Metadata of the chapter that will be visualized in SpringerLink

Book Title	Behaviour of Lithium-Ion Batteries in Electric Vehicles	
Series Title		
Chapter Title	Mechanical Design and Packaging of Battery Packs for Electric Vehicles	
Copyright Year	2018	
Copyright HolderName	Springer International Publishing AG, part of Springer Nature	
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Abstract

Safety and reliability are the two key challenges for large-scale electrification of road transport sector. Current Li-ion battery packs are prone to failure due to such reasons as continuous transmission of mechanical vibrations, exposure to high impact forces and, also, thermal runaway. Robust mechanical design and battery packaging can provide greater degree of protection against all of these. This chapter discusses design elements like thermal barrier and gas exhaust mechanism that can be integrated into battery packaging to mitigate the high safety risks associated with failure of an electric vehicle (EV) battery pack. Several patented mechanical design solutions, developed with an aim to increase crashworthiness and vibration isolation in EV battery pack, are discussed. Lastly, mechanical design of the battery pack of the first fully electric bus designed and developed in Australia is presented. The case study showcases the benefits of adopting modularity-in-design and highlights the importance of packaging space in EVs, particularly low-floor electric buses as weight distribution becomes a challenge is such applications.

Keywords (separated by '-')

Modular design - Thermal runaway - Bottom impact and crash protection - Vibration isolation - Gas exhaust/venting mechanism - Electric bus

Abstract

Safety and reliability are two key challenges for large scale electrification of road transport sector. Current Li-ion battery packs are prone to failure due to such reasons as continuous transmission of mechanical vibrations, exposure to high impact forces and, also, thermal runaway. Robust mechanical design and battery packaging can provide greater degree of protection against all of these. This chapter discusses design elements like thermal barrier and gas exhaust mechanism that can be integrated in battery packaging to mitigate the high safety risks associated with failure of an electric vehicle (EV) battery pack. Several patented mechanical design solutions, developed with an aim to increase crashworthiness and vibration isolation in EV battery pack, are discussed. Lastly, mechanical design of the battery pack of the first fully electric bus designed and developed in Australia is presented. The case study showcases the benefits of adopting modularity-in-design and highlights the importance of packaging space in EVs, particularly low-floor electric buses as weight distribution becomes a challenge is such applications.

Keywords: Modular design; Thermal runaway; Bottom impact and crash protection; Vibration isolation; Gas exhaust/venting mechanism; electric bus

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1 Introduction

Paris agreement has united 195 countries of the world who share a common goal of limiting the green-house gas emissions and gradually building a carbon-free society. Significant efforts are thus being focussed on increasing the share of renewable energy in the total energy generated in these regions [1]. However, the problem of intermittency affects all renewable energy resources. Use of battery packs to add an energy buffer and increase the flexibility of the electric grids is considered a reliable as well as an environmentally green solution for the problem of intermittency associated with renewable energy sources [2-4]. Also, battery powered vehicles have the potential to substantially cut the greenhouse gas emissions from the transport sector. Electrification of transportation sector is thus integral to the long-term climate control policies of all nations.

Among the commercially available battery chemistries, Li-ion batteries offer features such as high efficiency, high gravimetric and volumetric densities, longer lifespan and low maintenance requirements that are all essential for setting up an efficient energy storage system [5-7]. Currently, the cost of manufacturing an EV battery pack is about $500 per kilowatt hour. However, with efforts to modify the microstructure of electrode materials for Li-ion batteries [8-12], the cost is expected to decrease to $200 per kWh by 2020 and $160 by 2025 [13]. Lastly, Li-ion batteries containing non-toxic metals such as iron, nickel, manganese, cobalt, have been classified as "non-hazardous waste and safe for disposal in the normal municipal waste stream" by the U.S. government [14]. For these reasons, they are the preferred choice for the majority of high energy or high power applications in present times.

Li-ion batteries have long been used in a single-cell format for small portable electronic devices. Due to the fairly limited energy content of such cells, it was believed that failure of a single cell, which has been thoroughly investigated and relatively well understood [15-19], would have little impact beyond its surroundings. However, as these cells are now being scaled-up and configured to find applicability in energy storage system for electric grids and vehicle electrification programs, single cell failures affecting neighbouring cells and damaging the entire battery pack are regularly reported. A gap lies in our understanding of the behaviour of large battery packs under abusive conditions [20, 21]; therefore, careful consideration must be given to design of a Li-ion battery based energy storage system for the targeted application.

2 Design Considerations

A simplified representation of an electric bus is presented in Fig. 1. It shows in a block format, various electro-mechanical systems such as electric motors, electric HVAC unit, electric air compressor and various types of controls that demand energy or act as load for the installed battery packs.

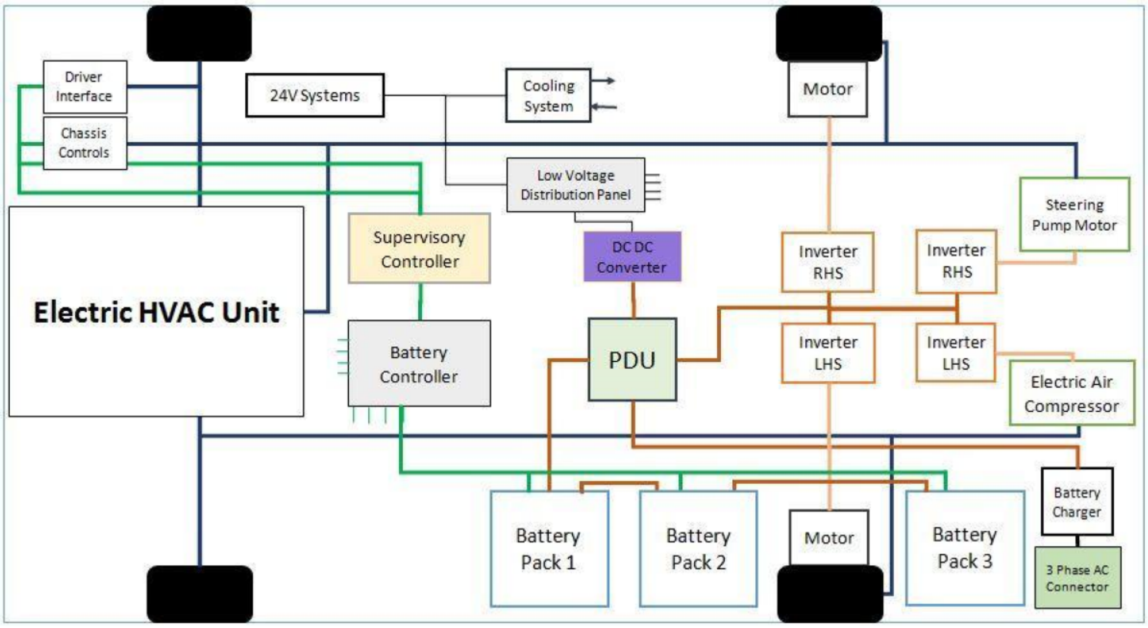


Figure 1 – Simplified representation of an electric vehicle. HVAC: Heating, Ventilation, Air Conditioning; PDU: Power distribution unit; L/RHS: Left/Right Hand Side

It can be easily inferred from this basic schematic that an EV battery pack communicates with different sub-systems and multiple parameters simultaneously through various interfaces. Different interfaces, as visualised in the case of an EV battery pack, are briefly described in Table 1 [22].

Table 1 – Definition of various system interfaces in an EV battery pack [22].

Interface	**Definition**	**Formed by**
Mechanical	Mechanical design features included for safety reasons	Cell spacers, damping pads, gaskets, valves
Structural	Members that provide required protection and isolation	Case, cover, end-plates, tie rods, cross members
Thermal	Regulates battery cell temperature	Coolant, fans, pumps, heat exchangers
Electrical	Transmits power from, and to, the battery pack	Bus-bars, cables, contactors, fuse, relays
Control	Monitor and regulate the state of battery pack	Battery management system, various sensors

Support	Vehicle body parts providing additional crash worthiness	Axles, chassis, seats, vehicle floor

Communication through each of these interfaces can influence reliability and safety of the battery pack and needs regulation. For example, it has been suggested that the battery temperature must be maintained below 50°C for safe operation [23, 24]. The vibration frequencies of the battery pack should also be suppressed to avoid resonance at typical natural frequencies of the vehicle suspension system and sprung mass from 0 to 7 Hz, the vehicle powertrain, i.e. driveline and gearbox, from 7 to 20 Hz, and the vehicle chassis system from 20 to 40 Hz [25]. Marginal deviations from the designed boundary can compromise the cycle life of the battery pack. It can also set in motion an uncontrolled chain of exothermic reactions resulting in the release of smoke or toxic gas and the development of high pressure events leading to premature failure, fire and explosions. These marginal deviations can be caused by excessive heat build-up or physical abuse of battery packs that includes puncturing or crushing the packs [26].

