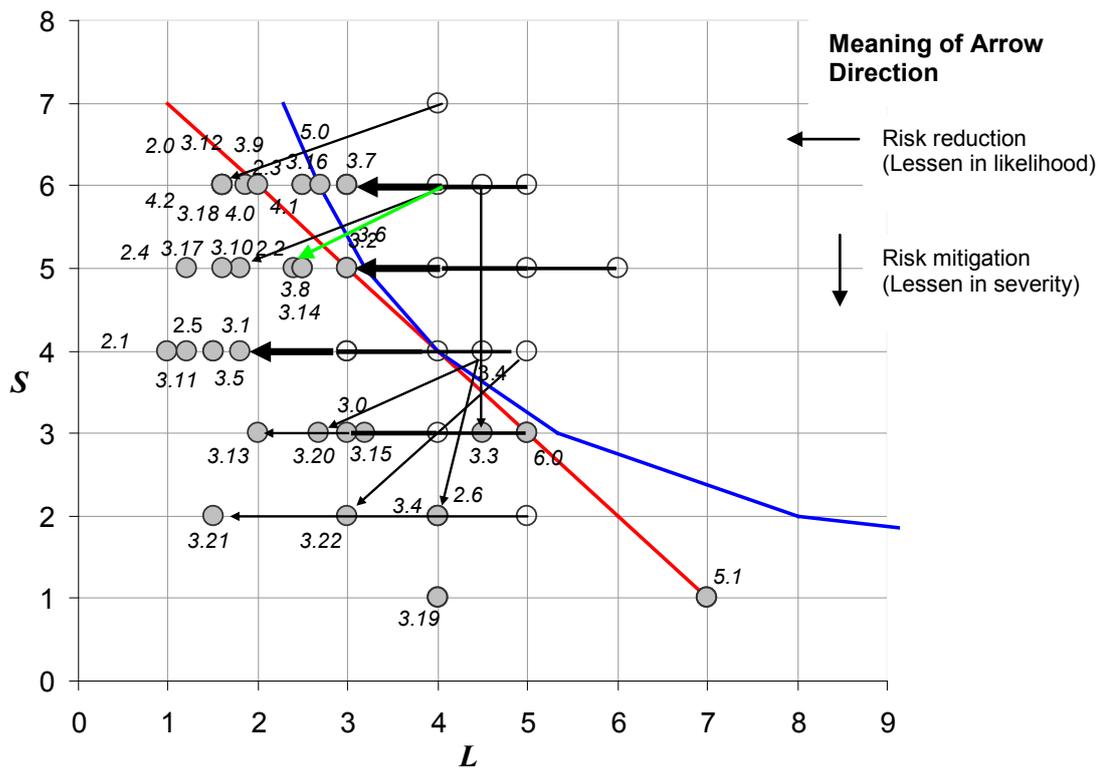
**Figure 5.4** Risk space for EV conversion risks.

Risk controls were then applied and the risks recalculated and re-plotted in Figure 5.5 below. For example the point 2.2 in Figure 5.5 above represents the risk of fire during charging which is assumed as (6 , 4.0). Appendix 3 shows the risk controls applied to this and an excerpt is given in the Table 5.4 below.

Risk ID - 2.2		$S$	$L$	$HRN$	Risk controls		$\frac{HC}{N}$	$HRN_c$	$S_c$	$L_c$
	Fire during charging	6	4.0	24	Use correct charger, BMS over temp cut-off switch	Use LA or LiFePO <sub>4</sub> battery chemistry	0.5	12	5	2.4

**Table 5.4** Excerpt from Appendix 3, Risk Control Matrix. BMS – Battery Management System. LA – Lead Acid.

The risk controls result in a modified Severity and Likelihood,  $S_c$  and  $L_c$  (5, 2.4). It is this controlled risk that is plotted in Figure 5.5 below. The risk of fire during charging with the risk controls above in place is now  $HRN_c = 12$ . The reduction in risk is shown by the green arrow in Figure 5.5 below.



**Figure 5.5** Risk space for EV conversion risk controls. See Appendix 3 for details.

As shown above most of the risks have been reduced to acceptable levels by the control measures proposed. It is interesting to note that most of the control measures result in a reduction in likelihood rather than a reduction in event severity (horizontal rather than vertical shift in risk). This means that the potential for high severity events still exist with EV conversions, however focus must be placed on reducing the likelihood. The controls must be robust and based on reliable measures to reduce the risk sufficiently. To achieve this robustness the control measures are recommended to have design characteristics such fault tolerance and redundancy. This design philosophy is shown by Prakash (2010) of Reva Electric Car where the Reva BMS has two (2) levels of protection for;

- over-temperature, b. over-voltage, and c. under-voltage, with further protection given by the power inverter as regeneration over-voltage and drive under-voltage protection (Figure 7.5).

A further note on risk management and public policy is made by discussing risk acceptability.

## 5.7 Risk Acceptability

Risk quantification cannot measure 'risk acceptability'. Decision makers must judge the benefits, resources and other factors such as public opinion. The perception of risk and the values of society must also be taken into account when making decisions about regulating a technological system. Griffiths (1982) argues that individual risk decisions are made by evaluating the following tradeoffs;

- (a) some benefit is gained by the individual at risk
- (b) everything reasonable (in whatever definition) is done to reduce it and
- (c) the individual then judges that he has a good bargain.

However, if some of the risks created by the individual are transferred to the public (as is the case with LVV EVs used on public roads) formal intervention may be needed if the risk can cause harm. Regulators must then make similar risk decisions where some judgement of 'risk acceptability' is implied by the legislation. These value judgements are essentially political decisions which cannot and must not be replaced by calculation (Griffiths 1982). Instead it is important to understand the issues which have particular relevance to the political space of converted electric vehicles in NZ. These are listed below:

### *Support for Regulation*

- ICE vehicles have an established history of car development and the public expectation of safety is high. The development of regulation for EVs can help to maintain and improve public road safety with EVs as part of the transport system.
- Regulation will help mitigate against poor public perception of safety in regard to EVs. This will make the 'market' for EVs stronger, and increase vehicle choice for consumers.

### *Against Regulation*

- Too many economic implications that impose safety measures can inhibit the growth of EVs in NZ. The question is how can we support the maintenance of high safety standards without it being an hidden tax on new technology (Griffiths 1982)?
- Currently there is 'freedom' to build EVs in NZ and use these without too much hindrance by regulations. During interviews it was found that the

EV conversion community in NZ is strongly opposed to the development of more LVV regulation.

- EVs benefit the NZ transport system by reduced vehicle emissions and offer potential savings directly to the vehicle user (Hyder 2009).

It would be great if NZ were to have a burgeoning EV conversion industry that produced safe, reliable and high performance vehicles. It should be the intention of future regulation to not inhibit the possibility of this happening regardless of how unlikely an EV industry in NZ may seem at present.

### **5.8 EV Risk Summary**

Figure 5.5 shows that the majority of risks associated with EV conversions are controlled by a reduction in the likelihood of a risk event occurring. This is shown by the majority of the risks moving from right to left rather than from top to bottom. With this type of risk it is important that the control is reliable as the severity level is still high. This reliability can be increased by system redundancy and/or component de-rating. Yang (2010) discusses a multi level approach to preventing thermal runaway in EV battery systems. This will be discussed further in Chapter 7 which discusses batteries.

## **Chapter 6 – EV Electrical Systems**

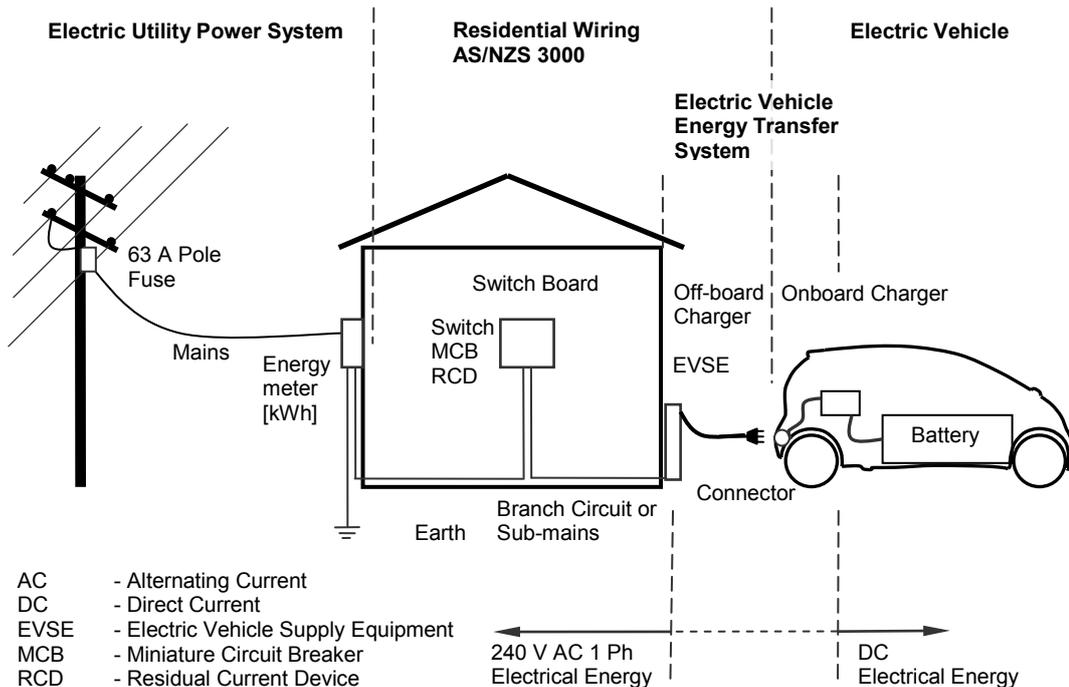
### **6.1 Introduction - Vehicle Safety Design for EV Conversions**

There are many simple things that EV converters can do to increase the safety of the finished vehicle. Many parts of the EV conversion can follow standard automotive engineering practice and incorporate available guidelines such as LVVTA Standards and the Hobby Car Technical Manual (Johnson 2007). What needs to be noted however, is that some engineering issues are unique to EVs and need specific attention to detail to minimise risk. The three major areas of risk for EV conversions identified by this project are; the electrical system, the traction battery and the braking system which will be discussed in that order.

You can expect EV converters to be highly innovative when designing and building conversions. It is not the purpose of this section to stifle innovation, but to put forward suggestions on the current best practice in EV safety design and to provide examples of how OEM EV manufacturers are solving the many new safety issues concerning EVs. This current Chapter will discuss EV electrical issues.

## 6.2 Background of the EV Electrical System

The following section on electrical safety for EVs takes a large portion of its recommendations from the EV standards such as ISO 6469. An EV electrical system can include a number of components that are not onboard the vehicle. Figure 6.1 describes the major components included in the 230 V electrical system in NZ.



**Figure 6.1** Typical NZ residential situation showing components of the EV electrical system. Telecoms and smart grid communication and control systems are not shown. Adapted from Bossche (2003) (p. 296).

The rating of EV supply equipment is thus concerned with all three parts;

- the utility infrastructure,
- domestic wiring and
- the electric vehicle.

NZ uses a 230 V Multiple Earth Neutral (MEN) electricity system where the neutral conductor of the distribution system is earthed at the source of supply, at regular intervals throughout the system and at each electrical installation connected to the system (StandardsNZ 2007). The EV traction circuit on the other hand uses a ‘floating’ traction circuit with a traction battery (DC), cables, motor

and other components isolated from the chassis of the vehicle and earth. The chassis is grounded during charging. The Table 6.1 below shows the system voltage classifications for the NZ electricity supply and the major international EV standards.

<b>Voltage class</b>	<b>DC Systems [V]</b>	<b>AC Systems [V] rms</b>
NZ Extra low voltage	$< 120$ <sup>1</sup>	$< 50$
NZ low voltage	$120 < V < 1500$ <sup>1</sup>	$50 < V < 1000$
NZ high voltage	$> 1500$ <sup>1</sup>	$> 1500$
NZ, PSV Rule 31001	$> 115$	$> 32$
SAE J2344	$> 60$	$> 30$
ISO 6469 class A	$0 < V \leq 60$	$0 < V \leq 25$ <sup>3</sup>
ISO 6469 class B <sup>2</sup>	$60 < V \leq 1500$	$0 < V \leq 1000$ <sup>3</sup>
FMVSS 305		$> 48$
UNECE R.100 'High voltage'	$60 < V < 1500$	$30 < V < 1000$
NCOP 14 (2011) HazV	$> 60$	$> 25$

**Table 6.1** Voltage classes of electric circuits.

<sup>1</sup> Ripple free DC

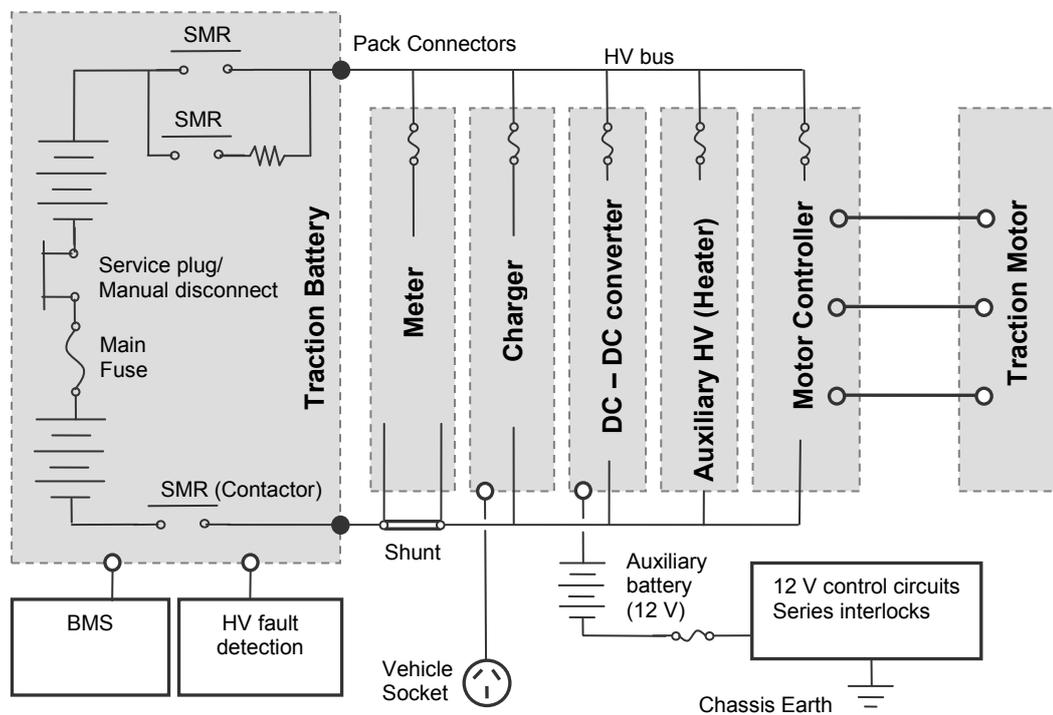
<sup>2</sup> Taking into account humid weather conditions

<sup>3</sup>  $\leq 10$  % ripple voltage (rms)

This Table shows that the NZ regulations have good consistency with the EV standards except for in the low voltage DC area. EV traction motors typically require 300 V or higher to provide sufficient motive force as required in full hybrids, EVs, and PHEVs (Pistoia 2010). Appendix 5 gives some traction system voltages for vehicles that are commercially available. The 2010 Toyota Camry Hybrid has a 650 V three phase traction circuit supplying the motor. Most EV conversions however, do not currently reach that voltage level with 60 – 144 volts being typical. With a large number of EV conversions below 120 V DC, the traction system then does not need to have an EWOFF. Higher voltages are beneficial as less current is required and thus smaller cables can be employed and reduced battery charging time is needed. Doubling the voltage will reduce the current by half and thus reduce the effective size and weight of the wiring installed (Pistoia 2010). We would expect EV conversion voltages to increase as EV conversions become more sophisticated/performance orientated.

The question of demarcation between brushless DC, which employs a series of pulses to the motor and AC which employs a waveform is answered by ISO6469-3 (2001). ISO6469-3 (2001) gives a definition; for non AC but repetitive pulse voltages if the peak duration is above 10 ms, the considered working voltage is then the max peak value. If the peak duration is less than 10 ms, the working voltage is then the RMS value (ie AC) (ISO6469-3 2001). Brushless DC motors can thus be regarded as ‘switched DC’ and not AC if they fall into the above definition.

Figure 6.2 shows a typical schematic of an EV traction and charging circuit.



**Figure 6.2** An example of a typical EV electrical circuit schematic.

### 6.3 EV Electrical Safety Hazards

EVs contain potentially hazardous levels of electrical voltage and current. It is important to protect people from exposure to uncontrolled releases of energy in normal and abnormal operating conditions. Electrical isolation is achieved through physical separation however, certain abnormal events such as impact, maintenance or wear can occur and lead to a degradation or failure of this isolation. If or when electrical components fail it is essential that they fail in a safe manner. ‘Fail to safe’ design should be considered. Both the ISO and SAE

standards have the requirement that a single-point failure of hardware, software or trained personnel to follow instructions should not result in an unreasonable safety risk (ISO6469-2 2009; SAE 2010).

The electrical hazard presented by the EV traction system is unique due to the battery size and the fact that you cannot turn a battery off. It is also not possible to ascertain the battery state from its external appearance without using measurement equipment. As EV traction batteries store a large amount of energy and are a low impedance energy source, a large energy release should be expected when short circuited. Even after disconnection of the battery the High Voltage (HV) hazard persists as lethal levels of electric energy are still present in the battery pack, and could also persist for some time within EV components due to capacitance. It is of utmost importance that an EV battery pack be treated with the same caution and respect as a full gasoline fuel tank in an internal combustion vehicle (Dhameja 2002). The design and management of the HV and high current traction system for EVs thus requires careful consideration.

The EV electrical system presents three major safety hazards for people (Pistoia 2010);

1. electrocution,
2. arcing resulting in ignition (fire) and
3. arc-flash (burns).

### **Electrical Safety**

The primary passive protection measures against EV electrical hazards are isolation and earthing. Protection against direct contact is provided by restricting access to live parts (this should only be possible with voluntary action) and protection against indirect contact is ensured by using insulation and by galvanic connection of exposed conductive parts (bonding or earthing). Secondary protection measures are provided by active devices such as a variety of automatic disconnects.

### **6.4 Isolation Breakdown Hazard**

The electrical systems of EVs are exposed to large fluctuations in temperature, a high level of vibration and may also be exposed to a variety of conductive contaminants. Electrically conductive fluids may be generated within the engine

compartment during abnormal operation or from environmental conditions such as rain, snow, and salt spray. Exposed high-voltage terminals may create arcing and arc-flash hazards. These electrically hazardous conditions may be exacerbated by a collision or accidental dropping of metal tools on exposed HV terminals or improper use of measuring instruments, such as low-cost multimeters resulting in arcing which can spray hot metal and cause burns and fire (Pistoia 2010). The following sections will discuss best practice solutions to the above issues.

### 6.4.1 Insulation

Isolating the HV system is a matter of specifying the correct insulation and providing appropriate separation and enclosure. Figure 6.3 gives an example of poor practice.



**Figure 6.3** EV conversion. A series string of 7 lead acid modules of 12 V each giving 84 V between the front and rear terminals. This arrangement, without terminal insulators, could conceivably be short circuited by somebody jumping on the bonnet of the car. The hazardous voltage (by some definitions) is also accessible without the use of tools.

### **6.4.2 Requirements and Testing of Electrical Isolation**

The standards give the same requirements for HV isolation testing. ISO6469-1 (2009) describes a detailed procedure for measuring the isolation resistance of both terminals of the HV battery pack. The requirement is that the isolation resistance shall be 100  $\Omega/V$  if not containing AC or 500  $\Omega/V$  if containing AC, without an additional isolation monitoring system. These minimum requirements are designed to limit harmful leakage currents to 10 mA DC or 2 mA AC respectively (SAE 2010). Isolation resistance should be measured at both the positive and negative HV bus. Isolation resistance measurement can be taken at the time of LVV certification and WOF although some training of certifiers will be needed. A vehicle with an isolation resistance monitoring system would not need to undergo this test.

### **6.4.3 Creepage Distance**

ISO 6469-1 has requirements to deal with leakage-current hazard between conductive parts at different potentials due to the risk of electrolyte and dielectric medium spillage under normal conditions (ISO6469-1 2009). Creepage distance is defined as the shortest distance along a surface of a solid insulating material between two conductive parts. The minimum creepage distance between two of the two battery pack terminals shall be;

$$d = 0.25U + 5 \quad \text{where}$$

$d$  = the creepage distance measured on the tested RESS, in millimetres (mm).

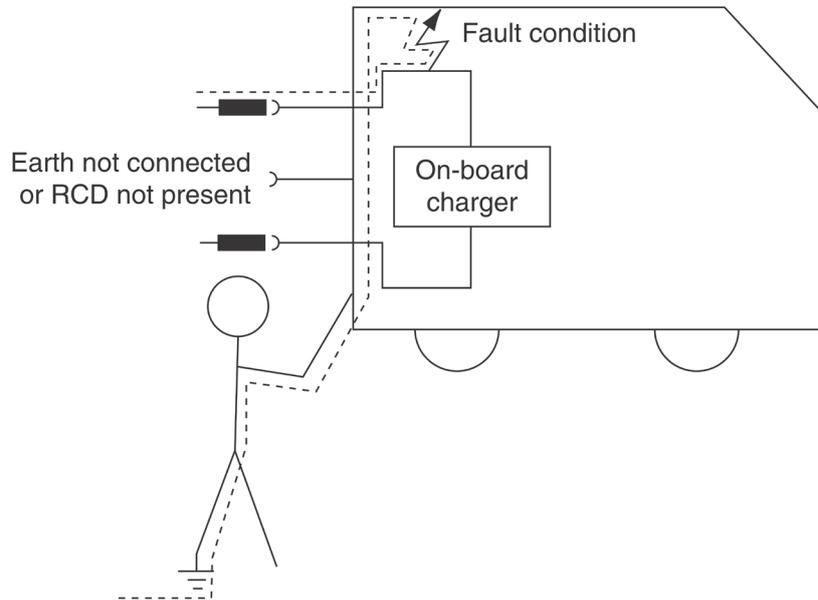
$U$  = the maximum working voltage between the two RESS terminals, in volts (V).

This creepage distance is also applied between any live part and the vehicle chassis with a reduced factor of 0.125. This requirement is easy for EV converters to follow and certifiers to test for and it is therefore recommended for inclusion in a LVV EV standard.

### **6.5 Earthing and Bonding**

Earthing and bonding is critical for charging safety and for proper function of the isolation resistance monitoring system. The conductive case of the battery box must be earthed to the vehicle body as well as all other metal components. The EV charger (and thus the vehicle chassis) must be grounded through the supply cable during charging. If an off-board charger is used then grounding of the

vehicle through this must also be assured. The hazardous situation is shown in Figure 6.4 below:



**Figure 6.4** Hazardous situation in mode 1 charging without proper earthing or RCD in supply circuit (Bossche 2003).

Bonding of the conductive EV components to the vehicle chassis is achieved through providing low resistance mechanical connections such as earth straps, bolting or welding. UNECE R.100 gives a requirement for the potential equalization resistance (continuity) between any two exposed conductive parts as  $0.1 \Omega$  (UNECE 2009). This is in line with the requirements of the standards.

UNECE R100 requires a measurement current of at least 0.2 A. ISO 6469 however states that the measurement current shall be at least 25 A or 1.5 times the traction circuit current, but these currents are not achievable during a LVV certification. The ISO value is to simulate a fault current whereas the UNECE value simulates a leakage current (Bossche 2003). Further research is required to decide what is appropriate for NZ vehicles. NZ EV conversions should have the equalisation resistance between major conductive components and the chassis tested during vehicle commissioning.

## 6.6 Automatic Disconnects

Many OEM vehicle manufacturers employ a combination of disconnect systems to provide redundancy for safety purposes and isolate the rest of the vehicle from the traction battery voltage. Dhameja (2002) states;

“... all OEM EVs have automatic high-voltage system disconnects as a primary safety design feature. These automatic disconnects include a combination of ground fault monitoring, an inertia switch, and/or a pilot circuit” (p. 149).

A number of disconnects can be used including:

- vehicle crash sensor (inertia switch, air bag),
- loss of isolation (ground fault),
- HV interlock loop – access panels, service (manual) disconnects, connectors interlocks etc,
- welded contactor detection,
- rollover sensor,
- smoke alarm,
- immersion sensor and
- condensation sensor.

SAE (2010) suggest the following instances of faults which might need to be indicated;

- loss of HV system isolation,
- low battery State of Charge (SOC),
- low oil pressure (analogous to engine oil pressure),
- over temperature, temperature fault or temperature out of range,
- hazardous voltage fault and
- failure of contactor to open when commanded (welded contacts).

It should be noted that in some situations it might be appropriate to substitute an interlock for a system which restrict access to non-user-serviceable functions and HV areas with the use of special tools coupled with appropriate labelling (SAE 2010).

## 6.7 Manual Disconnect

It is important that any automatic electrical safety systems be backed up by manual systems in case they fail to operate. As such a single pole manual disconnect should be located as close as possible to the electrical centre of the battery pack (Figure 6.5) so as to remove any voltage between the positive and negative battery output terminals. This requirement is one that is given in SAE J2344 (SAE 2010). The operation of such a device should not require a tool to operate, be easily accessible and labelled. A circuit breaker with a manual switch could perform this function. Below (Figure 6.5) is a photo of a manual disconnect (service plug) in a 1999 Toyota Prius.



**Figure 6.5** 1999 Toyota Prius manual HV disconnect located in the boot of the vehicle.

## 6.8 HV Isolation Fault Detection

A HV fault detection system ensures that vehicle drivers or emergency responders will not be subject to a hazardous shock by the accidental loss of isolation between the positive or negative electric buses with respect to the vehicle frame or chassis (Dhameja 2002). All OEM EVs employ such a system to ensure electrical safety.

Several different methods for achieving this exist;

- Residual Current Device (RCD) – uses a differential transformer to compare current flow on either side of the traction battery. Any ‘missing’ or ‘leaking’ current indicates the main contactor should be operated.
- Measuring or monitoring isolation (insulation) resistance. An isolation resistance monitoring system periodically or continuously monitors the insulation resistance between live parts and the electrical chassis (ISO6469-1 2009).
- Measuring or monitoring chassis voltage with respect to the bus voltage.

The different methods will have different operating characteristics or susceptibility to nuisance tripping. Further research is required to understand which methods might be the best to be mandated for use in NZ EV conversions. Some vehicle controllers or Battery Management Systems (BMS) may have a built in HV fault detection function.

It is reasonable that a requirement for an isolation fault detection system (also termed Ground Fault Interruption (GFI)) is made mandatory for EV conversions in NZ. As most conversions currently do not have any form of ground fault monitoring it would be best practice to align them with OEM vehicles which have these installed and with the requirement for domestic wiring to use RCDs. It is noted that the introduction of such a requirement would add extra cost, with a floating pack leakage detection for a DC system adding \$500 – 600 to the cost of a conversion (personal communication).

In Australia currently this is not a mandated requirement for EV conversions NCOP-14 (2011) states;

“A ground fault detection circuit or device may be used to identify that either the battery pack positive or battery pack negative have come into contact with the chassis or ELV (Extra Low Voltage) part of the vehicle, and flag this as a fault to the driver or service technician” (NCOP14 2011) (p. 13).

The standards (ISO 6469 and SAE J2344) also do not mandate an isolation resistance monitoring system. This situation represents a challenge to regulators and the EV conversion community as a high level of safety is desired but no precedent exists from international standards. Alternative methods to achieve HV isolation fault detection include the use of a pilot circuit running next to the HV

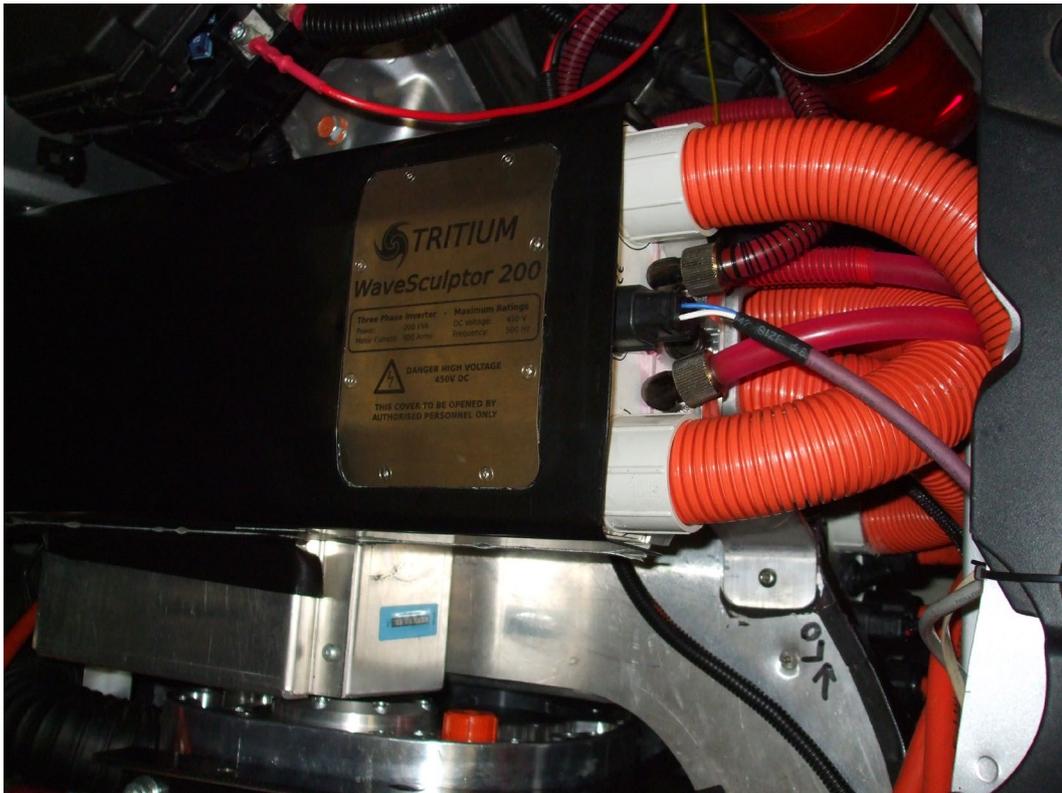
cable. This represents a more cost effective but less reliable solution to this issue. In the event that the HV cable is severed the pilot circuit is also severed signalling the HV contactors to automatically disconnect the HV cabling from the battery pack. An inertia switch also prevents HV discharge from the cables however, only during an accident.

It is recommended that at least one of the above three systems be employed in any EV conversion in NZ. This issue would benefit from discussions between the regulator, the NZ EV community and the authors of NCOP14 who have recently reviewed this issue.

### **6.9 HV Cable Identification, Labelling and Routing**

High voltage cables are routed between the EV battery pack, the electronic controller, the motor, the battery charging port, and other high-voltage components (Dhameja 2002). The HV cables should be located in areas where they are expected to be seen by emergency personnel. Under the floor (outside the passenger compartment) in the centre of the vehicle is the most common position for these cables and as such, if at all possible this route should be chosen. The Society of Automotive Engineers (SAE) has specified that orange cables are the standard colour for HV wiring in EVs (Dhameja 2002). This seems to have been adopted as the global standard for both positive and negative sides of the traction circuit. Orange conduit should be used to further protect these cables from the chassis. The orange colour is important to distinguish it from the ordinary low voltage wiring to enable it to be identified by maintenance technicians, emergency services workers and automotive dismantlers.

When choosing a HV cable suitable for an EV conversion both the voltage and current ratings *and* suitability for use need to be taken into account. Currently the 'rule of thumb' that welding cable should be used for EV power transmission is not correct as the voltage rating of the insulation is not taken into account. Welders operate at low voltage and high current and so welding cable insulation might not have the appropriate voltage rating for use in EVs. An example is one converted EV surveyed during this research used extra HV sleeving on the main cables to account for this. Flexible cable should be chosen to avoid breakage from vibration and cables should also be secured at regular intervals. Two examples of HV cabling practice for EV conversions are shown over the page.



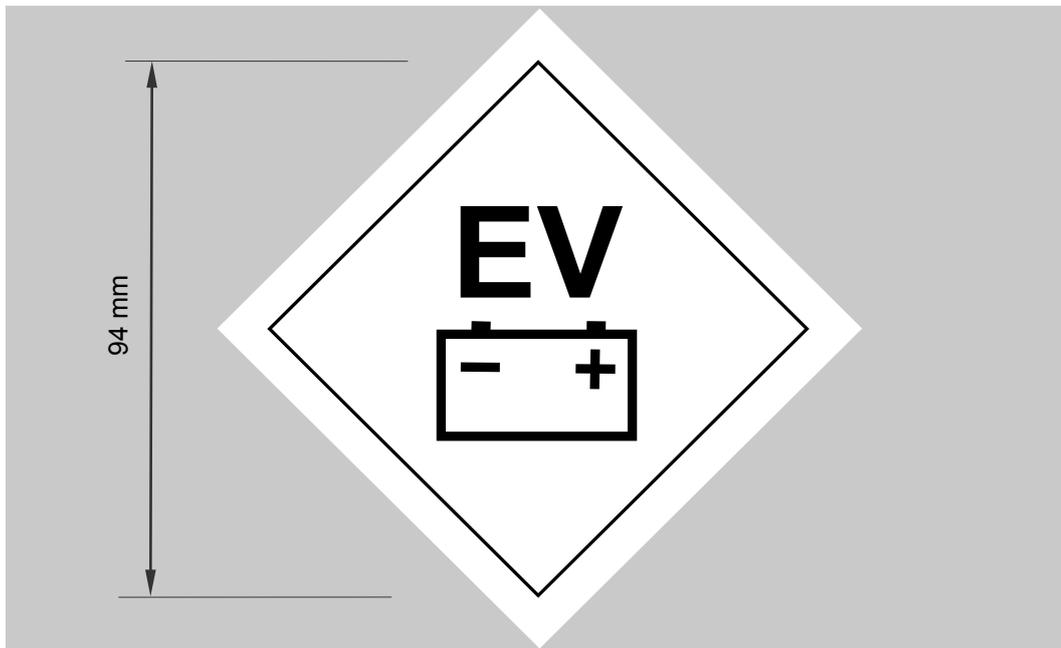
**Figure 6.6** Water cooled Tritium controller installed in an EV conversion.



**Figure 6.7** Blade Electron professional EV conversion.

## 6.10 Vehicle Labelling

Home or professional EV conversions represent a greater risk than do OEM manufactured EVs as they have not been through a type approval process. Furthermore, EV conversions are not readily identifiable by their body style or make and model badges and such should be subject to additional labelling requirements to facilitate quick identification by emergency services personnel. Voluntary labelling is already occurring on many vehicles as EV converters add their own labelling as a cultural identification. This labelling is currently not consistent, but in future may take the form of an alternative energy 'battery logo' affixed to the front and rear of the vehicle. No international standard format has been identified for this label however one is suggested for use in NZ, see Figure 6.8 below.

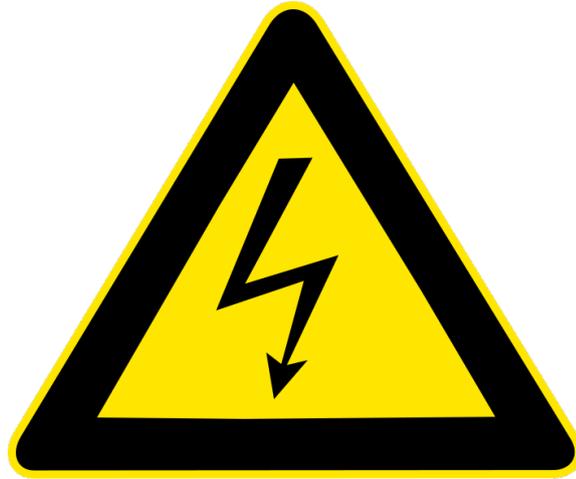


**Figure 6.8** Suggested bumper label for EV conversions.

### 6.10.1 Component Labelling

After identifying the vehicle as an EV, an emergency worker would expect to encounter HV cables and components in the area around the battery, charge point and motor. The labelling of the HV system should also warn of reasonably foreseeable hazards associated with operation, maintenance and rescue work. The EV standards require HV equipment to be identified and conspicuously labelled

using following internationally recognised symbol (ISO6469-1 2009; SAE 2010; NCOP14 2011);



**Figure 6.9** International safety symbol for ‘caution, risk of electric shock’ (at least 40mm high).

The international hazard symbols for the particular battery chemistry should also be clearly labelled on the battery pack and individual cells (NCOP14 2011).

### **6.11 Environmental Protection of Electrical Equipment**

The continued safe function of an electrical system is dependent on its resistance to water, rain, dust and condensation. The EV safety standards have requirements for environmental protection. SAE (2010) requires that total or partial immersion (as specified by the manufacturer) should not result in hazardous electric potential, current, gas or liquid emissions. ISO6469-3 (2001) gives requirements for water protection and a detailed test procedure for class B (>60 VDC, Table 6.1) equipment. The tests are to simulate washing, a heavy rainstorm and flooding. The critical areas for the washing test are the seals between two parts of the bodywork. Driving in flooded conditions is simulated by testing the vehicle in 10 cm of water at 20 km/h over 500 m. The requirement is for the insulation resistance monitoring system to shut down the vehicle if a fault is detected. NCOP-14 (2011) requires all batteries to be enclosed to provide water resistance and exclusion of foreign objects, to a rating of at least IP2X. See Appendix 4 for the meaning of IP (Ingress Protection) ratings. Appendix 4 also gives examples of IP code allocations for different vehicle installation situations.

EV converters and certifiers should employ common sense solutions such as sealed and ventilated enclosures which have appropriate IP ratings and mount inverters and other HV components high in the engine bay (external areas) to avoid water damage. The fitting of a water or emersion sensor close to HV components is recommended.

### **6.12 Contactors**

For high current applications a powered relay, or “contactor” is employed for switching the traction circuit. The HV contactors for an EV conversion should be carefully chosen as these are the primary HV controls. The contactors should be of the normal open type, requiring a low voltage control signal to enable current flow. They are designed to have minimal contact resistance and may have multiple current paths to reduce heating. They should have appropriate DC voltage and current ratings.

For higher voltages (>250 V) it may be required to use vacuum contactors to control arcing. Systems using higher voltages should also employ at least 2 contactors (one on each side of the pack) as there is a low chance of both contactors welding themselves in the closed position. The EV electrical system should also be designed to monitor the contactors with respect to proper operation and provide a warning signal upon malfunction (welding). The main contactors should be positioned as close as practical to the battery pack terminals or between sections of the pack to ‘split’ the pack into safer voltages (SAE 2010). Cai (2010b) discussed the GM Chevrolet Volt PHEV, which he stated as having 7 HV contactors to perform various functions in the vehicle and charging systems.

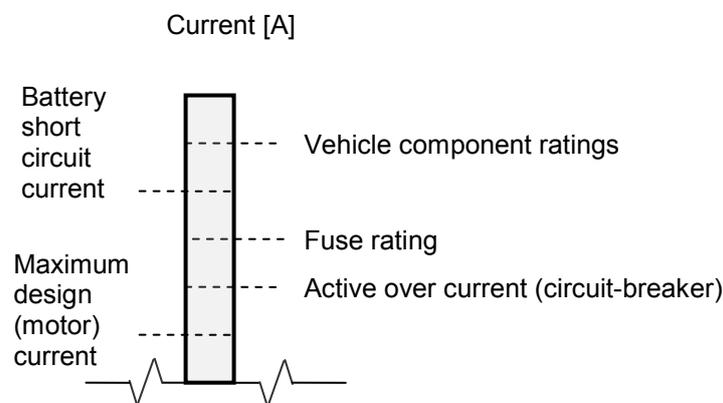
### **6.13 Traction System Circuit Protection; Fusing and Electrical Discrimination**

Components for EV traction systems should be properly rated. Pistoia (2010) states; “...for example, a traction power inverter should have a voltage rating of 150% of the bus voltage” (p. 508). The traction circuit bus should be rated to handle the battery short-circuit currents which will be at their highest when the battery pack is new. However (Korinek 2003) explains;

“Accurate battery short circuit current and resistance values are required to properly size and select the proper circuit protection device. Estimated

short circuit values can vary widely depending upon the test method and measurement technique. Multi-stepped discharge methods that use a large span in current and voltage provide the best accuracy in estimating battery short circuit current and resistance. Equipment that directly measures a battery's resistive properties can provide a reasonable alternative to discharge tests, with the use of correction factors" (p 7).