A reliable battery packaging design should address issues relating to thermal stability, vibration isolation and impact resistance at micro as well as macro level. Further, it should minimise thermal and mechanical interactions between different units of the battery pack at each level, i.e. at cell and module level, thus reducing the probability of failure of the battery pack itself. Design elements that can be optimized readily to achieve the required level of protection without much impact on available resources are called control factors [22]. Some of the most critical control factors of an EV battery pack are: battery cells and cell spacer type, number and location of gas exhaust nozzles, battery cooling system, and insulation coating thickness. A rule of thumb for identification of control factors is: any factor that lies outside the system boundary is not regarded as a control factor.

As aforesaid, battery cell type has a significant influence of design of the battery packs. For example, it has been found that packing density of a battery pack with *18650* type cells is 114 times more than that of a pack comprising large prismatic cells. Moreover, the packing density of a pouch cell is approximately 2 times lesser than that of a prismatic cell of similar nominal capacity mainly because of its smaller thickness and large surface area. It is therefore relatively easier to improve volumetric efficiency of the battery pack by packaging large quantities of smaller cylindrical cells in the available space than to use large prismatic or pouch cells [27].

Compactness of packaging design also has an appreciable impact on thermal performance of the battery pack. Research shows that increasing the cell-to-cell spacing for a battery pack from 1 mm to 10 mm can lead to a loss of approximately 1°C in the steady state cell core temperature, for all the three physical formats [28]. According to NASA Battery Safety Requirements Document (JSC 20793 Rev C), cell spacing is more critical for pack designs employing battery cells of gravimetric energy density greater than 80 Wh/kg [29]. It has further been ascertained that to alleviate cell-to-cell heat propagation in the instance of a single cell failure or a thermal runaway event, a minimum spacing of 2 mm is required for cylindrical cell formats. In addition, a physical barrier between neighbouring cells is required for the same reasons in battery packs that employ cell formats with side vents [30]. Other important design requirements are specified by various international standards; SAE standards applicable to mechanical design and testing of automotive battery packs are listed in Table 2 [26].

Table 2 – SAE standards governing mechanical design of automotive battery packs [26].

Standard	Title	Scope
SAE J240	Life Test for Automotive Storage Batteries	Life test simulates automotive service when the battery operates in a voltage regulated charging system
SAE J1766	Recommended Practice for EV & Hybrid Vehicle Battery Systems Crash Integrity Testing	Specifies test methods and performance criteria which evaluate battery spillage, retention and electrical isolation during specified crash tests
SAE J1797	Packaging of Electric Vehicle Battery Modules	Provides for common battery designs through the description of dimensions, termination, retention, venting system, and other features required in an EV application
SAE J1798	Recommended Practice for Performance Rating of Electric Vehicle Battery Modules	Common test and verification methods to determine EV battery module performance. Document describes performance standards and specifications.
SAE J2185	Life Test for Heavy-Duty Storage Batteries	Simulates heavy-duty applications by subjecting the battery to deeper discharge and charge cycles than those encountered in starting a vehicle
SAE J2289	Electric-Drive Battery Pack System: Functional Guidelines	Describes practices for design of battery systems for vehicles that utilize a rechargeable battery to provide or recover traction energy
SAE J2344	Technical Guidelines for Electric Vehicle Safety	Defines safety guideline information that should be considered when designing electric vehicles for use on public roadways
SAE J2380	Vibration Testing of Electric Vehicle Batteries	Describes the vibration durability testing of an EV battery module or battery pack.
SAE J2464	Electric Vehicle Battery Abuse Testing	Describes a body of tests for abuse testing of EV batteries.

SAE J2929	Electric and Hybrid Vehicle Propulsion Battery System Safety Standard	Safety performance criteria for a battery systems considered for use in a vehicle propulsion application as an energy storage system galvanically connected to a high voltage power train

2.1 Thermal Runaway Protection

Manufacturing defects or events such as physical abuse and internal short-circuit can push a battery cell into a state of thermal runaway. Thermal runaway is categorised as an exothermic chain reaction in which self-heating rate of a battery cell is more than 0.2 °C/min [31]. It can cause the battery to vent large quantities of flammable gases, emit jet of effluent materials and even combust spontaneously [32].

High temperature gases and effluents emanating from the damaged cell pose safety risk to material/property in close proximity of it and also to vehicle passengers and first responders. High pressure build-up inside the pack enclosure, due to the flammable gases, can also cause explosive failure of battery packaging if the gases cannot readily escape from the enclosure. It is thus recommended to include at least one pressure release valve, designed to set off at a pre-specified pressure, to minimise the safety risks posed to the EV and its passengers by an unknown point of failure. The damage to property and safety risks to the vehicle passengers and the first responders can be minimised by strategically controlling the direction of release of hot fumes and gases from the packaging. The damage can also be controlled by restricting thermal interactions between different entities of the battery pack. The point of egress of hot gases is controlled by incorporating one or more gas exhaust nozzles, shown in Fig. 2, that are designed to open during a battery thermal runaway event while the spread of thermal runaway to larger area of the battery pack can be prevented by placing appropriate thermal barriers in the packaging.