The battery manufacturers data on battery short circuit current should be used wherever possible. Fuses and circuit breakers are for excessive current protection of the circuit and should not be used as personnel protection devices as they are not sensitive enough (SAE 2010). Ground fault leakage detection or RCDs are used for this purpose. The principals of electrical discrimination should be used for coordination between the operating characteristics of two or more protective devices. Separate fusing of traction and charging circuits should be undertaken and High Rupture Capacity (HRC) type fuses should be utilised (NCOP-14 (2011). A simplified representation of the rating of circuit protection components is shown below;



**Figure 6.10** Rating of circuit components.

The various levels of protection circuit components should be chosen such that they have different failure modes and that the ratings do not overlap. This ensures an event which causes one set of components to fail does not propagate to form a cascading event and cause the remaining components to fail. A systematic design approach which includes the use of failure modes and effects analysis, fault tree analysis, and other methods can be used for circuit protection design (Pistoia 2010).

### **6.14 Electrical Design for Impact and Crashworthiness**

EV converters should use flexible conduit to prevent piercing or cutting of HV cables. The routing of high current cables under the vehicle floor should be considered to protect the cables from impact. Metal enclosures should be designed not to pierce the conduit in case of impact. The battery pack main terminals can also be located as far away as possible from each other in order to minimise the chance of contact during a crush event.

ICE vehicle manufacturers use inertia switches to de-energise electric fuel pumps in the event of a crash. Inertia switches should therefore also be a mandated requirement for EV conversions and be located in the front of the vehicle where the highest decelerations occur during frontal impact. Some OEM vehicles use the airbag sensor for this purpose.

### **6.15 EV Charging Electrical Safety**

The battery aspects of charging safety are discussed in Section 7.8 with the electrical safety aspects discussed here.

A typical EV charger consists of a number of electrical components;

1. a charging controller with ground fault interruption,
2. contactor/s,
3. a connector such as an SAE 1772,
4. a fuse (current overload).

The connection of the vehicle to the utility network is covered by the electrical standards such as those published by the International Electrotechnical Commission (IEC). Charging requirements thus, do not appear in the EV vehicle standards. UNECE R.100 however states some requirements about the connection of the vehicle to the mains network (Bossche 2003);

- The vehicle shall not be capable to move by its own means when connected to the network or to off-board charger. This corresponds to the “drive train interlock” specified in the IEC standard (IEC 61851).
- The components used when charging the battery from an external power source shall allow the charging current to be cut in case of disconnection without physical damage.

- The coupling parts likely to be live shall be protected against any direct contact in all operating conditions. On this subject, the IEC standard requires specific IP protection measures: IP55 in road position; IP44 when charging, also for the connector and the socket-outlet when not in use (see Appendix 5 for IP ratings).
- All exposed conductive parts shall be linked through a conducting wire plugged to earth when charging. This is also specified in the IEC standard. (Bossche 2003) (p. 327).

The first requirement above is for a charger interlock. A park brake and starting interlock for charging might be the simplest way to achieve this. The next two points concern the ratings of the connector, the IP 44 rating allows the vehicle to be charged outside. As part of the certification process this could be reduced if a restriction of ‘garage charging only’ is imposed.

The final point requires earthing of the vehicle chassis during charging to avoid the hazardous situation shown in Figure 6.4 above. A further level of safety is gained by adding an extra low voltage conductor in charge cable to form a pilot circuit. As Bossche (2003) explains;

“This infrastructure involved a dedicated socket-outlet, fitted with a 30 mA RCD and with an earth loop monitor which continuously controlled the integrity of the earthing circuit through injecting a small current in the “pilot” conductor, which returned through the protective earth conductor. If this loop was interrupted, the main contactor would open, cutting off the supply.”

The main functions of the pilot circuit are;

- verification of proper vehicle connection and
- verification of equipment ground

UL2231 - Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits covers ground fault protection requirements for charging circuits described as a Charging Circuit Interrupt Device (CCID). Communication of battery state and cooling ventilation requirements can also be made via the pilot wire. When the vehicle is plugged-in the HV connection is made first, then the pilot connection. Contactors are then switched to start the charging process. This requirement is mandatory for many charging standards such as SAE J1772 for modes 2, 3 and 4

charging. Professionally built EV conversions would be expected to employ such a system. This is not a requirement for low current systems (mode 1 charging).

### **6.16 Choice of System AC vs DC**

Power electronic components can fail and possibly fail closed, allowing current to continue to flow. A hard short in a DC brushed motor controller can result in an uncontrolled motor at full power. Brushless DC and AC induction motors need active switching to control motor speed and as such any failure of the controller components will cause the vehicle to stop. Certain controller/motor configurations can also cause wheel lock under failure conditions. These safety aspects should be considered and as a design guide, a single point failure in the controller components should not result in a safety risk.

### **6.17 Safety during Vehicle Operation and Maintenance**

#### **6.17.1 User Information**

SAE (2010) and ISO6469-2 (2009) both have requirements for an EV manufacturer to provide an;

- owners manual (including charging procedures),
- emergency response information and
- a service manual.

Toyota also publishes hybrid vehicle dismantling manuals for its vehicles. For EV conversions, especially those sold on the open market, this information needs to be available. For the home builder, providing this documentation will be prohibitive and so on-vehicle labelling might be more appropriate. An EV advocacy group could publish a set of 'standard documentation' for converted EVs.

#### **6.17.2 Functional Safety**

It is essential that a vehicle is able to be used in a safe manner, even when it is used by someone for the first time. The control layouts and switching functions should follow the many well established automotive conventions. The EV standards establish their own principals where these cannot be borrowed from ICE vehicle standards. ISO6469-2 (2009) gives requirements for starting the vehicle - the power on function must use two deliberate and distinct actions and it shall be

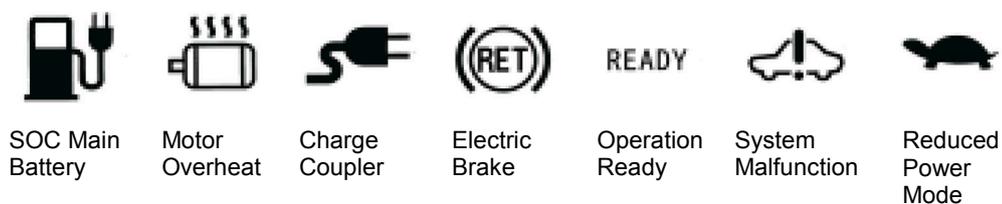
indicated (continuously or temporarily) that the propulsion system is ready for driving. A charging interlock is a common requirement discussed above.

Reversing or driving backwards also requires two separate actions. If only one control action is used to change the vehicle direction then a safety device must be fitted to only allow a direction transition when the vehicle is stationary or moving slowly. If a standard gearbox is used then the ICE vehicle standards shall apply. ISO6469-2 (2009) gives requirements for parking and it should be indicated whether the vehicle is drive enabled or not. SAE (2010) gives some guidelines for preventing vehicle rollaway due to the lower resistance of the electric motor.

Equipping the vehicle with a SOC gauge is a necessary safety requirement as it is hazardous to have the vehicle stranded on the side of the road. Vehicle safety systems such as headlights need to have priority over energy use. NCOP-14 (2011) has a detailed clause on this issue;

“An independent auxiliary ELV (nominally 12V) must be used to guarantee the supply of power to safety equipment such as lights, brake boosters and windscreen wipers in the event of a shutdown of the main battery system in the vehicle. (Typically this power supply is a 12V battery). The auxiliary supply must be capable of operating the hazard lights (four-way flashers) at normal duty cycle, for a minimum period of 20 continuous minutes. If the auxiliary supply is charged via a DC/DC converter from the main traction battery pack, then it must be supplied in preference to the traction circuit” (p. 17).

Readily identifiable indicators should be used such as those from ISO 2575: 2004 or those published by the Japanese Electric Vehicle Association (JEVA) shown in Figure 6.11 below.



**Figure 6.11** JEVS Z804 Electric Vehicles - Symbols for controls, indicators and telltales. (Bossche 2003) (p. 311).

The majority of the above requirements are easily included in EV conversion designs and should be included as part of an EV standard.

#### **6.18 EV Electrical Safety Summary**

Electrical safety of the EV HV traction system is an important aspect of EV design and thus should be a major focus of an EV conversion standard. The current regulations however sit in the area of electricity regulations rather than transport regulation. Safety principals for EV electrical systems are well established in international EV standards and general electrical standards and as such should be included in an EV conversion standard for NZ. A high standard of workmanship is expected securing of cabling keeping cables away from sharp edges and protecting cables under the vehicle against damage.

## Chapter 7 - EV Battery Safety



4

### 7.1 Introduction

The battery is the cornerstone of modern EV technology. Advancements in battery technology have been a major driver for the development of EV technology as vehicle performance has improved. This chapter will discuss the safety aspects of current EV battery systems. The focus will be on a systematic building of design methods for the safe installation and use of traction batteries for EV conversions. A detailed discussion of the chemistry of various cells is outside the scope of this thesis (much of this information can also be proprietary) however, the safety related nature of various cell chemistries is discussed with a particular focus on Lithium Ion (Li-ion) cells as these are becoming the cell of choice for EV conversions.

#### 7.1.1 The Function and Operating Characteristics of EV Batteries

The primary function of the EV battery is to store electrical energy for the operation of the vehicles traction system. The operation of an EV is similar to that of an ICE vehicle however in a pure BEV the vehicle must operate with the battery SOC in mind. This is similar to the ICE vehicle in that it needs to be periodically refuelled. The main difference is the limited energy storage capacity (which manifests itself in reduced vehicle range) and recharge time. The functions of the EV battery include;

- an acceptable recharge time (power acceptance),
- sufficient energy capacity (energy acceptance) typically 10 - 60 kWh,
- good discharge energy (deep discharge),
- a high cycle life,
- acceptable discharge power,
- high manufacturing tolerance for series applications,
- a high reliability,
- communication capability with controlling equipment and user interfaces,
- an appropriate pack voltage (60 – 400 V),
- discharge current up to C rate continuous and 3 C peak and

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<sup>4</sup> Battery warning symbol ISO 2575:2004

- reliable safety systems (Battery Management System (BMS) and thermal management)

The battery must perform these functions efficiently and safely. As stated by battery manufacturer Boston Power; “Safety is the most important criterion for electric car batteries” (Warner 2010).

### **7.1.2 The Cell, Module, Pack and Battery System; Some Definitions**

An EV battery pack is built up of electrochemical units or cells. The cell is the basic building block from which the pack is made up, it has a fundamental electrochemical voltage which may or may not be suited to the application. To make a practical battery a set of cells is put together to form a ‘module’. The cells are assembled in series and/or parallel and packaged in the form of a module. The standard automotive Lead Acid (LA) starter battery for example, is a set of six 2V cells connected in series to form a 12V module (Rand 2001). A ‘battery pack’ is made up of a number of modules connected in a sometimes complex array of series and/or parallel connections to form a pack which has the desired voltage, energy capacity and power capacity. This battery pack is part of the vehicles ‘battery system’. The SAE describes an EV battery system as follows;

“A battery system is a completely functional energy storage system consisting of the pack(s) and necessary ancillary subsystems for physical support and enclosure, thermal management, and electronic control”.

The battery system can include components from outside the vehicle such as an off-board charger or the charge control system used by a ‘smart grid’ utility operator. The use of the terms cell, module, battery, pack and battery system are used interchangeably in this thesis however, in some contexts the particular definition can be important. The acronym RESS (Rechargeable Energy Storage System) is used by many of the standards to describe the battery system.

### 7.1.3 Current Battery Chemistries for EVs

In the introductory Chapter Figure 1.6 (Giebel 2010) gives an overview of various electrochemical battery technologies and their application to EVs. The three main practical chemistries for EV batteries are; Lead Acid (LA), Nickel Metal Hydride (NiMH) and Lithium based chemistries. As (Pistoia 2010) explains;

“Traditional lead-acid (LA) batteries were replaced by nickel-metal-hydride cells in commercial hybrid electric vehicles (HEVs), while lithium-ion (Li-ion) cell formulations have found favor in pure battery electric vehicles (BEVs) and the next generation of plug-in hybrid vehicles (PHEVs)” (p. 494).

There are many battery chemistries that may be considered for EVs however, apart from the ones listed above they remain experimental and are generally not available to EV converters. Any chemistry outside the above three is not assessed by this thesis and include Nickel Cadmium (Ni Cad), Vanadium Redox, Sodium Nickel Chloride, Nickel Zinc batteries and Ultra Capacitors. The application of these other types of battery, or any battery for that matter to an EV conversion should be done with specialist knowledge of the safety risks of the particular battery chemistry and characteristics.

Although LA continues to be the major cell type used for EV conversions, this situation is rapidly changing as EV converters are learn about the performance benefits of Li-ion cells as these cells become more available. LA cell technology is dominant in industrial vehicle applications and e-bikes and will continue to be important for low cost EV conversions. Some EVs that have spent time on the road using LA cells are also commonly upgraded to Li-ion cells after the LA cells have degraded. Many new EVs available from OEM manufacturers are such as the Mitsubishi iMEV, the Nissan Leaf, Cheverolet Volt and the Tesla Roadster use Li-ion cells. Professional conversions such as the Hyundai/Blade Electron also use Li-ion cells as these vehicles tend to offer higher range and power performance.

It is expected that the use of Li-ion batteries will become the dominant technology for home and professional EV converters as the cost of these cells decrease and the availability increases. Other cell chemistries viable for EV use will also emerge in the medium to long term as this is an area of active research and investment.

This chapter will discuss in general terms the relative safety of these battery types, focussing on the safety requirements of Li based chemistries as these have performance improvements and are expected to become market dominant over LA chemistries. LA batteries have a proven safety profile in EVs and industrial vehicles and the engineering requirements are well understood. NiMH batteries are limited to the HEV application as these packs are engineered to be power optimised rather than the energy optimised designs used for BEV applications. Ramaraju Prakash (2010) discusses the switch from LA to a Li-ion chemistry for the EV manufacturer Reva Electric Vehicle. He states that; “All roads lead to Lithium Ion... But Li-ion does not come easy” (Prakash 2010). Many safety issues exist with Li-ion batteries. This chapter will show the risks of using this type of battery and discuss methods by which this risk can be reduced.

## **7.2 Lithium Battery Risks**

Whilst evidence of poor Li-ion battery safety in EVs or EV conversions is non-existent due to the small number of EVs in NZ and across the world, evidence is available from other uses of Li-ion batteries. Li-ion batteries are commonly used in portable devices such as laptop computers, cell phones and power tools. One NZ example of a Lithium Polymer (LiPo) battery failure is a fire which consumed part of a workshop and resulted in the NZ Fire Service issuing a fire safety warning, see;

[http://www.fire.org.nz/Fire-Safety/Research Investigation/Pages/Warnings.aspx](http://www.fire.org.nz/Fire-Safety/Research%20Investigation/Pages/Warnings.aspx))<sup>5</sup>

On the NZ Fire Safety Website they have also included a video link which details tests performed by an electrical engineer and fire safety officer. These tests show a damaged battery exploding with temperatures exceeding 1000°C highlighting the fire dangers of improper charging of damaged batteries *and* to damaged batteries in general.

Upon viewing this footage it is easy to imagine the potential risk of a fire involving an EV battery pack as it would be approximately 400 times larger. The severity of such an event is further increased by the fact that an EV fire has a high chance of occurring during overnight charging and is likely to take place in an

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<sup>5</sup> A full report of the investigation is also available from TVNZ (2010).

attached residential garage which could pose a serious threat to property and people if not contained safely.

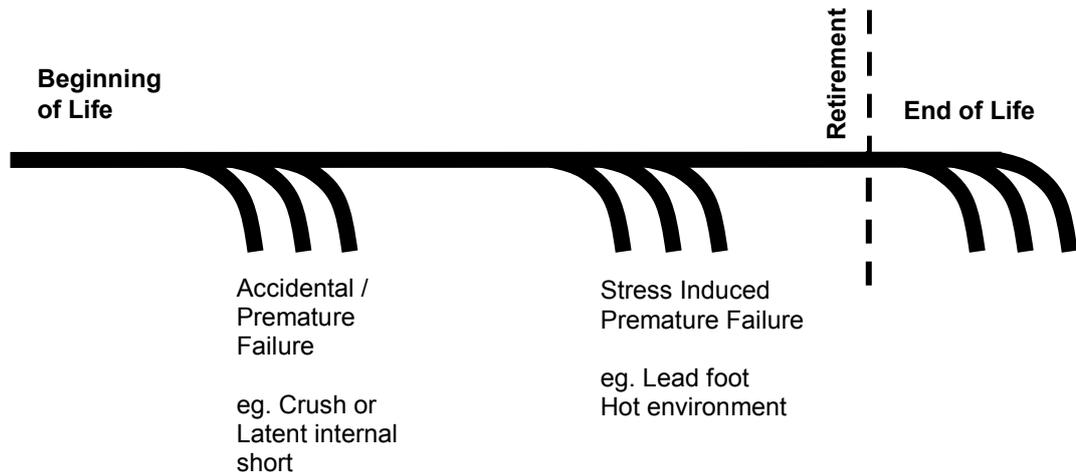
Portable devices do not generally have a battery energy capacity greater than 60 Wh compared to a medium sized BEV pack of 24 kWh (some vehicle pack capacities are given in Appendix 5 for comparison).

The ignition of laptop computer batteries is another well known example of lithium battery fires. World wide incidence of this type of failure have resulted in the NZ Fire Service issuing three Fire Related Product Recall Notifications since 2007 relating to laptop batteries and one for a Li-ion wireless headset battery. All these recalls relate to battery overheating, which could pose a risk of fire. Worldwide more than 2 million products containing Li-ion batteries have been recalled since 2006 (Pistoia 2010) (Table 18.1).

Tabaddor (2010) gives the Li-ion battery safety challenges as fire/explosion of the cell/pack caused by;

1. Electrical Hazards – e.g. external short-circuit, overcharge, over-discharge, cell imbalance. A cell manufacturing problem could also cause an internal short due to contaminant from process or defect with cell assembly.
2. Mechanical Hazards – e.g. shock, drop, crush, nail intrusion, vibration, mechanical abuse/crash leading to cell damage.
3. Thermal Hazards- e.g. overheating, thermal cycling.
4. Insufficient or lack of quality control measurements – complicated by global supply base of raw materials and battery pack components.

These safety issues must be addressed during all stages of the battery life cycle as well as the anticipated abuse of the battery as described in Figure 7.1;

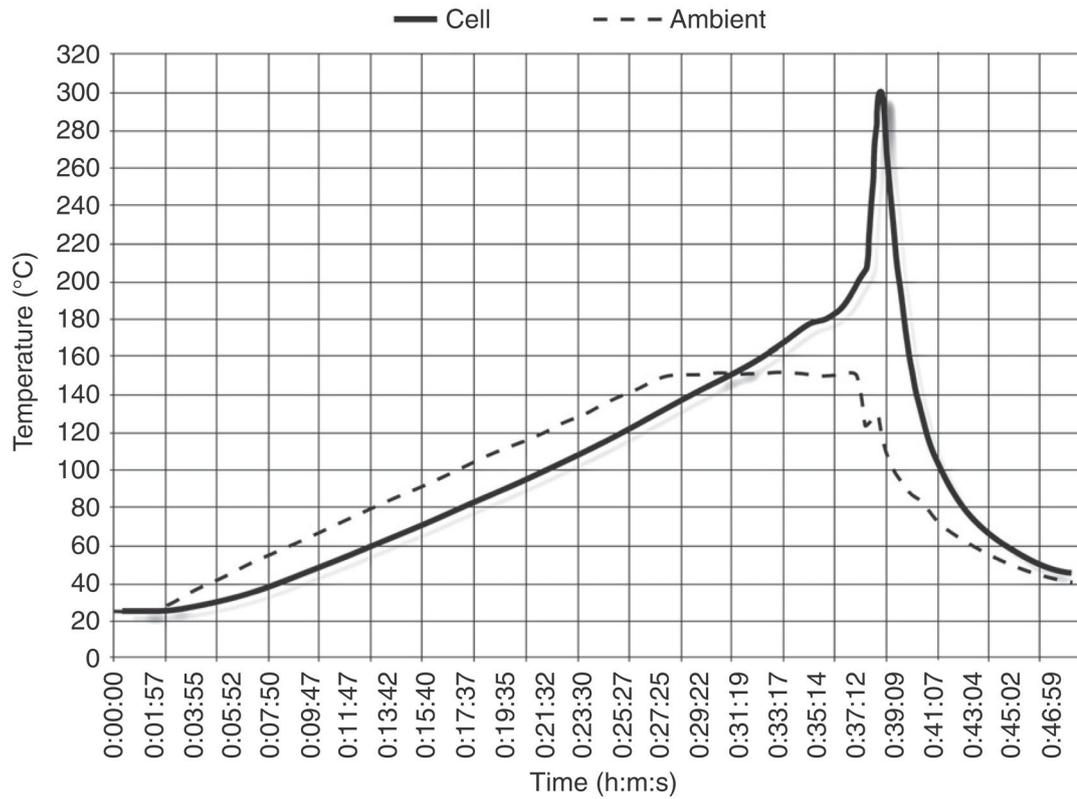


**Figure 7.1** “Undesirable behaviours” of EV batteries. Adapted from (Comsol 2010)

Two forms of stored energy are important when it comes to Li-ion battery safety; 1. the electrical energy of a fully charged battery and, 2. the chemical energy released during a fire of the lithium based cathode materials and flammable electrolyte (Pistoia 2010). Lithium is a highly reactive light metal that will react with atmospheric oxygen and water, has a density of  $0.5 \text{ kg/m}^3$  and a melting point of  $180^\circ\text{C}$ . Later it will be shown that the electrical energy that can be released during discharge, charge or short circuit (external or internal) can result in heating of the battery.

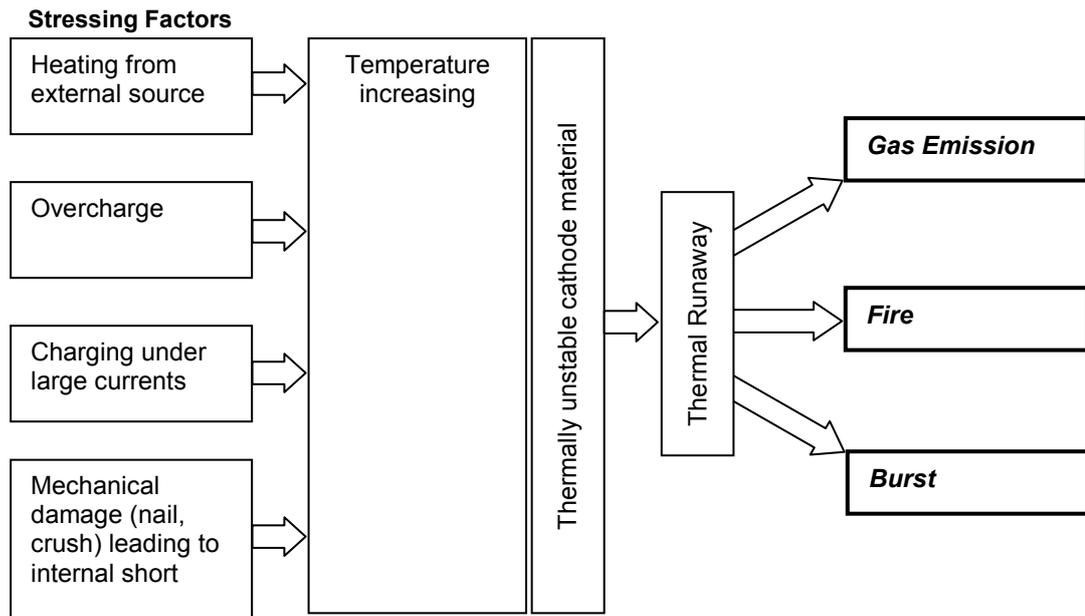
The second form of energy release happens when the cell or battery reaches a higher temperature and the lithium cathode material and electrolyte becomes active in combustion, the reactions being either fed by reactants from the battery chemistry or from an external source. Local combustion of lithium at the cell level will quickly lead to thermal runaway and propagation of the fire or explosion throughout the pack. This situation is illustrated by a heating test on a Li-ion battery carried out to UL-1642 Lithium Batteries. During this test the cell is heated to and held at  $150^\circ\text{C}$ . The results are discussed by Pistoia (2010) and shown in Figure 7.2.

“During the test performed, exothermic reactions within the cell caused its temperature to increase above the ambient temperature eventually resulting in the cell going into thermal runaway, venting and ejecting its internal contents” (p. 469).



**Figure 7.2** Cell surface temperature during heating test based on the UL1642 heating test (Pistoia 2010).

The critical links in this chain of events are described by Yang (2007) as 1. a heating source (either internal or external to the cell) leading to temperature rise and 2. a thermally unstable cathode material. A Figure from Yang (2007) is reproduced below to illustrate this;



**Figure 7.3** “What safety issue come from?” Adapted from Yang (2007).

Most cell failures, followed by thermal runaway are a result of a cell internal fault caused by the stressing factors listed in Figure 7.3 (Pistoia 2010). The chemical processes involved in these cell failure modes are summarised by Pistoia (2010). An example is given to illustrate the heating and thermal runaway of battery if the battery pack is short circuited. It is assumed that the pack heats in an adiabatic condition (very quickly so as to heat without heat transfer to its surroundings). The electrical energy stored in the battery pack is converted to thermal energy controlled by the battery's internal resistance. It is assumed that ambient temperature is 20 °C and that thermal runaway starts at 100 °C.

Li-ion Pack Specifications:

- Pack configuration; 88S1P (88 Series 1 Parallel)
- Pack weight 160 kg
- Voltage 360V
- Heat capacity  $C_p$  Range = 1000 – 4000 J/kg/K
- The cell internal resistance is assumed as 1.0 mΩ.

Placing the cells in series gives a pack internal resistance of  $88(1.0) = 88 \text{ m}\Omega$ . The short circuited pack will draw  $360/0.88 = 409 \text{ A}$  at a power of 147 kW. The energy it takes to heat the battery to 100 °C can be estimated from;

$$Q = m C_p \Delta T = (160)1000(80) = 12800 \text{ kJ}$$

At a heating power of 147 kJ/s [kW] this gives  $12800/147 = 87$  seconds to heat the pack.

This rough calculation shows that after during hard short circuit an EV battery pack could reach uncontrollable thermal runaway in approximately 1.5 – 6 minutes. It should be noted that the cell internal resistance will also decrease with increasing temperature and with the development of internal short circuits during the cells destruction.

The engineering effort expended on Li-ion cell level safety must be focused on eliminating or controlling the sources of battery heating or damage and choosing a cathode that is chemically stable, so the risk of a thermal runaway is reduced or eliminated. The implications of these findings and practical application of design methods are discussed in the Sections below.

### **7.3 Standards for EV Batteries**

The international standards for EV batteries are very much still under development with most of the major standards organisations in both the electrical and automotive fields having standards under development. Whilst the battery standards for consumer electronics are maturing Pistoia (2010) describes the EV situation as follows;

“...limited field experience and architectures which are still works in progress make it challenging to define an all encompassing standard that can provide an effective, one-size-fits-all baseline for abuse and safety characterization testing of these battery systems” (p. 479).

Tabaddor (2010) from Underwriters Laboratories gives an overview of selected EV battery standards which has been adapted, expanded and presented in Appendix 6. The major standard for Li-ion batteries currently in use are the UN transport regulations UN - 3090 for the shipment of lithium cells and batteries in bulk (as Class 9 dangerous goods). This standard seems to have been globally adopted and was developed after a number of uncontrollable lithium battery fires during transport and mishandling of battery shipments during the last decade. The standard is based on a series of eight abuse tests described in UN (2003) in section 38.3. A brief description of the tests is as follows;

- T1. Altitude Simulation (11.6 kPa for air transport)

- T2. Thermal Test ( $75 \pm 2$  °C for six hours)
- T3. Vibration (8 g at 200 Hz)
- T4. Shock (50 g)
- T5. External Short Circuit ( $0.1 \Omega$  at 55 °C)
- T6. Impact (drop 9.1 kg from 60 cm)
- T7. Overcharge (voltage twice recommended)
- T8. Forced Discharge (at maximum discharge current)

Cells used in EV conversions in NZ shall comply with this standard before they enter the NZ market, let alone used in an EV. The standards which are detailed in Appendix 6 are vehicle based or describe a standardised testing procedure which may or may not have pass/fail criteria. Although they have not been reviewed, they have been provided for completeness and to inform further research. All standards for Li based batteries are based on testing and so cannot be applied by the home EV converter. This area is very much still in development and it remains to be seen which standards will be globally dominant. The battery safety requirements of EV vehicle standards such as ISO 6469, are focused on system level safety and have been discussed above.

EV batteries which are tested at the cell or module level will also be tested at the vehicle level, as EV products that are manufactured by the major auto makers are rigorously tested before they enter the market. The introduction of EV technology represents a major product liability risk for car companies. These testing programs will as such always exceed the requirements of the standards set out for this purpose. Vehicle manufacturers battery/vehicle testing will involve crash testing (with battery focus), hot weather, cold weather, corrosion, water trough, pothole, dust incursion and battery vibration<sup>6</sup>. As this type of testing is outside of what even a professional EV converter can afford, careful and conservative design of the battery system must be undertaken.

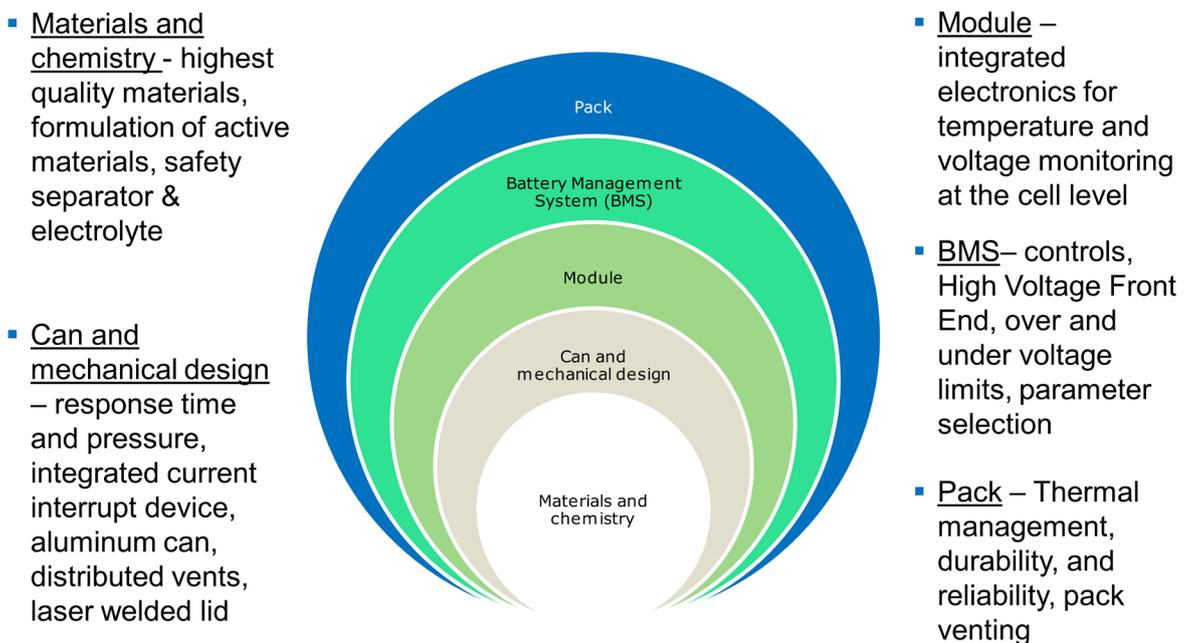
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<sup>6</sup> Video showing some of the tests being carried out on the Chevrolet Volt are available at <http://gmtv.feedroom.com/>

## 7.4 Battery System Design Process

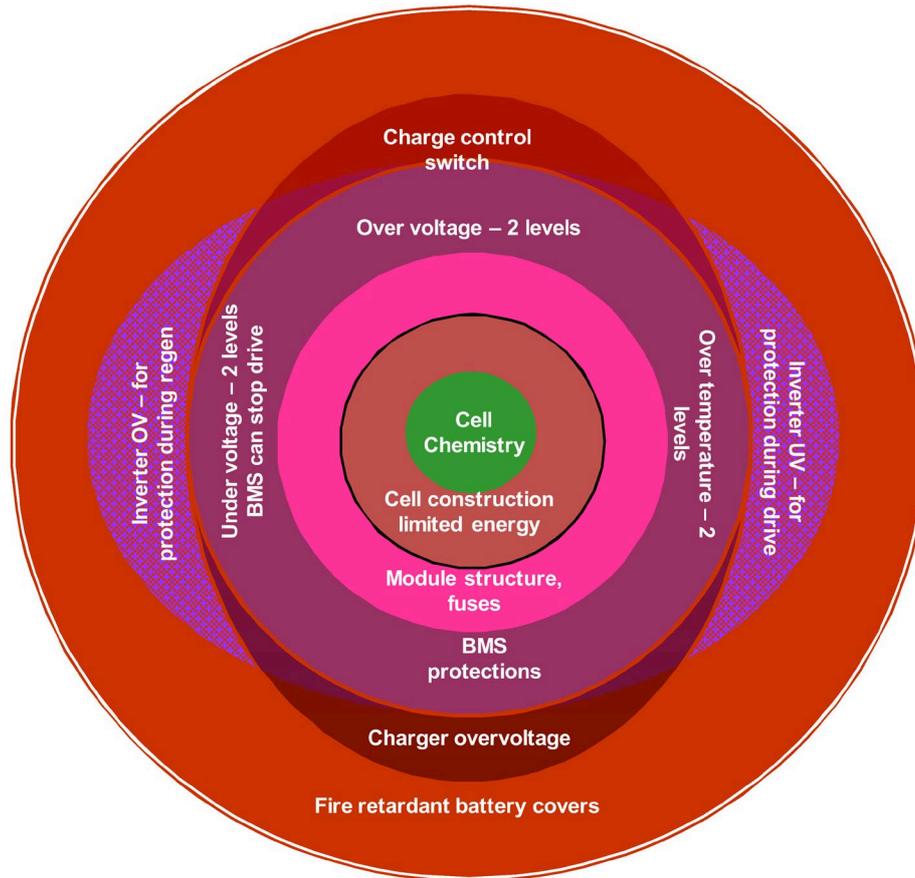
The development of EVs presents a unique situation to vehicle and battery manufacturers as they have to work together to develop the vehicle system as a product. Many automakers are investing in joint ventures with battery suppliers for this purpose. The finished vehicle is a collaboration. Similar collaborations have been identified as being required between regulatory bodies this was discussed in Chapter 3.

Many OEM EV manufacturers describe the design of the battery system for a vehicle application as taking a multi layered approach. This is best described in Figure 7.4 below;



**Figure 7.4** Battery system multilayer (onion) design approach from the battery manufacturer Boston Power perspective (Warner 2010).

The same design approach is also given by (Prakash 2010), (Yang 2010) and (Zhang 2010a). (Prakash 2010) gives a detailed technical overview of the REVA*i* EV battery pack design approach, which is shown below;



**Figure 7.5** Reva EV battery design, showing multilayered (onion) approach.

Yang (2010) describes how thermal runaway can be prevented at the cell, pack and system level. This design philosophy shows many layers of protection with redundancy built into overvoltage, undervoltage and over temperature systems. This architecture is consistent with the findings of the risk analysis given in Chapter 5 whereby high severity levels are controlled by reductions in likelihood. It was found that the likelihood control measures must be reliable to be effective in reducing overall risk. The multi layered approach allows the design of a system with the use of redundancy to achieve reliability. Pistoia (2010) discusses the identification of battery systems design defects and gives some examples of good design:

- The cell protection devices should be appropriately rated to handle the open circuit voltages
- The various levels of protection circuit components should be chosen such that they have different failure modes.

- The operating parameters of the various protection levels should be such that they do not overlap.

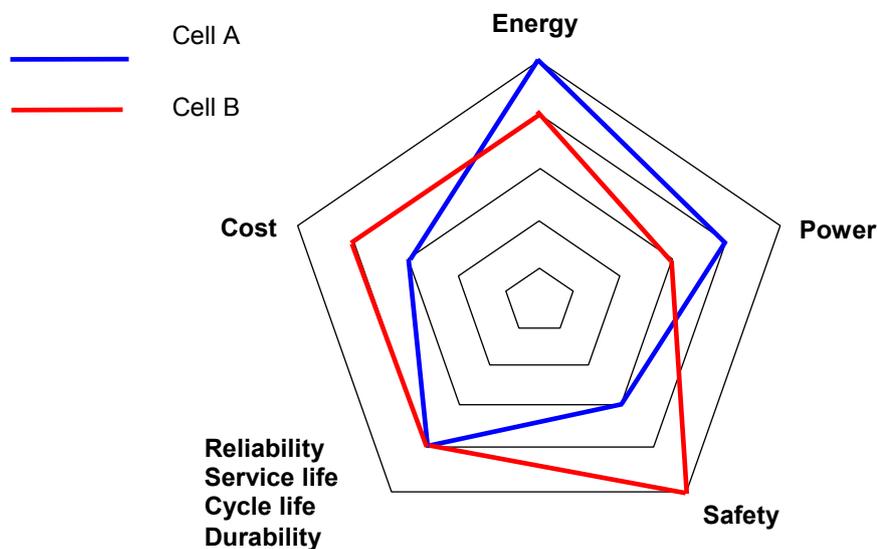
A systematic approach which includes the use of fault testing, failure modes and effects analysis, fault tree analysis, and other methods can be used to detect design flaws in the battery system Pistoia (2010).

It is recommended that EV converters use a multilayered approach when designing the safety systems for Li-ion battery systems. This gives an overview of the battery system design, in the subsequent sections the discussion will focus on each level of the battery system and the protections that might be employed.

## 7.5 Lithium Ion Cell Selection

Li-ion batteries suitable for EV applications are available from many different suppliers. China alone has 100 Li-ion cell manufacturers, 30 of which state that they are able to supply cells or modules for EVs (Giebel 2010). A major market for Li-ion batteries is currently for use in computers, power tools and in E-bike or E-scooters. These batteries may or may not be suitable for use as part of a large series string in an EV battery pack. In purchasing batteries for an EV conversion one must be mindful that there is no agreed understanding or applicability of the terms safety, quality and reliability and as such these terms can be freely interpreted by battery manufacturers. As these are relative terms a more objective assessment should be made using methods outlined in this chapter.

One method commonly used as a decision tool to select a suitable cell is to rank and compare 3 or more battery attributes on a radar chart as shown in Figure 7.6 below. An ideal candidate cell would rank highly in all attributes however this method is useful in arriving at a compromise when weighing up conflicting attributes.



**Figure 7.6** Radar chart comparing the attributes of two different cell types as used by (Giebel 2010; Warner 2010; Yang 2010; Zhang 2010b).