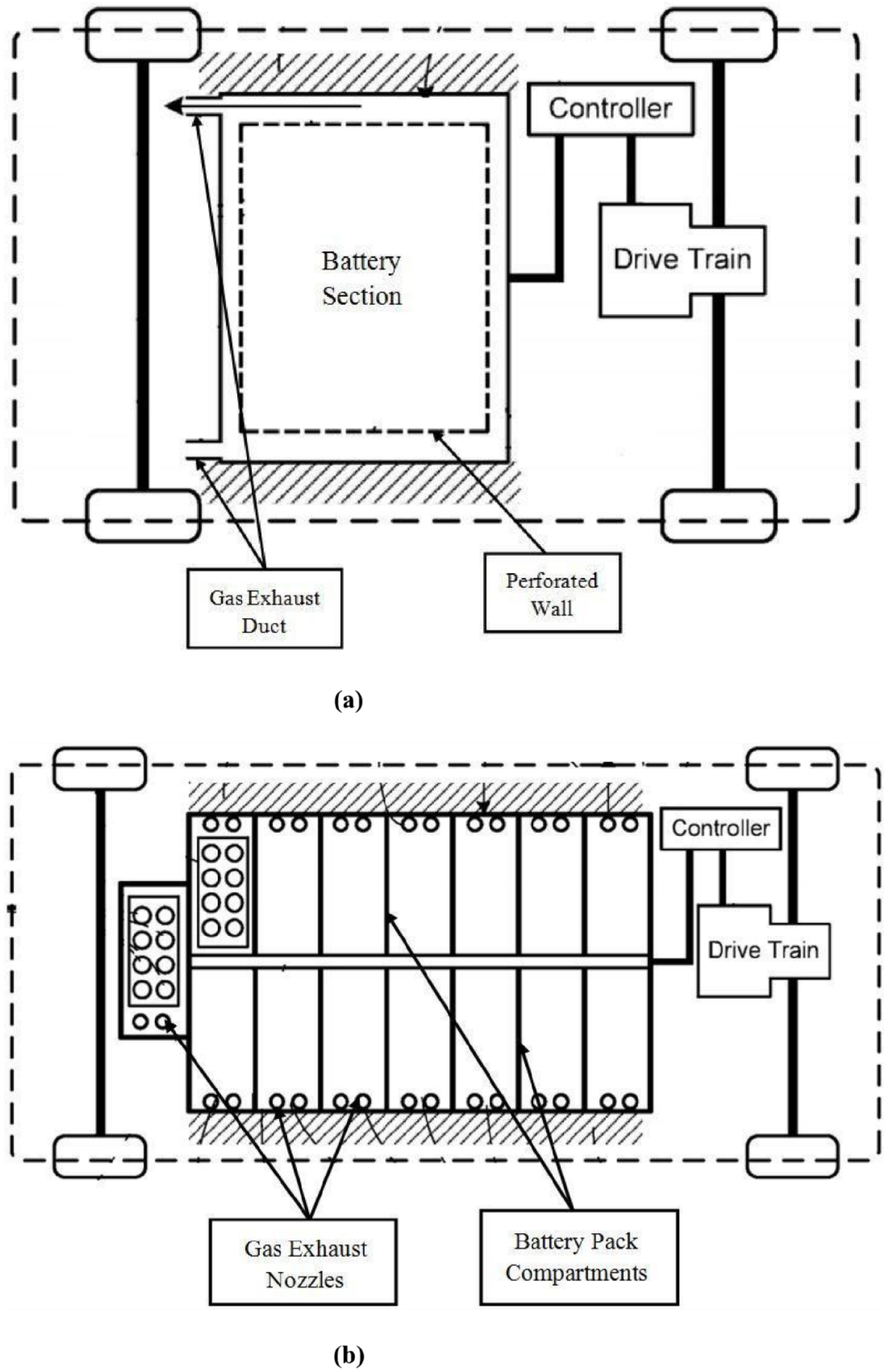


Figure 2 – Battery pack system with (a) hollow guide-ways or exhaust gas ducts and (b) multiple exhaust nozzle assemblies fitted in each battery compartment to exhaust hot gases and effluents generated during pack operation and/or thermal runaway event

2.1.1 *Point of egress*

A battery cell does not necessarily need to be in a state of thermal runaway to emit hot gases and effluents. An exhaust gas nozzle can minimize the vehicle damage and safety risks by directing the hot material in a direction where no one would get affected by the hot gases leaving the battery pack. During EV's normal operation, a seal keeps the nozzle assembly closed and restricts entry of road debris and moisture into the battery pack. A pressure equalization valve with cracking pressure in the range of 0.5 to 1.0 psi, i.e. much less than the pressure encountered during a thermal runaway event, is integrated into the exhaust nozzle to provide a means for handling pressure differentials due to non-thermal events (e.g., altitude variations). Hollow structural elements are included in the battery pack configuration to guide the flow of hot gas and material from the cell experiencing the thermal event to the exhaust nozzle.

Nozzle seal that keeps the gas exhaust nozzle closed during normal operations is held in its place by a nut. During thermal runaway, both the pressure and the temperature within the battery pack enclosure increases. Eventually, the nut melts and/or sufficiently deforms to allow the pressure within the pack enclosure to force the nozzle seal out of the nozzle. However, as the nozzle and its mounting assembly are fabricated from high temperature materials such as steel or ceramic, they do not get affected by the increasing temperature and continue to guide the hot gases in a direction that minimizes any personal loss or property damage.

Efficiency of the thermal design can be further increased by using perforated battery compartments. Effluents generated by the battery cells enter the hollow guide-ways formed within the battery pack through these perforations. The guide ways direct the effluents to a gas exhaust nozzle, which releases it out of the battery pack [33].

2.1.2 *Thermal barrier*

The increased temperatures associated with thermal runaway may cause the mounting brackets in close proximity of the battery region undergoing thermal runaway to melt or vaporize. As a result, the battery may no longer be held rigidly in its original position. As the affected battery cell/module moves, the spacing between battery components may be diminished, leading to decreased resistance to thermal runaway propagation. Battery cell/module movement may also compromise the battery pack cooling system, thus further increasing the thermal runaway propagation rate. Lastly, it should be noted that if the affected cell/module moves sufficiently, it may come to rest against an adjacent cell/module. If it does, the heat transfer process between the two regions would switch from radiation and convection to a combination of radiation, convection and thermally more efficient process of conduction. Further, in applications where a stacked-type battery configuration is used, i.e. a layer of battery cells arranged vertically over another layer, gravitational forces may expedite the movement of the top layer once the bracket(s) begins to melt and/or vaporize. It is therefore important to restrict the movement of the battery cell or module undergoing thermal runaway to minimise the risk of thermal runaway propagation.

Firstly, cross members can be used to divide the battery pack into multiple compartments. The packaging design presented by US Patent No. 8663824 also demonstrated how a central battery pack member can be employed to further separate the right and the left compartments in addition to providing a channel for connecting power and data lines. In the design, module mounting flange of the battery module is captured by the upper and the lower cross-members of the packaging frame. The arrangement allows easy positioning and holding of the battery modules at their place in the compartment. It also creates an air gap between the top and bottom surfaces of the packaging and the battery modules [33]. The air gap reduces the probability of occurrence of conductive heat transfer between the neighbouring battery modules.

Secondly, battery cells can be held in their pre-specified location by using rigid spacers that are friction fit or bonded between neighbouring cells of the battery module. In general, the spacer assembly selected for integration within the cell mounting bracket depends on the type and shape of the cells employed within the battery pack. Since the primary function of cell spacers is to keep the cells fixed in place during thermal runaway, to save mass and attain a higher specific energy rating for the battery pack a pair of much smaller spacers with an upper spacer and a lower spacer is preferred over one long spacer running from top to bottom of the cells [34]. Although just one spacer can be used, such as one located near the top or bottom, or near the centre of the cells, use of one spacer is not preferred as it still permits some movement. Height of the spacers used is usually in the range 1-5% of the overall battery height. Cell spacers perform a dual role in the case of prismatic cells and pouch cells. Besides their primary function, i.e. providing cell-holding functionality, they provide the binding pressure necessary to counteract the internal spring forces and to prevent the cell windings from expanding as a result of it.

Battery cell spacers create sufficient binding on the cell sides without covering so much of the cell surface area that cooling becomes ineffective.

2.2 Structural Stability

In the absence of adequate compressive force needed to maintain a uniform contact, delamination of electrode layers occurs in pouch cells and prismatic cells, which affects their performance and reliability. Delamination of the electrode layers can be avoided through usage of external structures that may include either hard plates stacked on each side of the battery cell or clamps made of thread rods. Although the stacking plate method provides significant advantage during manual assembly of battery packs, it is more expensive on a mass production basis. Also, holding clamps may make the pouch cells more vulnerable to mishandling during assembly process and to localised stress development due to unbalanced clamping force [27].

The solid structure created through metallic or rigid plastic casings typically used for the prismatic and the cylindrical battery cells prevents foreign objects such as nails from penetrating the electrochemical system. The metallic casings provide a greater degree of tolerance to pressures generated inside the battery cell because of gas generation and venting; a safety feature absent in pouch cells owing to their soft packaging.

Main structural issue with the prismatic cells is that their corners can be left vacant due to elliptical windings. It results in uneven pressure distribution in electrodes but the problem can be alleviated by filling vacant corners with solid material. Table 3 compares different battery cell formats according to structural characteristics considered important from safety perspective.

Table 3: Comparison of structural characteristics of different types of battery cells [35]

Criteria	Small Cylindrical	Large Cylindrical	Prismatic	Pouch
Casing	Metal	Metal	Semi-hard plastic or Metal	Aluminium soft bag
Connections	Welded nickel or copper strips or plates	Threaded stud for bolt or threaded hole for bolt	Threaded hole for bolt	Tabs that are clamped, welded or soldered
Retention against expansion	Inherent from cylindrical shape	Inherent from cylindrical shape	Requires retaining plates at ends of battery	Requires retaining plates at ends of battery
Appropriateness for production runs	Good: welded connections are reliable	Good	Excellent	Excellent
Field replacement	Not possible	Possible	Possible	Not possible
Delamination	Not possible	Not possible	Possible	Highly possible
Compressive force holding	Excellent	Excellent	Poor	Extremely Poor
Local stress	No	No	No	Yes
Safety	Good, integrated with PTC	Good, integrated with PTC	Good, integrated with PTC	Poor, no safety features included
Heat shrink wrapping	Yes	Yes	Depend on casing material	No