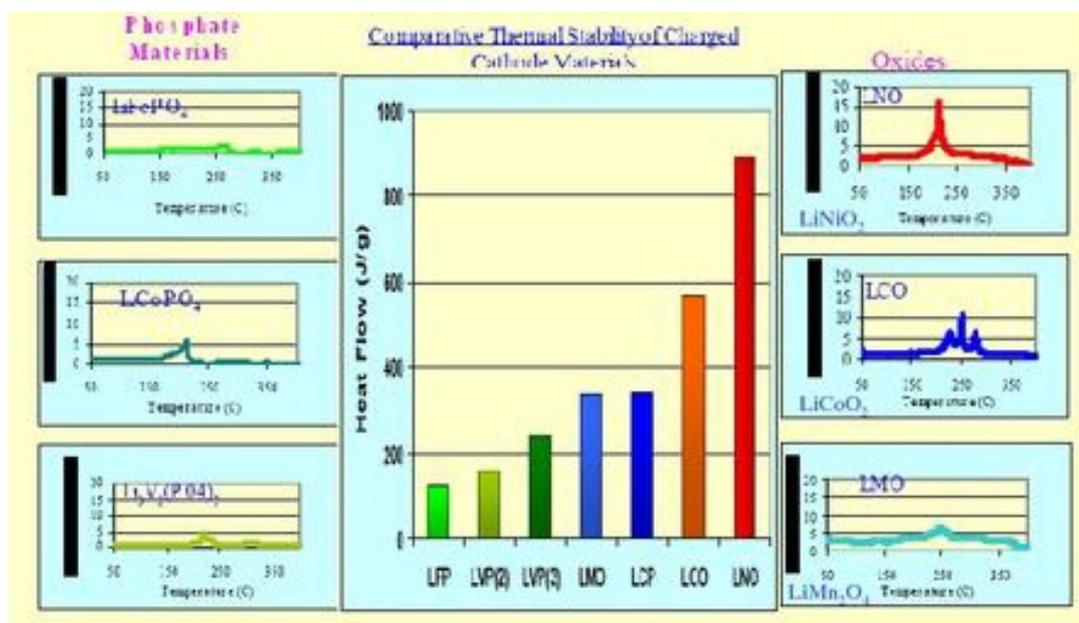
The above figure shows Cell A as a cost effective, high performance cell that ranks low in safety. Cell B has a good safety profile whilst compromising on performance and cost. A cell with a lower safety profile will need extra levels of protection which would also increase the cost.

The level of safety of a Li-ion cell is controlled by the following factors;

1. a stable cathode material,
2. special separator & electrolyte design,
3. the presents of a cell Current Interrupt Device (CID),
4. the presents of a Positive Temperature Coefficient (PTC) Resistor,
5. the presents of a safety vent to relive internal pressure, and
6. high cell quality and manufacturing tolerance resulting in the elimination of internal short circuits. Internal short circuits are a common and dominant failure mode for Li-ion cells.

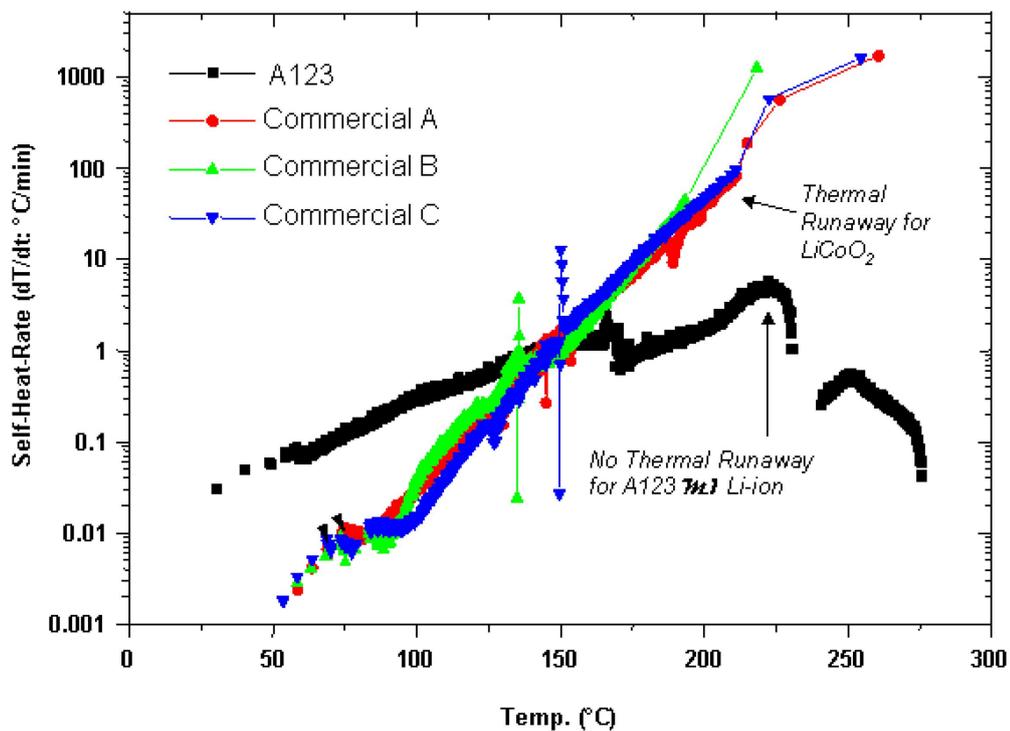
These safety mechanisms are often referred to as passive or internal safety features as they are inherent in the cell design. The availability of these safety features should influence the selection of the cell by the home EV converter.

A knowledge of the thermal stability of the battery chemistry is important in assessing the safety of the battery and in the design of the protection systems that ensure the safe operation of the battery system. Thermal stability is measured experimentally by using a Differential Scanning Calorimeter (DSC) to measure the heat flow [W/g] of a material whilst it is being heated over a temperature range. Heat flow measurements of the battery are taken in the fully charged condition. These measurements give plots as shown in Figure 7.7 below;



**Figure 7.7** The Thermal Stability of Charged Cathode Materials. Adapted from (Yang 2007).

From Figure 7.7 it can be seen that the phosphate materials (Lithium Iron Phosphate ( $\text{LiFePO}_4$ ) in particular) have a much lower peak and overall heat flow. (Yang 2010) describes that the lithium iron phosphate materials are very stable chemically, as the  $\text{FePO}_4$  is a stable chemical agent due to the very strong P-O chemical bond which results in no active Oxygen release even at temperatures of  $500^\circ\text{C}$ . This ‘locking effect’ means that the oxygen is unavailable for reaction with the Lithium. Mn and Co oxide cell chemistries evolve free oxygen upon heating which results in a thermal runaway reaction releasing large amounts of heat. The charge, discharge and thermal controls around these cell chemistries must be much more rigorous to achieve the same risk level as a  $\text{LiFePO}_4$  cell. This point is reinforced by showing another set of test results given in Figure 7.8.



**Figure 7.8** HEV safety. Heating test results (Li 2010).

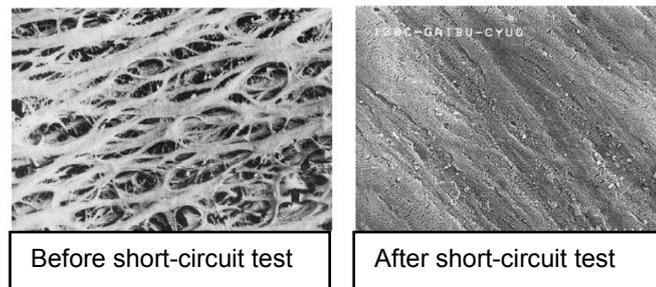
The thermal runaway propagation reaction after explosion or fire is extremely dangerous as a failure in one cell will propagate to the rest of the battery pack.  $\text{LiFePO}_4$  cells which display no thermal runaway represent a good solution for the home EV converter, in terms of a safety and performance compromise. It is recommended that the use of other cell chemistries especially those of metal oxide type cathode be done with extreme caution and with full knowledge of the risks

involved. A full safety ranking of proprietary cells for use by EV converters is outside the scope of this project however this is a subject which deserves further research by the LVVTA and/or an EV converters advocacy group.

### 7.5.1 Cell Safety Features

Balakrishnan (2006) discusses the various types of cell safety features. Manufacturers of Li-ion cells have attempted to further enhance the safety of the individual cell by special design of the electrolyte and separator. A major function of the separator is to keep the cell plates in close proximity but to prevent a short circuit of the charged plates by providing a mechanical barrier. The careful design of the separator is important because if the separator is penetrated for example by a piece of metal from poor manufacturing cleanliness, this may result in an internal short circuit which would release a large amount of energy causing battery heating.

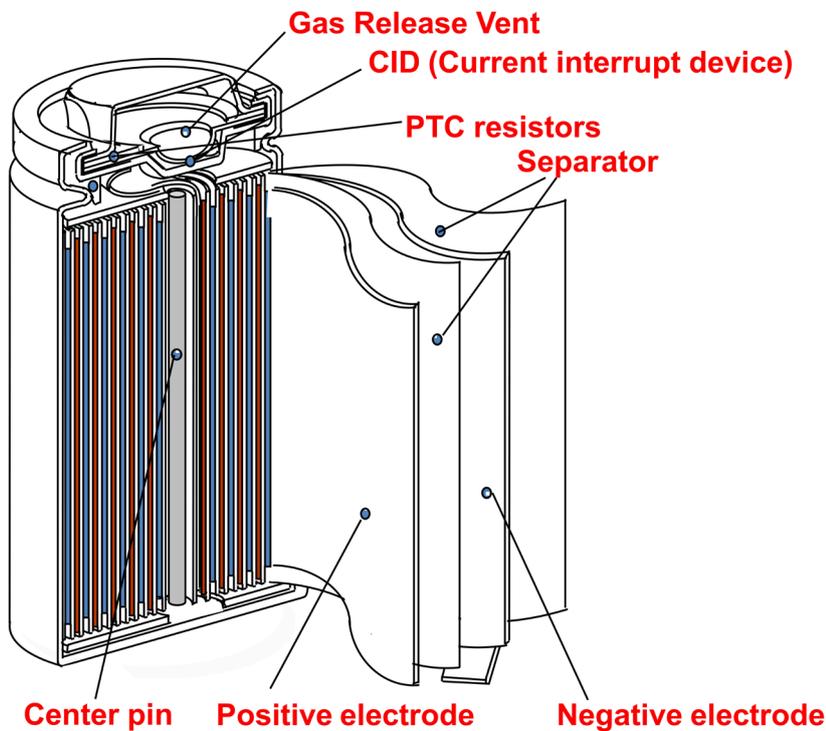
Other than good quality control, another strategy that is employed in cell safety is separator shutdown. This method uses a special separator design which prevents an internal short circuit during abuse conditions. Figure 7.9 shows a SEM of a polyethylene separator designed to shutdown upon short circuit. This process will ruin the battery but preventing heat production from the short circuit.



**Figure 7.9** Separator shutdown (Yang 2010).

A Current Interrupt Device (CID) protects the cell against internal short circuit if the pressure in the cell increases. A CID in a ‘can’ type cell is a small mechanical diaphragm switch which responds to cell internal pressure, isolating the cell from the pack. A PTC resistor can be used to limit the current in the cell as it heats up. A PTC resistor sharply increases resistance as the temperature increases, acting as a current limiting resistor. Some manufacturers will use flame retardant

electrolytes and safety vents to protect against fire and explosion. A higher level of safety is assured by the selection of cells using these devices. The location of these devices in a cylindrical can type Li-ion cell is shown in Figure 7.10.



**Figure 7.10** Safety design on Li-ion Cell (Yang 2010)

The use or reuse of cells from other applications is an issue as some EV converters may have a source of second-hand cells they may want to use for their vehicle. OEM batteries protection devices are tailor made for specific applications and risk levels. A battery which was designed for a power tool or cell phone may not be suitable for an EV application.

Some reasons for this are;

- Cell manufacturing tolerances. Cells designed to be used in a battery pack will be designed to have cell characteristics close to each other. The battery manufacturers' quality control process might classify statistically uncertain cell characteristics into groups for use in a particular pack (Xuezhe 2010). With a cell that is designed for individual use, tolerances are less important. Employing a series string of such cells in a pack could cause an individual cell thermal hazard due to for example greatly differing internal resistance between cells.

- Risk level. Battery performance and safety tend to be inversely related. A cell designed for a high performance application might not be suitable for an EV application because of increased risks due to the much larger pack capacity and the closer proximity to human contact.
- An EV converter might take a pack from a Chevrolet Volt (Several Toyota Prius packs could also be wired together to make a useful BEV pack) written off in a crash (the batteries in these vehicles are positioned to be protected in a crash) and then reused in an EV conversion. Whilst the pack might have good energy storage capacity, the EV converter does not have the benefit or knowledge of the OEM controlling electronics and BMS.

It is well known that energy density and power density are important requirements for EV cells, however Bostock (2010) describes that the for Jaguar Land Rover design "...safety, cost and life are more important design factors at present, no deterioration of which will be acceptable if higher energy densities become available". This safety focused design approach is what is recommended for EV conversions in NZ. External safety systems such as the Battery Management System (BMS) will be discussed in the following sections on module, pack and system level safety.

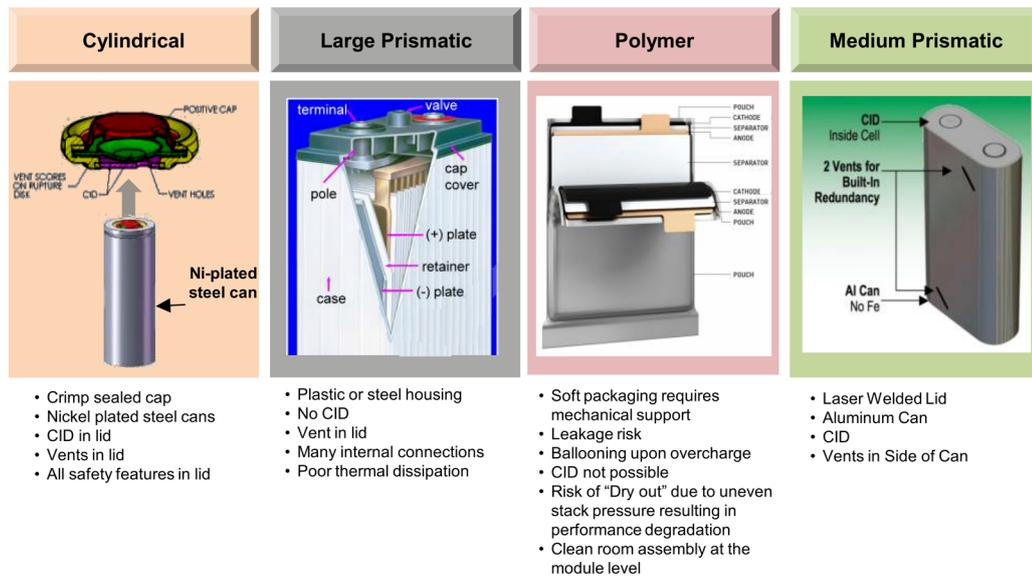
### **7.6 The Implication of Cell Size on Battery Pack Design**

In a battery pack assembled for use in an EV conversion the smallest assembled component might be a cell or a module. Many different sizes of cells/modules are available to the EV converter. The sizes range from a 2 Ah 18650 (pronounced eighteen six fifty) format cell used in consumer electronics to a large format prismatic cell of hundreds of Ah. The energy contained in a 200 Ah 4.0 V nominal cell is  $200(4.0) = 800 \text{ Wh} = 2880 \text{ kJ}$ . If this cell is short circuited or is damaged in a vehicle accident this energy is suddenly released and could result in fire or explosion. The smaller cell however has 100 times less energy to release increasing the chances of containing the failure. Tesla motors' Gene Berdichevsky (2006) describes the process of choosing a cell for the Tesla Roadster;

“We started our design by purposely picking a small form factor battery cell. This cell is called the 18650 because of its measurements of 18mm

diameter by 65mm length (i.e., just a bit larger than a AA battery). Due to its small size, the cell contains a limited amount of energy. If a failure event occurs with this cell, the effect will be much less than that expected from a cell many times larger” (p. 2).

The Tesla Roadster uses 6831 of these 2 Ah 18650 cells, the pack constructed from 11 modules of 621 cells each. Warner (2010) also discusses the safety related issues of choosing different cell sizes for use in EV battery packs this is summarised in the Figure 7.11 below.



**Figure 7.11** “Safety characteristics differ between form factors” (Warner 2010). An overview of the pros and cons of various cell packages.

Many different forms of cell packaging will emerge in the EV conversion market, everything from user installed fully packaged battery packs with supporting electronics to different sized modules will become available. There is no right or wrong answer for the EV converter, however the use of a large or small size of cell will affect the design of the pack architecture and supporting systems. Both design approaches are used in current production vehicles, the Tesla approach shown above can be compared to the Mitsubishi i-MiEV which uses 50 Ah cells packaged in 4 cells per module with 22 modules in the pack, using an 88S1P configuration (88 series, 1 parallel) to give a pack voltage of 360 V. The EV converter is much more likely to use large format prismatic cells as they are packaged more conveniently for use in a conversion. The large number of electrical connections required (usually made by spot welding tabs on to the

terminals) when using 18650 cell and the packing of a large number of cells in the form of a module, such as that used by Tesla, is unlikely to be achievable by most EV converters. Whereas the fire/explosion propagation risk is greater with a large cell, the larger the series cost and BMS requirement for small cells will also discourage the use of these for EV conversions. Pistoia (2010) lists the cell size issues to be investigated as;

1. The number of cells that must go into thermal runaway to cause the entire battery system to go into thermal runaway.
2. The requirements of cell balancing and the effects of differential cell ageing on the safety and performance of the battery system.
3. The probability and effect of propagating circuit board failures.
4. The orientation and placement of the cells in the battery to minimize the propagation of a cell failure.

In summary, the battery system design is influenced by the choice of cell size. The use of large format prismatic cells in EV conversions should be carried out with special attention paid to cell isolation, both from an electrical and fire/explosion propagation point of view.

### **7.7 Module and Battery Pack Protection**

The application of module level safety solutions represent safety systems which are applied external to the cell. The safety of the electric vehicle battery system at module and pack level is largely managed by supporting systems such as the Battery Management System (BMS) and its measurement, monitoring, calculation communicating and control actions. These actions are classified as active safety features. These safety systems can be physically integrated into the module/cell or be externally connected to the cell as part of the BMS. The safety methods that can be applied at the module level are the following;

- external short circuit fuses,
- cell/module isolation,
- thermal management,
- voltage management. Under Voltage (UV) and Over Voltage (OV),

- mechanical packaging for physical, electrical and chemical containment,
- cell internal-short detection (internal resistance measurement),
- charge balance devices on each module/cell,
- PTC devices, thermal cut-offs, bimetal switches, thermal fuses and pressure fuses,
- monitoring electronics to prevent the cells from being overcharged and overdischarged, and
- electrical disconnects.

The mix of protection devices used will depend on the risks involved in the use of a particular cell chemistry. Pistoia (2010) states;

“Some electrochemical battery cells have strict safe operating limits for temperature, voltage, and current, while others can be abused without much concern for safety” (p. 499).

For example an E-bike with a 48V LA battery system might have voltage monitoring only, be charged on a timer and have no BMS. In Figure 7.11 from Warner (2010) it can be seen that not all safety features are available in each cell type, therefore the choice of active safety system should be chosen to compensate for the weaknesses in the cell design. It is suggested that for Li-ion cells the minimum requirement would be at least one level of active protection for OV, UV and thermal for each cell/module. The BMS is discussed in the section below.

### 7.7.1 The Battery Management System (BMS) and Motor Controller

The BMS is the heart of the vehicles safety system. Batteries do not offer any information on the state of the battery without external measurement. This section is here to give background to various BMS functions and provide guidance for the selection of a suitable BMS. The goal of the BMS is first to protect and then to improve performance of the battery pack. The function of a BMS is to;

- ensure that the battery is operated within safe limits and achieves optimum performance over its life.
- prolong the battery's calendar and cycle life
- provide information on the battery's current state and performance,
- and balancing the electrochemical cells

The BMS achieves this by performing monitoring, measuring, calculating, communicating, control and balancing functions. A typical BMS system provides the following functionality (Pistoia 2010);

- cell state monitoring,
- charge and discharge current measurement and limiting,
- cooling/heating system management,
- communications between the battery and the vehicle,
- high-voltage relay control and
- state of health and state of charge monitoring and estimation.

Zhang (2010a) from Lishen Battery in China gives the BMS design requirement for safety and reliability as;

#### *Safety*

- Multiple redundancy and safety backup
- Service plug
- Voltage, current, temperature, water incursion, collision, overturn, fire detection, condensation handling, gas venting
- Pack thermal prevention
- Multi level fusing
- High voltage insulation and chassis insulation.

#### *Reliability*

- Thermal management

- Air cooling and/or water cooling/heating
- Temperature monitor by controller board
- Cell balancing – prolong battery life
- Mechanical robustness

Underlying different BMS design philosophies is the fact that voltage and temperature need to be measured or monitored and controlled. Pistoia (2010) explains the basic requirements;

“Typical measurements in a BMS often include voltage, temperature, and current – although cell pressure may also be measured in some applications. Measurements for voltage and temperature may be done at the individual battery cell level or at the pack level, or both. Current is typically measured only at the pack level but could be measured in both the positive and negative sides of the battery” (p. 501).

By assessing the above level of risk it would seem prudent that one level of active voltage and temperature monitoring is the minimum requirement for Li-ion batteries in EV conversions. A battery pack with cells that are susceptible to internal short circuit will need a BMS that will monitor the individual cell/module voltage rather than just at the pack level. A sharp drop in voltage in a cell compared to other cells in the pack indicates an internal short in that cell.

An example of two separate levels of voltage control is as follows; first a SOC calculator which uses measured voltage values to control charge and discharge functions and secondly a high/low voltage threshold monitor which operates a failsafe control. As discussed above this multi-layered approach provides some level of redundancy.

BMS electronics should be designed to be fail safe, that is if a failure occurs in the circuit board or electronics then the system reverts to a safe state, that is with the main contactors open.



**Figure 7.12** The BMS wiring for half of the LiPo pack which is shown under construction in Figure 7.24.

### 7.7.2 BMS Selection

A BMS may be as simple or as complex as the vehicle and cell chemistry requires. A management system could simply be a temperature monitor in the form of a fuse used to prevent thermal runaway. The complexity of BMSs can vary widely but must match the requirements of the cell used, alternatively the BMS complexity might also influence the choice of cell. Giebel (2010) states that the Volkswagen approach is;

“...with Chinese Li-Ion it is best to go for safe technology with the advantage of needing a simple BMS”.

The battery manufacturer’s guidance to the correct BMS selection should be sought as they are the expert in safety issues surrounding the particular chemistry and construction. The battery manufacturers warranty requirements may in fact require the use of a specific BMS. It is also important to ask these questions when purchasing cells from an intermediate source. Pistoia (2010) explains that;

“When researching a battery management system (BMS), finding a similar application will likely assist in the selection of the battery and management system” (p. 494).

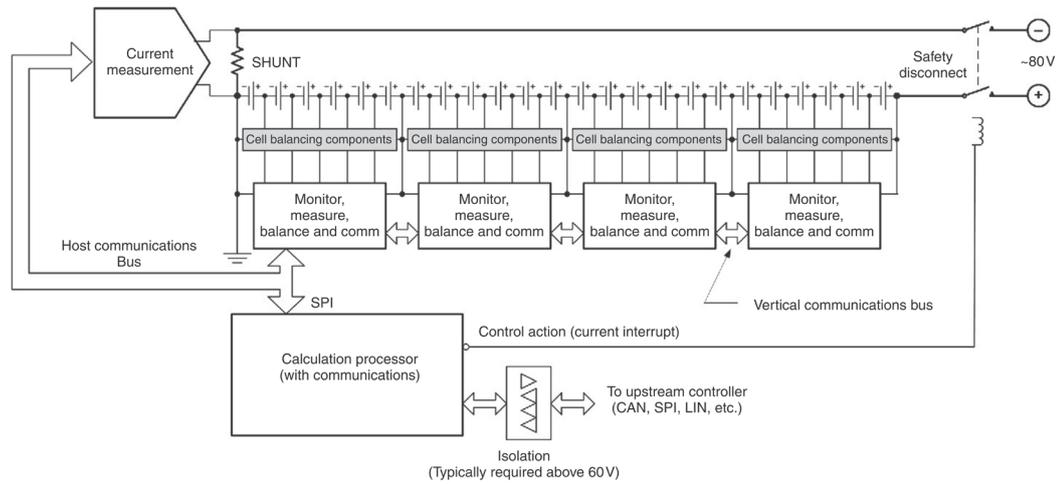
NCOP-14 (2011) has a clause on battery management with specific recommendations for lithium batteries;

“For series strings of batteries, some form of charge or balance management should be implemented. The necessity of this requirement will be dependent on the battery chemistry and technology used in the vehicle. This is especially critical with lithium chemistry batteries which must be maintained within strict upper and lower voltage limits and upper temperature limits. Some form of device to monitor these limits on each individual cell or group of parallel cells should be present. If a monitoring device is fitted, the monitoring device must be capable, of either audibly or visually by means of a flashing lamp, warning the driver of an impending disconnect with sufficient time for the driver to safely park the vehicle before disconnection occurs” NCOP-14 (2011) (p. 18).

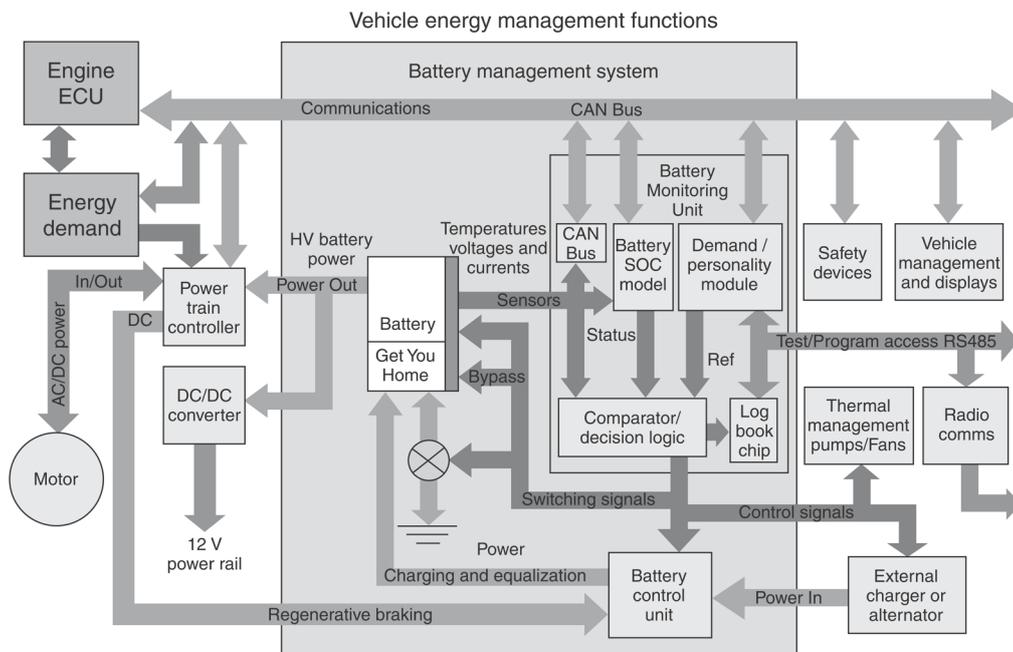
This clause represents a good summary of recommendations for lithium cells. Although not required in all BMS, onboard self-diagnostic features are becoming more critical in vehicles.

### **7.7.3 Examples of BMS Architecture**

There are two types hardware architecture 1. centralised, 2. distributed. Centralised BMS have all the components all in one location and are often collocated with the pack (Figure 7.24). With a distributed architecture the functions of the BMS are repeated for each module (Figure 7.26), the BMS electronics are then mounted directly to the module terminals. Below are some schematic representations of BMS architecture.



**Figure 7.13** Example of HV BMS block diagram (Pistoia 2010) (Figure19.5 p. 512).



**Figure 7.14** Protection control circuit used for a HEV battery from (G.L. Plett 2006)

### 7.7.4 BMS Summary

The BMS for EVs are significantly different from traditional management systems employed in consumer and industrial products such as laptops, cellular phones, two-way radios, power tools, and portable power products. Although the basic functions for monitoring, measurement, calculation, communication, control and balancing exist, the implementation is more critical due to the physical size,

power, energy, and end usage of such batteries in vehicles. By selecting the appropriate functions required by the vehicle type and the battery cell chemistry, a proper BMS can ensure a robust, safe, reliable, high-performance battery system (Pistoia 2010).

### **7.8 Charging and Battery Balancing**

Li-ion battery charging is an often overlooked but safety critical issue. Unlike LA batteries which can withstand over-charging (overcharging is used to equalise the battery pack at full charge), Li-ion batteries are sensitive to overcharging and may present a fire risk. The charging of EVs is most often carried out at the home and at night, and so the risk of a battery fire during charging must be reduced to an absolute minimum. The battery charger reverses the chemical reaction in the cell used during discharging by forcing an electric current through it. The functions of a Li-ion battery charging system are;

- charging the battery,
- controlling the charge – controlling current and voltage (power) to avoid battery damage and enhance the batteries life,
- stabilising – balancing the charge between cells,
- terminating – finishing the charge to prevent over voltage.

Most important of all, the charger must be suited to the battery type including chemistry, size, voltage and power rating.

(Pistoia (2010) describes how to charge a generic Li-ion cell;

“Charging a Li-ion cell is a precise operation requiring features which control when and how the cell is charged. Li-ion cells are usually charged using the constant current–constant voltage charge profile which involves the cell charged at a constant current until its voltage reaches the predetermined limit (typically 4.1 or 4.2 V) followed by a constant voltage charge state until the current decreases to a predetermined low value” (p. 473-4).

The most important function from a safety perspective is terminating the charge to avoid overcharging the cell. Li-ion cells must not be trickle charged (continuous low-current charging) as is done with LA cells, because of the risk of overcharge and damaging reactions at the anode and cathode (Schalkwijk 2002; Pistoia

2010). A battery charger that was designed to charge LA batteries is not suitable for Li-ion. Care must also be taken with chargers that use a series of pulses or a waveform to charge the battery (used with NiMH or NiCad) as these devices must be tuned to the timing of the electro-chemistry. Schalkwijk (2002) explains;

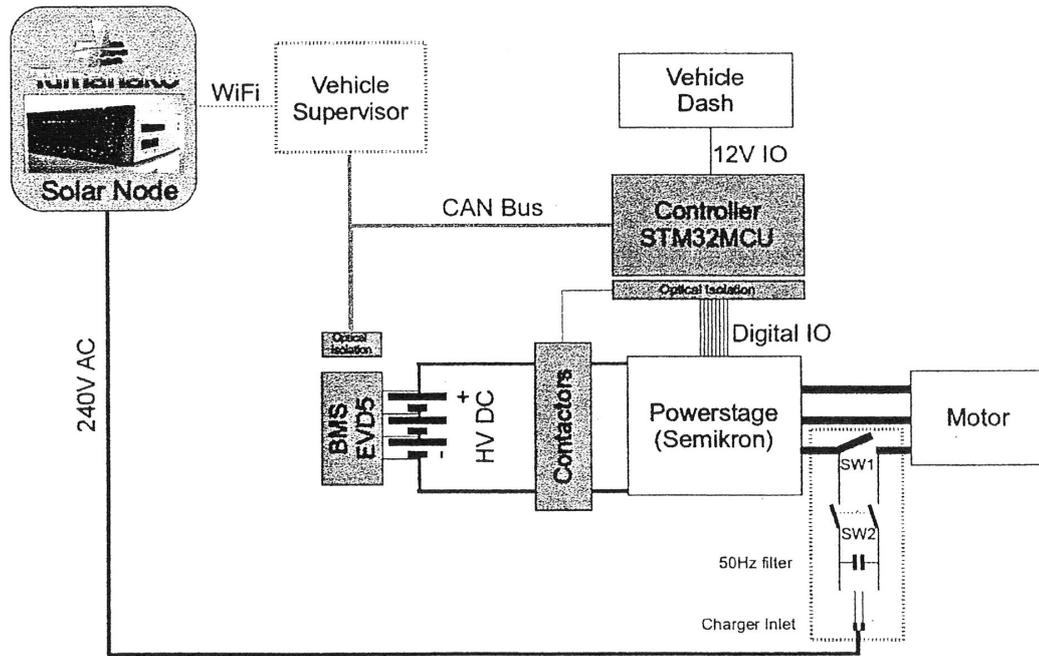
“The electrode processes of the lithium-ion battery are different and do not respond well to the same type of pulse waveforms used for the other chemistries” (p. 465).

A timer based charge control method is not suitable for Li-ion cells. Battery temperature and cell aging are again issues to be considered as these factors affect the battery internal resistance, as Pistoia (2010) explains;

“The rate of Li<sup>+</sup> transport through the SEI (Solid Electrolyte Interface/Interphase) layer is hindered at low temperature. Hence, charging the cell in this state can result in lithium plating at the SEI/electrolyte interface if the rate at which Li-ions arrive at the surface of the negative electrode material exceeds the rate at which they can diffuse from the surface into the bulk of the particles. Lithium plating at the surface of the negative electrode material can result in dendrite growth and hence in an internal short circuit” (p. 475-6).

An EV battery charger can be temperature compensated or the battery pack can be fitted with heating to overcome this issue. A high quality product will have heating fitted for cold weather charging.

A battery charger can be integrated with the motor controller to make dual use of the motor controllers power electronics. An example of such a system is shown in the schematic in Figure 7.15 over the page.



**Figure 7.15** Tumanoko EV components and V2G showing integrated charger (Court 2010).

### 7.8.1 Fast Charging

Standard domestic wiring in NZ operating at 240 V will generally be able to charge an EV battery pack at power levels up to about 3 kW (the Chevrolet Volt has 3kW charger (Cai 2010b)) this is defined as mode 1 charging. At this charge rate a 16 kWh pack will take over 5 hours to charge, as such fast charging at higher power levels is desirable. The batteries electrical and thermal acceptance capacity however need to be taken into account as Dhameja (2002) explains;

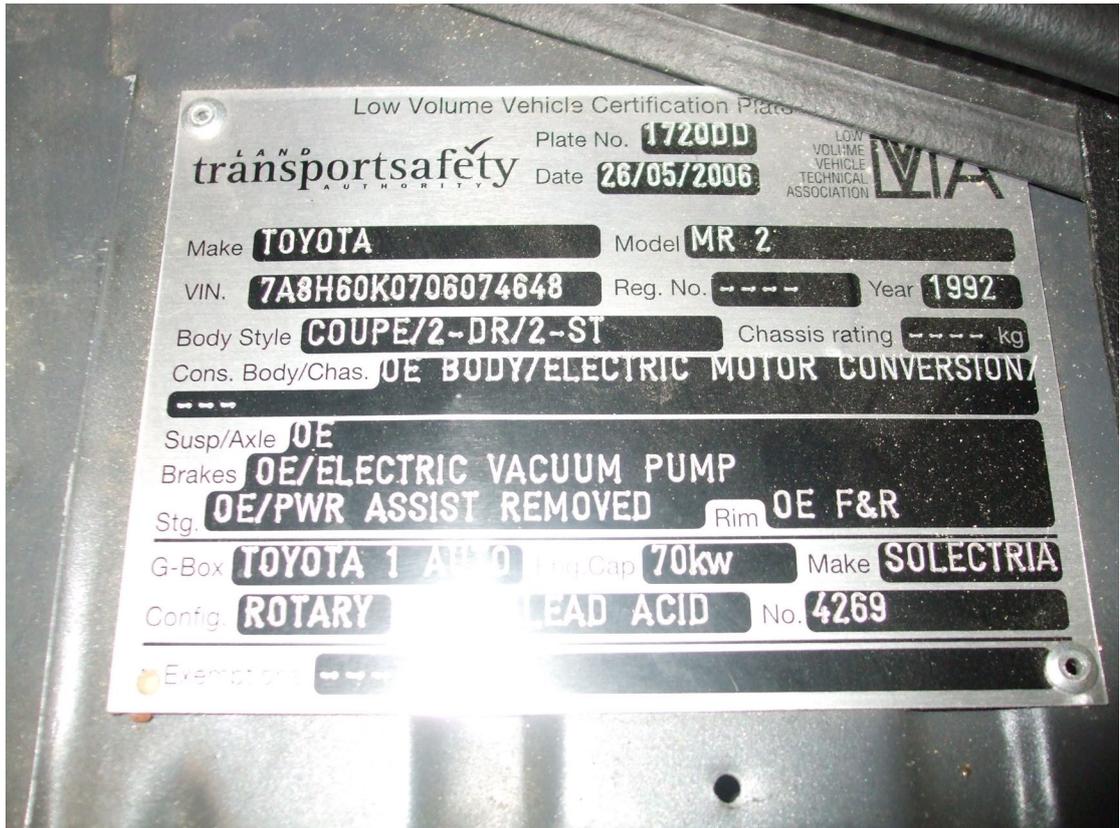
“The fast charging technique for traction batteries account for the battery charge acceptance. The charger adjusts the charge rate continually to match the ability of the battery to accept the charge. Danger from excessive overcharging can be avoided, and the battery modules can arrive at the charge in 20 to 30 minutes. This fast charge also enhances the battery life and provides higher battery efficiency (charge recovery)” (p.95).

### **7.8.2 On-Board or Off-Board Charger**

The charging of an EV's battery raises many issues, for example an EV battery pack charger is not necessarily found on-board the vehicle and several chargers might be used in different locations. The charger could be off-board either in a private garage or provided in a public place such as a car park. This raises the question as to how to be sure that these different chargers are suitable for the particular vehicle. The charger provided in a public place is the subject of consumer law. As there is a contract for the provision of energy the provider of the charging service must make sure that the vehicle is not damaged. The risk here is mitigated by the coercive effect of commercial liability.

For the off-board charger at home it could be argued that the charger is not part of the EV conversion and should not be part of a LVV certification.

It has been argued within this thesis however, that the battery charger is an important safety related component of the EV, whether it is on-board or off-board. It has also been shown that an off-board charger is part of the 'battery system' by the definition given in Section 7.1.2 above. Based on these safety concerns the charger should be included in the certification process and information on the battery charger (as it was certified) should be included on the LVV plate. Figure 7.16 shows a LVV certification plate.



**Figure 7.16** LVV certification plate.

Charger safety interconnects are discussed in the electrical safety Section 6.15 above.

### 7.8.3 Charge Balancing

A large string of cells connected in series as those commonly found in EVs can become unbalanced with regard to voltage. Protection is required for each Li-ion cell/module as this unbalance can be caused by differences in cell internal resistance or self discharge rate due to normal manufacturing variation. The pack voltage is equal to the average of the cell voltages, however no two cells in a battery are identical or manufactured exactly the same (Dhameja 2002). Differences in temperature due to the cells position in the pack can also cause cell imbalance. A cell with a lower manufactured internal resistance will be the first cell to reach 100% SOC. Dhameja (2002) states;

“This cell will be the first to undergo repeated overcharge and overdischarge, eventually resulting in the failure of the battery” (p. 133).

After a number of cycles, the rapidly weakening cell can be driven below the manufacturers minimum voltage specification or in an extreme case the cell can be forced into voltage reversal by the rest of the pack. This is a dangerous situation characteristic of Li-ion cells as Pistoia (2010) explains;

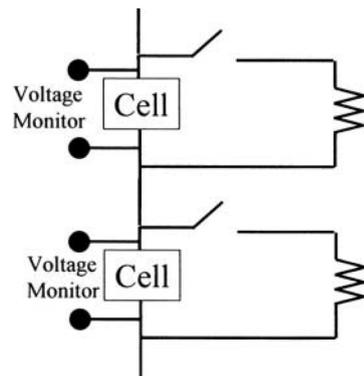
“If the Li-ion cell is overdischarged frequently, dendrite growth may start to occur between the negative and positive terminal which can eventually lead to an internal short” (p. 475).

Identifying and isolating a weaker battery is an important safety feature of the Battery management System (BMS). Schalkwijk (2002) and Pistoia (2010) reinforce this point by stating that;

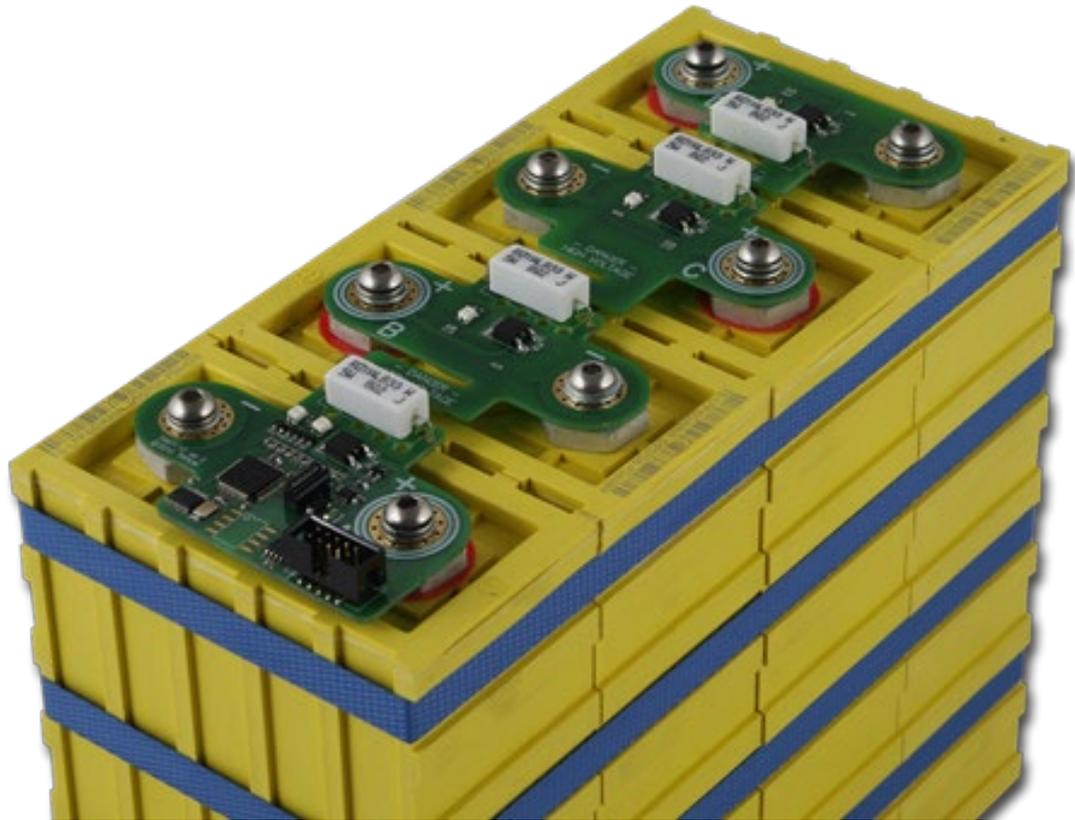
“...due to the normally larger sizes of batteries in electric traction vehicles, balancing often becomes a requirement” (Pistoia 2010) (p. 504).

“Voltage control is paramount for lithium-ion batteries and most manufacturers require cells to be controlled to within  $\pm 25$  to  $50$  mV per cell” (Schalkwijk 2002) (p. 463).

Cell balancing takes place as pack approaches 100% SOC, the cells in the pack are controlled to allow the undercharged batteries to gain an equalization charge, while the fully charged batteries are not overcharged. The simplest method is the ‘bleed’ or ‘bypass’ or ‘resistive’ method (Figure 7.17), this approach connects a low value resistor across the battery cell that is at a higher voltage or SOC, thus bypassing some of the charge current around that cell Pistoia (2010).



**Figure 7.17** Resistive cell equalisation. When the cell reaches a cut-off, the switch is thrown, bypassing the charging current around the cell (Schalkwijk 2002).



**Figure 7.18** A four cell balance controller for a 60Ah cell. Balance current 500mA. Voltage accuracy 4mV. Temp accuracy 2°C. Isolation Rating 950 V DC. From; <http://www.tritium.com.au/products/TRI67/index.html>

The disadvantage of this method is that some of the charging energy is dissipated in the bypass resistor affecting the efficiency of the vehicle. A charge transfer or ‘active’ balancing approach is a more suitable, but more complex method. Energy from the higher voltage cells is transferred to the lower cells with minimal losses using a transformer or inductive method (Pistoia 2010). A table given by Xuezhe (2010) (Figure 7.19) lists the benefits and weaknesses of each method.

Method Feature	Passive Balance	Active Balance	
		Transformer	Inductor
<b>BMS design</b>	simple	complicate	
<b>Lose of energy</b>	all	Depend on the efficiency	Depend on the cell uneven distribution
<b>Time</b>	long	short	medium, Depend on the cell uneven distribution
<b>Current (general)</b>	<100 mA	1 – 10 A	0.01–1A
<b>Application</b>	less uneven cells, HEV	uneven, large capacity cells	
<b>Support</b>	O2: OZ890 Linear: LTC6802 AD: AD7280	Infineon	TI bq78PL114 bq78PL112

**Figure 7.19** Cell balancing methods (Xuezhe 2010).

The suitability of a particular cell balancing system should be assessed with guidance from the battery manufacturer and by assessing the systems accuracy and current capacity.

A special form of battery charging is that from regenerative braking. Battery issues around regenerative braking are discussed in Section 8.5.6. The regenerative braking power limit may be controlled by a separate system to the charger.

#### **7.8.4 Charger Summary**

The battery charger is a safety critical component of EV conversions, whether it is on-board or off-board and as such it should be part of the EV certification. Three issues have been identified;

1. charger must be correct for the chemistry,
2. correct and reliable voltage termination,
3. reliable cell balancing.

## 7.9 Discharging

The control of pack discharge is a task usually performed by the motor controller and or BMS. The main function is to control the power by measuring or monitoring current and temperature for both the battery pack and the traction motor. Lithium cells must also not be overdischarged as this can lead to internal short circuits and cell failure. An example of battery damage caused by excessive current in an electric race car is given in Figure 7.20 below:



**Figure 7.20** Heat damaged battery terminals of a Li-ion cell caused by excessive discharge current under abuse conditions.

## 7.10 Pack Architecture and Design

The battery pack enclosure must perform several functions. The key design criteria for the battery housing of an EV conversion are found to be;

- that it must fit into the vehicle structure,
- provide mechanical impact and vibration protection,
- contain hazardous material (safety and environmental) and isolate failures (pack splitting),
- comply with impact standards,
- be light weight,
- be low cost,
- have access for inspection and maintenance,
- allow for cooling and ventilation,
- be corrosion resistance,
- provide environmental protection (water, dust, condensation),
- have features to prevent short circuits and,
- be fire resistance.

Battery packs in OEM vehicles take many different forms as the designers rationalise these sometimes conflicting design requirements. Each vehicle and cell type match will have its own solution. Electronic components and supporting systems will also be collocated with the battery pack. The battery pack architecture should also facilitate mechanical protection from impact and cell isolation, both with to limit the fire/explosion propagation reaction and from an electrical perspective. Cooling and ventilation of the battery pack will be discussed in a section below.

The first challenge for an EV converter is to find a way of inserting the pack into the vehicle whilst keeping the structure of the vehicle intact. Cutting a section of the floor out of the vehicle to utilise the space vacated by the fuel tank is a common and accepted method of integrating the pack into the vehicle structure. Figure 7.21 shows how this is successfully achieved in a Mazda 3.

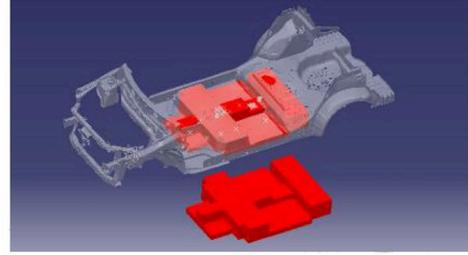
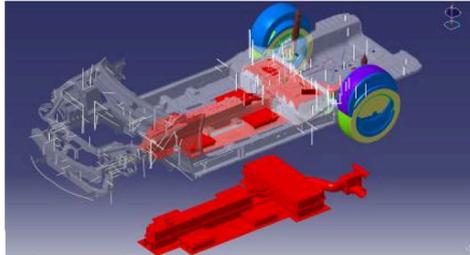
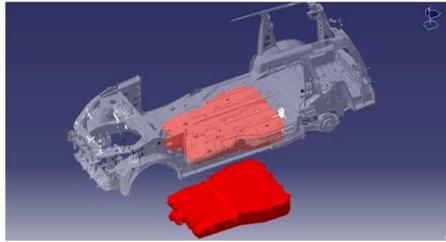


**Figure 7.21** The boot floor of a hatch cut-out either side of the chassis rails to allow a LiPo pack to be partially recessed.

### **7.10.1 Battery Positioning**

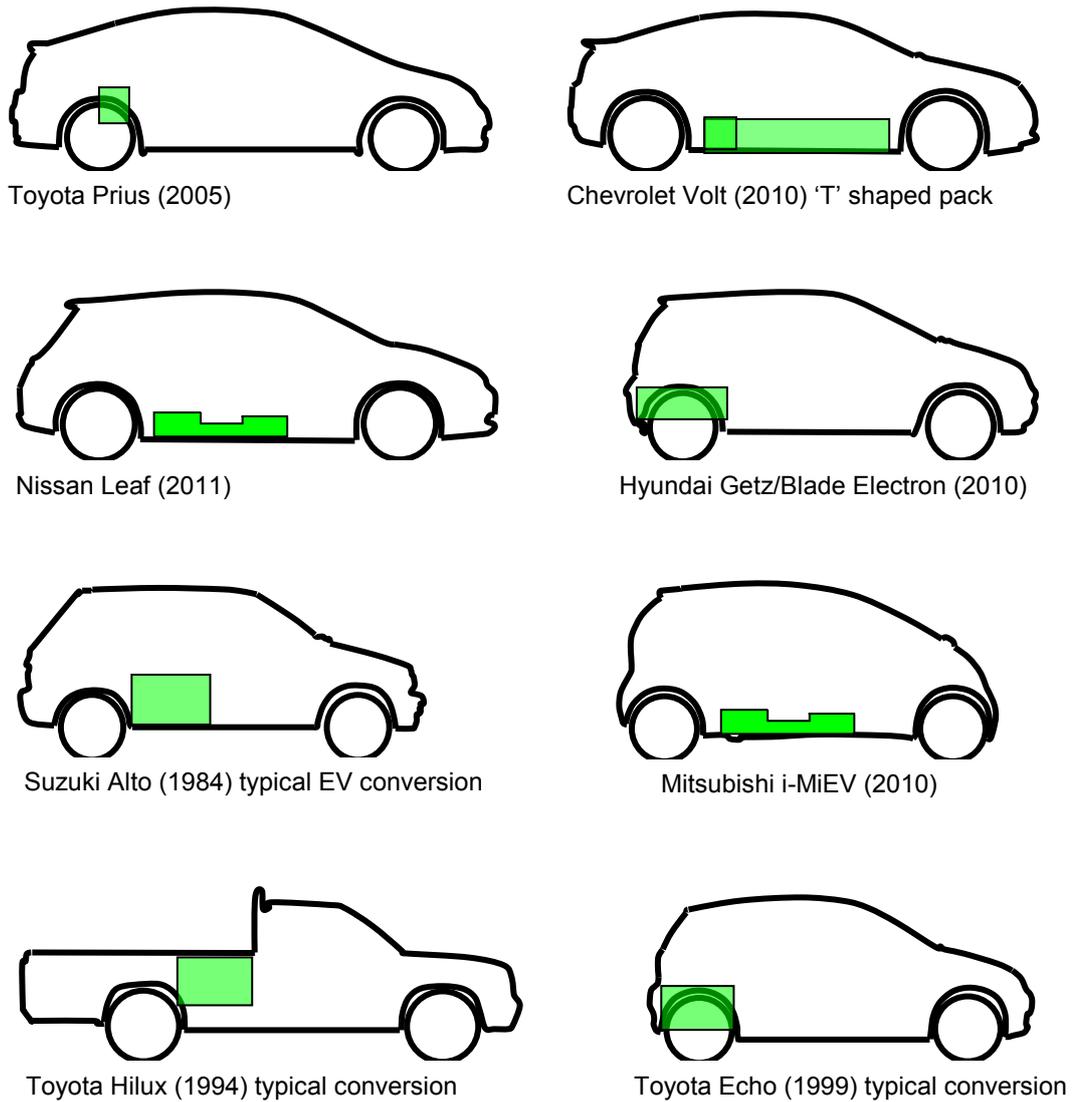
The positioning of the battery pack must ensure that sufficient ground clearance is maintained and consideration must be given to maintaining a crush zone at the front, rear and sides of the vehicle. OEM battery packs are also inserted from underneath the car, however ease of access for maintenance may be compromised and the homebuilt EV is likely to need more maintenance than an EV from a major manufacturer.

The positioning of some OEM vehicle batteries is shown in Figure 7.22 below.



**Figure 7.22** Haitec monolithic packs standardised for swapping. Three forms of pack shape; box, ‘T’ and underseat (Jen 2010).

A review of battery pack locations for a number of OEM and conversion EVs was undertaken and the results are displayed in Figure 7.23 below;

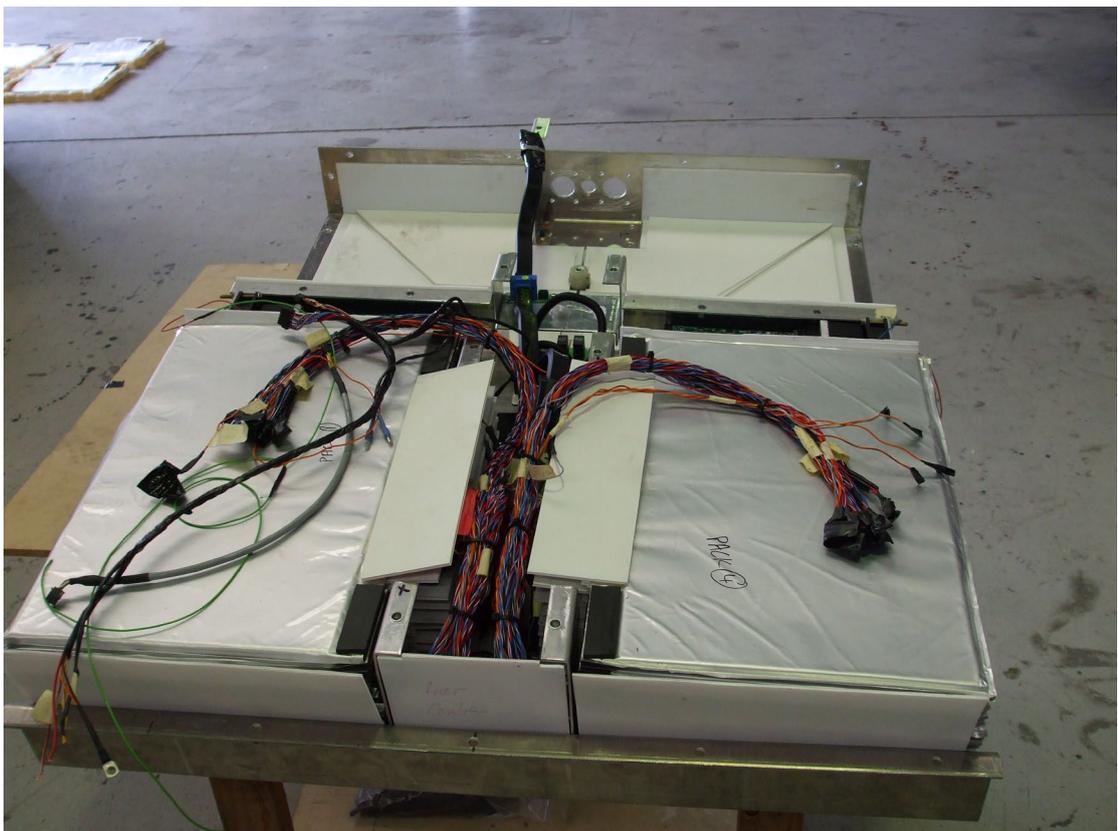


**Figure 7.23** Typical positioning of EV battery packs in OEM and converted vehicles

The results show that all vehicles surveyed with the exception of two EV conversions position the battery pack between the vehicles axles. Whilst the position of the battery pack in EV conversion will vary from vehicle to vehicle, the majority of designs make use of the rear luggage compartment. The pack should not extend beyond the vehicles wheels as the battery is best positioned low and in the centre of the vehicle for superior handling dynamics, and between the wheels for protection from impact.

### 7.10.2 Pack Layout

The pack layout will most likely be determined by the cell type chosen and interconnection of the terminals and supporting electronics. Consideration should be given to dividing the pack into equal sections, both physically and electrically to reduce the severity of a failure event. A pack can be split in two by a simple metal divider or the parts can be separated and positioned in the front and rear of the vehicle, as is commonly done with LA conversions. The strategy of using battery pack separators will also slow the spread of a fire which breaks out in the battery pack. Steel rather than aluminium separators should be used to resist a high temperature lithium fire. The Toyota Prius battery pack has the service plug (switch) and fuse in the electrical centre of the pack to half the voltage. An example is given in Figure 7.24.



**Figure 7.24** A Lithium Polymer (LiPo) pack under construction, using pouch type cells. Aluminium sheet is folded to make the box and then lined with plastic coreboard. A cover will be fitted once the second half of the pack and BMS is assembled. The BMS and HV contactors are located in the centre of the pack.

## **7.11 Battery Impact, Restraint and Containment**

Vehicle impact and crashworthiness design has become the most stringent structural design criteria for motor vehicles. This project is concerned with two areas impact safety design;

1. crash worthiness design for occupant protection,
2. electrical design for impact and
3. the safety of the high voltage battery system during impact.

This section will discuss the latter issue of the battery system impact, the former being discussed in the chassis section, page 182 and electrical section page 71.

Modern passenger vehicles must undergo a set of crash tests into a barrier at 48 km/h. NZ has adopted the major international standards for frontal impact as listed in Land Transport Rule 32006/1 Frontal Impact. In a typical EV conversion the structure of the battery restraint system will be a box, a set of racks or hold down frames. The standards for the design of battery restraints are described in terms of the g force they must withstand, or by testing standards.

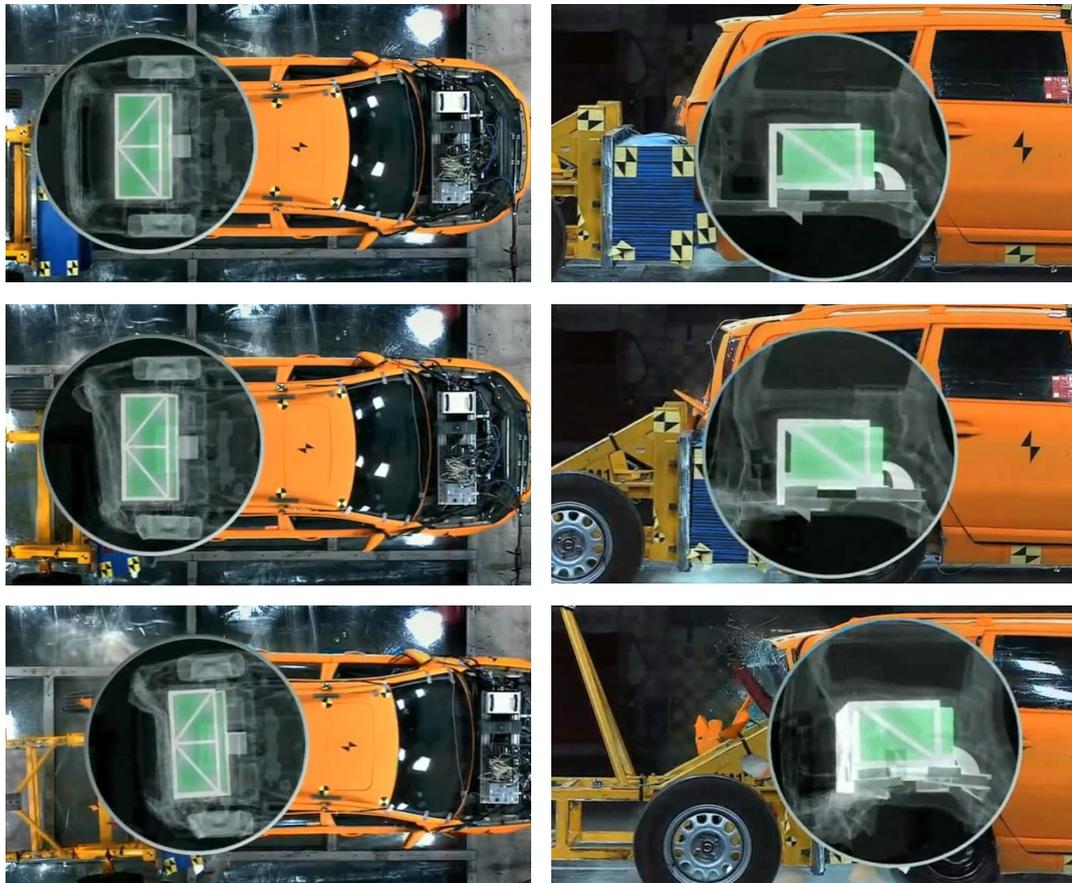
ANCAP does not currently test the integrity of the battery or electrical system after the impact test even though this is a requirement of a number of the international EV standards. It is recommended that ANCAP update its procedures in this area.

The FMVSS 571.305 (48 km/h) has a requirement for post crash electrical and electrolyte spillage testing and ISO6469-1 (2009) also gives specific requirements for the crash testing of EVs, the general requirements from these standards are as follows;

- no battery penetration into the passenger compartment,
- battery movement shall be restricted,
- no spilled electrolyte in the passenger compartment,
- no battery ejection from the vehicle,
- no electrical short circuit.

For converted EVs built in NZ vehicle certifiers must assess the risk of the above requirements for a particular vehicle and battery configuration. It must also be noted that for some battery systems rear impact could be a more stringent requirement.

Volvo testing of a prototype battery system showing the crush zone before the battery is impacted is presented in Figure 7.25;



**Figure 7.25** Volvo full scale crash test PHEV (Volvo 2009). Available from <https://www.media.volvocars.com/> accessed 19,01,2011.

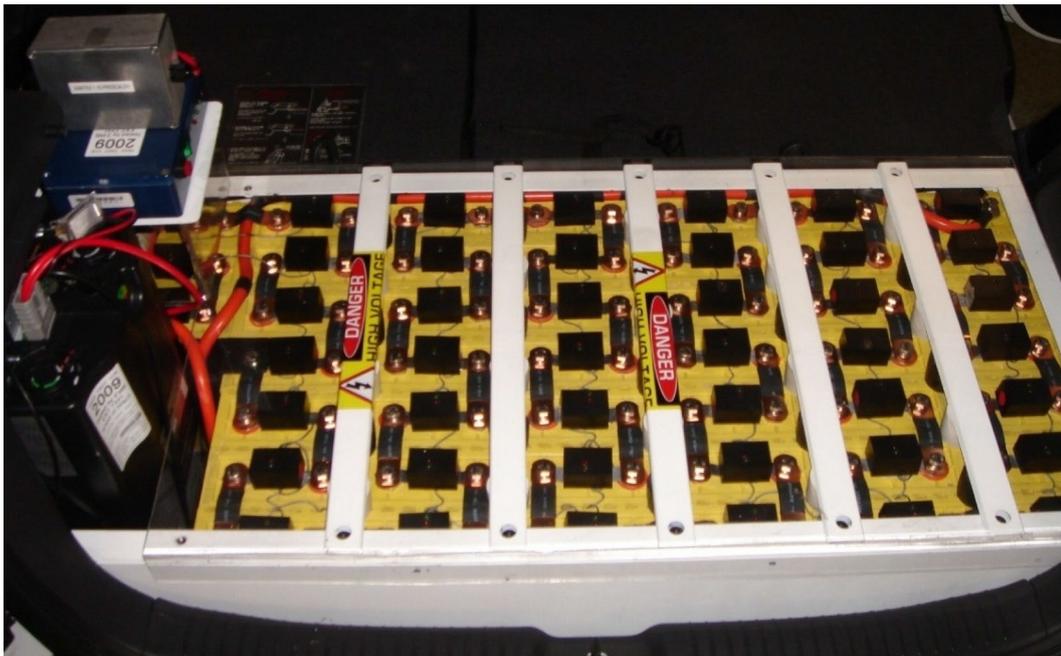
The main requirements of the structure are for strength and controlled deformation. A calculation design method might be used by EV converters. For this method NCOP-14 (2010) gives loading conditions for EV conversions in the form of impact forces. These are;

- |                            |   |          |
|----------------------------|---|----------|
| frontal impact             | – | 20 g,    |
| side impact                | – | 15 g,    |
| rear impact                | – | 10 g and |
| vertical (rollover) impact | – | 10 g.    |

Protection against chemical leakage is dependent on the risk of the chemistry and whether solid or liquid electrolyte is present. The use of a containment system is particularly important for LA conversions. It was found that many LA converted

EVs have no acid containment. The acid containment system deployed can depend on whether the battery contains liquid, gel, or solid electrolytes.

An opportunity exists for further research into battery pack restraint and impact performance, especially the testing of systems. Ip (2008) and Tietzel (2009) describe the design of a battery restraint using Finite Element Analysis (FEA). The pack used 122 kilograms of Thunder Sky batteries fitted to a Hyundai Getz. The frame was made from 25 x 3.0 angle and the upper bars from 25 x 13 RHS.



**Figure 7.26** Battery restraint system. The design used plastic hold down blocks (~50 mm high) to separate the terminals from the upper bars and a transparent plastic cover. The BMS architecture used here is the distributed type with the BMS mounted directly to each battery module (Tietzel 2009).

FEA design techniques could be used to produce standard designs for EV conversion for use by EV converters. Tietzel (2009) questions modelling the battery modules as a rigid body by applying the design acceleration as a pressure to the side of the enclosure. The use of straps or tie rods to secure the modules together inside the pack would justify this assumption. Light weight steel strapping such as that used in the packaging industry could be used to strap the modules together. Particular attention should be paid to insulation and/or grounding of the straps, corner protection of the modules and thermal expansion.

Damaged Li-ion cells can pose a severe fire risk during charging. If an EV fitted with Li-ion batteries is involved in a minor accident and it is intended that the batteries be reused, testing must be carried out to verify that they are still in good condition and if there is any doubt, the batteries must be retired.

## 7. 12 Battery Pack Cooling and Heating

The thermal management system of a Li-ion EV conversion will provide either heating or cooling action depending upon the battery pack conditions. The goals of the cooling/heating system are;

- to prevent the battery cells overheating – causing thermal runaway,
- to have the cells working at their most efficient temperature (Li-ion cell performance is highly temperature dependent) and
- to create an isothermal battery pack – an even temperature from cell to cell will minimise charge imbalance during cycling.

The heating/cooling system needs to operate whilst the vehicle is in use (moving) and when it is stationary (parked or charging). The first point is the only a safety issue (if the pack has a charge equalisation system that can rebalance the cells). Heating of the pack is necessary under cold winter conditions when the vehicle is first started and the discharging of the pack during normal driving has not yet warmed the cells. As this may be less important considering NZs mild winter conditions, the heating aspect of the pack will not be covered in detail. The cooling of power electronics are briefly discussed as this is less of a safety issue, and the manufacturers of these components will provide details on how their product should be cooled.

Battery packs may be air cooled or liquid cooled by forced or passive means. A liquid cooling system requires an extra level of integration that might not be achievable by most EV converters. The Chevrolet Volt uses liquid cooled thermal fins inserted between the pouch type cells to provide heating and cooling. These fins turn the battery pack into a huge radiator<sup>7</sup>.

The sources of battery pack heating during normal use are;

1. the cell, due to normal exothermic and resistive cell processes during discharge and charge,
2. the ambient temperature and
3. resistive heating of associated electronics and wiring connections.

The internal heat generation of the battery pack can be estimated using a simulated driving profile and a knowledge of the internal resistance and heating

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<sup>7</sup> An animation of the battery operation is available at <http://gmtv.feedroom.com/>.

characteristics of the cells in the pack, or alternatively it can be measured during electrical cycling in an isothermal air-flow calorimeter.

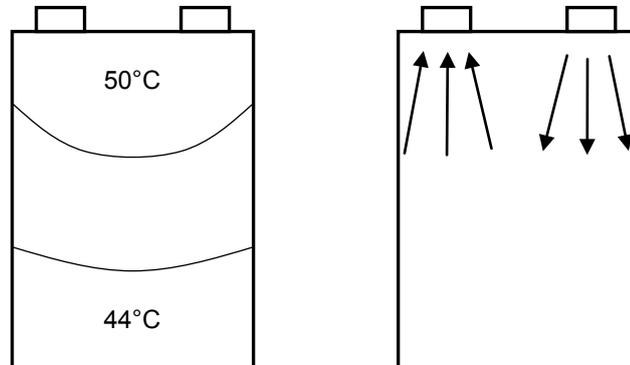
The temperature limits specified by the cell manufacturer should be observed. Densham (2010) suggests that the maximum cell temperature allowable for a generic Li-Ion cell is  $T_{\text{cell max}} = 55 - 60^{\circ}\text{C}$ . Pistoia (2010) also states;

“In general, whenever a charged Li-ion cell is exposed to temperatures above  $60^{\circ}\text{C}$ , there is a risk of initiating exothermic reactions within the cell. The heat generated by these reactions may result in a rise in the cell temperature, which in turn activates additional exothermic reactions” (p. 467).

Isidori (2010) also gives some design targets for Li-ion battery pack temperatures;

- maximum cell temperature,  $T_{\text{cell max}} \leq 40^{\circ}\text{C}$
- temperature within an individual cell,  $T_{\text{within cell}} < 5^{\circ}\text{C}$  and
- temperature between cells in the pack  $T_{\text{between cells}} \leq 5^{\circ}\text{C}$ .

Figure 7.27 describes how high currents resulting in an uneven current density can cause temperature differences within a cell.



**Figure 7.27** Cell uneven temperature.

This Figure shows that the positioning of the temperature sensors within the battery pack could be critical to cell safety.

The ambient temperature exposure of the HEV batteries will depend upon the location of the cells within the vehicle under summer conditions (Pistoia 2010). A Figure presented by Pistoia (2010) gives a vehicle dashboard temperature of over  $100^{\circ}\text{C}$  for a 40 degree maximum atmospheric temperature day, strongly suggesting that a high ambient temperature must be considered by the designer.

High performance controllers are water cooled for example, a 30 kW power controller running at 97% efficiency would represent a heat loss of 900 W, this is a significant heat load. Staunton (2008) states that power electronic loads will be running at approximately  $\sim 50^{\circ}\text{C}$  with the motor generators (traction machines) at about  $\sim 80^{\circ}\text{C}$ . The major electronic heat sources must be placed away from the pack and with separate cooling. The above data shows that EV heat loads generally have lower temperatures than ICE vehicles due to them being more efficient machines. Staunton (2008) states that this can cause cooling issues as;

“A low heat load is not necessarily any easier to manage than a high heat load. This is because heat transfer is dependent on temperature change.

$$Q = mC_p\Delta T \text{ ”.}$$

Staunton (2008) gives an example of two systems that require cooling. The EV represents many smaller heat loads at lower temperatures therefore Staunton (2008) concludes that each load needs to be cooled individually and as such the cooling system complexity increases as the operating temperature decreases.

A simple calculation can show the resistive heat loss from an EV power pack at operating at a certain current level (Densham 2010). The power lost, if not removed by the cooling system will result in heating of the battery pack. By Ohms law the peak power loss in each cell is given by,  $P_c = I^2(R_c)$

Where  $I$  is the maximum pack current and  $R_c$  is the cell internal resistance.

An example calculation of maximum pack power loss (Densham 2010) is given below;

$$I = 200 \text{ A (Tesla Roadster)}$$

$$R_c = 1.0 \text{ m}\Omega$$

$$P_c = 200^2 (0.001) \approx 40 \text{ W}$$

$P_{pack} \approx 4000 \text{ W}$  with 100 cells installed. This figure represents peak power lost

Densham (2010) suggests that a realistic value for average power lost would occur at 40 A i.e.  $P_{pack} = 40^2 (0.001) 100 = 160 \text{ W}$ . A more accurate assessment can be made by considering the current load during a standard drive cycle or other knowledge of vehicle operation using the equation below;

$$P_{pack} = N_c \int_0^t I^2(t) R_c dt$$

Battery charging and regenerative braking will also cause battery heating by the same resistance mechanism.

The above calculation requires knowledge of the battery's internal resistance at either the cell, module or pack level. This internal resistance cannot be measured directly with an ohmmeter as the total cell impedance is due to resistances exhibited by the battery terminal, the battery plate welds and other plate-to-plate connections, the ionic conductivity of the electrolyte and the activity of the battery during the electrochemical processes occurring at the plate surfaces (Dhameja 2002).

A DC load test or an AC impedance test must therefore be used to determine the cell impedance. The EV home builder is not likely to have the knowledge or equipment to measure cell internal resistance. The ambient temperature, cell and battery life, and discharge history are all factors that affect the AC impedance (Dhameja 2002). An ageing battery pack will generate an increasing amount of heat as it gets older and the internal resistance increases. End of life impedance can be as much as 200% that of beginning of life. The stated internal resistances for CBAK Power Batteries is given by Deng (2010) and reproduced below showing a large variation.

Type [mm]	Voltage [V]	Capacity [Ah]	IR [mΩ]
18650	3.6	2.0	70
26650	3.2	2.2	≤8
26650	3.2	2.7	≤20
36800	3.2	5.5	≤10
(20148130)	3.2	20	≤2
(20148240)	3.2	50	≤3
(42148240)	3.2	100	≤2

**Table 7.1** CBAK battery specifications. Cylindrical- ØxL. (Prismatic- TxWxH). (Deng 2010).

Detailed thermodynamic design of the of the battery cooling system can take place assuming a knowledge of vehicle use, pack heat capacity, ambient air temperature, heat transfer and aging and temperature characteristics of the pack. An alternative method for the EV converter is to test the thermal performance by monitoring the pack temperature during a defined test cycle. A subjective method

such as ‘...if you can hold your hand on the battery pack for one minute then it is below 50 °C ‘is inadequate, and a test cycle to simulate high performance operation should instead be selected.

### **7.12.1 Thermal Management Design**

The design of a battery pack thermal management system involves steady state heat transfer analysis. The model will consist of four parts, a heat transfer model, a heat generation model, an ambient temperature model, and a vehicle operation model (Dhameja 2002).

(Gene Berdichevsky 2006) describes the design concepts and thermal performance of the Tesla Roadster battery pack which is liquid cooled;

“This cooling system design is especially effective because we have chosen to combine thousands of small cells rather than several large ones to build an ESS, dramatically increasing the surface to volume ratio. For example, with seven thousand 18650 cells the surface area is roughly 27 square meters. If there were an imaginary set of 20 much larger cube-shaped cells that enclosed the same volume, the surface area would be only 3.5 square meters, more than seven times smaller. Surface area is essential to cooling batteries since the surface is where heat is removed; more is better. Also, because of their small size, each cell is able to quickly redistribute heat within and shed heat to the ambient environment making it essentially isothermal. This cooling architecture avoids “hot spots” which can lead to failures in large battery modules” (p. 4).

The primary design of a thermal management system should keep the battery sufficiently insulated. The insulation will help to obtain an acceptably high operating temperature during winter and cooling during summer by means of cooling during the charging period (Dhameja 2002).

A pack fitted with insulation will keep the cells on the outside of the pack warmer as they are not cooled by conduction through the pack wall. As such it will be easier for the cooling system to be able to control the pack the isothermally. The many requirements listed above and in the section on impact indicate that a multi layer casing is required to perform all these functions. An example would be first a steel layer on the outside (impact and structural containment) then foam (thermal insulation) and then plastic (electrical insulation).

The secondary design criteria is that the circulation and the cooling air flow should be properly distributed in space in order to ensure a minimum temperature difference between the individual battery modules (Dhameja 2002). For this reason it is good practice to install spacers between modules (to provide air gaps) and dividers to split the battery pack into individually cooled sections. In hot weather the pack could be cooled by a cool air bleed taken from the cabin air-conditioning.

During certification the certifier should look for aspects of good design of the cooling system such as, the inlet and out let of the battery pack cooling system should be as far away as practical from each other. The air tightness of lid as well as the positioning of the temperature sensors is important. The air flow should be arranged from the bottom to top of the pack to take advantage of the thermosiphon effect.

### 7.13 Venting of Gasses during Charging

Many Li-ion batteries do not require venting as they are fully sealed however no rechargeable battery should ever be placed in a fully sealed container. LA batteries will be used for EVs in the future so it is useful to review the requirements for the ventilation of these batteries. The Li-ion battery system may still need ventilation to remove smells from the operation of the electronics and contactor arcing.

A charger for a flooded LA battery pack applies a continuous low current charge (trickle charge) as it approaches 100% SOC. This is referred to as trickle charging. Continued charging drives the process of electrolysis of the water in the cell resulting in the evolution of hydrogen gas. Many EV and industrial battery standards deal with the issue of hydrogen explosion hazard. The standards identify the hazard to exist in two areas;

- explosive risk in the vehicle,
- explosive risk in garaging the vehicle during overnight charging.

ISO 6469-1: 2009 Part 1 has a vehicle focus and as a general requirement states that;

“No potentially dangerous concentration of hazardous gases and other hazardous substances shall be allowed anywhere in the driver, passenger and load compartments”.

The first task is to identify if the particular battery chemistry and design emits hazardous gasses during normal operation and charging. The Hydrogen generated will rise in the battery compartment and is explosive where the concentration of hydrogen exceeds a hydrogen/air ratio of 4 %, this is defined as the lower explosion limit (Bossche 2003). Dilution and mixing of the explosive gasses to below this threshold is the accepted solution to this problem. The amount and type of ventilation (natural or forced) required will depend on several factors including the rate of hydrogen production and the physical dimensions of the battery enclosure. In the following calculation a safety factor of 5 is applied to the lower explosion limit so the design hydrogen concentration effectively becomes 0.8 %. SAE (2010) gives the hydrogen concentration limit as 2.0 %.

### 7.13.1 Estimating the Ventilation Requirement

The standard BS EN 50272-3:2002 BSI (2002) Safety Requirements for Secondary Batteries and Battery Installations - Traction Batteries gives an accepted method of calculating the ventilation air-flow rate for LA battery systems. The gas generation in a vented flooded cell is calculated from the overcharge current from which the battery will produce a certain amount of hydrogen. BSI (2002) calculates the necessary ventilation airflow for a battery location or compartment by the following formula;

$$Q = v q s n I_{gas} C_n / 100 \quad [\text{m}^3/\text{h}]$$

Where;

$Q$  = ventilation air flow [ $\text{m}^3/\text{h}$ ],

$v$  = necessary hydrogen dilution factor =  $24 = (100-4)/4$ ,

$q$  =  $0.42(10^{-3})$  [ $\text{m}^3/\text{Ah}$ ] generated hydrogen at 1 Ah overcharge current,

$s$  = safety factor = 5,

$n$  = number of cells,

$I_{gas}$  = current producing gas during the gassing phase of charge [A/100Ah]

$C_n$  = nominal capacity [Ah].

For a generic analysis the above formula is simplified to:

$$Q = 0.05 n I_{gas} C_n / 100 \quad [\text{m}^3/\text{h}]$$

BSI (2002) states that where standard chargers are used and no detailed information regarding the charge characteristic is provided,  $I_{gas} C_n / 100$  shall be calculated to be a minimum of 25 % of the rated charger output current in Amps. For a more detailed calculation the end of charge current,  $I_{gas}$  must be known, BSI (2002) gives a table providing typical maximum values for various charger characteristics.