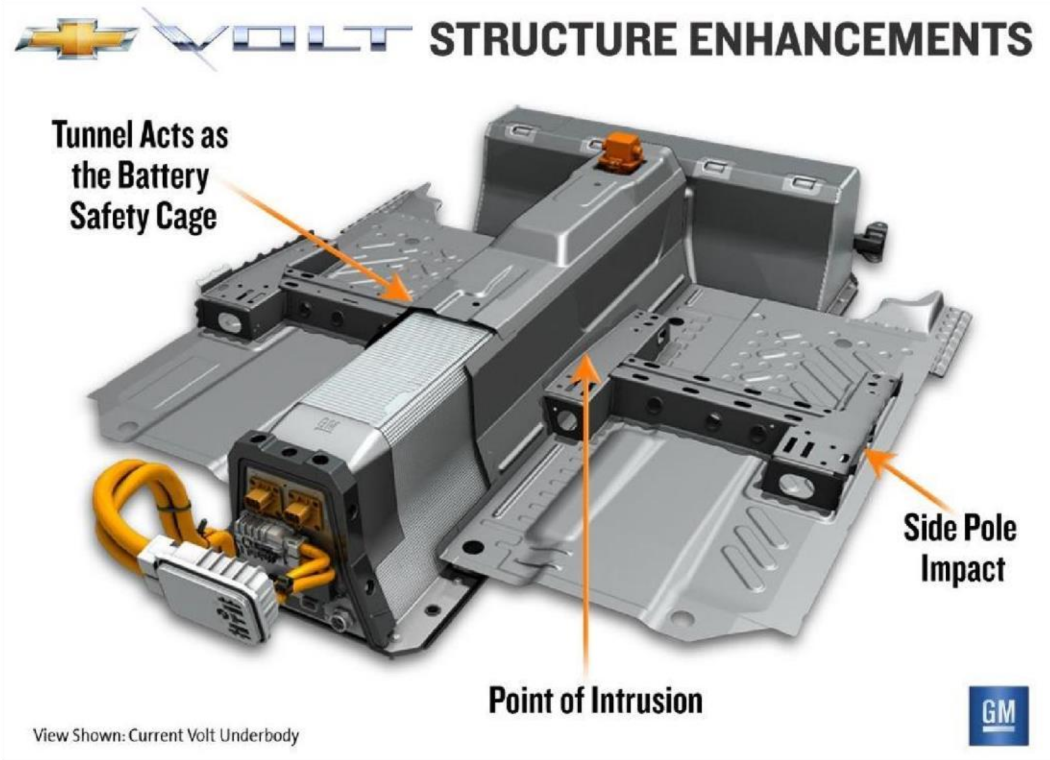
2.2.1 Crash protection

Maintaining structural integrity of the battery pack during crash conditions is another challenge for EV designers. For this purpose, two packaging architectures - the "T- shaped" architecture and the "Floor" configuration - are primarily utilised for EV battery packs.

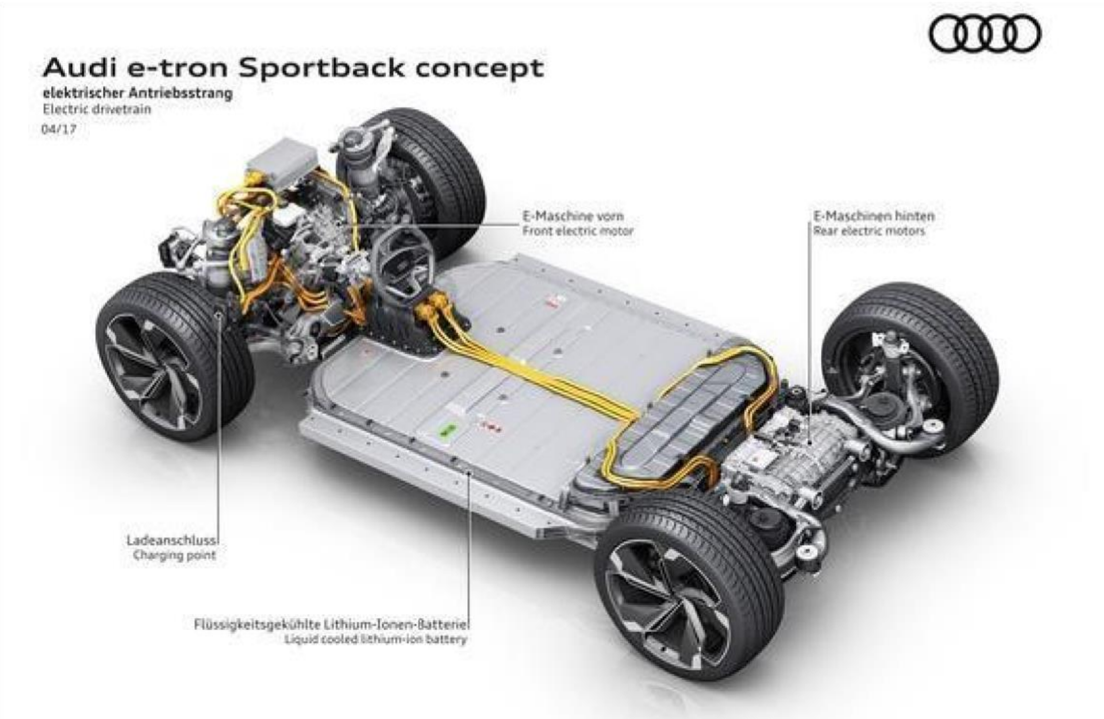
The "T-shaped" architecture seen in Fig. 3(a) is used in GM Chevrolet Volt. It enables the battery modules to be arranged inside the primary safe zone of the vehicle, i.e. the area beneath the rear passenger seats and extending along the tunnel between the two rows of seats. It prevents the battery pack from direct frontal impact and side impact loads through usage of vehicle structure as a crash barrier at the expense of interior cabin space and sometimes passenger comfort as well.

In contrast, the "Floor" configuration used in Tesla Model S and Audi e-tron Sportback concept, seen in Fig. 3(b), involves arranging the battery cells in a slab format under the vehicle floor. It maximises the available cabin space to be used either by the vehicle occupants themselves or for storing their luggage. In addition, such configuration increases the vehicle stability during various driving manoeuvres by lowering its centre of gravity. However, it also reduces the ground clearance of the vehicle thus exposing the battery pack to dangers of ground or bottom impact.

Battery cells are traditionally protected against the bottom impact via metal or plastic shell casing enclosures in conjunction with module and battery pack housings and vehicle body structure including transverse cross members, doors and floor. Furthermore, as floor panel can only resist impact from small stones on a gravel road, armour made of 1-6 mm thick metallic sheet, with a monolithic or a sandwich structure or even their combination is used as a protection against bottom impact. Polymeric coating is applied to it for rust protection.



(a)



(b)

Figure 3: Battery packaging architectures (a) T-shaped architecture used in GM Chevrolet Volt [36], and (b) Floor architecture used in Audi e-tron Sportsback concept [37]

Research has shown that severity of the damage to the protective armour plate is affected by the tip radius of the impacting body, the distance of the indentation point to the nearest boundary of the battery module and the exponent of the power law hardening curve. It has further been reported that other thinner protective members of the battery pack rupture soon after the armour is breached thereby exposing the battery cells to damage from road debris and other sharp objects [38].

To restrict this damage to a minimum, a multifunctional granular battery assembly (GBA) pack, in which the battery cells are organized in a bimodal packing arrangement along with collapsible and sacrificial metal tubes, has been proposed. GBA can function as an energy storage system and a stress control plus energy dissipation unit simultaneously. Simulation studies rate it as 2.6 times more effective than a metal foam structure of equivalent density in reducing the probability of battery pack failure during crash conditions. A reduction of over 5% in the head injury criterion of EVs due to the use of GBAs has also been observed as opposed to likelihood of head injury arising from an impact to an EV occupant employing traditional battery packs. However, disadvantages of employing GBA in place of a conventional battery pack include a decline of 35% and 13% in the volumetric capacity and gravimetric capacity of the vehicle, respectively. More importantly, the metal tubes of a GBA add approximately 3% to the gross vehicle weight that could influence not only EV driving range but also its rolling resistance [39].