### 7.13.2 Natural or Forced Ventilation

BSI (2002) gives the requirement for natural ventilation as;

Each inlet and outlet minimum area,  $A = 28 Q$  [ $\text{cm}^2$ ] ( $Q$  in [ $\text{m}^3/\text{h}$ ])

Minimum ventilated room free volume,  $V = 2.5 Q$  [ $\text{m}^3$ ]

Air velocity for natural ventilation is assumed to be 0.1 [ $\text{m/s}$ ]

From the above formulas it can be seen that it is unlikely that natural ventilation can be used to ventilate the battery pack during charging as the free volume

requirements would be difficult to achieve due to space restrictions in the vehicle (unless the battery cover is opened prior to charging). Forced air flow provided by non sparking fans would then be needed to ventilate the gasses. Potential ignition sources also must to be kept away from the battery area (>500 mm away) as regardless of ventilation, the dilution of the gases cannot always be assured close to the cells (BSI 2002). BSI (2002) states that the interlocking of chargers and ventilation fans should be considered.

### **7.13.3 Garage Ventilation**

Another alternative approach is taken by UNECE (2002) Regulation 100 for BEVs and the SAE recommended practice J1718. SAE J1718 is aimed at determining the concentrations of hydrogen gas emitted by an electric vehicle being charged in order to know whether or not forced air ventilation is required in the garage (Bossche 2003).

The general requirements are similar such as;

“...not allow potentially dangerous accumulation of gas pockets ... battery compartments containing battery modules which may produce hazardous gasses shall be safely ventilated” (UNECE 2002).

UNECE Regulation 100 (2002) uses a hydrogen emission test during normal charging and places limits on hydrogen emissions, which must not be more than 125 g during a five hour normal charge, or than 42 g in case of charger failure, the duration of the failure must be limited to 30 minutes.

Bossche (2003) questions the applicability of using a hydrogen limit and asks where the value of 125 g of hydrogen emission comes from.

“In a typical garage of 50 m<sup>2</sup>, this corresponds to a concentration of 2.8 % of hydrogen; this value is below the 4 % lower explosion limit, but is higher than the 0.8 % specified in EN 1987-1. With the 42 g hydrogen emission in case of failure added, one comes to a total hydrogen emission of 167 g; the corresponding volume becomes 1872 dm<sup>3</sup>, giving a concentration of 3.75 % in the garage, just under the explosion limit” (p. 325).

Single garages in NZ are considerably smaller than the example given above so it is highly recommended that adequate ventilation be installed in garages that house EVs with LA batteries during charging.

### **7.14 Battery Certification Issues**

Specific issues have been discussed throughout this Chapter however, it is important to clarify the required certification thresholds applicable during the vehicles life. Recertification should be required if a vehicles battery is replaced with a non OEM item or a battery of a different chemistry. A change (increase) to the vehicles pack size also requires a fresh look at the vehicle's safety systems. A 15% threshold is proposed for this. The LVV plate (Figure X) makes no mention of battery capacity or the number of cells or manufacturer of the cells which presents an opportunity of abuse by uncertified modification.

### **7.15 Battery Summary**

Li-ion batteries are ubiquitous technology in portable devices, the engineering of this technology for EVs however is more critical due to the battery size. There are still unknowns in the use of EV technology that will be discovered as the technology develops. For example, what are the dangers of a lightning strike for a grid charging battery pack? Different battery technologies need different protection mechanisms to minimise the risk of that particular cell.

For EV conversion a multilayered design and certification approach should be taken using a mixture of active and passive safety features. A comprehensive set of design tools and rule prescriptions is difficult to write for EV conversions as much of the design is dependent on the cell selection, form factor and space restriction. The EV home builder however is most likely to use large format prismatic cells/modules due to pack packaging and BMS complexity issues. Cells which are sensitive to overcharge and over-discharge should utilise a BMS with individual cell monitoring and balancing capability.

With the use battery chemistries and design which minimizes the risk of failures coupled with of adequate safeguards in the form of redundant protection, well designed thermal management and ventilation systems EV converters can achieve a safe and high performance conversion.



### 8.1 Introduction

The single most important active safety feature of a vehicle is the brake. The conversion of an ICE vehicle to electric drive will generally utilise the existing brakes of the vehicle as designed by the OEM, with or without some modification. This chapter will outline a number of ways the substitution of an electric motor will affect the performance of the OEM brake system, whether the brakes are modified or not. In this Chapter it becomes clear that the characteristics of the substituted electric motor provides new challenges and opportunities for brake system design. The major issues that have been identified during this research include:

1. The added battery weight increases the overall weight of the vehicle which will affect the power requirements brake system. A Centre of Gravity (COG) change will also affect the fore-aft brake balance (brake proportioning) of the OEM brake.
2. The substitution of the ICE (with engine braking) with an EV motor that has no auxiliary braking (regeneration) capability also affects the power requirements of the braking system during long descents. It has been found that most homebuilt EV conversions use DC motors without regeneration.
3. There is a need to design and supply a supplementary vacuum energy supply to the OEM brake to replace the inlet manifold vacuum source after conversion.
4. The use of the EV motor as a high power auxiliary brake or regenerative brake raises safety issues of correct brake control and proportioning (braking one axle only). Wheel lockup similar to 'shift locking' in ICE vehicles can occur. Brake signal control during regenerative braking is also discussed.
5. Battery energy and power capacity limitation during regenerative braking.
6. Anti skid braking (ABS) and Electronic Stability Control (ESC) issues.

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<sup>5</sup> ISO 2575: Road vehicles - Symbols for controls, indicators and tell-tales. Brake warning symbols (red).

7. Certification. Simple and cost-effective means must be developed by which vehicle brake compliance can be assessed or tested.

This Chapter will discuss these issues and make suggestions for EV conversion guidelines for safe modification of vehicles. The automotive brake systems will first be discussed to identify where electric vehicle brake systems differ and how changes in vehicle mass and mass distribution affect the brakes. OEM brakes with vacuum boosters are then discussed and a design method for a vacuum pump substitution is given. Next, the many complex systems for electric regenerative braking control are discussed in relation to the EV converter. The results of ICE engine brake deceleration testing are given to show the design limits for regenerative braking. Each section is summarised with recommendations.

The substitution of an engine with an electric motor should be seen as a vehicle modification that requires the brake system to be recertified (as a LVV) even if no modification has strictly been made to the brake system (it is common practice for EV converters to use vehicles that have no vacuum booster so that the brakes do not need any modification). This recertification of the vehicle brake system is justified by the fact that international type approval systems for brakes such as UNECE Regulation 13 (2008) require a new type approval to be undertaken if the vehicle has a different engine type or any regenerative braking system is added.

### **8.1.1 Brake System Comparisons**

The purpose of this section is to discuss the differences between ICE (hydraulic with vacuum boost assist) and electric vehicle brake systems (not EBS as in air brake systems) and identify the critical safety issues with regard to the design of EV brake systems. Three functions of the braking system are given by (Happian-Smith 2002). The braking system must;

1. decelerate a vehicle in a controlled and repeatable fashion and when appropriate cause the vehicle to stop and,
2. should permit the vehicle to maintain a constant speed when travelling downhill and,
3. hold the vehicle stationary when on the flat or on a gradient.

In addition, this must occur under normal and emergency braking situations with a fully or lightly loaded vehicle, straight and curve line braking, and in a variety of

environmental conditions including low friction road surfaces. This research has added ‘modified vehicle’ to this list.

In Table 8.1 below the brake system is split into subsystems and the method by which these subsystems are applied is given for three brake system types including electric braking. For the purpose of this thesis ‘electrical braking’ does not include a ‘Brake by Wire’ Electro-Mechanical Brake (EMB) system, which is a friction brake system with electrical energy source, modulation and transmission systems.

	<b>Standard ICE Vehicle</b>	<b>(EMB) Electromechanical Brake (Brake by Wire)</b>	<b>Electric Brake</b>
<b>Energy source</b> Generates and stores or releases energy	Pedal effort Vacuum Servo	Electrical	Kinetic energy of the vehicle
<b>Modulation system</b> Controls the level of braking	Driver Valves Electronic control ABS Sensors	Driver Electronic control ABS Sensors	Driver Electronic Control ABS Sensors
<b>Transmission System</b> Transmits energy	Brake fluid, lines and hoses Pistons Cables	Electric current Electric cable	Electric current Electric cable
<b>Energy Storage</b> Stores or Dissipates Energy	Thermal	Thermal	RESS Thermal
<b>Foundation Brakes,</b> Generate forces to oppose vehicle motion	Friction Brakes	Friction Brakes	Electromechanical Generator

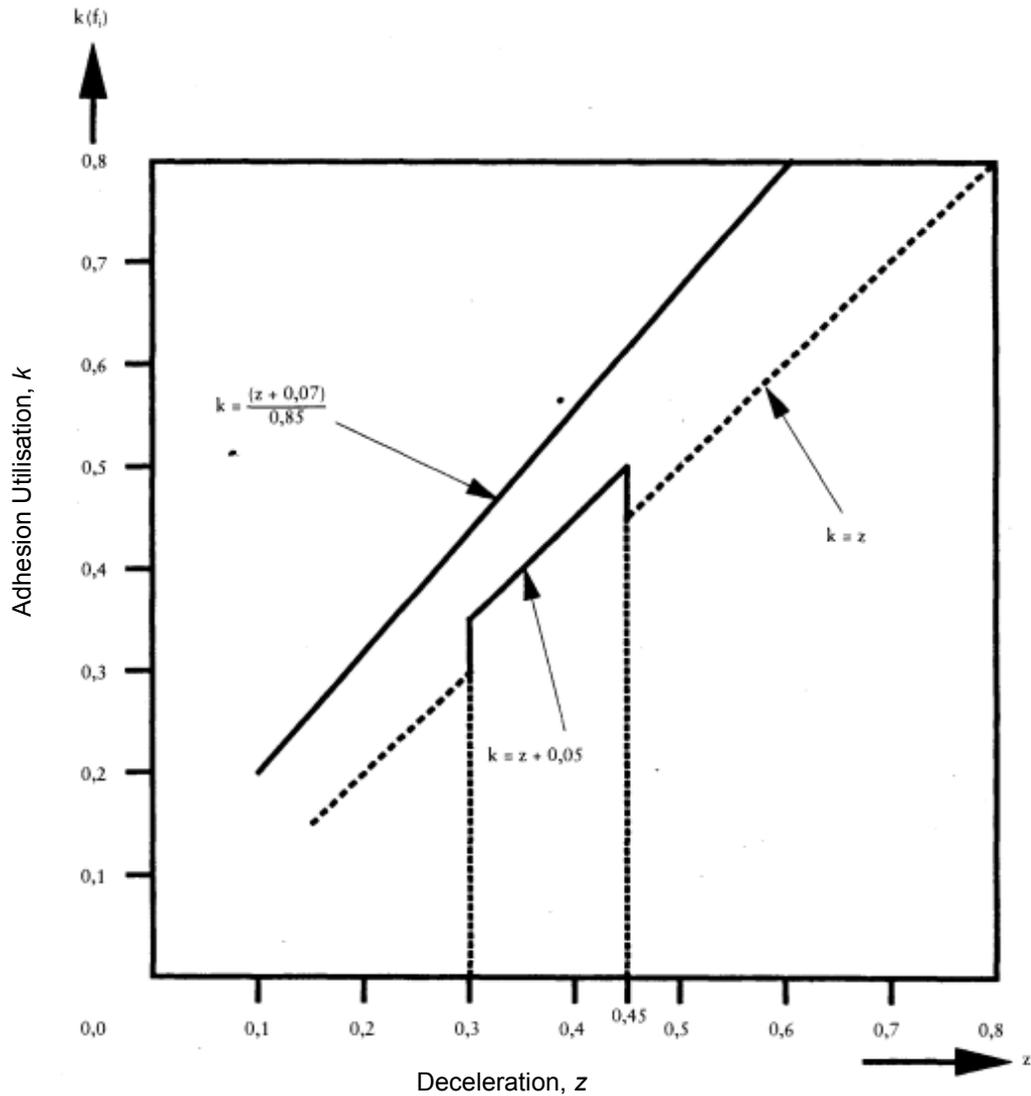
**Table 8.1** Brake system designs.

## **8.2 Vehicle Brake System Requirements**

Braking systems for EVs must comply with the current brake regulations for ICE motor vehicles. Of the many regulatory requirements for brake systems some of the most important are system redundancy (Service Braking, Secondary Braking and Park Braking) and the efficient use of available tyre-ground adhesion. Many types of auxiliary brakes are also fitted to vehicles, the most common being the engine compression brake. These aspects, concentrating on vehicle safety are discussed in the Section below.

### **8.2.1 Brake Proportioning and Adhesion Utilisation**

Road vehicles must perform to strict stability criteria under a variety of braking conditions and loading. Friction between the vehicle tyre and road surface provides directional control and stability against disturbances such as lateral gradient, side wind or left to right brake imbalance. When an axle locks under braking there is reduced friction in both the longitudinal direction and lateral direction and so the vehicles ability to travel in a straight line is reduced. Happian-Smith (2002) gives an analysis to show that the yaw moment produced if the rear axle of a vehicle locks first, has a destabilising effect causing the vehicle to spin. This analysis shows it is preferable to design the vehicle for front axle lock in preference to the rear as this is a stable condition and directional control can be regained by simply releasing the brakes. This basic requirement is met through compliance with the European brake standard UNECE Regulation 13 (2008) which states that for all states of load of the vehicle, the adhesion utilisation curve of the rear axle shall not be situated above the front axle for all load cases and values of deceleration between 0.2 and 0.8 g (Annex 10 3.1.2.). The adhesion utilisation shall also lay below the line  $k = z(0.007)/0.85$ . This requirement is shown graphically in Figure 8.1 below.



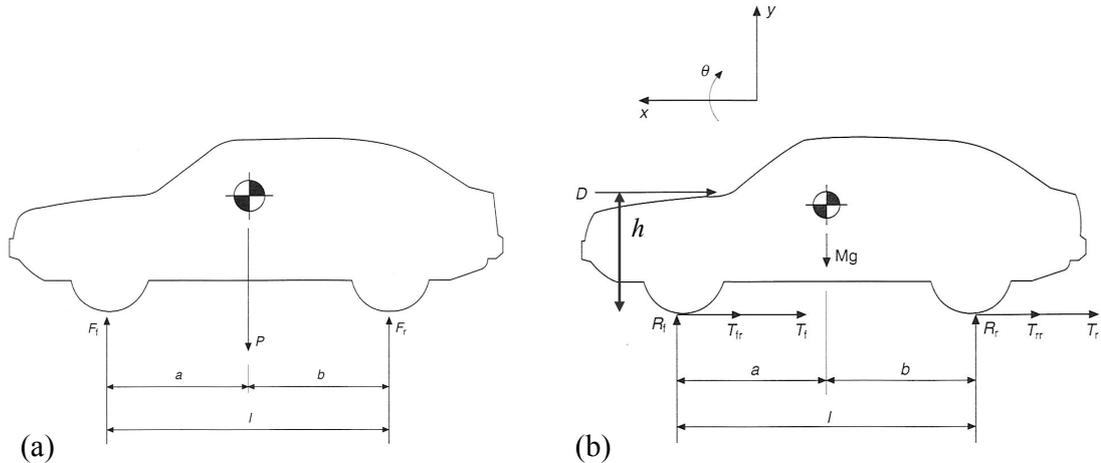
**Figure 8.1** Diagram 1A of Annex 10 (UNECE 2008). For all states of vehicle load, the adhesion curve of the front axle shall be situated above that of the rear axle.

Happian-Smith (2002) states that;

“...compliance of the braking system to the constraints defined in (Figure X) above ensures that the rear wheels do not lock in preference to the front wheels and that the proportion of braking effort exerted at the front of the vehicle is limited so that the braking system does not become to inefficient” (p. 462).

Static weight distribution is generally not equal among axles ( $a \neq b$  in Figure 8.2(a) below) and weight is transferred to the front axle during deceleration

(Figure 8.2(b)). This weight transfer is dependent on deceleration,  $z$ , centre of gravity height,  $h$  and vehicle wheel base,  $l$  as given in the equations below.



**Figure 8.2** (a) Static axle loads (b) Free body diagram of the decelerating vehicle (Happian-Smith 2002).

$$R_f = F_f + \frac{Pzh}{l} \qquad R_r = F_r - \frac{Pzh}{l}$$

For maximum braking efficiency, where both axles are on the point of locking, the brake force on each axle will be in proportion to the weight carried by each axle. As most vehicles have a fixed brake ratio, the ideal brake ratio changes with vehicle deceleration,  $z$  a variable brake ratio is therefore required to fully utilise the available tyre-ground adhesion, and the choice of a fixed brake ratio is compromised.

The Individual Vehicle Approval Standards in the UK (IVA-M1 2009) state that; “The braking ratio of the axles, for all values of total brake force must be less than the friction force ratio (taking into account weight transfer) between axles in running order” (an exception is made for ABS equipped vehicles). This requirement also ensures a front axle locks first characteristic. Although it seems reasonable that this check be made for vehicles in NZ this test is not practical as it requires equipment not available in NZ, such as a brake pedal effort measuring device and two sets of brake rollers. After plotting the brake ratio for the axles a theoretical method can be used to take into account weight transfer. In the absence of this method a deceleration test such as the one described in IVA-M1 (2009) can be used:

“Drive the vehicle on a level road at a steady speed of approximately 20mph and apply the service brake sufficient only to obtain wheel lock.

Observe whether all the wheels of the rear axle(s) lock prior to both wheels of the front axle” (p. 93).

An observer is required for this test.

Happian-Smith (2002) lists the factors other than deceleration affecting weight transfer as:

- change in vehicle weight,
- change in weight distribution,
- the effect of gradients,
- the effect of cornering,
- varying road surfaces and weather conditions including split friction surfaces, and
- the GoG moving forward and down due to vehicle pitching under severe braking. (Happian-Smith 2002).

Removing an ICE, full fuel tank and other components from a vehicle and replacing these with an electric motor, controller and battery pack could result in a change in the first two vehicle properties listed above. The effect of these factors will be discussed in further detail.

A converted vehicle should seek to keep the above variables within the vehicle manufacturers limits so that the vehicle’s brakes perform as designed. Many people interviewed during this project who had converted EVs told me that they had been able to keep the front-rear weight distribution ratio ( $F_f/F_r$ ) close to the manufacturer’s empty weight value. It was discovered that this is also something that LVV certifiers look for.

People who had used LA batteries for their conversion placed batteries in the front and the rear of the vehicle so that the rear did not become too heavy. The removal of rear seating positions so the vehicle did not go over weight was also common to this type of conversion. The MkIII Blade Electron (Hyundai Getz) and Energetique evMe (Mazda 2) conversions with lighter Li based batteries have the battery pack located entirely in the rear of the vehicle.

### 8.2.2 Vehicle Design Process

An important outcome of a successful EV conversion is to ensure the brake system is not overloaded during sudden decelerations and long descents. The energy,  $E$  required to be dissipated during a braking event is given by;

$$E = \frac{1}{2}mv^2 + \frac{1}{2}Iw^2$$

Where  $m$  is the vehicle mass,  $v$  is vehicle velocity,  $I$  is the rotational inertia of the rotating components and  $w$  is the rotational speed.

This shows that not only the mass of the vehicle has an effect on deceleration but also the rotational inertia and gear ratio of the rotating components, such as the wheels, drive train and motor. The rotational inertia only has an impact when the brake system is power limited but is not important when the brake system is traction limited, as when the wheels are locked up the rotating components have already come to a stop. The substitution of the electric motor will most likely result in a reduction of the drive system rotational inertia as electric motors tend to be lighter however, this would need to be confirmed by measurement.

Weighing the vehicle before modifications take place is important. Axle weights should be recorded for the lightly loaded and fully laden condition (all seating positions occupied). The designer should make sure to include a full tank of petrol as the weight of fuel will also be removed from the vehicle (unless it is a HEV). Obtaining manufacturers' maximum axle ratings for light vehicles can be difficult as they are generally not published. If available, this data can be used and should not be exceeded when the vehicle is loaded with passengers and payload. If the data is not available then the fully laden condition should be taken as the GVM. A calculation such as the one given in IVA-M1 (2009) 44, Annex 2 should be used to calculate the GVM and can be included in an LVV EV standard. Weights for calculation and loading purposes in NZ are given as 80 kg/person (LVV Suspension standard (195-00(00)) and in Australia 68 kg/person + 13.6 kg of luggage/person as in the (ADR Definitions). Using ADR requirements could be advantageous to the designer as luggage is placed in the rear luggage compartment.

The European calculation as given in UNECE (2009) is as follows;

“The mass of the driver and, if applicable, of the crew member is assessed at 75 kg (subdivided into 68 kg occupant mass and 7 kg luggage

mass according to ISO Standard 2416 - 1992), the fuel tank is filled to 90 per cent and the other liquid containing systems (except those for used water) to 100 per cent of the capacity specified by the manufacturer” (p. 22).

The weight distribution among the front and rear axles should be shown to be within the manufacturers limits by choosing a worse case occupant loading before and after modification.

One vehicle certifier explained that under certain circumstances, you could justify and increase in GVM rating of the vehicle due to a change in the use of the vehicle. The vehicle has now been modified to become an ‘EV city vehicle’ which can expect lighter chassis loadings from dynamic sources because of reduced mileage capability and lighter duty city use. The reduced mileage capability is due to a short range (say less than 60 km/charge) and/or long recharge time. Research is needed to quantify the new loadings to be used in any LVV standard however any increase in GVM rating would generally not exceed 20%.

As mentioned above, a common and acceptable method of keeping the vehicle within its manufacturers GVM is to remove rear passenger seating positions. To make this a permanent modification the seat and seatbelt should be removed or the seat belt removed and the seat labelled. An example is the 5 seater Hyundai Getz EV conversion, as shown in Figure 8.3.



**Figure 8.3** Rear centre seat label fitted to Blade Electron Mk III.

The use of the term ‘occupants’ rather than ‘passengers’ would make this label less ambiguous as ‘passengers’ could be interpreted as not including the driver.

### **8.2.3 Effect of a Change in CoG Height**

The conversion of a vehicle to electric drive can in general, have the effect of lowering the CoG as the substantial weight of batteries is added low in the vehicle (for common battery locations see Section 7.10.1). This will reduce the amount of weight transfer to the front axle during braking resulting in a vehicle which is over-braked on the front axle. This modification will result in the vehicle retaining its front axle locks first characteristic, a safe condition. It will also have the effect of reducing adhesion utilisation on the rear axle resulting in reduced braking efficiency on the vehicle overall. A modified vehicle fitted with ABS will be more tolerant of CoG height changes. It should be noted that under severe braking the vertical change in height of the CoG equates to approximately 5% of its original height (Happian-Smith 2002). Before and after measurements of CoG height can be made by the converter to ensure CoG height remains approximately equal and some methods are detailed in Appendix 7.

The Australian vehicle EV modification standard NCOP-14 (2011) has recently been reviewed and handles the preceding issues in the following way;

“Because mass distribution is an important factor in maintaining good handling and braking characteristics of a vehicle, it must be considered carefully in the design of a conversion or (ICE vehicle). For example, a significant reduction of front axle mass may lead to poor cornering behaviour as a result of loss of traction together with deterioration in braking performance. Care should therefore be taken to minimise changes in mass distribution. Where this is unavoidable, brake bias must be adjusted to take into account the changes in mass distribution. Locating the battery pack entirely behind the rear axle should be avoided as it may lighten steering and/or cause the vehicle to yaw in a dangerous manner, particularly if the vehicle has a relatively large rear overhang. Vehicles with front wheel drive may also lose drive traction. Vehicles displaying any of the above undesirable characteristics will be rejected by Registration Authorities” (p. 20).

This type of requirement is very subjective and does not require the design to be proven by engineering measurements or calculation. Some simple measurements and calculations described above could be developed for NZ EV converters to use however, this would result in a small increase in compliance costs.

### 8.3 Vacuum Brake Boosters

A vacuum booster is fitted to most ICE vehicle brake systems to increase the brake line hydraulic pressures and allow the driver to decelerate a heavy vehicle while maintaining the brake pedal force and pedal travel within acceptable limits. The conversion of an OEM vehicle to battery electric will generally have the following effects on the vacuum booster system:

- An increase in the unladen weight of the vehicle due to the extra weight of batteries will put extra demands on the brake system, thus correct booster function is critical.
- ICE engine braking *may not be replaced* by regenerative braking making correct booster function critical (most EV conversions in NZ use cheaper DC motor/controller sets that do not have regeneration capability).
- Removal of the ICE will remove the engine manifold vacuum energy source for the brake booster. This vacuum is used by the brake booster during engine idle and higher levels of vacuum are available during downshifting deceleration.

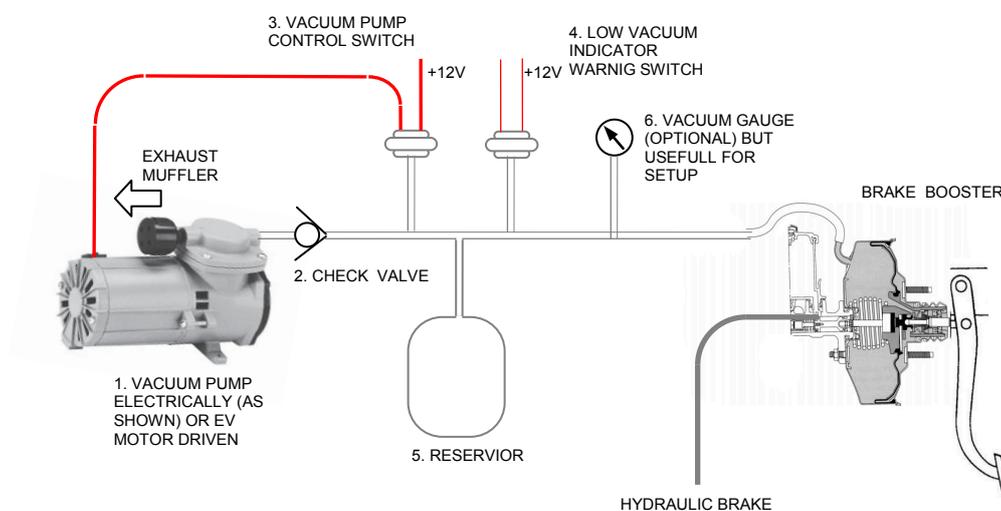
During an EV conversion, an increase in vehicle weight is likely therefore it is critical for a safe conversion that the brake system is modified in a safe manner. When a driver downshifts during a brake manoeuvre the engine produces a negative torque ( $-T \propto \dot{\theta}$ ) as well as a higher manifold vacuum to the booster. Both these effects mean that less brake pedal force is required by the driver for a given deceleration rate. This effect is absent with an EV (even if retro-fitted with a vacuum booster system). It is justified that extra design and certification effort is directed at the brake system and in particular the vacuum booster. To further illustrate this point UNECE (2008) states that;

“...where the use of an auxiliary energy source is essential for the operation of a braking device, the energy reserve must be such as to ensure that, should the engine stop, the braking performance remains sufficient to bring the vehicle to a halt in the prescribed conditions”.

Removal of the ICE will remove the engine manifold vacuum energy source for the brake booster. This will greatly increase the braking force required for a given deceleration as vacuum boosters increase the brake system gain (boost ratio) by 3 to 4 for smaller cars and as much as 9 for a large car. Brake systems are usually

designed for a gain not greater than 4 to 6 in order to ensure safe vehicle deceleration in the event of a boost failure (Limpert 1999). A new source of vacuum is required to replace the manifold vacuum.

The EV conversion industry standard solution to this problem is to fit an electric vacuum pump and control circuits with or without an auxiliary vacuum reservoir. Many products and kits are available through EV equipment suppliers. A schematic of a generic system showing the components of a good design is given in Figure 8.4 below.



**Figure 8.4** Generic vacuum pump brake system.

### 8.3.1 Vacuum system requirements

The retrofit vacuum system requirements are;

- Sufficient vacuum during all vehicle operating conditions.
- Sufficient energy capacity (vacuum storage) during all vehicle operating conditions and during pump failure (UNECE 2008).
- High Reliability
- Controllable linear boost characteristic(Limpert 1999)
- The system must react at a speed comparable to the OEM system (IVA-M1 2009).

Compliance with the vacuum system requirements for an EV conversion raises many issues. The first is what are the OEM specifications for the vacuum for a particular conversion? As this data is not published by the automakers some measurements of engine vacuum were taken on a selection of vehicles. Some devices which are commonly used to measure engine manifold vacuum are shown in Figure 8.5 below. For the vacuum testing the vacuum gauge shown in Figure 8.5 (b) was used with a scale zero to -100 kPa This device was bought for under 40 NZD. Standard pneumatic tubing and brass fittings were used to plumb the gauge into the vacuum line either before or after the check valve.



**Figure 8.5** (a) Automotive vacuum test gauge 0 to -100 kPa (anticlockwise) integrated with fuel pump pressure tester (b) Vacuum gauge 0 to -30 inHg (100 kPa) (anticlockwise).



**Figure 8.6** Tee junction and pneumatic line for vacuum gauge.

Two vehicles (a Toyota Vitz and Ford Mondeo) were chosen for this test to represent vehicles which are commonly subject to EV conversion. Engine intake manifold vacuum varies with the engine operating mode. In the engine off or stalled condition the manifold vacuum is zero (unless the engine is driven by the gearbox), at full throttle the vacuum is also close to zero. The engine idle and engine braking conditions are the relevant conditions for brake booster performance. Testing showed that at engine idle (closed throttle) the manifold pressure is at its maximum and a generic brake booster needs at least 16 inHg (-54 kPa) of vacuum at idle. Under hard engine braking (down shifting) manifold vacuum can reach 23 inHg (-85 kPa) further reducing pedal force for a given deceleration. Limpert (1999) uses a value of 23.3 inHg (-79 kPa) in a generic brake boost analysis. Details of the vacuum values measured during this project is given in Figure 8.2 below.

Vehicle	Nominal engine size [l]	Tare [kg]	Idle $\pm$ 2 kPa	Hard braking [kPa] $\pm$ 5 kPa 50 km/h in 2 <sup>nd</sup>
Toyota Vitz (Echo)	1.0	900	-65	-85
Ford Mondeo	2.0	1500	-70	-82

**Table 8.2** Measured manifold vacuums. Note: Vacuum was measured with a new or freshly cleaned air filter.

The above figures are only a guide for EV converters with the point of this exercise to explore the variance in manifold vacuums given the lack of available data. Ideally it is recommended that measurements of each converted vehicle are used for both design and testing the vacuum system.

It is also useful to review commercial 12V vacuum pumps and EV vacuum kits to assess their suitability. An EV converter might source a pump originally designed for another purpose to provide a vacuum source. For example, it is conceivable that a cost effective 12 V tyre inflation pump could be modified for use in an EV conversion. It is not the intention to exclude this however a converter must show that the device is suitable in terms of performance, design and reliability. This would include an assessment of pressure (vacuum), flow rate and pump motor duty cycle. A table of products advertised as suitable for EV conversions is given in Appendix 8.

### 8.3.2 Vacuum System Design

The braking system reaction speed is related to the volumetric capacity of the system, as there will be a delay of the service brake operation with the reaction time of the remotely applied electric vacuum pump. The vacuum system requires volume which can be provided by the booster volume ( $V_B$ ) line pipes ( $V_L$ ), or a reservoir ( $V_R$ ) fitted to the system. Adequate volumetric capacity in a vacuum system serves a number of purposes of which those relevant to vacuum boosters are;

- to supplement pump suction,
- to maintain system vacuum, and
- As an emergency power source.

Vacuum energy capacity can be estimated by calculating the reduction in vacuum during braking. The vacuum should not reduce below say 16 inHg (-54 kPa) during single full stroke brake application. In the following analysis, for a single-diaphragm booster, it is assumed that the vacuum pump is slower to respond than the time it takes to apply the brake.

The initial system volume,  $V_1 = V_{B1} + V_L + V_R$  where;

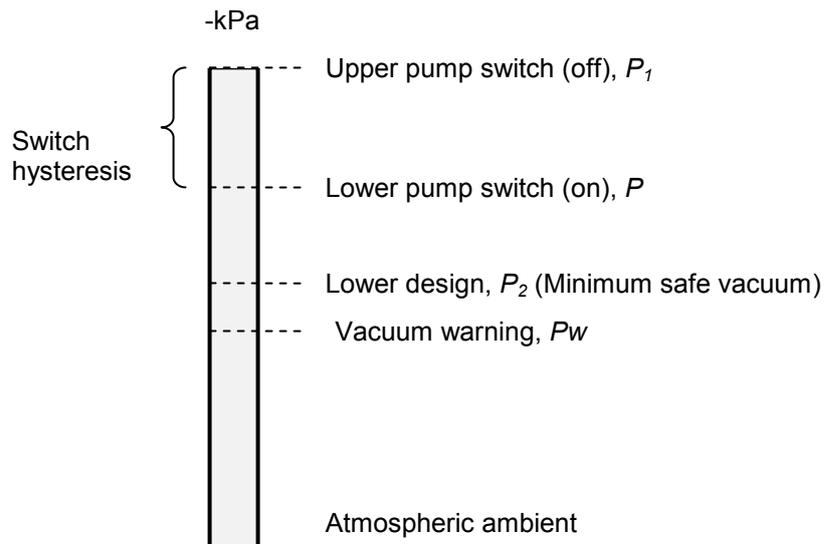
VB1 is the initial booster volume,

VL is the volume of the vacuum hoses and,

VR is the reservoir (accumulator) volume (see Figure X).

The system volume after brake application is  $V_2 = V_{B2} + V_L + V_R$ . Where VB2 is the booster volume after brake application calculated from the pedal travel, pedal ratio and booster diaphragm radius.

The required minimum system volume can be estimated by considering the reduction in vacuum during one full brake application. It is assumed that the pump runs intermittently, the vacuum is as such delivered by the capacity of the system and reservoir. The change in vacuum must not result in a pressure higher than -54 kPa, or a value decided after the vehicle is tested by measuring the OEM vacuum requirements for a particular vehicle model. In the following example a standby system vacuum, P1 of -70 kPa is assumed. The system design pressures are shown graphically in Figure 8.7 below.



**Figure 8.7** System vacuum pressures

*Calculation Example:*

For an ideal gas undergoing a reversible adiabatic process the relation is  $P_1V_1^\lambda = P_2V_2^\lambda$ . Where  $\lambda = 1.4$ . The minimum reservoir volume,  $V_{Rmin}$  can be calculated by choosing the minimum system vacuum,  $P_{2min}$ :

$$V_{Rmin} = \frac{[P_1(V_{B1} + V_L)] - [P_{2min}(V_{B2} - V_L)]}{P_{2min} - P_1}$$

Typical dimensions for a generic brake system are:

Pedal travel  $S_p = 0.1$  m. Maximum pedal travel should not exceed 150mm (Limpert 1999).

Pedal ratio  $l_p = 2.4$  (by measurement of brake pedal lever)

Booster  $\varnothing$  8 in (203 mm)

Initial Vacuum,  $P_1 = 101.3 - 70 = 31.3$  kPa Absolute (Std Atm = 101.3 kPa)

Minimum vacuum,  $P_{2min} = -50 = 47.3$  kPa Absolute

Vacuum line ID, = 6.0 mm

Vacuum line length, L = 1.0 m

Booster stroke is calculated to be  $0.1/2.4 = 0.0416$  m from this the booster volume is estimated to be,  $V_{B1} = \pi(0.203/2)^2(0.0416) = 1.3(10^{-3})$  m<sup>3</sup> (Neglecting push rod diameter). The  $V_{B2}$  is conservatively taken as zero (fully exhausted booster). The energy stored in the elastic flexibility of the system materials is neglected. Line volume is calculated as  $V_L = \pi(0.003)^2(1) = 2.8(10^{-5})$  m<sup>3</sup>. Taking the brake system properties from above and applying equation below the  $V_{Rmin}$  is evaluated as;

$$\begin{aligned} V_{Rmin} &= \frac{[31.3(1.3(10^{-3}) + 2.8(10^{-5}))] - [47.3(0 - 2.8(10^{-5}))]}{47.3 - (31.3)} \\ &= 2.7(10^{-3}) \text{ m}^3 \\ &= 2.7 \text{ litres} \end{aligned}$$

The final system properties are then:

$P_1 = -70$  kPa

$P_2 = -54$  kPa

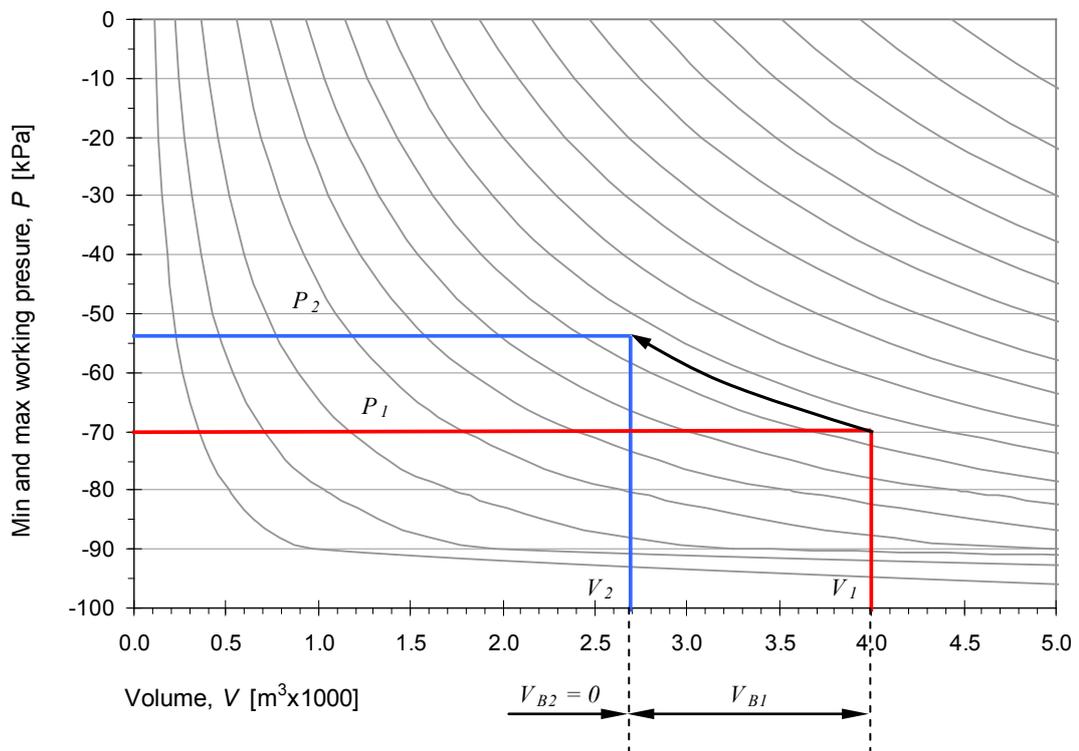
$V_1 = 4.0(10^{-3})$  m<sup>3</sup>

$V_2 = 2.7(10^{-3})$  m<sup>3</sup>

$$V_{Rmin} = 2.7 \quad \text{litres}$$

For this example the line volume is negligible when compared to booster volume and reservoir volume. A reasonable sized reservoir is required to keep  $P_2$  within the limits defined (-54 kPa).

To ease the calculation of system size, a  $PV$  chart with adiabats plotted can be used. This graphic aid is based on the adiabatic change of condition and is thought to be sufficiently accurate for most reservoir system problems. The previous example is plotted below to show the graphical calculation method in use.



**Figure 8.8** System volume calculation, characteristic curves.

The red lines represent the charged vacuum system before brake application. During a full brake application the volume change of the booster cavity shown by  $V_{B1}$  and the  $PV$  plot follows the black arrow resulting in the final pressure  $P_2$ .