In addition, side impact resistance of battery packs can be increased by including a pair of collapsible side sill assemblies and multiple cross-members in the battery pack design. In general, hollow cross-members should be used to gain benefits from high strength to weight ratios of hollow structures. However, both the material and the configuration used for the cross-member can vary with its location in the battery pack. For example, cross-members located in the centre of the battery pack are thicker than other cross-members to provide additional strength at the areas that are used for seat mounting assembly [40].

However, in EVs with air-cooled batteries, due to the large cross-sectional area of the air-ducts, minimal packaging space is available to provide cross-braces for the battery assembly. US Patent 8276696 demonstrates a packaging design in which the inlet/outlet ducts for an air-cooled battery are modified and utilised as structural members to increase the impact resistance of the battery pack. As per the design, the forced air system includes an inlet duct for providing air to the battery and an outlet duct for directing exhaust air from the battery and a fan. At least one of those ducts is configured as a structural member to provide structural support and protect the battery assembly. The duct arrangement that extends between opposite sides of the vehicle is attached to the shock tower on each side providing support and protection to the battery assembly. The ducts, which are traditionally made of plastic, can be made of steel, aluminium, carbon fibre or any other suitable material in EV applications. Due to fewer parts being used, it also provides a more efficient and compact packaging solution [41]. In other words, benefits in terms of energy density (Wh/L) can be realised with this design, but the compromise in terms of specific power (W/kg) and cost of the system needs to be made.

2.2.2 *Vibration isolation*

Vertical low-frequency vibrations are transmitted continuously to an EV structure as it is driven on a highway. Also, travelling over uneven surfaces, such as holes, grade crossings or bridge abutments, produces shocks that cause vertical vibrations. As a result, dynamic mechanical loads develop on the electrical subsystems such as terminal connectors and bus bars in a battery pack, which can result in loss of electrical continuity and fatigue failure of the casing [42].

In order to prevent this, a compressive force is usually applied to the top surface of the battery packs through tensioning bolts and retainer frame. US Patent 7507499 illustrates one such design for stabilizing a battery pack in EVs by using a cover-pad-tray retention arrangement. The design comprises of four beams, coupled at right angle to one another through four connectors to form a rectangular frame structure. Each beam engages one of the four sides of the battery pack. Positive connection between frame and the battery pack is maintained through tensioning bolts. The arrangement uses two types of damping pads, flat and L-shaped, to absorb vibration and prevent movement of the modules with respect to one another along the Z-axis. The L-shaped damping pads are placed adjacent to each of the corner connectors. They bear against the frame structure to provide relatively small pressure areas at the corners and push the separate battery modules of the battery pack laterally towards one another; on the other hand, the flat damping pads are positioned at the lower and upper corners of facing sides of the adjacent battery modules. A tray that could be bolted to a part of the vehicle structure provides the support to the battery pack.

Tensioning bolts are fastened after assembling the frame so that the beams are drawn against the corner pads in the longitudinal and lateral directions to peripherally squeeze the battery modules of the battery pack towards one another. Fastening the bolts also compresses the damping pads placed between the individual battery modules making them stationary with respect to one another. Fig. 4 presents a perspective view of the design [43].

Weight distribution of the vehicle can also influence the degree of vibration isolation and ride quality. A battery mounting frame structure for achieving uniform vehicle weight distribution and to maintain a low centre of gravity was presented by US Patent 8561743. As seen in Fig. 5, the rectangular mounting frame is divided into two sections, front and rear by a girder that has been welded to the frame [44]. Furthermore, a beam member divides the front section into two equal rectangular areas. In the two front rectangular areas, the batteries are arranged in a vertical direction such that the long side is oriented in transverse direction and the short side is oriented in longitudinal direction of the vehicle whereas the batteries in the rear rectangular section are arranged such that the shortest side is oriented in the vehicle transverse direction.

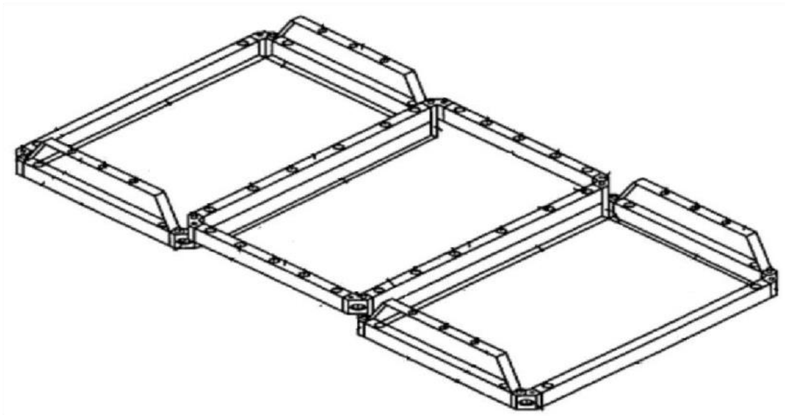


Figure 4: Perspective view of a framing arrangement employed with a compact battery pack design [43].

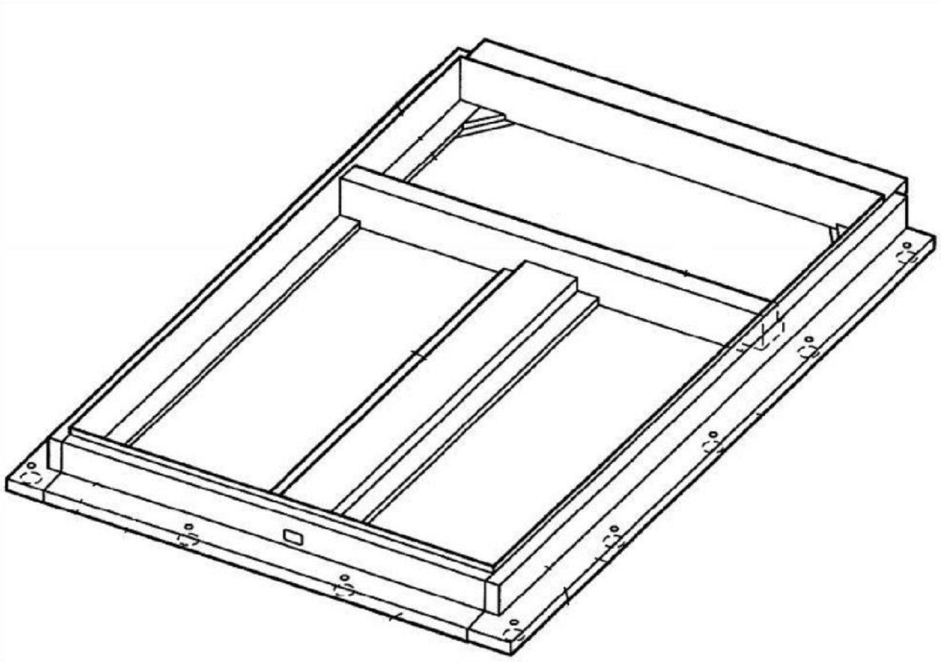


Figure 5: Perspective view of battery mounting frame [44]

As a result of this arrangement, the weight of group of batteries mounted in the rear section is substantially equal to the total weight of group of batteries mounted in the two front columns. Subsequently, centre of gravity of the battery assembly is located around an intersecting point of median of the group of batteries in vehicle transverse direction and median of the same group in longitudinal direction. This point is located to the rear of the graphical centre of the vehicle and is preferable in terms of weight balance of the vehicle in the front-aft direction, considering that the electric motor, the battery charger and the inverter are housed in the front compartment [44]. A clear advantage of this configuration is that the mounting frame can be used for various types of vehicle. This means that even when the layout of seats of the vehicle is changed; it is possible to realize an optimum weight distribution and thereby vibration isolation by simply modifying the number of battery stacks in the group without making major alterations to the dimensions of the battery mounting frame.

3 Case study – Swinburne eBus Battery Pack

In 2014, a collaboration was formed between Swinburne University of Technology, Bustech, Malaysian Automotive Institute (MAI) and Excellerate Australia to build a prototype demonstrator electric bus. The latter two stakeholders were the relevant government bodies for Malaysia and Australia, respectively, and provided significant funding for the project. Bustech are a bus manufacturer based in Queensland, Australia and have been designing and building buses since 1995, with a current production rate of 250 buses per year. The demonstrator had ultra-low floor architecture and was built using off-the-shelf hardware, where available, so that new and innovative technology opportunities could be identified that address the integration for a modular systems architecture approach. It was intended to be the first step in a bus development program, and enabled the development of sub systems and integration of the driveline system and functional features.

The battery pack could not be sourced "off the shelf" and was therefore designed by the Swinburne engineering team from cell level. The design was based around available packaging space in the demonstrator vehicle platform and availability of suitable off-the-shelf components. This section is about mechanical design of the first fully-electric city bus built in Australia.

3.1 Battery Cell Selection

Table 4 represents prominent battery manufacturers for automotive applications. K2 energy batteries are widely used in Chevy and are small cells. They have more thermal durability and increased life cycle as claimed by the manufacturer. However, these cells are smaller in size resulting in 27% volumetric losses when arranged within the packs. The A123 provides a modular concept where seven cells within module are arranged in series whilst three are in parallel. A123 module is found easy to package and due to its excellent characteristics, such as high energy-to weight ratio, can operate at high voltages and show low self-discharge rates. The CALB CAM72 battery cells are similar to Thunder sky batteries, and their ready availability and meeting the capacity requirement make them suited to this research.

Table 4: Analysis of some commercial Li-ion battery cells considered.

		A123	**SINOPOLY**	**CALB**	**K2**
		3P7S Module	LFP300 AH	CAM72	K226650E Cell
Cell Data	Cell Capacity, Ah	60	300	72	3.2
	Cell Voltage, V	23.1	3.2	3.2	3.2
	Cell capacity, kWh	1.386	0.960	0.230	0.010
	Cell Max Voltage, V	25.2	3.6	3.6	3.65
	Cell Min Voltage, V	17.5	2.5	2.5	2.5
	Peak C Rating (discharge), A/Ah	5	1	3	4.0625
	Cont. C Rating (discharge), A/Ah	3	0.33	2	1
	Cell mass, Kg	12.3	9.5	1.9	0.082
	Cell volume, L	8.8	5.896	0.849	0.036

	Cell Internal Resistance, mΩ	8.17	0.8	1	19
Pack Data	No. in series	27	200	200	200
	No. in Parallel	7	1	6	134
	Total no. of cells	189	200	1200	26800
	Pack Capacity, kWh	262	192	276	274
	Continuous current per cell, A	60.7	401.8	67.0	3.0
	Peak current per cell, A	82.8	548.0	91.3	4.1
	Peak C Value, A/Ah	1.4	1.8	1.3	1.3
	Continuous C Value, A/Ah	1.0	1.3	0.9	0.9
	Nominal Pack Voltage, V	623.7	640.0	640.0	640.0
	Max Pack Voltage, V	680	720	720	730
	Min Pack Voltage, V	473	500	500	500
	Peak Pack Current, A	580	548	548	548
	Continuous Pack Current, A	425	402	402	402
	Pack Internal Heat Generation, kW	6	26	5	5
	Pack cell mass, kg	2325	1900	2280	2198
	Pack cell volume, L	1668	1179	1019	964

CALB CAM72 cells were selected for the demonstrator eBus requirement, with specification as shown in Table 5. These cells are aluminium alloy shelled, rechargeable lithium-iron-phosphate energy cell. They are widely used in high speed electric vehicle, energy storage for frequency control, high power renewable energy integration, and other high power applications.

Table 5: CALB CAM 72 battery specifications.

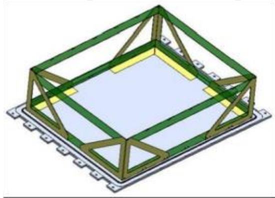
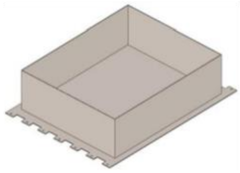
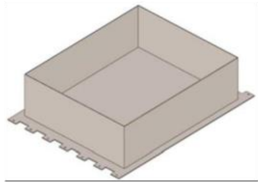
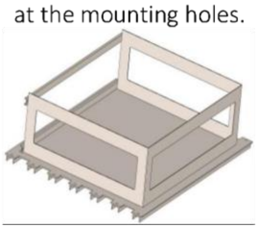
Capacity	72 Ah
Nominal Voltage	3.2 V
Cycle Life	≥ 2000 cycles
Internal Resistance	≤ 1mΩ
Max. Charge Rate	1C
Charging Cut-off Voltage	3.65 V
Max. Discharge Rate	2C
Discharge Cut-off Voltage	2.5 V
Charge Time	4h nom, 1h fast
Weight	1.9 ±0.1kg
Dimensions, L×W×H (in mm)	135×29×222
Charging Temperature	0 – 45° C
Discharging Temperature	-20 – 50° C
Ambient Humidity	< 70%
Shell material	Aluminium alloy

3.2 Battery Pack Design

Several iterations of battery cell layout inside the pack were considered to meet packaging space, operation and safety requirements. A list of various design options is presented in Table 6 and related weight calculations for the pack are summarised in Table 7.

Table 6 – Various design options considered for battery pack construction.

Design Options			
Design Option1	Parts	Weight (kg)	Details
	Al Base plate, 10 mm	22.03356	
	Corner supports; top & bottom fix, 2 mm		
	Misc.	10	

	Total	**32.03356**	Initial Aluminium 6061, 10 mm base plate; considers CALB individual plastic cell protection; Initial design with 4 corner supports and 2 fixes for top and bottom and not sufficient for restraining the movement (longitudinal, lateral and vertical) of the cells inside the pack & also does not provide the ease of manufacturing and mounting solution 
Design Option2			
	SS Base plate, 5 mm	42.34558	SS base plate, 5 mm; welded box side plate, 2 mm - 4pc. Cells are to be fitted from the top; no access to tie up the cells together longitudinal and lateral direction due to the welded side plates. Sealing would be easier due to the welding 
	Welded box, 2 mm		
	Misc.	10	
	Total	**52.34558**	
Design Option3			
	SS Base plate, 4 mm	36.32606	SS base plate, 4 mm; welded box side plate, 2 mm - 4pc. Cells are to be fitted from the top; no access to tie up the cells together longitudinal and lateral direction due to the welded side plates. Sealing would be easier due to the welding 
	Welded box, 2 mm		
	Misc.	10	
	Total	**46.32606**	
Design Option4			
	SS Base plate, 5 mm	60.87677	SS base plate, 5 mm; U-beam 7pc underneath the base plate aligned with the mounting holes; enough restraining from longitudinal, lateral and vertical direction; weight is higher than other options; can think about putting one C section by the side instead of 2 to decrease the weight depending on the compressive load calculation; enough space for restraining by the metal straps surroundings; U beams are supporting with the stress generation at the mounting holes. 
	u beam 7pc, 40x20x3 mm		
	C section, 2pc, 25x12x3 mm		
	Welded corner support, 2 mm		
	Misc.	2	
	Total	**62.87677**	
Design Option5			

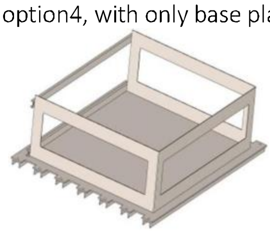
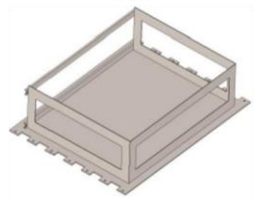
	SS Base plate, 4 mm	54.85725	Same design up as option4, with only base plate thickness 4 mm. 
	U beam 7pc, 40x20x3 mm		
	C section, 2pc, 25x12x3 mm		
	Welded corner support, 2 mm		
	Misc.	2	
	Total	**56.85725**	
Design option6			
	SS Base plate, 5 mm	**48.0425**	Same restraining design set up as option4; U beams underneath are removed from this to decrease the total weight of the battery box 
	C section, 2pc, 25x12x3 mm		
	Welded corner support, 2 mm		
	Misc.	**2**	
	Total	**50.0425**	

Table 7 – (a) Initial assumptions used to calculate battery pack size, stiffness and strength, and (b) Mass calculation for battery pack designs that were considered.