### 8.3.3 Vacuum Consumption Rate and Pump Flow

A cyclic brake fade test as described in the LVV brake standard LVVTA (2000) is not adequate to test the vacuum system as the pedal applications occur over a relatively long period of time (2 minutes). The vacuum pumps capacity to

recharge the vacuum system must be tested separately using repeated pedal applications over a prescribed period of time. The basis for this test might be a full brake application rate of one stroke every two seconds. Using data from the example above a theoretical pump flow rate of at least 39 l/min will be required. The Table in Appendix 8 shows this is within the stated flow rate of the Thomas pump model, 107CDC20. Physical testing can take place in a stationary vehicle with the vacuum system at its maximum operational vacuum,  $P_1$ . It is suggested that the system must sustain five full pedal applications of the service-brake with full release of the brakes after each application over a ten second period without  $P_2$  being reached or the vacuum warning signal ( $P_w$ ) being triggered. The test suggested above takes guidance from the requirements for the testing of a heavy passenger service vehicle compressed air brakes (NZTA 2006).

#### **8.3.4 Pressure Gauge Requirements**

Heavy vehicles in NZ that have compressed air braking systems must be fitted with at least one pressure gauge that is readily visible to the driver at all times from the driver's normal driving position. This gauge indicates to the driver the pressure in the service brake reservoirs (NZTA 2006). Whether a requirement for a vacuum gauge is introduced for low volume EVs is open to debate. A pressure warning light or audible signal should certainly be introduced as required by NCOP-14 (2011), however whether this is supplemented or replaced by a vacuum gauge is not clear. The heavy vehicle requirement for a compressed air gauge is not strictly applicable to vacuum systems as the vacuum is only a supplementary source of energy, supplementing the force from the driver's foot. A simple low-cost warning buzzer or light would seem to provide adequate warning of vacuum failure. An EV converter who has had a vacuum gauge fitted for setup and testing purposes may leave it installed to supplement the warning signal.

#### **8.3.5 Certification Issues**

The certification procedures given in LVVTA (2000) and Johnson (2007) are generally adequate for the assessment of vacuum pump retrofitted OEM brake systems. Special consideration however must be given to the adequacy of the vacuum source and control regime. Theoretical calculation and design as outlined in this section can be provided to the certifier to show that the vacuum system

requirements outlined above have been met. Apart from the visual inspection of the system design, materials and workmanship, the certifier must also perform physical tests to prove compliance. The recommended tests for vacuum systems are listed below:

- Test ICE vehicle for OEM idle vacuum and deceleration vacuum. This will provide data for system design.
- Pedal Sink Test on start up - release vacuum.
- System capacity test with pump off. Vacuum held by check valve. One (1) full brake application. Measure system pressure ( $P_2$ ) after pedal is released.
- A stationary pump capacity test. A number of full pedal applications of the service-brake with full release of the brakes after each application over a certain defined period without  $P_2$  being reached or the vacuum warning signal ( $P_w$ ) being triggered.

### **8.3.6 Recommendations for Vacuum Systems**

A well designed vacuum system should include the following attributes as well as those given in LVVTA (2000) Section 2.3:

1. 12 V (or other) vacuum pump limited to or just above OEM idle vacuum to prevent over vacuum which could make the brakes very sensitive and difficult to control. A pump flow rate capacity to replenish the system during a cyclic brake fade resistance test such as described by Johnson (2007) in section 19.12.
2. Vacuum hoses supplied to approved standards and installed correctly.
3. A check valve fitted as close as possible to the vacuum pump.
4. A pump control vacuum switches which switch with differential vacuum (not absolute) and has hysteresis. An absolute vacuum switch will give reduced brake performance at high altitude. A pressure drop of 11.5 kPa is expected at 1000m above sea level (desert road central north island). Pressure drop due to storms will not have significant effects. 2.3 kPa drop in pressure is experienced with a 990 hPa storm event when compared with standard atmospheric pressure (1015 hPa). The pump must actuate above 54 kPa or other design value.

5. Low vacuum warning indicator must light if the vacuum drops below 54 kPa or other design value. EEC (1971) requires an 'optical or acoustical signal when the energy, in any part of the installation preceding the control valve, falls to 65 % or less of its normal value.'
6. A system capacity to allow compliance with a cyclic brake fade resistance test such as described by Johnson (2007) in section 19.12.
7. A vacuum system capacity to ensure that, should the vacuum pump stop, the braking performance remains sufficient to bring the vehicle to a halt.
8. Booster runout point (saturation) should not be reached for decelerations less than 0.9 g (Limpert 1999). A modified OEM brake system will meet this requirement.
9. The energy source for the vacuum pump motor must be given priority over other vehicle functions in the event of circuit failures. The use of an auxiliary 12 V battery assures this.
10. The calculated service efficiency with the servo depleted must be at least 30% (IVA-M1 2009) - A modified OEM brake system will meet this requirement.

## 8.4 Auxiliary Brakes and Regenerative Brakes



<sup>9</sup>

### 8.4.1 Introduction

Engine braking passively reduces wear on brakes and helps the driver to maintain control of the vehicle. Active use of engine braking (shifting into a lower gear), is advantageous when it is necessary to control speed while driving down very steep and/or long slopes. It should be applied before regular disk or drum brakes have been used, leaving the brakes available to make emergency stops. Improper engine braking can cause the wheels to skid (also called shift-locking), especially on slippery surfaces such as ice or snow. In a skid caused by over-braking the vehicle will not regain traction until the wheels are allowed to turn more quickly, meaning the driver must reduce engine braking (shifting back up) to regain traction. It is useful to review the regulatory definitions of brake systems to understand how electrical braking devices fit into this system.

### 8.4.2 Electric Auxiliary Brakes Regulatory Definitions

Electrical devices for reducing the speed of a moving vehicle, or bringing it to a halt, or holding it stationary are generally defined as being a “braking devices” or a “brake” (EEC 1971). An engine brake is also defined as a “brake” in EEC (1971) when the (braking) forces are derived from a controlled increase in the braking action of the engine transmitted to the wheels. Section 1.17. EEC (1971), defines a ‘Retarder’ as;

“...means an additional braking system having the capability to provide and to maintain a braking effect over a long period of time without a significant reduction in performance. The term ‘retarder’ covers the complete system including the control device.” From these definitions we can say that engine or motor braking, which is part of the vehicle brake system, is both a brake and retarder and as such should be taken into account in the overall brake system design”.

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<sup>9</sup> NZ road signs from <http://www.nzta.govt.nz/>

### 8.4.3 Types of Electric Auxiliary Brake

Several types of auxiliary brake technologies are in current use on motor vehicles including engine (compression) brakes, various types of exhaust brakes (diesel engines) and hydraulic retarders. The engine brake is the most common and is intrinsically present with petrol powered ICE vehicles. This type of brake is activated when the driver lifts the foot off the accelerator with the transmission in gear and clutch engaged (for automatic transmissions low gear must be selected). In the petrol engine most of the retarding torque is provided by the engine pistons working against the vacuum created by the closed throttle valve.

The torque production in an ICE vehicle during engine braking is analogous to viscous damping. The amount of torque produced ( $-T$ ) is approximately proportional to the engine speed,  $\dot{\theta}$  ie;

$$-T \propto \dot{\theta} \text{ or } -T = C \dot{\theta}$$

where  $C$  is the engine braking coefficient. The capacity of a generic ICE for engine braking is that it will produce approximately 45 to 50% of the base power of the engine without any special provision to increase the retarding effect (eg exhaust brakes) (Limpert 1999). This capacity for power dissipation is very useful and sometimes essential on long descents and for improving friction brake life. The electric motor on the other hand has a 100% capacity for producing braking effect through regenerative braking and/or resistance braking and/or plug braking. The 'four quadrant' control capability of the electric motor torque verses speed is shown in Figure 8.9 below;

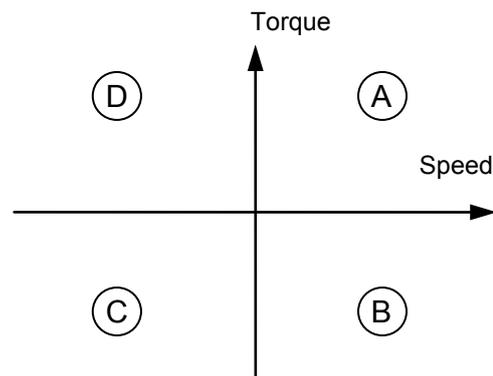


Figure 8.9 Electric motor four quadrant capability. Quadrant A and C represent forward and reverse motoring respectively. Quadrant B and D represent forward and reverse braking.

It is important to consider how this braking is controlled so that the result is a safe and controlled deceleration. Hughes (2006) describes the various types of electric motor braking and their control, of which regenerative braking is the most important for EVs. These have been summarised in the Table 8.3 below:

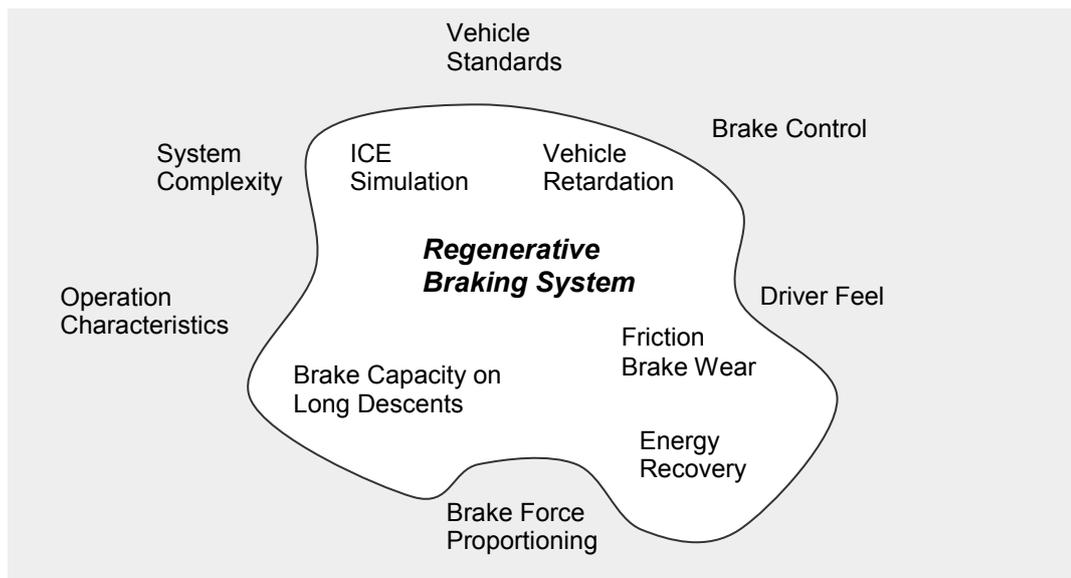
Brake	Motor Type	Control	Energy
<b>Dynamic Braking</b>	DC	Switch resistor across armature brushes or simply short circuit for high power braking	Dissipated as heat in resistor and motor windings
<b>Plug Braking (Reversal)</b>	AC	Interchange two of the 3ph supply leads. High currents generated (greater than starting). Switch off supply before going into reverse	Dissipated as heat in motor windings
<b>Injection Braking</b>	AC	DC current fed into stator	Dissipated as heat in motor windings
<b>Regenerative</b>	AC & DC	Motor switched to generator	Energy recovered to supply (RESS) or dissipated in resistor

**Table 8.3** Electric motor braking and control. Note: For the purpose of this thesis electrical braking does not include a 'Brake by Wire' Electro-Mechanical Brake (EMB), which is a friction brake system with electrical energy source, modulation and transmission systems.

## 8.5 Regenerative Braking

Regenerative braking in an electric vehicle is a type of auxiliary brake. Regenerative braking is the most important braking technology for electric motor vehicles as it takes advantage of the intrinsic characteristics of the electric motor to act as a generator and recover a portion of the kinetic energy of the vehicle during braking. Regenerative braking then returns this energy to the battery thereby improving the energy efficiency of the vehicle. As with engine compression braking, regenerative braking torque decreases to zero as the vehicle comes to a rest and as such, it is a suitable replacement for engine compression braking in an EV conversion.

The design of regenerative braking systems involves complex compromises and competing design goals and these issues have been summarised in Figure 8.10 below. The following section will discuss regenerative braking in more detail.



**Figure 8.10** The competing design considerations of regenerative braking systems for EV conversions.

### 8.5.1 Regenerative Brake Power

A large amount of energy is consumed in braking. For example a 1000 kg vehicle stopping at 0.9 g from a speed of 100 km/h (27.7 m/s) stops in a time of 3.1 s. The energy absorbed is 383 kJ and the power required is 122 kW. This amount of power cannot be absorbed by the electric motor alone as the vehicle may only

have a 40 kW electric motor installed. The battery pack will also be limited by the maximum power it can accept. To meet this demand there is a strong argument that a hydraulic brake system is needed to supplement the electric braking so that the regenerative brake system is controlled in an integrated manner.

### **8.5.2 Is Regeneration Necessary? The case of Automatic Transmissions**

Vehicles with automatic transmissions always have gear selector positions for low gears (the '2' and '1' positions) to provide the engine braking function. The Toyota Prius uses a 'B' position to select the engine 'braking function' of the automatic transmission. Anecdotal evidence suggests drivers of automatics do not use these 'gears' very much as automotive mechanics report that these vehicles need more frequent friction lining replacement. This suggests that vehicles can be safely operated without regenerative retardation.

Regenerative braking should always be considered in regard to a vehicle's safety system as it is another way of converting kinetic energy and slowing down the vehicle. The majority of the current EV conversions do not have regenerative braking as they use low cost DC motors and controllers without regeneration capability. This gives the vehicle a neutral gear coasting effect when the accelerator is not depressed. An electric motor has no engine compression like an ICE so if the regular braking system fails there is no alternative system to decelerate the vehicle. Whilst it is not suggested that all EVs must have regeneration, it is strongly recommended that EV converters use traction systems which have regenerative capability. Furthermore, the lack of regeneration in an EV conversion should be considered a modification of the brake system and if no regeneration is present, then careful design of the remaining brake system must be undertaken.

### **8.5.3 Types of Regenerative Brake and their Control Strategies**

EV technology provides opportunities for new user interfaces with the vehicle brakes such as user selectable regeneration control, single pedal acceleration/braking and regeneration user displays. This section will discuss how this new technology is being deployed.

Ehsani (2004) identifies and discusses the two basic questions of regenerative braking control which can be summarised as:

1. how to distribute the total braking forces required between the regenerative brake and the mechanical friction brake so as to recover the kinetic energy of the vehicle as much as possible and,
2. how to distribute the total braking forces on the front and rear axles so as to achieve steady-state braking (and good front rear brake proportioning).

The basic brake control strategies for a hybrid braking system which has regenerative and mechanical brakes, are analogous to hybrid power systems and can be described in the same terms; series braking (series hybrid), parallel braking (parallel hybrid), and series-parallel braking (series-parallel hybrid). Optimal driver feel or optimal energy recovery control strategies can also be employed (Ehsani 2004).

An additional, simpler method which is common with EV converters has been termed by the author as 'fixed regeneration'. Each of these brake control strategies including fixed regeneration are discussed below.

### **8.5.3.1 Series Braking**

The shortest braking distance and optimal braking efficiency requires the braking forces on the front and rear wheels to follow the ideal braking force distribution curve shown in Figure 8.1. Series braking involves control strategies which requires the regenerative brake to be applied first and then the hydraulic brake provides any additional braking power. These systems are highly integrated and require active control of both electric regenerative braking and mechanical braking forces on the front and rear wheels they are also usually integrated with an ABS system.

Due to development costs of this type of system series braking is unlikely to be utilised by the home or professional EV converter.

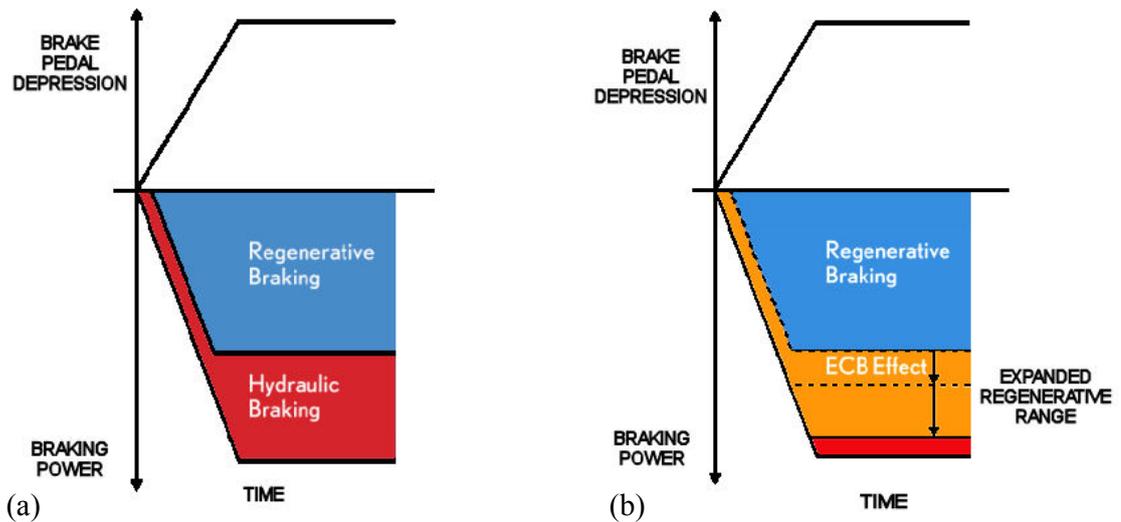
### **8.5.3.2 Parallel Braking**

Parallel braking involves the simultaneous application and control of both brakes. Ehsani (2004) describes in detail parallel braking as;

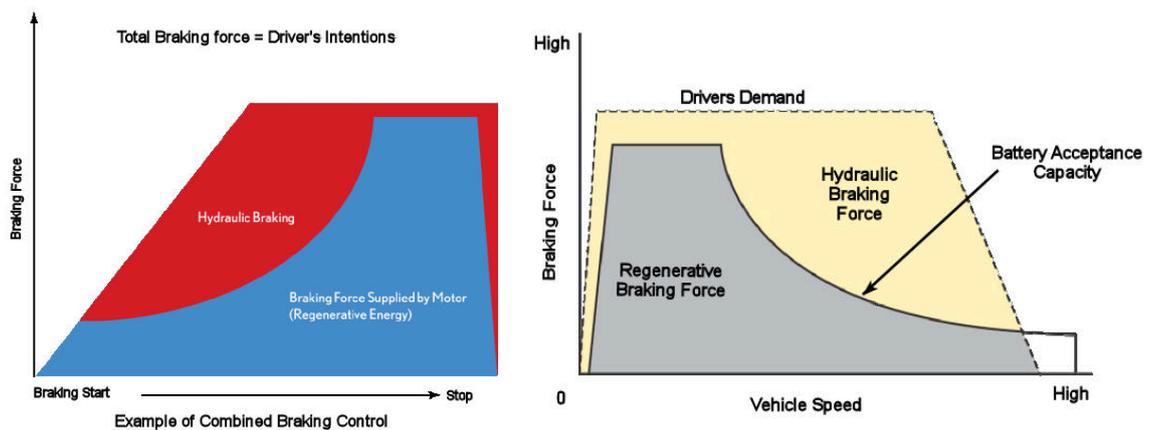
“The parallel braking system does not need an electronically controlled mechanical brake system. A pressure sensor senses the hydraulic pressure in the master cylinder, which represents the deceleration demand. The pressure signal is regulated and sent to the electric motor controller to control the electric motor to produce the demanded braking torque. Compared with the series braking of both optimal feel and energy recovery, the parallel braking system has a much simpler construction and control system. However, the driver’s feeling, and amount of energy recovered are compromised.” (Ehsani 2004, p.343).

### **8.5.3.3 Series-Parallel Braking**

In practice vehicle products which come from large auto manufacturers will employ complex brake control topologies to achieve conflicting design goals. In vehicles like the Toyota Prius, engine braking is simulated by computer software to match the feel of a traditional automatic transmission. For long downhill runs the driver can shift the gear selector to ‘B’ mode. The drive system then acts like a lower gear, if necessary employing higher engine speed in the ICE to dissipate energy preventing the battery from becoming overcharged by the regenerative brake. Some control strategies from the Toyota Prius are given in the Figures below.



**Figure 8.11** Toyota Lexus brake control, adapted from Williamsen (2007) (a) Regenerative Braking (Gen 1) (b) Electronically Controlled Braking (ECB)(Gen 2)



**Figure 8.12** (a) Electronically controlled braking (b) Brake Force Proportioning Toyota Gen 1 (Williamsen 2007).

### 8.5.3.4 Fixed Regeneration

Fixed regeneration- a term coined by the author describes a simple and common control strategy that is used by EV converters. In fixed regeneration the vehicle is designed so that the regeneration is activated when the accelerator pedal is released (throttle off regeneration). The regeneration can be modulated on the accelerator pedal or just switched on when the pedal is released. Regeneration systems with a power adjustment knob on the dash-board are also common. If regeneration is modulated on the accelerator pedal and a large amount of

regeneration is set, then both acceleration and braking can be actuated on the same pedal. This is a new type of vehicle control and while offering some advantages to the expert driver, it could be disconcerting and dangerous for most drivers as the modulation for braking is the reverse of the brake pedal (release pedal for greater deceleration). For this reason and the fact that large braking forces on a single axle can cause axle lock on low friction surfaces, large amounts of regeneration on the accelerator pedal is not recommended. Fixed regeneration however, is recommended for the EV converter as it represents a cost effective solution without requiring a large amount of integration with the friction brake system (as with series and parallel braking). Throttle off regeneration also negates the need for integration with the ABS system.

EV converters should aim to keep the feel of the vehicle controls similar to before the conversion which includes using regeneration to simulate engine braking. This will avoid any dangerous surprises when a new driver uses the vehicle for the first time. This is especially important for professional converters who sell their products on the open market. Professional converters also need to design their vehicles carefully due to their higher liability.

Although it is beneficial to set regeneration high in order to recover as much kinetic energy from the vehicle as possible, relying on driver feel has inherent risks such as front axle lockup on low friction surfaces which will limit the amount of regeneration possible. To establish a practical limit for regenerative braking power some vehicle tests were carried out. These are discussed in Section 8.6.

#### **8.5.4 Brake Standards and Regenerative Braking**

To gain an understanding of the legal requirements of regenerative brake systems, a review of UNECE (2008) was undertaken. Currently in NZ international vehicle standards including UNECE (2008) which detail requirements for regenerative braking, are cited and applied as approved standards by the Land Transport Rule, Light Vehicle Brakes. The definitions used within these standards are similar to those discussed in the previous section on auxiliary brakes. The definition for regenerative braking as provided in UNECE (2008) has been applied in this research and is detailed as:

“2.12 *Electric regenerative braking*; means a braking system which, during deceleration, provides for the conversion of vehicle kinetic energy into electrical energy.” (UNECE 2008, p.11)

UNECE (2008) identifies two regenerative braking categories, depending if they are part of the service braking system or not. Section 2.17.2 defines Category A as a regenerative braking system not part of the service braking system and Category B as a regenerative braking system which is part of the service braking system.

This corresponds with the previous categorisation of regenerative brake types where Category ‘A’ would include fixed regeneration and Category ‘B’ would include the Series and/or Parallel control schemes.

The legal requirement for the different categories of regenerative brakes is defined by UNECE (2008) in Regulation No.13. Relevant sections from this document have been cited and can be referred to in Appendix 9. Regulation 13 (UNECE 2008) shows that low technology (low cost) options are available to the EV converter while still meeting requirements. These options however, are likely to include a fixed regeneration control scheme. A recent draft version of NCOP14 (2011) addresses this issue as detailed below;

“Regenerative braking, if used, should not alter the balance between front and rear braking characteristics of the original vehicle. As a general guideline, regenerative braking should not exceed the deceleration levels generated by the original internal combustion engine and must never disconnect the friction braking system. Service braking systems that are modified to include regenerative braking as part of the service braking system are not covered by these Guidelines and advice must be sought from the relevant Registration Authority if this type of modification is contemplated. Similarly, advice must be sought from the relevant Registration Authority if an ICV is to be designed to have regenerative braking incorporated in the service braking system. (For the purposes of these Guidelines, activation of regenerative braking by either lightly touching or applying pressure on the brake pedal means that regenerative braking is part of the service brake system and therefore not covered by these Guidelines)” (NCOP-14 2011, p. 20).

### **8.5.5 Regeneration Control by the Driver**

The ‘selectable engine braking’ of automatic transmission equipped vehicles (discussed on page 158) provides a precedent for regenerative braking systems to have a driver selectable on – off function. The ‘off’ position would serve as a ‘coasting function’ and the ‘on’ position used for braking and long descents. To allow easy use by the driver it would be best to position this switch as a steering column stalk switch behind the steering wheel. An example of a two position stalk switch can be seen on heavy diesel vehicles to switch the exhaust retarder.

The selectable engine brake is defined as an ‘Independent retarder’ by UNECE (2008) section 1.17.1 and is defined as a retarder “...whose control device is separate from that of the service and other braking systems”. A dash board mount is not recommended for this switch as an unsuitable location would require the driver to let go of the steering wheel to activate the brake. UNECE (2008) section 5.2.18.1.1. also does not allow the use of a stalk switch for vehicles less than 3500 kg as it states that “...regenerative braking shall only be activated by the accelerator control and/or the gear neutral position”. If a manual gearbox and clutch is retained as part of the conversion, regenerative braking can be disengaged by the driver at anytime.

This implies that the control of brake power should be exclusively handled by the brake pedal and rules out any dash board control of regeneration, activation or power. The regeneration power must then be set and fixed by the vehicle’s manufacturer or modifier.

There are some significant advantages for including a stalk type on – off switch for regeneration, as a coasting function (off) facilitates energy efficient driving and the regeneration function (on) supplements braking power. It is recommended that this area is debated further, including the development of additional safety features that would support this system such as a warning light to alert the driver to any failure of the regenerative brake.

### **8.5.6 Battery Considerations**

As discussed earlier, the battery packs power acceptance capacity must not be exceeded in regeneration or in battery charging. Although it is noted that this

power capacity is different from energy capacity during charging, both must be taken into account when designing a regenerative braking system.

Dhameja (2002) describes the charge acceptance (power) as follows:

“...The charge acceptance (due to batteries internal resistance) curve describes the maximum charge rate, which the battery is capable to accept (i.e., convert into stored electrochemical energy). Anything above this charge rate constitutes an overcharge. Thus the battery pack can be driven into an overcharge at any time, in any state of charge by excessive charge current process (Dhameja 2002, p. 96)

Dhameja (2002) goes on further to say:

“A battery in a battery pack can be reduced to a weak state by excessive discharge rates. These conditions of abuse are characterized by short powerful bursts of charging current at excessive voltages during regenerative braking. Regeneration can exceed the absolute maximum charge acceptance ability of the battery if it is not properly managed. This condition exceeds the charge acceptance ability of the battery in the range of 80 to 100% SOC (the charge acceptance ability of the battery in 100% SOC is zero). Under these conditions, the battery becomes a large heat sink” (p. 134).

This highlights the requirement that a regenerative braking controller needs detailed information about the charge acceptance curve (internal resistance) which is dependent on SOC, temperature and battery age. Lower temperatures result in higher internal resistance.

A worse case scenario could be a person driving down from the top of a hill on a cold morning in an EV which has been charged overnight. If the controller is not monitoring the battery SOC and the cooling capacity is exceeded, then the battery could overheat leading to disastrous consequences. Although high temperature cut-off sensors and contractors would avoid this possibility, a safer strategy is to control RESS charging by using the controller electronics to determine both the energy and power to the RESS.

UNECE (2008) also notes that electric regenerative braking capacity is influenced by the electric SOC and state that during brake design, curves shall be plotted taking into account the electric braking component under the minimal and

maximum conditions of delivered braking force. These curves have been given in Figure 8.12 above. The hyperbolic curves are the regeneration power limit.

A simple calculation of a typical pack power capacity can be made using the specific power figures published by manufacturer. For a 24 kWh Li-ion battery pack the specific power would be 24kW calculated from a specific energy of 100 Wh/kg and specific power of 100 W/kg ((Dhameja 2002) gives a range of 20 – 220 W/kg). The regeneration controller would need to be limited to this value. Notwithstanding the above complexities, simple control of regeneration can be achieved by a controller or BMS high voltage cut-off (excess energy) at 100% SOC and a high power cut-off (excess power). These requirements should allow safe regeneration operation if we take a conservative estimate of the battery charge acceptance capacity at 99% SOC, -10° C temperature (NZ) for an aged battery.

#### **8.5.7 Regeneration and Brake Lights**

Not all vehicle decelerations normally result in illumination of the vehicles brake signal. ICE engine vehicles brake lights do not illuminate under engine compression braking. UNECE (2008) states that as electric regenerative braking systems produce a retarding force upon release of the throttle pedal (fixed regeneration, Category A), this will not generate a braking signal to illuminate stop lamps. Regeneration systems of Category B should require a deceleration level at which the brake signal is illuminated to be decided by the designer. The following section will show by deceleration testing that this value is likely to be between 0.1 and 0.2 g.

## **8.6 ICE Engine Brake Capacity**

NCOP-14 (2011) states;

“As a general guideline, regenerative braking should not exceed the deceleration levels generated by the original internal combustion engine and must never disconnect the friction braking system” (p. 20).

To ascertain the level of engine compression controlled braking acceptable for ICE vehicles, it was decided to test the engine braking capacity of some vehicles. It has already been shown that engine braking (regeneration) must be limited to below 0.2 g to avoid drive axle lockup on low friction surfaces and to achieve compliance with international standards. In this section the methodology and results of the deceleration testing is described and discussed.

### **8.6.1 Instrumented Passenger Cars**

The vehicles chosen for the deceleration test were a 1999 Toyota Vitz (Echo) four door hatch and a 2005 Ford Mondeo station wagon. The vehicles were chosen to represent potential vehicle models that could be suitable as a donor vehicle for an EV conversion. These vehicles were also readily available to the author for testing purposes. Although an obvious limitation is that only two vehicles were tested, the primary objective of the deceleration test was to measure the deceleration characteristics of ‘typical’ vehicles during down shifting. The data obtained from these two vehicles provided a starting point to discuss this area.

The instrumentation that was fitted to the vehicle was a Gulf Coast Data Concepts Model X6-2 three axis accelerometer. The X6-2 was configured with a range of  $\pm 2$  g and a sample rate of 40 Hz. The accelerometer was recalibrated using the method given on the website <http://www.gcdataconcepts.com/calibration.html>. The data, recorded as a .csv file, was analysed and plotted in a spreadsheet. The accelerometer was mounted on the passenger’s side floor of the vehicle using a steel mount which was fabricated for this purpose. This is shown in the Figure 8.13 below. The bulls-eye bubble and adjustment screws were used to set up the accelerometer to be level for testing. A detailed setup and testing procedure is described in Appendix 7. During data analysis the roll error introduced by road

camber was corrected using euler rotation of the data about the x-axis. The average road camber measured using this method was between 1.6 and 3.6°. The error due to vehicle pitching during deceleration was neglected as an analysis of pitch angle versus deceleration showed that for decelerations of interest (around 0.1g) the error would be around 0.5°.



**Figure 8.13** X6-2 accelerometer mounted to the floor of a test vehicle.



**Figure 8.14** The Toyota Vitz 1999 (1000 cc) test vehicle.

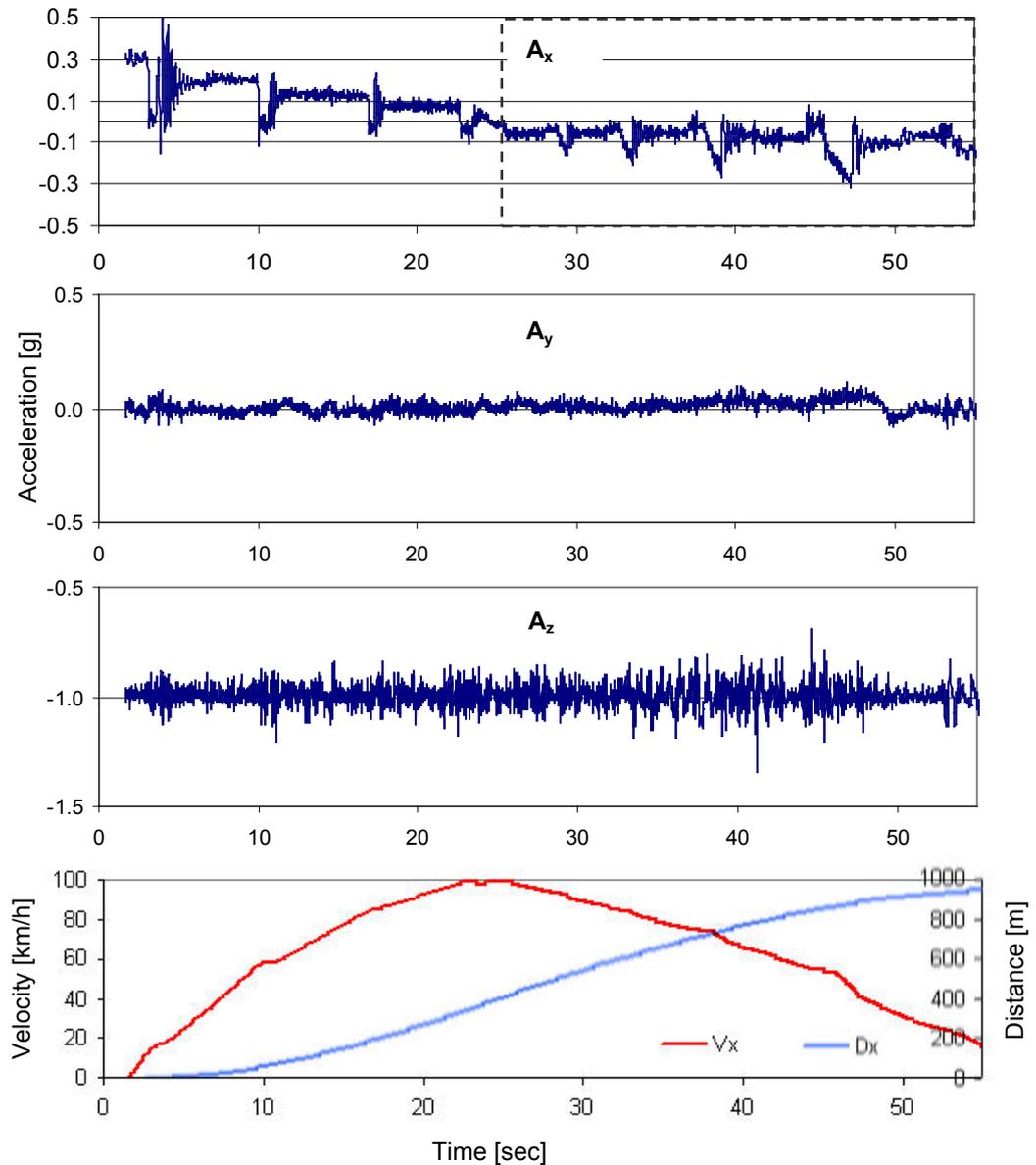


**Figure 8.15** Ford Mondeo 2005 (2000 cc) test vehicle.

The tests were conducted on a straight, level road with some camber. The days for testing were chosen for low traffic density and calm wind conditions.

### **8.6.2 Results**

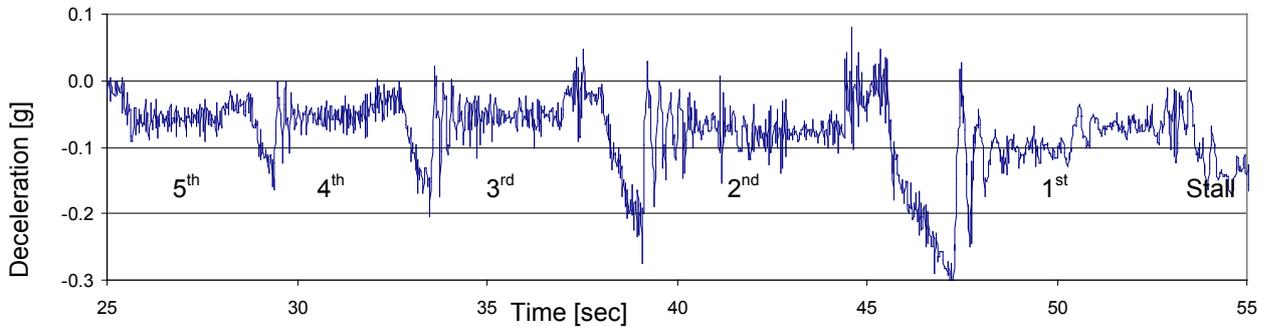
The tests were carried out by decelerating the vehicle from 100 km/h by changing gear at the appropriate time and recording the deceleration history. A typical plot recorded is shown below.



**Figure 8.16** Data plots for a typical test run (run-009) 1999 Toyota Vitz (Echo).  $A_x$  - vehicle braking and acceleration,  $A_y$  - lateral acceleration,  $A_z$  - vertical acceleration (gravity and road noise). Velocity and distance integrated from acceleration data is also shown.

The  $A_x$  plot clearly shows the gear changes made the first gear change (1<sup>st</sup>-2<sup>nd</sup>) was very rough (the clutch and driveline oscillations are evident) with a 2<sup>nd</sup> gear acceleration of around two (2) g. The engine braking deceleration period (25 -55 sec) is reproduced below for more clarity and discussion. The  $A_y$  plot shows the

lateral acceleration due to the vehicle turning, body roll and road noise. This plot was corrected for road camber by an Euler rotation of  $2.7^\circ$  so that the  $-0.05\text{ g}$  average is now approaching  $0.0^\circ$  as shown. The plot of  $A_z$  shows gravity,  $g$  and road noise.



**Figure 8.17** Typical engine braking deceleration plot Toyota Vitz (Echo) 1000 cc.

The first slope represents the accelerator being released at 100 km/h with fifth gear engaged. The  $5^{\text{th}} - 4^{\text{th}}$  gear change is shown as slight reduction in deceleration (clutch depressed) and then a sharp increase as the clutch is released followed by oscillations due to clutch and driveline flexibility. During the  $2^{\text{nd}} - 1^{\text{st}}$  gear change at approximately 45 km/h these oscillations are violent. Decelerations during in-gear coasting (ignoring gear change transients) are fairly constant at around  $0.05\text{ g}$ ,  $1^{\text{st}}$  and  $2^{\text{nd}}$  decelerations are slightly higher but not exceeding  $0.1\text{ g}$ . Average decelerations for in-gear coasting for the three vehicles tested are given in Table 8.4 below.

Vehicle	5th	4th	3rd	2nd	1st
1999 Vitz (Echo) 1000cc	0.046	0.045	0.043	0.076	_____
2006 Ford Mondeo 2000cc	0.040	0.053	0.074	0.075	_____

**Table 8.4** Average decelerations for in-gear coasting [g].

The above measurements taken during deceleration testing have shown that any regenerative braking system with a fixed control scheme should have the maximum deceleration limited to  $1.0\text{ g}$ . Simulation of engine braking by the regenerative brake can be achieved with regeneration set to  $0.05\text{ g}$ , however a limit of up to  $0.1\text{ g}$  could be justified if energy recovery is to be maximised. To

avoid axle locking on low friction surfaces and to ensure the design of the brake system complies with UNECE (2008), a deceleration of more than 0.2 g should not be permitted. UNECE (2008) states specific requirements for the distribution of brake force among the axles between 0.2 and 0.8 g

### **8.6.3 Testing and Certification of Regenerative Brakes**

The setup, workmanship and control scheme of fixed regenerative brakes are easily inspected and certified. The deceleration levels however, are more difficult to evaluate due to the low acceleration values involved. Deceleration values such as those seen during the testing are not readily measured using a pendulum type brake tester such as a Tapley meter commonly used by vehicle certifiers. Vehicle certifiers should be able to judge by 'feel' the level of regeneration that is appropriate for a certain vehicle. This deceleration should be set to simulate the engine braking of the donor vehicle. UNECE (2008) requires vehicles with regenerative braking systems of category A (fixed regeneration) to undergo behaviour tests carried out on a track with a low adhesion coefficient (coefficient of adhesion of 0.3 or less). During testing, transient conditions such as gear changes or accelerator control release shall not affect the behaviour of the vehicle and wheel locking is not allowed. These behaviours can be subjectively explored by the vehicle certifier, however the use of a low adhesion coefficient surface is not possible as such controlled conditions are not available. In light of this, vehicle certifiers should be conservative when setting regeneration level. The certifier must also keep in mind the how the battery SOC (power acceptance) effects the performance of the regenerative braking system. It may be appropriate to test the vehicle at 50% SOC so the regeneration is at its most effective. This could be particularly important with a mild hybrid vehicle with a relatively small battery pack.