(a)

Basic Inputs	
Total plate Length, L (mm)	1008
Effective length, l (mm)	1008
Width b (mm)	769
Material	Al 6061
	AISI 316 SS
Modulus of Elasticity, E (GPa)	68.9
	210
Gravity	9.81
Gravity load	1
Cell weight (kg)	1.9
Total cell in a row	22
Total cell in a column	6
U beam dimension	40x20x3
C Section Dimension	25x12x3
Type of support	Fixed

(b)

Weight calculation of the total pack			
Items	**No.**	**Weight, kg**	**Unit Weight, kg**
Total cell in a pack	132	250.8	1.9
BMS	1	2.426	2.426
Contactors	4	1.72	0.43
Current sensor	1	0.067	0.067
CM0711	1	0.6	0.6
Connectors	2	0.5	0.25
Relays	2	0.4	0.20
DC-DC converter 5W	1	0.2	0.20
MSD	1	0.3	0.30
Com. Connector, HD34-24	1	0.18	0.18
Washer, N16 Nord lock	528	0.4224	0.0008
Screws	264	0.66	0.0025
Bus-bar	528	3	
Total weight of elec. accessories, kg		261.275	
Design Option1		**293.309**	
Design Option2		**313.621**	
Design Option3		**307.602**	
Design option4		**324.152**	
Design option5		**318.133**	
Design option6		**311.318**	

3.2.1 Final design: base plate

Due to the constraint of loading from underneath the eBus, a "tooth" mounting system was proposed as the best strategy to increase package space and provide secure attachment to the vehicle. This mounting system is similar to bus fuel tank mounting, which is designed to hold a similar mass with full fuel tank. Also, it requires short development time. Bolt sizing was based on restraining the pack under the required loading with a safety factor of 1.5. High safety factor accounts for reduced validation via physical testing and limited information about internal cell architecture.

Figure 6: Battery base plate and frame structure with bay walls; made of SS304

The “tooth” mounting system requires both base plate and frame to be laser/water cut from same sheet to ensure minimal tolerances; however bus frame limitations require individual mounting on each side, which must be controlled for. Base plate has cut outs to reduce weight and a thin sheet welded on top to seal from external elements.

The “tooth” mounting system allows the battery pack to vertically pass the bus mounting area and then, with lateral translation, line up the mounting holes. It requires a lifting tool/device to raise the pack into the vehicle and allow small adjustments to assist with lining up position for both the vertical movement, but also the lateral movement. The positioning of the top packs requires a 0.5 m vertical raise inside the bus frame, which means the dimensions for the tool will be restricted to within the pack dimensions (700 x 850 – allowing additional clearances).

3.2.2 Final design: casing

The outer casing is not a load bearing part, it is in place to assist with sealing and mounting of external attachments, this requires some strength component; however it cannot be so rigid as to cause loss of sealing or support too much weight. Composite materials can provide a lot of flexibility in material choice, with mixtures of chopped strands and more, however lead time was found to be a severe problem in this case due to the requirement of a mould. A metal such as stainless steel was therefore considered as an option through a much simpler design.

Another important issue is that tight packaging constraints in an EV restrict the space available for mounting casing to the base plate while providing a good seal to the pack. Good sealing requires a uniform compression load around the outer edge of the pack to ensure the sealant (compression material) is always engaged and functioning. This, in turn, requires analysis of mount spacing to ensure this requirement is met. Manual silicon sealing can always be used around the battery box to ensure a proper seal is achieved.

3.2.3 Final battery pack assembly

The final pack assembly consisted of a stainless steel plate (4 mm thickness) for the base plate and channel sections (20×20×3 mm) welded underneath the base plate as reinforcements. The base plate has the toothed profile at the longitudinal end to mount the pack into the bus frame. The battery pack contains 132 CAM72 prismatic type cells in 6 rows of 22 cells (Connection: 66S2P). Longitudinally the rows are divided into two sections (separated by 10 and 12 battery cells) by a 2mm stainless steel sheet in the middle. Each row of cells is placed individually and restrained by a side metal plate. Restraining the battery link bars and clearance for the pressure relief vents of the cells are also considered in the design.

The design includes the electrical accessories (BMS, contactors, sensors etc.) required for internal and external interfaces, all mounted in a position to optimise packaging, function and safe operation. Also included are Manual Service Disconnect (MSD) and terminal connectors, allowing quick and safe isolation of the battery packs during scheduled maintenance. The electrical insulation between the cells and the metal frame on each side was also considered through the inclusion of high-density polyethylene (HDPE) sheets where required.

According to the standards EN 60664 – 1:2007 and VDE 0110 – 1, clearance distance (the shortest distance between two conductive parts or between a conductive part and the bounding surface of the equipment measured through air) should be dimensioned to withstand the required impulse withstand voltage. For connections with low voltage mains, rated impulse voltage is considered the required impulse withstand voltage. However, additional clearances may be necessary to account for mechanical effects like vibration and applied forces. On the other hand, creepage distance, which is the shortest path between two conductive parts or between a conductive part and the bounding surface of the equipment, measured along the surface of the insulation, is defined on the basis of long term root mean squared (rms) value of the working voltage.

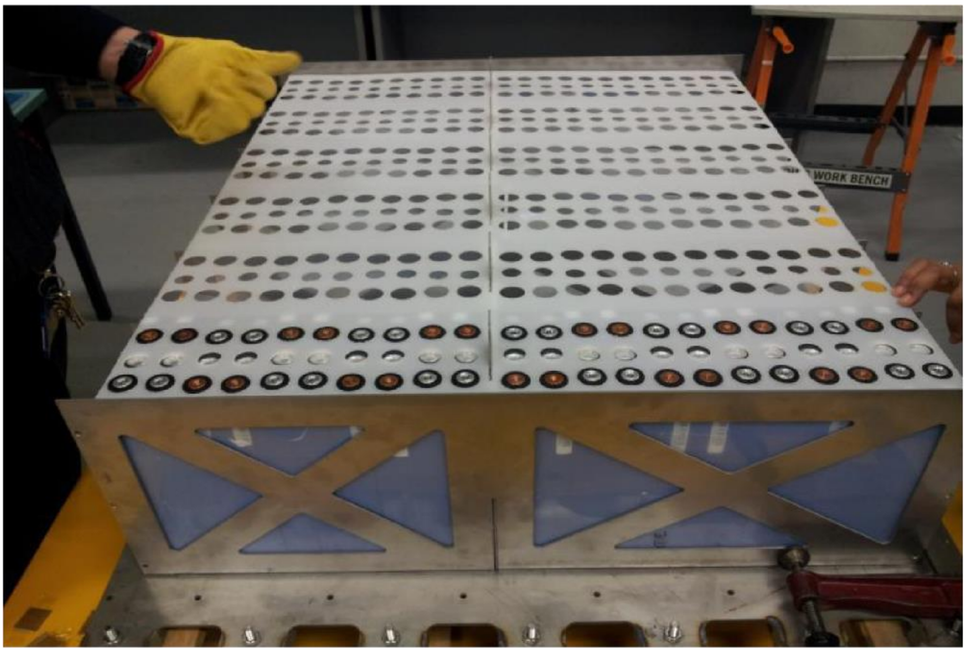


Figure 7: Battery pack showing top plastic layer 1 (1.5mm) sitting on the cells with clearance holes for terminals and pressure relief vent.

As a general rule of thumb, the required clearance is equal to the shortest creepage distance for any application. The outer surface of the battery cell is considered as the bounding surface, as though metal foil was pressed into contact with accessible surface of insulating material (plastic HDPE or Nylon, Fig. 7).

For 250 V, the recommended air clearance would be 5 mm and the creepage distance would be 8 mm. In this case, creepage distance was taken as 8 mm for the insulating material.