### **8.7 Vehicle Stability**

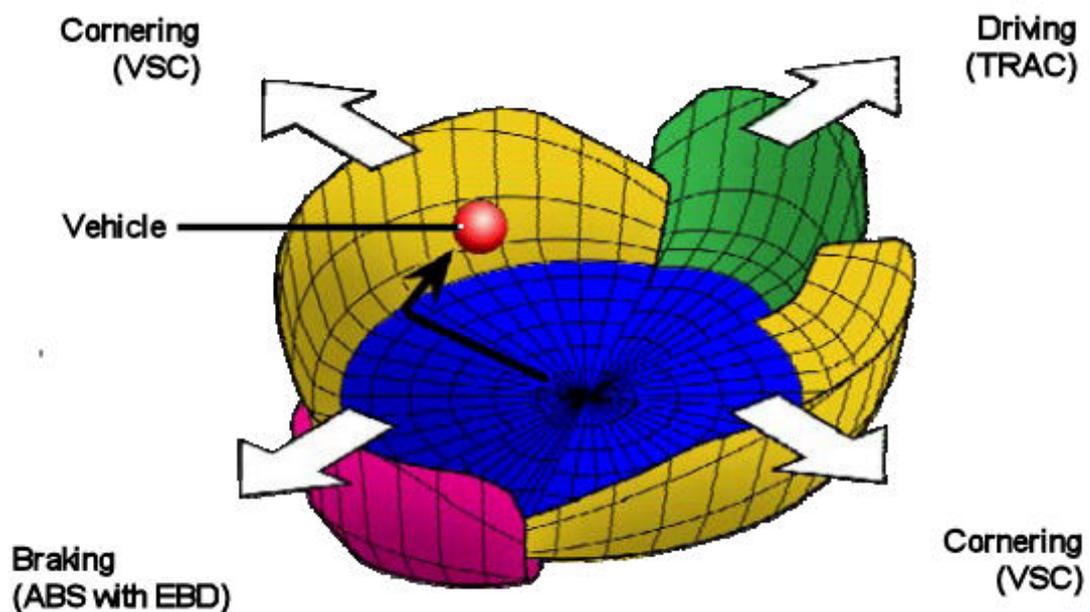
The effect of regenerative braking on vehicle stability during braking depends on which axle the brake acts on. Front axle regeneration will increase the brake force on the front axle and cause the front axle to lock first. Although this is a stable condition, it should be noted that the vehicle braking efficiency will reduce. Rear axle regeneration will increase the tendency for the rear axle to lock first. This

configuration is not recommended because of weight transfer during braking. During this research it is assumed that regeneration is on the front wheels only and it is not recommended that EV converters install regenerative braking on the rear wheels only. Vehicle certifiers should be extremely wary of this configuration and ask for evidence of careful design.

The regenerative braking system should also be ‘failure tolerant’ in case the electric transmission is compromised in any way. For example a short-circuit of the motor armature can cause maximum braking torque leading to axle lock, which may result in negative consequences (Bossche 2003).

### 8.8 Anti Skid Braking (ABS) and Electronic Stability Control (ESC)

Modern vehicles are increasingly fitted with electronic controls for braking and stability as standard equipment. These control systems improve the handling of the vehicle during extreme events. International studies confirm that ESC is highly effective in helping the driver maintain control of the car, thereby saving lives and reducing the severity of crashes. An example of how this particular system is integrated in the Toyota Vehicle Stability Control (VSC), is shown below



**Figure 8.18** Toyota VSC. Each function has its own control area. Each operates independently (Williamsen 2007).

In NZ, EV home converters tend to select older vehicles without ABS or ESC for conversions. One reason for this is to keep the cost of the donor vehicle low, but another reason is that the electronic vehicle systems do not need to be integrated into the conversion. This research suggests that this situation does not result in the safest EV fleet. If the effects of the conversion on the electronic systems of the vehicle can be kept to a low level, a safer vehicle will be the result as the newer vehicle is more likely to have other safety features such as a crush zone and airbags. EV converters should be encouraged to convert later model vehicles.

The Low Volume Vehicle Standard for Braking Systems, LVVTA (2000) allows the removal of an ABS braking system from a vehicle. It remains to be seen if a similar clause would be introduced for ESC. The brake systems of EV conversions with ABS fitted will be less affected by conversion factors such as a change in mass distribution.

Currently, it is not a legal requirement to have ESC so its removal from a particular vehicle would be accepted. This general rule however, fails to account how ESC may have been used by manufacturers to suppress or design-out undesirable handling characteristics. A well known example is the early Mercedes A Class which failed a stability test (the elk/moose test) shortly after its introduction in 1998. The vehicle suspension was subsequently redesigned with an ESC system which means its removal could affect the safety of the vehicle.

Integration of the ESC systems into the EV conversion can be problematic if the sensors include engine speed and/or torque. A requirement to keep ESC in the vehicle after conversion will likely exclude these vehicles from being converted. This would result in older vehicle (without ESC) being converted resulting in an older converted EV fleet with its associated reduction in safety engineering. Many vehicles include an off-switch for the ESC and these vehicles could be suitable for conversion. A certifier must judge which case is appropriate.

The inclusion of a highly integrated ESC as standard equipment in vehicles represents a challenge for EV converters as ESC designs which integrate engine sensors may preclude the vehicle from electric motor substitution.

## 8.9 Braking Summary

The substitution of an ICE with an electric motor and battery pack has many effects on the brake system. An increase in vehicle Tare mass, change in mass distribution, the removal of brake booster vacuum source and the removal of ICE engine braking are major issues when considering an EV conversion. During a successful EV conversion, changes in vehicle mass should be kept to a minimum by careful accounting of mass changes before and after the conversion. Brake force distribution should be adjusted for vehicles which have had significant change to either longitudinal and or vertical CoG.

The original specifications of the OEM vacuum source should be replicated by an alternative such as a vacuum pump. Testing of the OEM system before conversion provides the required design data for a detailed design, however testing showed the range of OEM manifold vacuum to be within -65 to -85 kPa. A simplified graphical design method can be used for vacuum reservoir sizing.

Removal of the ICE has the effect of removing engine compression braking as a supplementary source for long and/or steep descents. Engine braking is not always replaced by electric regenerative braking so the cumulative effect of increased weight, poor vacuum performance and no engine braking may have a serious effect on the vehicles brake capacity. For this reason the inclusion of regenerative braking in an EV conversion is strongly recommended. Deceleration testing showed that regenerative braking for accelerator controlled regeneration should be set below 0.1 g for engine braking simulation and must never exceed 0.2 g to preserve the vehicles OEM brake force distribution.

The functioning of the braking system is of utmost importance when it comes to the safe operation of the vehicle. The safe modification of a brake system for an EV conversion is possible by taking into account a number of design and vehicle certification issues outlined in this chapter.

## **Chapter 9 - Auxiliary Systems**

### **9.1 Introduction**

This chapter is a brief over-view of the auxiliary systems for EVs. Although the Sections in Chapter 9 deviate from the previous chapters about electrical, brake and battery safety systems, the following topics have been included as they have been identified as important in contributing to a vehicle's overall safety performance. These include;

- Power Steering
- Window Demisting
- EV Motors
- Vehicle Noise and Pedestrian Safety
- Chassis Loading, Tyre Loading and Vehicle Handling
- Occupant Impact Protection, Airbags and Crash Testing

### **9.2 Power Steering**

Vehicle power steering systems are hydraulic electro-hydraulic or electrical steering servo to reduce the steering wheel force required by the driver. The most common is a hydraulic system with the hydraulic pump being belt driven off the ICE. Whilst the electro-hydraulic and electric OEM systems may not need any modification, removing the ICE during a conversion means that the source of energy is lost and must be replaced. This is most commonly achieved by installing an appropriately sized auxiliary electric motor and drive belt. An example is given in Figure 9.1 below.



**Figure 9.1** The power steering motor (retrofitted) and pump in an EV conversion.

Control of the motor should drive the pump when the vehicle is in the ‘on’ or ‘ready’ mode. OEM systems are designed to ‘fail to safe’ (in the event of belt drive failure) as the steering system will still operate in the event of hydraulic pressure loss, albeit with higher steering wheel force required. NCOP-14 (2011) states that power and capacity must be sufficient for the original application to function correctly.

### **9.3 Window Demisting**

Removal of the ICE will also affect the performance of the window demisting system as the waste heat from the ICE (vehicle heater) is no longer available. The international EV standards do not discuss this issue. EV conversions need to

comply with general requirements but it is interesting to see that the Glazing, Windscreen Wipe and Wash, and Mirrors Rule has no requirement for demisting equipment. The requirement to keep the windscreen clear is a requirement of the *operator*, not the *equipment*. The Passenger Service Vehicle (PSV) rule however, does have requirements for windscreen equipment (section 6.10).

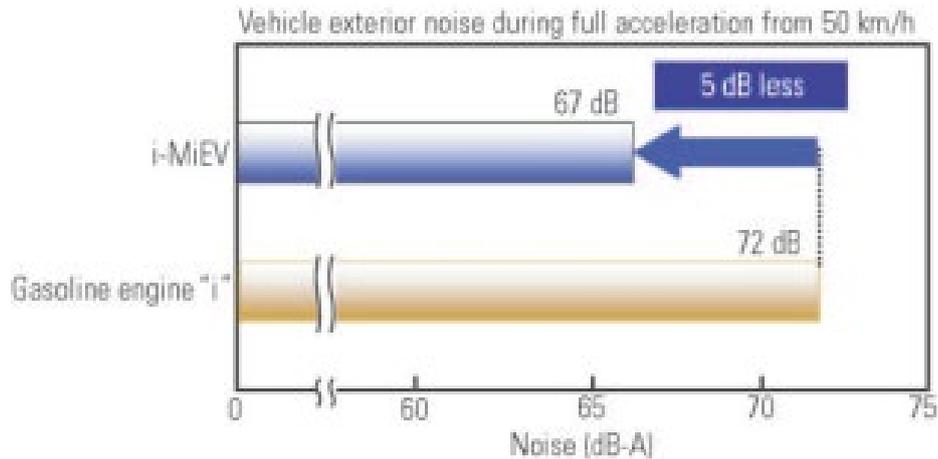
It is proposed that window demisting equipment should be recommended for EV conversions but not mandated (unless they will be used as PSVs) as the windscreen in most vehicles can be kept clear by the operator using a cloth. The EV conversion industry offers a number of products to provide an alternative heat source for the vehicle heater and the windscreen demisting equipment or homemade equipment such as a modified 230 V domestic hot water heating element can be used as a heat source.

#### **9.4 Vehicle Noise and Pedestrian Safety**

EVs are generally much quieter than ICE vehicles and as such emit less traffic noise pollution. The noise emitted from ICE vehicles has also been gradually reducing over the last few decades. EVs are so quiet that there is a safety concern that pedestrians may be less aware of EVs. Furthermore EVs do not generate any noise when at a standstill unlike an ICE vehicle that has the engine idling. It will be a significant challenge for EVs that they must emit an appropriate sound to make people aware of their movements (Hyder 2009).

High noise emissions EVs during battery charging from the charger itself or from cooling fans is also considered a problem (Bossche 2003). Charger noise is an environmental issue and falls outside the scope of this research.

Figure 9.2 shows a reduction in noise of 5 dB for the Mitsubishi iMiEV verses the ICE base model, the i Car.



**Figure 9.2** i MiEV exterior noise from (Kazunori 2007)

Although a primary concern is for sight-impaired pedestrians who are accustomed to aural cues to sense vehicles, sighted pedestrians such as runners, cyclists and children are also affected by the increased risks associated with a decrease in exterior noise from EVs.

In 2009 the National Highway Traffic Safety Administration published a study that investigated pedestrian and bicyclist crashes that involved hybrid electric vehicles (HEV) and to compare the results to ICE vehicles under similar circumstances. The study found that HEVs have a higher incidence rate of pedestrian and bicyclist crashes than do ICE vehicles in certain vehicle manoeuvres. HEVs were two times more likely to be involved in a pedestrian crash during slowing or stopping, backing up, or entering or leaving a parking space than ICE vehicles. These vehicle manoeuvres were studied as a group, as the difference between the sound levels produced by the hybrid versus ICE vehicle is the greatest at low speed (NHTSA 2009).

NZ vehicles have a maximum noise limit of 81 dB measured by a drive-by test however currently, there is no minimum noise requirement. The Vehicle Equipment 2004, Rule 32017 has a requirement for ‘audible warning devices’ to be fitted to vehicles, but this term is not defined and it is likely that it is referring to a vehicle’s horn. The following clause also states that a “... bell, siren or whistle must not be fitted to a motor vehicle if it is audible outside the motor vehicle” (NZTA 2004).

The NZ regulation therefore, does not allow an ‘engine noise simulator’ to be fitted to a very quiet vehicle, but allows reverse warning signals. It would be

useful to clarify these points in any amendments to allow quiet vehicles such as EVs to have these devices fitted. In 2010 Toyota began sales of an onboard device designed to automatically emit a synthesized sound of an electric motor when the Prius is operating as an EV at speeds up to approximately 25 km/h. The device will be available in Japan for approximately 150 USD. The increased risk from very quiet vehicles is preventable through vehicle designs which take into account the multi-sensory nature of traffic detection and avoidance. Regulations that require vehicles to emit a minimum level of sound would also help to address this. As the major responsibility for avoiding an accident is with the driver, EV drivers in particular need to be made aware of the specific safety issues that EVs pose to the public given that they emit little or at times, no noise. EV safety education aimed at drivers and the general public can help to address this.

NCOP-14 (2011) recommends the use of closed circuit televisions, proximity sensors or reversing alarms for EV conversions.

### **9.5 Chassis Loading, Tyre Loading and Vehicle Handling**

Adding an electric motor and battery pack to a vehicle can place high demands on the vehicles chassis and tyres. The battery can represent a significant physical load to the vehicle in terms of mass and volume. Consequently, the battery exerts a significant factor in the vehicle design. The Gross Vehicle Mass (GVM) of the vehicle must never be exceeded without an engineering assessment and strengthening of the vehicle chassis components. Calculation methods for chassis loadings were discussed in Section 8.2.2 (p. 139) (Brake Proportioning and Adhesion Utilisation). Common methods of achieving this are up rating the rear suspension with stiffer springs or ‘air shocks’. Standard design and certification guidelines for this purpose already exist in the form of the LVV standards and the NZ Hobby Car Technical Manual.

The certifier must also ensure front axle is not too light to cause steering instability. As a rule of thumb when a vehicle is loaded to its maximum permitted gross weight and its rear axle is loaded to its maximum permitted weight, the front axle weight must not be less than 30% of the maximum gross vehicle weight. This can be assessed by comparing the before and after fore-aft weight data, lightly and fully-loaded and confirmed by a subjective handling test.

## **9.6 Occupant Impact Protection/Airbags/Crash Testing**

When modifying a vehicle that has the latest occupant impact protection systems installed it is important to ensure that the functioning of these systems stays intact. The impact protection of batteries and electrical components is discussed in the respective sections.

LVV standards for modified impact protection already exist, these are LVV standards Frontal Impact 155-30 (00) and Interior Impact 155-40 (00). These standards do not contain any specific requirements for EVs. An EV conversion will modify the stiffness of the frontal structure of the vehicle as the ICE is replaced with an electric motor and other supporting components such as the controller and possibly even batteries. The general principals listed by LVVTA (2002) to keep OEM occupant protection systems intact include the following;

- minimise additional longitudinal stiffening forward of occupant cell and
- minimise risk of deformation of occupant cell and
- minimise the likelihood of penetration of components into the occupant cell.

LVVTA (2002) also gives some general construction requirements and a stringent process for the permanent removal of airbags.

The international EV standards require impact testing (LVVTA (2002) also gives circumstances that require testing) which is outside what EV converters can access or afford. The first EVs to undergo crash testing have been hybrids with the Toyota Camry Hybrid model tested by ANCAP in Australia early in 2010 (the Prius also has a long history).

The Camry Hybrid model achieved a similar score to the ICE model with both vehicles receiving a four star ANCAP rating. Another EV conversion which has been tested in both EV and ICE variants is the Hyundai Getz. The Blade Electron is a BEV conversion of the 2002 – 2010 Hyundai Getz. The Blade Electron (Hyundai Getz) passed the ADR 73 offset frontal impact testing requirements at Autoliv in late 2009. The crash data however is not comparable to the Hyundai Getz ICE model testing carried out by ANCAP as the impact speeds were different for the two tests. The ANCAP test was carried out using a 40% offset test at 64 km/h whereas the ADR 73 test (equivalent to UNECE Reg.94) uses 40%

offset carried out at 56 km/h. These results however show that it is possible to design EVs and EV conversions to comply with international impact standards. EV converters tend to use older donor vehicles as these primarily cost less (shown to be important in Chapter 2) and secondly, are easier to modify as the safety systems such as ABS, air bags and crush structures are not as integrated. Recent vehicles however, are safer than older vehicles due to the structural design and the introduction of safety systems such as airbags. The improvement of vehicle structures is shown in Figure 9.3 by a downward trend in ‘A pillar’ rearward displacement during recent crash tests. Paine explains from his study of historical ANCAP test results;

“Residual rearward displacement of the A-pillar (adjacent to the upper hinge of the front door) gives an indication of the integrity of the passenger compartment. Large displacements are usually associated with catastrophic collapse of the roof, driver's door and floorpan” (Paine 2009) (p. 4).

Similar results for brake pedal rearward movement, measured Head Injury Criteria (HIC) and chest compression for drivers dummies are also shown over this period.

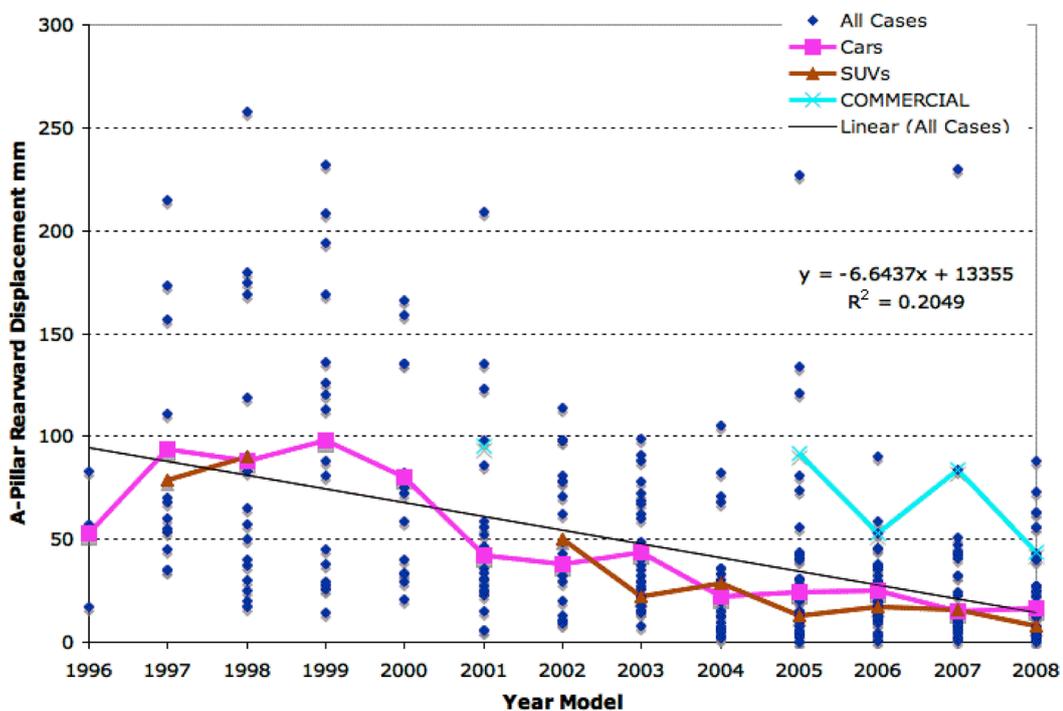


Figure 9.3 ‘A’ pillar rearward displacement from historical ANCAP testing.

After a period of development where impact absorption was the key, vehicle structures (occupant cells) are now becoming stiffer and are being supplemented by protective devices such as air bags and seatbelt pre-tensioners.

For these reasons it is recommended that EV converters are encouraged to use recent/newer model vehicles for EV conversions insofar that they have adequate knowledge of how these systems work to avoid a poor modification. The alternative is to use chassis from older model vehicles without airbags.

Huang describes the airbag deployment as a function of the timing of the airbag and occupant movement;

“...the desired sensor activation time is determined by the relative travel (displacement) of an unbelted occupant in the compartment. The computation of sensor activation time is based on the assumption that (1) an unbelted occupant moves forward 5 inches in the compartment before the air bag is fully deployed, (2) the time to fully inflate the air bag is 30 ms, (3) the depth of the fully deployed air bag is 10 inches, and (4) the initial distance between the torso and the steering hub where the air bag is packaged is 15 inches” (p. 71) (Huang 2002).

The airbag sensor tells the airbag when to inflate and the triggering of the sensor is dependent on the characteristics of the structure. The crushability of the structure in front of the sensor or sensors must remain unchanged. Adding stiffness to the structure will cause the airbag to deploy too early and vice-versa. This is especially relevant in some vehicles where the air bag system employs multiple sensors and complex algorithms to trigger the airbag.

More research into the effects of an EV conversion on the occupant protection systems of vehicles is required. The difference in mass and stiffness between the ICE removed and the replacement components is critical. This subject could benefit from the use of Finite Element Analysis (FEA) to assess the structural differences before and after an EV conversion.

## **9.7 Electromagnetic Compatibility (EMC)**

EVs are subject to EMC issues as they make use of electromagnetic power conversion. EMC is an important technical issue as the EVs inverters, converters and commutator circuits all switch very high currents and are a source of electromagnetic energy. As many of the international EV standards including ISO 6469-2 and SAE J2344 have requirements for EMC, it is important to briefly evaluate how these will affect NZ EV converters<sup>10</sup>.

The requirement in NZ is for all electrical products to conform to various levels of EMC standards. As the EV is a source and a potential receiver of electromagnetic energy, emissions and susceptibility must be considered (Bossche 2003). EV conversions are exempt if supplied in a total quantity of no more than 10 per annum (Sanjai 2004). Above this threshold EMC testing would need to be conducted and as the EV represents a level 3 product, these must be tested by an accredited testing body.

Simple methods can be employed to reduce the radio frequency interference of converted EVs such as matched impedance and shielded power cables. The power cables in the Toyota Prius and Blade Electron are shielded to reduce electromagnetic interference. Alternating current systems should achieve a power factor close to one so the voltage and current harmonics are reduced. To assess radio emissions some EV converters also used an informal method such as a handheld AM radio to test for interference before and after modification to improve the vehicle's interference performance.

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<sup>10</sup> Although EMC issues will not be discussed in detail here, Bossche (2003) provides a detailed description of international EMC standards relating to EVs.

## **Chapter 10 - Consumer Issues**

### **10.1 Introduction**

Environmental performance is very different from energy performance and measuring all vehicles against environmental performance holds many challenges. Defining the way a vehicle is used and charged is the key to this measurement, as the environmental burden is shifted to the energy supplier.

Establishing a standard way of reporting on EV environmental performance is important as there have been many documented claims of ICE vehicle CO<sub>2</sub> performance being misrepresented in advertising. This is expected to be no different for EVs when they emerge on the market.

### **10.2 Energy Use (Fuel Economy Labelling)**

The procedures for measuring energy consumption performance for pure ICE or pure EV vehicles are well established. Fuel economy needs to be displayed to the public in comparable units - the fuel saver website uses \$ fuel cost per year.

The energy use of BEV's is typically expressed in watt-hours per kilometre (Wh/km), and can be defined and measured at the battery pack terminals or the wall plug. This value typically ranges from about 124 Wh/km for small EVs to up to 249 Wh/km for larger vehicles (Pistoia 2010). A standard should be chosen for NZ where the energy consumption is measured at the charger supply and not at the battery terminals as energy is consumed during charging by charger, battery efficiency and cooling/ventilation equipment. It is important to capture this energy use because it is part of the total EV energy cost. The efficiency of the power generator and grid should not be considered as consistent when evaluating energy use with ICEs. For example, energy is lost in the extraction, refining and delivery of petrol but this is not counted in ICE calculations.

The energy consumption for EVs in Wh/km can be converted into an equivalent value such as litre/100km to provide a consistent comparison with ICE vehicles. Conversely the ICE value for fuel efficiency given in l/100km can be multiplied by 9.695 to yield Wh/100km (assuming a lower heating value for petrol of 35 MJ/l and 1 MJ = 277.77 Wh).

PHEV are more difficult to test as different operation modes are available in the same vehicle. Test procedures for PHEV should take into account both EV and

HEV operation modes (Bossche 2003). PHEV energy consumption varies with the way the vehicle is used. The drive cycle chosen for testing needs to make an agreed assumption on the battery recharge frequency. The energy consumption tests need to be more closely defined. SAE J1711 uses a Partial Charge Test (PCT) which represents the charging habits of a driver who never supplies external charge to the vehicle and a Full Charge Test (FCT) which represents the driver who recharges the battery every day from an off-vehicle source (Bossche 2003). The charging efficiency is also affected by the particular charge rate employed. SAE J2841 gives utility factor definitions for PHEV using 2001 US Department of Transport national household travel survey data. A utility factor would need to be defined for NZ by utilising the latest NZ household travel survey data. An example of the importance of standardised testing to provide a consistent comparison between ICE vehicles and EVs is given here.

The bi-annual AA Energywise Rally organised by the NZ Automobile Association, the Energy Efficiency and Conservation Authority (EECA), and Gull Petroleum NZ is designed to promote vehicle fuel efficiency. Vehicles compete against each other with the supreme winner being the vehicle which costs the least to run over the entire event.

Although the intent of the event is positive, it is biased as it does not demonstrate the vehicles' 'cost' in terms of typical day-to-day conditions. The event is also discriminatory against BEVs as the course covers hundreds of kilometres per leg which is well outside the range of most EVs. EVs however, typically have a range performance well within the average daily requirement of most people. It is expected that this event in the current format will cease to be relevant once a greater number of OEM EV models are available on the NZ market.

## **Chapter 11 - Conclusion**

### **11.1 Conclusion**

It has been shown that Electric Vehicles (EVs) are a good choice for sustainable transport technology in NZ to mitigate concerns about peak oil, energy security and climate change. The EV represents a spectrum of vehicle technology which includes BEVs, HEVs, PHEVs, REV and FCVs all with their own particular issues regarding regulation and technical standards.

During research for this thesis it was discovered that NZ has a base of EV enthusiasts and engineers with the knowledge and capability to produce ICE to EV conversions to a reasonable standard and performance. A cost analysis however, has shown that the extra capital cost of EVs currently on the market cannot be justified on the basis of reduced energy costs over the life of the vehicle (based on 2010 cost of petrol and electricity). The purchase cost of EVs is currently the most important cost factor. EVs and converted EVs therefore represent a hibernating (dormant) technology that could emerge under the right economic conditions.

The recent development of new interest in EV technology has highlighted the need for technical safety focused standards to govern the modification and scratch building of EVs in NZ. No LVV Standard for EV conversions currently exist however LVV certifiers have been using an unofficial standard to certify vehicles. The need for a LVV technical standard for EV conversions has been identified by government regulators. Although it might be difficult for NZ regulators to justify the expense of implementing new standards considering the small number of EV vehicles being built, standards need to be in place before they are needed.

A strong argument for the development regulations for EV conversions is to mitigate against the risks associated with new technology. This is not only to protect public safety but also the integrity and the future market perception of EVs.

The EV does not fit into the same regulatory framework as the ICE, as such government regulators need to collaborate across many new areas to regulate for EVs. Many areas of current legislation have been identified which affect EVs including clauses in the Land Transport Rules. This legislation affects EVs whilst not having been written specifically with EVs in mind. One regulation is the Electricity Safety Regulation (2010) where it is unclear whether EVs are required

to be certified by an Electrical Warrant of Fitness (EWOFF). Implications for EVs that are hired or leased are also identified. Without further clarification, it is likely that the requirement for a EWOFF for EV conversions has been adopted by the certification community without it being an actual legal requirement. These areas need urgent clarification to avoid further confusion. Any new LVV standard for EV conversions must also clarify the roles and demarcations (electrical and mechanical) of the certifiers involved in assessing the EV conversions compliance.

During this research it was discovered that currently, EV's cannot be identified in the NZ vehicle fleet using the motor vehicle register. Changes must be made to the motor vehicle register to include classifications for ICE, BEV, HEV, and PHEV. The safety profile of these vehicle types can then be assessed by future research into EV accidents.

The EV is a new technology (rather than a mix of existing technologies) that presents unique challenges to regulators and the automotive industry to foresee the risks of EVs. This thesis implemented a formal risk management process to identify appropriate risk controls for EV conversions. The 'first draft' risk analysis showed that most EV risks related to electrical, battery and braking safety are controlled by implementing a reduction in risk event likelihood, rather than a reduction in risk event severity. This indicates that risk controls need to be reliable in order to be effective.

A literature review of the major international EV safety standards found many recommendations relevant to EV conversions which have been discussed throughout this work including UNECE Regulation 100 (2010) which is recognised by NZ.

The design of EVs requires unique engineering solutions in order to reduce the inherent safety risks of the technology however, there are many simple things that EV converters can do to increase the safety of EV conversions.

The three major areas of technological risk for EV conversions identified by this project are; the electrical system, the traction battery and the braking system.

EV conversions contain potentially lethal levels of electrical voltage and current. An EV electrical system can include a number of components that are not onboard the vehicle thus making certification more difficult. The need for a clear certification of both the on and off board charging components was identified.

When electrical components fail it is essential that they fail in a safe manner. A number of technical requirements have been identified which should be implemented in LVV standards.

Chapter 7 focused on a systematic building of design methods for the safe installation and use of traction batteries for EV conversions. EV converters are learning about the performance benefits of Li-ion cells and these cells are rapidly becoming the 'cell of choice' for OEM vehicles as well as EV conversions. Cells which are sensitive to overcharge and over-discharge such as Li-ion cells embody a particular safety risk for EV converters. A multi layered design approach to the safety systems surrounding the battery system should be undertaken, with the choice of active safety protection chosen to compensate for the weaknesses in the cell design. Methods by which the design and certification of battery cooling and ventilation systems can take place were also identified.

The single most important active safety feature of a vehicle is the brake. The substitution of the ICE with an electric motor during an EV conversion will have an effect on the vehicles brake system – if the brakes are modified or not. The cumulative effect of increased weight, poor vacuum performance and no engine braking may have a serious effect on the vehicles brake capacity and safety. Therefore the brake system must be carefully assessed during an EV conversion. A design method for a retrofit vacuum pump has been developed. Research showed that regenerative braking for accelerator controlled regeneration (fixed regeneration) should be set below 0.1 g for engine braking simulation and must never exceed 0.2 g to preserve the vehicles OEM brake force distribution. This finding was supported by carrying out deceleration testing on two vehicles.

The correct functioning of the vehicles auxiliary systems such as the power steering, heating and window demisting equipment can be assured by providing substitute power sources (electric motors) supplied preferentially by the vehicles battery. A functioning window demisting system is a recommended but not an essential requirement.

The lack of vehicle noise emitted by EVs has raised concerns about pedestrian and child safety. EV converters are thus encouraged to incorporate safety equipment such as noise generating devices, closed circuit televisions, proximity sensors or reversing alarms into their vehicles.

EV converters should do everything possible to keep OEM occupant protection systems such as crush zones and airbags intact. Recent crash testing of EVs (and EV conversions) has shown that it is possible to design a vehicle that complies with international standards. EV converters however tend to use older donor vehicles (>15 years old) as these cost less and are easier to modify as the safety systems such as ABS, air bags and crush structures are not as integrated. To encourage EV modifiers to use safer, newer vehicles more research into the effects of an EV conversion on the occupant protection systems of vehicles is required. The difference in mass and stiffness between the ICE removed and the replacement components is however critical.

Although not a safety issue Electromagnetic Compatibility (EMC) compliance issues will affect professional EV converters who produce more than 10 vehicles per annum.

With the use of battery chemistries and design which minimises the risk of failures, coupled with adequate safeguards in the form of redundant protection, well designed thermal management and ventilation systems, EV converters can achieve safe and high performance conversions. Several interviewees expressed the opinion that with the right controls EVs could be safer than ICE vehicles. Although there are different risks in the use of EV technology, findings from this thesis do support this claim by showing that EV conversion methods can produce EVs that are as safe, if not safer than ICE vehicles.

The future challenge for NZ regulators and EV converters is to develop and implement new standards without imposing undue costs on the EV industry. A number of EV converters are strongly opposed to more regulation in this area. The key is to involve the EV community in the development of an EV standard however currently NZ has no formal advocacy group for EV converters. It is strongly recommended that such a group be formed to become an active voice in this process.

## **11.2 Recommendations for Further Research**

Research areas that were identified as outside the scope of this project but important for the development of EV technology in NZ were outlined in Section 1.1. Instead, this section focuses on recommendations for further research that have resulted from dominant issues identified in this thesis. These are summarised below.

An iterative risk analysis of EVs is important as more EVs enter the mainstream. A risk analysis should use EV accident data as this information becomes available. A particular area of interest will be pedestrian accidents involving EVs in NZ.

To encourage EV modifiers to use safer, newer vehicles more research into the effects of an EV conversion on the crashworthiness and occupant protection systems of OEM vehicles is needed. The impact testing of several typical EV conversions could be carried out to facilitate this. It is strongly recommended that a set of guidelines on the safety and use of various proprietary batteries be developed to inform EV converters and certifiers during the design of an EV conversion and certification process.

Research on how EVs are used in NZ could inform national policy making for EV incentives and develop an effective measure of EV use. More information in this area would also help address the technical issue of energy use of plug-in vehicles as discussed in Chapter 10.

## **Appendix**

### **Appendix 1. Organisations Interviewed**

The organisations interviewed include:

- NZ Transport Agency (NZTA)
- Low Volume Vehicle Technical Association (LVVTA)
- Australian Electric Vehicle Association (AEVA)
- Meridian Energy (Wellington)
- NZ Motor Trade Association (MTA)
- NZ Ministry of Economic Development (MED) Energy Safety Service
- Standards Australia (Sydney)
- RMIT University, School of Aerospace , Mechanical and Manufacturing Engineering (Melbourne)
- Australian New Car Assessment Program (ANCAP)
- Blade Electric Vehicles (Castlemaine)
- Energetique
- Toyota Motor Corporation Australia (Melbourne)
- Betterplace (Sydney)
- Various EV home builders and EV component suppliers in NZ and Australia.

## **Appendix 2. Land Transport Rules Affecting EVs.**

### **NZ Transport Law**

The NZ Acts of Parliament and regulations relating to transport are administered by the NZ Transport Agency (NZTA) under the guidance of the Ministry of Transport. No specific regulations for electric vehicles exist in NZ. The safety of vehicles is governed by the Land Transport Act 1998. Section 6 of this act requires “vehicles to be safe and operated in compliance with rules.” Ordinary transport rules made by the Minister are administered by the NZTA. The NZ Land Transport Rules are a set of documents which dictate the requirements for vehicle standards and use.

The set of rules comprises of the following which have been identified to affect or relate to EVs and EV conversions.

### **Dangerous Goods 2005, Rule 45001/1**

This rule allows the use of batteries in vehicles as a source of motive power even though they may be considered dangerous goods if transported for any other purpose. As such the Rule does not apply to the transport on land of dangerous goods that are:

1. required for the motive power or control of the vehicle and are contained within the fuel system, electrical system or control system; or
2. required for the operation of ancillary equipment on the vehicle and are contained within the fuel system or electrical system; or

Section 6 (Segregation) could be used as a guideline for the segregation of batteries and passengers and liquid containing systems such as batteries.

### **Door Retention Systems 2001, Rule 32001/1**

Not specifically related to EVs.

### **Driver Licensing 1999, Rule 91001**

Electric vehicles are of the “Automatic type”.

### **External Projections 2001, Rule 32008/1**

Not specifically related to EVs.

### **Frontal Impact 2001, Rule 32006/1**

A modification to a motor vehicle such as an EV conversion will affect its frontal impact performance as designed by the manufacturer. The modification;

- must not prevent the vehicle from complying with the rule; and
- must be certified as specified in *Land Transport Rule: Vehicle Standards Compliance 1998*.

The manufacturer's operating limits is defined as;

1. in relation to a motor vehicle, the allowance provided by the vehicle manufacturer in terms of performance capability and dimensions, relative to deterioration, malfunction or damage beyond which the safe performance of the vehicle, as defined by the vehicle manufacturer, is compromised; and
2. in relation to a system, component or item of equipment, incorporated in or attached to a vehicle, the allowance provided by the system, component or equipment manufacturer in terms of performance capability and dimensions, relative to the deterioration, malfunction or damage, beyond which the safe performance of the system, component or item of equipment (and consequently the vehicle) is compromised.

### **Fuel Consumption Information 2008, Rule 33020**

Only applies to petrol, diesel, LPG or CNG vehicles not BEVs. Providing fuel consumption information for BEV and PHEV will be a challenge however it is important that these vehicles compared directly and accurately with ICE vehicles. Energy consumption information would be a better title.

### **Glazing, Windscreen Wipe and Wash, and Mirrors 1999, Rule 32012/1**

This rule has no requirement for demisting equipment so a modification to the vehicles heating system is allowed. The requirement to keep the windscreen clear is a requirement of the operator, not the equipment. The PSV Rule however does have requirements for windscreen equipment (section 6.10) 6.10(1) states that "The front windscreen and side windows (of the PSV) used by the driver must be equipped with effective demisting equipment, adjustable from the driver's seat.

**Head Restraints 2002, Rule 32010/1**

Not specifically related to EVs.

**Heavy Vehicle Brakes 2007, Rule 32015**

Not specifically related to EVs.

**Heavy Vehicles 2004, Rule 31002**

Not specifically related to EVs.

**Interior impact 2001, Rule 32001**

Not specifically related to EVs.

**Land Transport (Road User) Rule 2004, Rule 61001**

Only excessive noise is limited, not minimum noise levels. The windscreen must be kept clear. A driver of a motor vehicle fitted with a forward windscreen must at all times keep the windscreen clean and clear so that the driver's view forward is not impeded or obstructed.

**Light-Vehicle Brakes 2002, Rule 32014**

A parking brake needs to be fully mechanical. An engine brake or a driveline retarder, if fitted in a vehicle, must be designed and constructed so that its use does not cause the drive axle wheels of the vehicle to lock.

**Operator Licensing 2007, Rule 81001**

A rental or taxi company need to comply with electricity regulations, ie the four yearly EWOFF inspections.

**Operator Safety Rating 2008, Rule 81002**

Not specifically related to EVs.

**Passenger Service Vehicles 1999, Rule 31001**

Section 6.2 gives the requirements for fire fighting and protection against fire. The main sections are headed; materials and design, fuel tanks and protection against

fumes and, gases and fire extinguishers. Electric PSVs may require different design solutions to that of standard EVs.