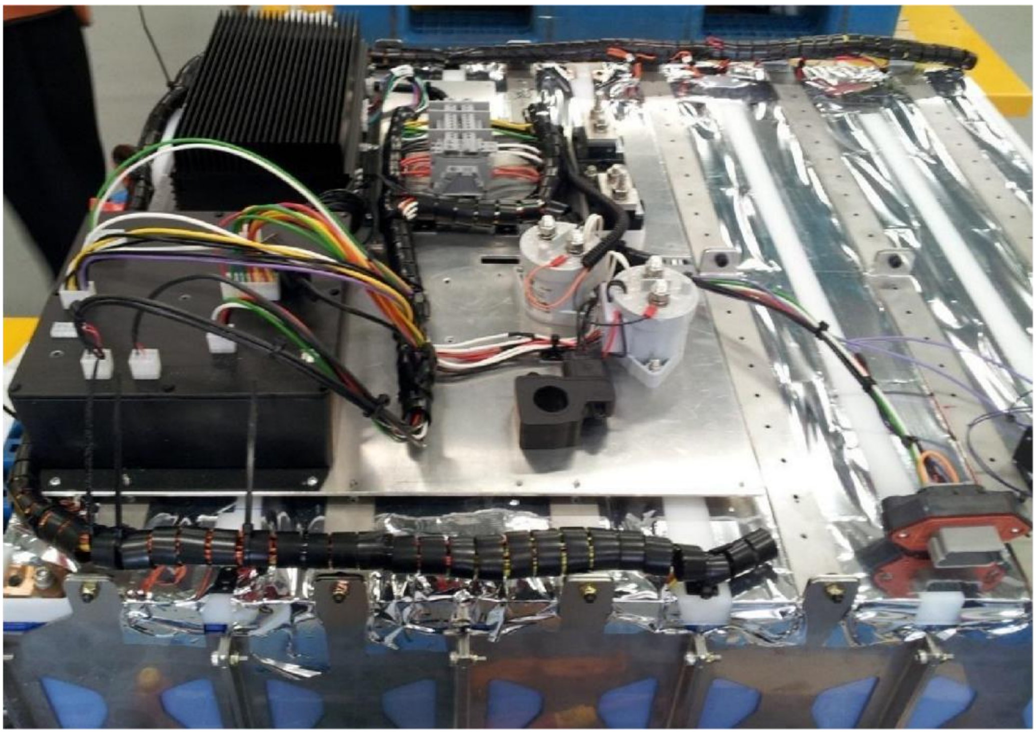


Figure 8: Battery pack with added insulation tape, metal cell retaining strap and additional accessories; BMS, battery controller, current sensor, contactors, fuses and other accessories were installed on a separate plate and bolted to the metal strap

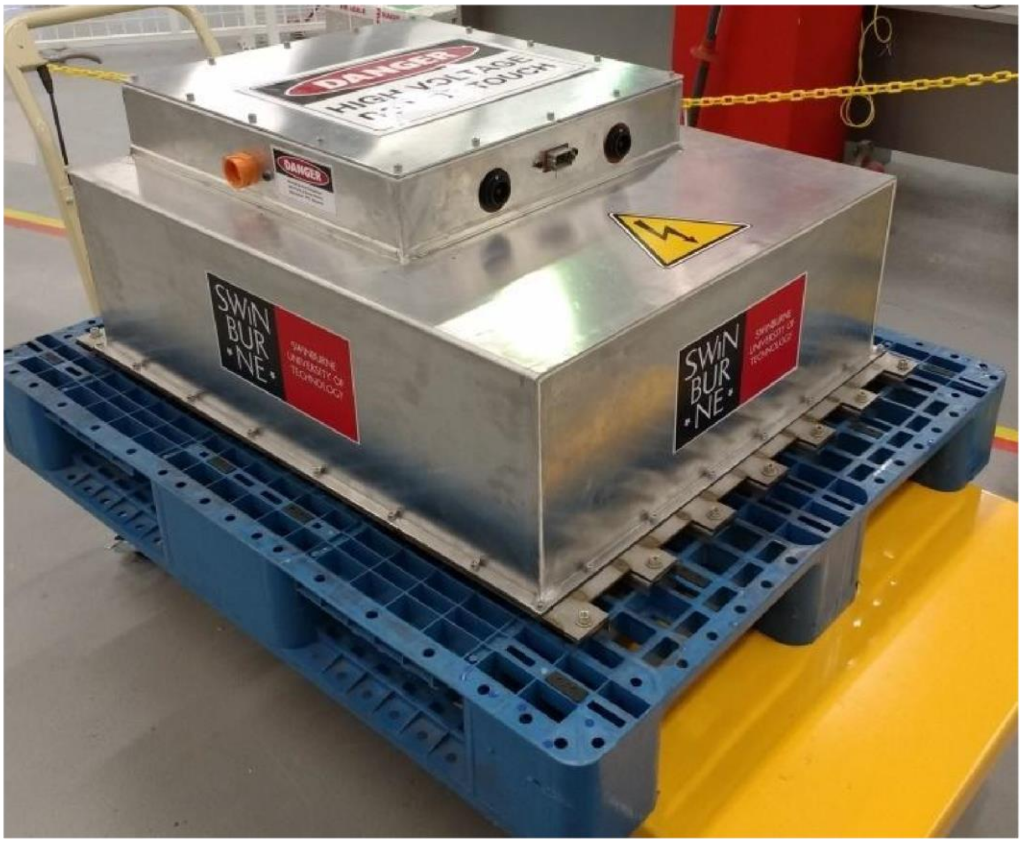


Figure 9: Complete battery pack ready for fitment to bus.

The outer case housing (Fig. 9) was designed to seal the battery pack. The top cover of the housing allows access to the electrical accessories (contactors, current sensor, fuse), including battery controller and management system, without dismounting the whole outer case from the pack. One manual service disconnect (MSD) connected to each battery pack but mounting facilities for the MSD were made available on both sides of the battery box. Nine identical and swapable 30 kWh, 211 V (nominal) battery packs were designed for placement on the bus. To achieve the most efficient use of available space the battery packs were set up as 3× parallel strings of 3× packs in series. A modular architecture was chosen to allow for future expansion of the battery system and to help with the weight distribution.

Battery pack testing comprised of testing battery packs individually as well as the integration into the working string of batteries to simulate the actual energy storage and battery system on board the Bus. The battery pack was tested on charge and discharge for a period of 6 hours at a range of current capacities up to 25A. A smooth rise and lowering of battery cell voltage was recorded, results as expected. Energy delivery was continuous with no interruptions. The endurance of the packs was established and the analysis of the battery cell voltage and behaviour indicated an equal performance per cell. The battery cells electrical stability was verified. Three battery packs were integrated as one string to deliver energy at different levels using a small induction motor used as load. Results of test were the verification of energy delivered, instrument adjustment and software control operation.

Lastly, the majority of the packaging space was at the rear of the bus, due to the low-floor design. However, placing excessive weight on the rear axle restricts the number of passengers that can be carried in the bus. Priority was therefore given to placing batteries forward of the rear axle to help distribute the weight forward, which meant very tight packaging constraints, but increased passenger count on the bus. The high-voltage distribution unit (HVDU) is the central point for all electrical energy transfer in the bus, connecting batteries, high-voltage components and chargers to ensure power is distributed where and when it is required. This was positioned as centrally as possible to reduce excessive cable lengths and therefore reducing system energy losses, especially to the motors that require the largest amount of power. The positioning of the remaining components was then based on proximity to functional systems, such as DC-DC converter closest to the 24V system distribution, or due to component requirements like ingress protection.

4 Summary

In this chapter, mechanical design elements affecting safety and reliability of EV battery packaging are discussed. Forces like mechanical vibration, impact energy and ambient temperature variations interact with the battery pack through different interfaces. These interactions need to be controlled for safe and reliable operation of battery pack. Restricting battery cell movement is found to be one of the successful strategies to achieve a higher degree of protection against all of them and mechanisms that can be used for this purpose are presented. Other mechanical design solutions to increase crashworthiness and vibration isolation of the EV battery pack are also discussed. Lastly, a case study focussing on mechanical design of an eBus battery pack at Swinburne University of Technology in Australia is presented.

The eBus case study highlights the importance of modularity on full-proofing the battery packs against future uncertainity. It can also be learnt from this case that designing a battery pack for a high voltage system can provide a very hazardous environment, especially if the workshop space is not equipped to deal with the required voltage. A practical design option is to produce smaller packs at a low voltage, making the work and handling of packs much safer. Using smaller individual battery packs not only improves user safety but also offers benefits in terms of prototype manufacture and testing of the packs. The increased number of packs means more complexity at a system level, which should be weighed heavily with the benefits mentioned here.

Acknowledgement

Financial support from the Cooperative Research Centre for Advanced Automotive Technology (AutoCRC), Australia for undertaking this research study is duly acknowledged. Also, support of the eBus project team at Swinburne University of Technology was useful in development of this chapter.

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