Requirements exist for electrical voltages of more than 32 volts AC or 115 VDC (Section 6.5). There is no mention of standards that must be met, but general requirements are given and 6.5(2) states that; “Inspections must be carried out by a person registered under either section 75 or section 77 of the Electricity Act 1992”. The Toyota Prius is commonly used as a PSV and has a traction system utilising more than 115 V.

Windscreen demisting equipment is required to be fitted to the vehicle.

### **Seatbelts and Seatbelt Anchorages 2002, Rule 32011**

Not specifically related to EVs.

### **Seats and Seat Anchorages 2002, Rule 32004**

Not specifically related to EVs.

### **Setting of Speed Limits 2003, Rule 54001**

Not specifically related to EVs.

### **Steering systems 2001, 32003/1**

Not specifically related to EVs.

### **Traction Engines 2010, Rule 63001**

Not specifically related to EVs.

### **Traffic Control Devices 2004, Rule 54002**

A road controlling authority can set aside a specific area of roadway for a class or classes of road user (such as EVs). EV parking and charging infrastructure is facilitated by this.

### **Tyres and Wheels 2001, Rule 32013**

Not specifically related to EVs.

### **Vehicle Dimensions and Mass 2002, Rule 41001**

Not specifically related to EVs.

**Vehicle Equipment 2004, Rule 32017**

Section 2. does not allow an 'engine noise simulator' to be fitted to a 'very quiet vehicle'. However reverse warning signals are allowed.

**Vehicle Exhaust Emissions 2007, Rule 33001/2**

For a battery electric car - totally powered by electricity - you must show it meets safety standards. But you don't need to provide: evidence that it meet emissions standards fuel consumption information.

**Vehicle Lighting 2005, Rule 32005**

Not specifically related to EVs.

**Vehicle Repair 1998, Rule 34001**

Not specifically related to EVs.

**Vehicle standards compliance 2002, Rule 35001**

This Rule sets out requirements to control the entry of vehicles into, and operation of vehicles in, the NZ land transport system including EVs. Section 10.6 establishes the LVV system

**Work Time and Logbooks 2007, Rule 62001**

Not specifically related to EVs.

### Appendix 3. Risk Control Matrix

**Definition of Controls**

- Avoid**            Prevent
- Mitigate**        Lessen in severity or intensity
- Reduce**          Lessen in likelihood
- Transfer**        Pass risk another party (ie insurance)

Risk Assessment						Controls						Reduced Risk		
Risk Category	Risk ID	Risk Description	S	L	Hazard Risk Number (HRN)	Avoid	Mitigate ( $\Delta S$ )	Reduce ( $\Delta L$ )	Transfer	Accept	Hazard Control Number (HCN)	Hazard Risk Number $HCN_c$	$S_c$	$L_c$
ICE Risk Evaluation	1.0	Vehicle fire unrelated to accident	5	2.5	12.5	 Actual risks						12.5		
	1.1	Vehicle fire after accident	7		0							0		
	1.2	Pedestrian minor injury accidents 2008	5	2.2	11							11		
	1.3	Pedestrian serious injury accidents 2008	6	1.8	10.8							10.8		
	1.4	Pedestrian fatal accidents 2008	7	1.0	7							7		
	1.5	Annual likelihood of vehicle crash 2008	0	5.5	0							0		
	1.6				0							0		

<b>Electrical Safety</b>	2.0	Electrocution during manufacture and maintenance	6	4.0	24			Insulate, label and use interlock switches to access HV areas			0.4	9.6	6	1.6
	2.1	Fire from electric short/arc	4	3.0	12	short circuit warning and interlock.	Remove combustible materials from around cables	Insulate hazardous voltages, restrain HV cables from chafing, remove sharp objects from penetrating cable			0.5	6	4	1.5
	2.2	Fire during charging	6	4.0	24	Use correct charger, BMS over temp cut-off switch	Use LA or LiFePO <sub>4</sub> battery chemistry	Use LA or LiFePO <sub>4</sub> battery chemistry			0.5	12	5	2.4

		2.3	Electrocution after impact	6	4.0	24			Insulate hazardous voltages with flexible conduit and install crash interlock switch, battery enclosure insulation with pack installed in safety cell.			0.4	9.6	6	1.6
		2.4	Short circuit	5	4.0	20	detection and control					0.3	6	5	1.2
		2.5	Soft short	4	4.0	16	detection and control					0.3	4.8	4	1.2
		2.6	Motor over temp leading to damage	2	4.0	8				Not safety related		1	8	2	4.0
<b>RESS</b>	<b>Cell level risks</b>	3.0	Internal short of cell leading to heat and pressure generation and resulting in cell thermal runaway	5	4	20		Use LA or LiFePO <sub>4</sub> battery chemistry, BMS detection and isolation	short resistant cells, electrode separators			0.4	8	3	2.7
		3.1	External short	4	3	12			Good mechanical design and insulation			0.5	6	4	1.5
		3.2	Cell overcharge	5	6	30			BMS detection			0.5	15	5	3.0

								and control.						
	3.3	Cell Fire	6	5	27	Good BMS thermal control	Use LA or LiFePO <sub>4</sub> battery chemistry,				0.5	13.5	3	4.5
	3.4	Elevated temperature	4	5	20	Good BMS thermal control	Use LA or LiFePO <sub>4</sub> battery chemistry,				0.4	8	2	4.0
<b>Module level risks</b>	3.5	Short circuit	4	3	12			Good mechanical design, insulation and termination			0.6	7.2	4	1.8
	3.6	Over charge	5	6	30	Correct charger		BMS detection and control			0.5	15	5	3.0
	3.7	Module Fire	6	5	30	Install over temp cut-off switch	Install fire extinguisher	BMS temp control			0.6	18	6	3.0
	3.8	Elevated temperature	5	5	25	Install over temp cut-off switch		BMS temp control			0.5	12.5	5	2.5
<b>Pack level risks</b>	3.9	HV Short circuit	6	5	30			Good mechanical design, insulation and termination			0.5	15	6	2.5

	3.10	Over charge (energy)	5	6	30	Correct charger and BMS		BMS detection and control, controller regen limited, active cell balancing and charge control			0.3	9	5	1.8
	3.11	Over Charge (power)	4	5	20	Charger power correct		controller regeneration limited			0.2	4	4	1.0
	3.12	Pack Fire	7	4	28	Install over temp cut-off switch	Install fire extinguisher	BMS temp control			0.4	11.2	6	1.9
	3.13	Elevated temperature	3	4	12	Install over temp cut-off switch		BMS temp control			0.5	6	3	2.0
	3.14	Crush	5	5	25			Design crush zone, install pack in vehicle safety cell			0.5	12.5	5	2.5
	3.15	Drop	4	4	16		Use LA or LiFePO <sub>4</sub> battery chemistry	Design crush zone, install pack in vehicle safety cell			0.6	9.6	3	3.2
<b>Battery system</b>	3.16	Short circuit	6	5	30			Good mechanical design, insulation and termination			0.5	15	6	2.5

	3.17	Over voltage	5	4	20			BMS and charger			0.4	8	5	1.6
	3.18	Chassis fault leading to energising of body	6	4	24			Insulate hazardous voltages, restrain HV cables from chafing, remove sharp objects from penetrating cable			0.4	9.6	6	1.6
	3.19	Loss of HV continuity	1	4	4					Reset switches or replace fuse	0	4	1	4.0
	3.20	Contactors fail closed	4	5	18		Fuse of correct rating installed	Use high quality contactor			0.5	9	3	3.0
	3.21	Over discharge resulting in under voltage (energy)	2	5	10	BMS management		active cell balancing		Replace damaged battery pack	0.3	3	2	1.5
	3.22	Over discharge resulting in heat generation (power)	4	5	20	controller power limited	Fuse of correct rating installed				0.3	6	2.0	3.0
<b>Brakes</b>	4.0	Brake failure	6	5	30			correct design of vacuum brake system			0.4	12	6	2.0

		4.1	Loss of stability on low friction surface	6	4	24			Limit regeneration and check vehicle balance			0.4	9.6	6	1.6
		4.2	Loss of stability during cornering	6	4	24			Check vehicle balance			0.4	9.6	6	1.6
<b>Vehicle Use</b>		5.0	Pedestrian accident	6	3	18			Introduce engine noise simulation, pedestrian education		Trade increased risk for environmental benefits	0.9	16.2	6	2.7
		5.1	RF Interference	1	7	7					Accept increased AM band pollution, small numbers of EV conversions	0	7	1	7.0
<b>Auxiliary Systems</b>		6.0	No demist, accident due to lack of vision	3	5	15						0	15	3	5.0

#### Appendix 4. IP Codes

First characteristic numeral	Additional letter	Brief description	
		Protection against ingress of ...	Requirements
0	-	not protected	none
1	A	Back of hand (no protection against intentional access)	Sphere of 50 mm Ø shall not fully penetrate and shall have an adequate clearance from hazardous parts
2	B	Finger	Jointed finger of 12 mm Ø may fully penetrate but shall have adequate clearance from hazardous parts
3	C	Tool (e.g. screwdriver)	Rod of 2.5 mm Ø, 100 mm length may fully penetrate, but shall have adequate clearance from hazardous parts
4	D	Wire	Wire of 1.0 mm Ø, 100 m length may fully penetrate but shall have adequate clearance from hazardous parts
5	D	Wire	
6	D	Wire	

Table A4.1

Second characterising numeral/ letter	Protection against the ingress of ...	Requirements
0	Not protected	none
1	Falling drops	Vertically falling drops shall have no harmful effects
2	Falling drops when enclosure tilted up to 15 °	Vertically falling drops shall have no harmful effects
3	Spraying water	Water sprayed at any angle of up to 60 ° from the vertical shall have no harmful effects
4	Splashing water	Water splashed against the enclosure from any direction shall have no harmful effects
4K	Splashing water at high pressure	Water splashed at high pressure against the enclosure from any direction shall have no harmful effects
5	Water jets	Water projected in jets against the enclosure from any direction shall have no harmful effects
6	Power water jets	Water projected in powerful jets against the enclosure from any direction shall have no harmful effects
6K	Power water jets at high pressure	Water projected in powerful jets at high pressure against the enclosure from any direction shall have no harmful effects
7	Water with temporary immersion	Ingress of water in quantities causing harmful effects shall not be possible when the enclosure is temporarily immersed in water under specified conditions of pressure and time
8	Water with continuous immersion	Ingress of water in quantities causing harmful effects shall not be possible when the enclosure is continuously immersed in water under specified conditions
9K <sup>6)</sup>	Water with high-pressure/steam jet cleaning	Water directed at a high pressure against the enclosure from any direction shall have no harmful effects
<sup>6)</sup> A water protection grade 9 without a supplementary letter has not yet been specified		

Table A4.2

DIN 40 050 Table 9, Examples of the allocation of degrees of protection against water for passenger vehicles.

Type of vehicle	Site of mounting or assembly	Exposure to water	Second characteristic numeral/ supplementary letter
Private car	Passenger area	Not particularly exposed	0
	Engine compartment shielded at the bottom	Not exposed to splashing water or water jets. Only light drizzle on individual insignificant points.	3
	Engine compartment open at the bottom, protected areas	Only indirectly exposed to splashing water or water jets	4
	Engine compartment open at the bottom, exposed areas	Directly exposed to splashing water or water jets.	4K
	External mounting	Directly exposed to splashing water or water jets.	4K

**Table A4.3.** From DIN 40 050 Road Vehicles Degrees of protection (IP codes) Protection against foreign objects, water and access for Electrical equipment.

## Appendix 5. Selected Vehicle Battery Details

Vehicle/Ref	Cell Ah	Cells/ Module	Modules/ Pack (Cells/Pack)	Voltage [V]	Capacity [kWh]	Wh/kg	W/kg	Power [kW]	Mass [Kg]	Battery Range [km]	Speed [km/h]
Tesla Roadster (Gene Berdichevsky 2006; Yang 2010)	2.0 (18650 format) 3.1 for new pack	621	11 (6831)	375	53			200	450	378	200
Mitsubishi Imev (K Hanada 2007; Yang 2010)	50	4	22 (88)	360	16	140	1000			160	130
Nissan Leaf (Hyder 2009)					24					160	
Chevrolet Volt PHEV (Hyder 2009)					16					64	
Toyota Prius HEV		6	28 (168)	201						-	
Hyundai Blade Electron (Hyder 2009)					16					100	
Coda Sedan (Zhang 2010a)			(728) 104s7p	333	33.8	90				144 - 196	128

	<b>97 Prius (Generation I) Japan Only</b>	<b>00 Prius (Generation II)</b>	<b>04 Prius (Generation III)</b>	<b>2010 Prius (Generation IV)</b>
<b>Form Factor</b>	Cylindrical	Prismatic	Prismatic	Prismatic
<b>Cells (Modules)</b>	240 (40)	228 (38)	168 (28)	168 (28)
<b>Nominal Voltage [V]</b>	288.0 V	273.6 V	201.6 V	201.6 V
<b>Nominal Capacity [Ah]</b>	6.0Ah	6.5Ah	6.5Ah	6.5Ah
<b>Specific Power [W/kg]</b>	800 W/kg	1000 W/kg	1300 W/kg	1310 W/kg
<b>Specific Energy [Wh/kg]</b>	40 Wh/kg	46 Wh/kg	46 Wh/kg	44 Wh/kg
<b>Module Weight [g]</b>	1090g	1050g	1045g	1040g
<b>Module Dimensions</b>	35(oc)x384(L)	19.6x106x275	19.6x106x285	19.6x106x285

**Figure X.** Toyota Prius battery specifications adapted from <http://www.toyotapriusbattery.com/>.

## Appendix 6. EV Li-ion Battery Standards

EV Li-ion Battery Standards from (Engineers 2010; Tabaddor 2010). (Bossche 2003) gives a table of standards (p.438) for other battery chemistries.

Standard	Detail
UL 2580 (2011)	<p>Batteries for use in Electric Vehicles</p> <ul style="list-style-type: none"> <li>- Covers: Rechargeable cells, modules, battery packs and battery systems for use in electric vehicles (over 60 VDC)</li> <li>- Evaluates: Hazards associated with fire, electric shock and personal injury</li> </ul>
ISO 12405	<p>Electrically propelled road vehicles — Test specification for lithium-ion traction battery packs and systems</p> <ul style="list-style-type: none"> <li>- Scope covers performance, reliability and abuse testing for high power lithium ion battery systems used for propulsion applications</li> </ul>
IEC 62660 -1	<p>Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 1: Performance testing for lithium-ion cells</p> <ul style="list-style-type: none"> <li>- Scope covers performance testing for high energy lithium ion cells for propulsion of BEV and HEV applications</li> </ul>
IEC 62260 -2	<p>Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 2: Reliability and abuse testing</p> <ul style="list-style-type: none"> <li>- Scope covers reliability and abuse testing for high energy lithium ion cells for propulsion of BEV and HEV applications</li> </ul>
SAE J2380 (2009)	<p>Vibration Testing of Electric Vehicle Batteries</p> <ul style="list-style-type: none"> <li>- Scope; testing of a single battery (test unit) consisting of either an electric vehicle battery module or an electric vehicle battery pack</li> </ul>
SAE J1797 (2008)	<p>Recommended Practice for Packaging of Electric Vehicle Battery Modules</p> <ul style="list-style-type: none"> <li>- Recommended Practice provides for common battery designs through the description of dimensions, termination, retention, venting system, and other features required in an electric vehicle application</li> </ul>
SAE J2289 (2008)	<p>Electric-Drive Battery Pack System: Functional Guidelines</p> <ul style="list-style-type: none"> <li>- Scope: common practices for design of battery systems for vehicles that utilize a rechargeable battery to provide or recover all or some traction energy for an electric drive system. It includes product description, physical requirements, electrical requirements, environmental requirements, safety requirements, storage and shipment characteristics, and labelling requirements. It also covers termination, retention, venting system, thermal management, and other features.</li> </ul>
SAE J1766	<p>Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing</p> <ul style="list-style-type: none"> <li>- Scope: defines test methods and performance criteria</li> </ul>

		which evaluate battery system spillage, battery retention, and electrical system isolation in Electric and Hybrid Electric Vehicles during specified crash tests.
SAE J2464	EV & HEV Rechargeable Energy Storage System (RESS) Safety and Abuse Testing Procedure	- Abuse testing is performed to characterize the response of a Rechargeable Energy Storage Systems to off-normal conditions or environments that could reasonably be expected to occur
SAE J2929 Not published	Electric and Hybrid Vehicle Propulsion Battery System Safety Standard: Lithium-based Rechargeable Cells	- Defines a minimum set of acceptable safety criteria for a lithium-based rechargeable battery system to be considered for use in a vehicle propulsion application as an energy storage system connected to a high voltage power train
UN-T (UN-3090)	Shipment of Lithium cells and batteries in bulk (class 9 dangerous goods)	- Under United Nations transportation regulations primary lithium and rechargeable lithium ion and lithium polymer cells and batteries must comply with the UN T1 - T8 testing requirements given in (UN 2003) - Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria.
BATSO 01 (2008)	Manual for Evaluation of Energy Systems for Light Electric Vehicle – Secondary Lithium Batteries	
USCar USABC FreedomCAR SANDIA EUCAR		
Chinese (Chengwei 2010)	( QC/T744-2006) • Nickel-Metal hydride Batteries for Electric Vehicle ( QC/T743-2006) • Lithium-ion Batteries for Electric Vehicle ( QC/T742-2006) • Lead-acid Batteries for Electric Vehicle ( QC/T741-2006) • Ultra capacitors for Electric vehicles	

**Table A6.1** EV Li-ion battery standards.

## **Appendix 7. Brake Test Procedure**

The following outlines the methods used for brake booster vacuum and engine brake deceleration testing.

### **Preliminary**

- Collect vehicle ID data
- Fill fuel tank
- Set tyre pressures to manufacturer's requirements
- Clean or change engine air filter
- Weigh vehicle Tare weight.
- Measure and calculate vehicle CoG height and axle weights using the modified reaction, null point, weight balance or pendulum method. The null point method used is described below.
- Measure and calculate front and rear axle spring rates. Calculate and plot theoretical pitch angle vs deceleration.
- Calibrate accelerometer using guidelines given at <http://www.gcdadataconcepts.com/calibration.html>
- Fit accelerometer to passengers floor area and level with bullseye. Vehicle must be on a level surface with driver sitting in the vehicle. Confirm that
- Run straight line braking to set up accelerometer x axis with vehicle centre line.  $A_y$  data should average at zero
- Fit vacuum gauge to vehicle and check operation
- Set accelerometer to level using bulls eye level. Check  $A_z$  reads -1.00
- Have clip board on hand to record notes.
- Record engine vacuum at idle, 3000 RPM and Max RPM

### **Standard Test Runs Engine Brake**

Roll down from 100 km/h (2 in each direction). Record direction.

Roll down from 100 km/h with engine braking, changing gear when appropriate. (2 in each direction). Record direction. Record speed at which deceleration gear changes take place.

## Standard Test Runs Engine Manifold Vacuum

Measure Idle vacuum (1 Vacuum test only)

Measure hard engine braking vacuum down hill (1 Vacuum test only)

## Data Analysis

Down load data files

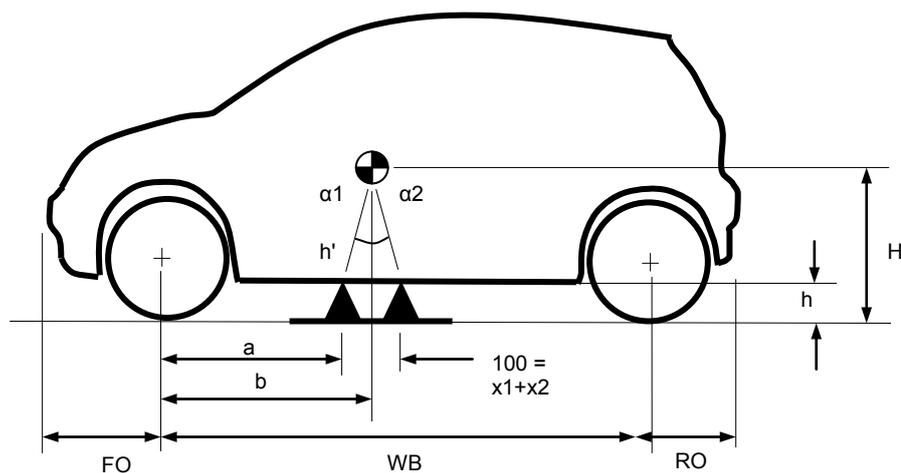
Analyse in spreadsheet (Ref)

Analyse acceleration errors with respect to deceleration pitch angle.

Make Euler rotations to correct for road camber.

## CoG Height by the Null Point Method

The null point method requires a platform that has two parallel knife edges several inches apart from each other. In this method the vehicle is placed so the CoG is between the two knife edges. The vehicle is then tilted in either direction until the vehicle balances on one knife edge. This indicates when the vehicle CG has rotated outside the stable zone between the knife edges. Therefore, the CoG height can be calculated from the two tilt angles. This method is more accurate than the modification reaction method, but requires a special rig (Price 2008) shown below.



**Figure A7.1** Null point method

Figure A7.2 on the following page shows the vehicle balanced on the knife edges.



**Figure A7.2** Vehicle balanced on knife edges. Protractor with 0.5° accuracy shown.

## Appendix 8. Commercial EV Vacuum Pumps

Manufacturer Supplier	Model	I [A]	Max Vacuum [kPa]	Flow Rate l/min	Time to - 50 kPa vacuum 2l reservoir [s]	Cost [USD] Pump only
MES DEA	70/6E	2.5	-65		12	
	70/6E2	5	-72		6	
EV Source	#310-VACP- K		>-15		1.6	358 Kit
	Gast #310- VACP	4.5-6	-76.2			255.88
SSBC	Electric Vacuum Pump Kit		>-16			265
KTA Kit/Gast	Gast MOA- V111-JH	6.8	-81.3			395 Kit
Thomas/ EV Parts	107CDC20	8.5	-77.5	39.6		325.55
Everything EV	VP1	2.5	-60			£458

**Table A9.1** Commercial EV vacuum pumps.

## **Appendix 9. Relevant Excerpts in from UNECE (2008)**

UNECE (2008). Uniform Provisions Concerning The Approval of Vehicles of Categories M, N and O with Regard to Braking U. Nations. Geneva, UNECE.

### **Regulation No. 13.**

#### **2. Definitions**

2.14. "Phased braking" is a means which may be used where two or more sources of braking are operated from a common control, whereby one source may be given priority by phasing back the other source(s) so as to make increased control movement necessary before they begin to be brought into operation (p. 10).

#### **Category A (Regeneration Not Part of Service Brake)**

5.2.1.24.1 The electric regenerative braking shall only be activated by the accelerator control and/or the gear neutral position for vehicles of category N1 (<3500 kg)

5.2.1.24.2. In addition, for vehicles of categories M2 and N2 (>3.5 and < 5 tonnes), the electric regenerative braking control can be a separate switch or lever.

5.2.1.24.3. The requirements of paragraphs 5.2.1.25.6. and 5.2.1.25.7. also apply to Category A regenerative braking systems (p. 32).

#### **Category B (Regeneration Part of Service Brake)**

5.2.1.7.2. In the case of (light) vehicles equipped with electric regenerative braking systems of category B, the braking input from other sources of braking, may be suitably phased to allow the electric regenerative braking system alone to be applied, provided that both the following conditions are met:

5.2.1.7.2.1. Intrinsic variations in the torque output of the electrical regenerative braking system (e.g. as a result of changes in the electric state of charge in the traction batteries) are automatically compensated by appropriate variation in the phasing relationship ... (p. 25)

5.2.1.7.2.2 Wherever necessary, to ensure that braking rate remains related to the driver's braking demand, having regard to the available tyre/road adhesion, braking shall automatically be caused to act on all wheels of the vehicle (p. 26).

5.2.1.25.6. The operation of the electric regenerative braking shall not be adversely affected by magnetic or electric fields.

5.2.1.25.7. For vehicles equipped with an anti-lock device, the anti-lock device shall control the electric regenerative braking system of either category (p. 32).

5.2.1.25.1. it must not be possible to disconnect, partially or totally, one part of the service braking system other than by automatic means... (p. 32).

5.2.1.25.2. the service braking system must have only one control device;

5.2.1.25.3. the service braking system must not be adversely affected by the disengagement of the motor(s) or by the gear ratio used (p. 32).

5.2.1.18.3. For vehicles fitted with an electric regenerative braking system of either category, all the relevant prescriptions shall apply except paragraph 5.2.18.1.1. above. In this case, the electric regenerative braking may be actuated by the accelerator control and/or the gear neutral position. Additionally, the action on the service braking control must not reduce the above braking effect generated by the release of the accelerator control.

## References

- Ashtiani, C. (2007). Battery Hazard Modes and Risk Mitigation Analysis. USABC. United States Advanced Battery Consortium.
- BERR (2008). Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plug-in Hybrid Vehicles, Department for Business Enterprise and Regulatory Reform: Department for Transport.
- Balakrishnan, P. (2006). Safety Mechanisms in Lithium-ion Batteries. *Journal of Power Sources* 155: 401–414.
- Bossche, P. V. D. (2003). The Electric Vehicle: Raising the Standards. Faculteit Toegepaste Wetenschappen Vakgroep Elektrotechniek en Energietechniek. Brussels, Vrije Universiteit Brussels. Phd.
- Bostock, P. (2010). Examining the EV Battery Energy Density Needs for Luxury Vehicles. EV Li-Ion Battery Forum 2010. Beijing, China. Dufresne
- BSI (2002). Safety Requirements for Secondary Batteries and Battery Installations — Part 3: Traction batteries. BS EN 50272-3:2002. British Standards Institute.
- Cai, S. (2010b). EV recharging Infrastructure - Understanding the Requirements from a Vehicle Manufacturer Perspective. EV Li-Ion Battery Forum 2010. Beijing, China. Dufresne
- Cai, S. (2010a). General Motors Vehicle Electrification Strategy. EV Li-Ion Battery Forum 2010. Beijing, China. Dufresne
- Cheng, T. (2010). Comparing Cathode vs Anode Future Research Investment for Achieving Competitive Advantage and Lowering Costs of Li-Ion Batteries. EV Li-Ion Battery Forum 2010. Beijing, China. Dufresne
- Chengwei, X. (2010). Overview on Power Batteries for Electric Vehicles in China. EV Li-Ion Battery Forum 2010. Beijing, China.
- Comsol (2010). Batteries and Fuel Cell Simulation. IEEE Spectrum. Institute of Electrical and Electronics Engineers. Webinar.
- Court, P. (2010). Renewable Energy, Smart Grids and Electric Vehicles in an Open-source Context. ESR Newsletter. Auckland, Engineers for Social Responsibility. 26.
- Davis, T. (2010). Having range anxiety? The Sydney Morning Herald. Sydney: p.3.
- Deng, Z. (2010). CBAK Power Batteries for EV, PHEV. EV Li-Ion Battery Forum. Beijing, China. Dufresne

- Densham, B. (2010). BMU - 4 Critical Decisions. EV Li-Ion Battery Conference. Beijing, China 321. Dufresne
- Dhameja, S. (2002). Electric Vehicle Battery Systems. Butterworth-Heineman.
- Dirr, N. (2008). A Feasibility Assessment for Electric Vehicles and the NZ Grid. Dunedin, University of Otago. Department of Physics. MSc.
- Donovan (2008). Managing Transport Challenges when Oil Prices Rise. New Zealand Transport Agency Research Report. Wellington, NZTA.
- ECE (2009). Uniform Provisions Concerning the Approval of Category M2 or M3 Vehicles with Regard to Their General Construction. R 107 U. ECE.
- EEC (1971). Council Directive of 26 July 1971 on the approximation of the laws of the Member States relating to the braking devices of certain categories of motor vehicles and of their trailers (EEC). 71/320/EEC.
- Ehsani, M. (2004). Fundamentals, Theory, and Design Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, CRC Press.
- Erwan B, Hemery S. (2008). Electric Vehicles Demand Forecast. Electricity Commission. Wellington.
- EUCAR. (2009). The Electrification of the Vehicle and the Urban Transport System Recommendations on key R&D by the European Automotive Manufacturers, July 2009. 11. European Council for Automotive R&D.
- FMVSS (2005). FMVSS, Motor Carrier Vehicle Safety Standards Part 571.135: Standard No. 135; Light vehicle brake systems. Part 571.135. US Department of Transportation.
- FMVSS (2009). FMVSS, Motor Carrier Vehicle Safety Standards Part 571.305 Standard No. 305; Electric-powered vehicles: electrolyte spillage and electrical shock protection. US Department of Transportation.
- G.L. Plett, M. J. K. (2006). Advances in HEV Battery Management Systems. SAE Technical Papers 2006-21-0060. Society of Automotive Engineers.
- Garrett, (1998). Vehicle fires and the introduction of premium unleaded petrol into New Zealand. Journal of The Royal Society of New Zealand 28(2): 321-328.
- Berdichevsky G, Straubel JB, Toomre E. (2006). The Tesla Roadster Battery System. Tesla Motors.
- Giebel, T. (2010). Understanding how Power Train Strategies Impact the Requirements of an EV Li-Ion Battery. EV Li-Ion Battery Forum 2010. Beijing, China. Dufresne

- Griffiths, E. R. F. (1982). *Dealing with Risk: The planning, management and acceptability of technological risk*, Manchester University Press.
- Happian-Smith, E. J.(Ed) (2002). *An Introduction to Modern Vehicle Design*. Warrendale, P.A. Society of Automotive Engineers.
- Huang, M. (2002). *Vehicle Crash Mechanics*. CRC Press.
- Hughes, A. (2006). *Electric Motors and Drives*. Elsevier.
- Hyder, et. al (2009). *National Cost-Benefit Assessment of the Early Uptake of Electric Vehicles in New Zealand, Methodology, Assumptions and Results*. Wellington. Meridian Energy, Contact Energy.
- Ip, C. S. (2008). *Battery Restraint System Design and Performance Evaluation for Renewable Energy Vehicle Project*. School of Mechanical Engineering. The University of Western Australia. BE: 56.
- Isidori, R. (2010). *Evaluating EV Energy density in Cold Winter Conditions and Achieving Stability*. EV Li-Ion Battery Forum. Beijing, China. Dufresne
- ISO6469-1 (2009). *ISO 6469-1: 2009 Electrically Propelled Road Vehicles - Safety Specifications - Part 1: On-board Rechargeable Energy Storage System (RESS)*. International Standards Organisation.
- ISO6469-2 (2009). *ISO 6469-2: 2001 Electrically Propelled Road Vehicles - Safety Specifications - Part 2: Vehicle Operational Safety Means and Protection Against Failures*. International Standards Organisation
- ISO6469-3 (2001). *ISO 6469-3: 2009 Electric Road Vehicles - Safety Specifications - Part 3: Protection of Persons Against Electric Hazards*. International Standards Organisation
- IVA-M1 (2009). *Individual Vehicle Approval Manual for Vehicle Category M1. Vehicle and Operator Services Agency*. London. Version: 4.01.
- Jen, F. (2010). *Learning How to Apply Geographic, Demographic and Grid Senarios into the EV Ecosystem*. EV Li-Ion Forum 2010. Beijing, China. Dufresne.
- Johnson, T. (2007). *The New Zealand Hobby Car Technical Manual*. Tauranga, The New Zealand Hot Rod Association (Inc), Low Volume Vehicle Technical Association.
- Kazunori (2007). *Development of Next-Generation Electric Vehicle “i-MiEV”*. Mitsubishi Motors Technical Review No 19: Pp 66 - 70.
- King, S. (2007). *Electric Vehicles and New Zealand: Identifying Potential Barriers and Future Considerations*. Wellington. NZ Ministry of Transport.

- Korinek, P. (2003). Calculated vs Actual Short Circuit Currents for VRLA Batteries.p 7.
- Lazar, J. (2009). EV Standards In Australia, A Scoping Study. Sydney, Standards Australia. Version 1.0.
- Li, Y. (2010). Designing Power Systems According to the Demand Curves of Driving Schedules. EV Li-Ion Battery Forum 2010. Beijing, China.
- Limpert, R. (1999). Brake Design and Safety. Society of Automotive Engineers.
- LVVTA (2000). LVVTA Low Volume Vehicle Standard 35-00(00) Braking Systems. 35-00(00). Low Volume Vehicle Technical Association. Wellington.
- LVVTA (2002). Low Volume Vehicle Standard 155-30 (00) (Frontal Impact). 155-30 (00). Low Volume Vehicle Technical Association (Inc). Wellington.
- LVVTA (2004) Low Volume Vehicle Code- Issue 4. Low Volume Vehicle Technical Association. (Inc). Wellington.
- MED (2010). Electricity (Safety) Regulations 2010. 2010/36. N Z Government. Wellington, Ministry of Economic Development.
- Morfee, P. (2010). Risk Assessment for Regulatory System Design. UNECE wp6 Extended Bureau Meetings. Stockholm, UNECE.
- MOT (2009). Pedestrian Crash Statistics for the year Ended 31 Dec 2008. Ministry of Transport, Wellington, New Zealand
- MOT (2010). The New Zealand Vehicle Fleet : Data Spreadsheet 2.0, Ministry of Transport, Wellington. New Zealand.
- Nakamura, T. (2010). Examining the Japanese Battery ans Materials Stratigies for Cost Effective Energy Storage. EV Li-Ion Battery Forum 2010. Beijing, China.
- NCOP-14 (2011). National Code of Practice for the Construction and Modification of Light Vehicles (VSB 14) - National Guidelines for the Installation of Electric Drives in Motor Vehicles. Australian Motor Vehicle Certification Board Working Party. NCOP 14.
- NHTSA (2009). Incidence of Pedestrian and Bicyclists Crashes by Hybrid Electric Passenger Vehicles, US National Highway Traffic Safety Administration.
- NZ AA (2010). 2010 Car Running Costs Folder. Auckland, The New Zealand Automobile Association (Inc).
- NZTA (2004). Land Transport Rule, Vehicle Equipment 2004. Rule 32017. New Zealand Transport Agency. Wellington, Ministry of Transport.

- NZTA (2005). Heavy Vehicle Selection Guide. Wellington, New Zealand Transport Agency. Wellington, Ministry of Transport.
- NZTA (2006). Land Transport Rule, Heavy-vehicle Brakes. New Zealand Transport Agency. Wellington, Ministry of Transport.
- Paine, M. (2009). Injury and Structural Trends during 12 Years of ANCAP Frontal Offset Crash Tests. Enhanced Safety Vehicles (ESV09). Stuttgart, Germany, ESV09.
- Parker (2008). The End of Oil? Some Optimistic Musings. University of Otago Magazine. Dunedin, University of Otago. Pp. 16 - 17.
- Pistoia, G., Ed. (2010). Electric and Hybrid Vehicles, Power Sources, Models, Sustainability, Infrastructure and the Market. Amsterdam, Elsevier.
- Prakash, R. (2010). Li-Ion Battery Program for a small size city car. Li-Ion Battery Forum 2010. Beijing.
- Price, D. (2008). Estimation of Uncertain Vehicle Center of Gravity using Polynomial Chaos Expansions
- Rand, D. (2001). Understanding Batteries, RSC Paperbacks.
- Rekker, J. (2009). So You Want to Make an Electric Car. A practical Guide to Converting from Petrol to Battery Electric for Around Town Driving. NZ. (DVD)
- Riley, L. (1976). Heyday of Battery Power. Christchurch Star. Christchurch. P. 5. (Newspaper)
- SAE (2010). SAE J2344: Guidelines for Electric Vehicle Safety. Society of Automotive Engineers.
- Sanjai, R. (2004). Radio Communications (EMC Standards) Notice 2004 No. 2. Radio Spectrum Management. Wellington, Ministry of Economic Development. . No. 2.
- Scardino, R. (2009) Tesla Roadster, Toyota Prius, VW Touareg Crash in Denmark. [www.allcarselectric.com](http://www.allcarselectric.com), accessed 20,12,2010.
- Schalkwijk, W, Ed. (2002). Advances in Lithium-Ion Batteries, Kluwer Academic.
- Simpson, A. (2006). Cost-Benefit Analysis of Plug-In Hybrid Electric Vehicle Technology. 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition (EVS-22) Yokohama, Japan, National Renewable Energy Laboratory

Standards NZ (2007). AS/NZS 3000: 2007. Electrical Installations (known as the Australian/New Zealand Wiring Rules), Standards Australia/Standards NZ. AS/NZS 3000.

Standards NZ (2008). AS/NZS3001:2008 Electrical Installations – Transportable Structures and Vehicles including their Site Supplies. AS/NZS3001:2008. New Zealand.

Standards NZ (2009). AS/NZS 31000:2009 Risk Management - Principals and Guidelines.

Staunton N, P. V., Maughan R (2008). Controlled Cooling In Hybrid Electric Vehicles. Hybrid and Eco-Friendly Vehicle Conference 2008. The University of Warwick.

Tabaddor, P. (2010). Quality and Safety Standards Needed for Validating next generation Li-Ion Batteries. EV Li-Ion Battery Forum 2010. Beijing, China. Dufresne.

Tietzel, C. A. (2009). Battery Cage Mechanics for the Renewable Energy Vehicle Project. School of Mechanical Engineering, The University of Western Australia. BE: 109.

MOT (2009). Regulatory Impact Statement RUC Electric Vehicle Exemption. NZ Ministry of Transport.

MOT (2002). Land Transport Rule Light-Vehicle Brakes 2002. New Zealand Transport Agency. Wellington, NZ. Rule 32014. NZ Ministry of Transport.

TVNZ. (2010). "Wairau." Fire Scene Investigation 13 September. Retrieved 19 Nov, 2010, from <http://tvnz.co.nz/fsi/fire-scene-investigation-s1-e2-video-3775736>.

UN (2003). Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria. UN. Geneva. (ST/SG/AC.10.11/Rev. 4).

UNECE (2008). Uniform Provisions Concerning The Approval of Vehicles of Categories M, N and O with Regard to Braking U. Nations. Geneva, UNECE. Regulation No. 13. United Nations Economic Commission for Europe.

UNECE (2009). Uniform Provisions Concerning The Approval of Battery Electric Vehicles With Regard to Specific Requirements for the Construction and Functional Safety. R. 100. UNECE. Geneva. Regulation No 100. United Nations Economic Commission for Europe.

Warner, J. (2010). Comparing and Predicting Materials for the Next Generation EV Battery. EV Li-Ion Battery Forum 2010. Beijing, China. Dufresne

- Williamson, P. M. (2007) Toyota & Lexus Hybrid Brake Integration. Toyota.
- Willums, J. O. (2010). EV or Battery - Leasing? Examining New Financing Models to Market Cost Effective EVs. EV Li-Ion Battery Forum 2010. Beijing, China. Dufresne.
- Wolkin, M. V. (2010). Battery Switch: Quicker than Quick Charge. EV Li ion Battery Forum 2010. Beijing, China, Dufresne.
- Xuezhe, W. (2010). Lessons Learnt from Using Cell Management Technology to Maximise Battery's Capacity and Life. EV Li-Ion Battery Forum 2010. Beijing, China, Dufresne
- Yang, M.-H. (2010). Predicting Heat Release to Prevent Thermal Runaway Propagation and Achieving Long Term EV Li-Ion Safety. EV Li-Ion Battery Forum 2010. Beijing, China. Pp. 187-197. Dufresne.
- Yang, M. H. (2007). Safety of Lithium Batteries Regarding their Chemistry. BATSO Workshop 2007. Nuremberg, Germany, BATSO.
- Zhang, N. (2010a). Materials & Safety in EV Applications at Module Level. EV Li-Ion Battery Forum 2010. Beijing, China. Dufresne
- Zhang, Y. (2010b). Modelling & Field Test Results: Lifetime of LiFePO<sub>4</sub> based Battery for EV Applications. EV Li-Ion Battery Forum 2010. Beijing, China. Dufresne