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# Review of mechanical design and strategic placement technique of a robust battery pack for electric vehicles

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ABSTRACT

In an electric vehicle (EV), thermal runaway, vibration or vehicle impact can lead to a potential failure of lithium-ion (Li-ion) battery packs due to their high sensitivity to ambient temperature, pressure and dynamic mechanical loads. Amongst several factors, safety and reliability of battery packs present the highest challenges to large scale electrification of public and private transportation sectors. This paper reviews mechanical design features that can address these issues. More than 75 sources including scientific and technical literature and particularly 43 US Patents are studied. The study illustrates through examples that simple mechanical features can be integrated into battery packaging design to minimise the probability of failure and mitigate the aforementioned safety risks. Furthermore, the key components of a robust battery pack have been closely studied and the materials have been identified to design these components and to meet their functional requirements. Strategic battery pack placement technique is also discussed using an example of Nissan LEAF battery packaging design. Finally, the disclosed design solutions described in this paper are compared with the Chevrolet Volt battery pack design to reveal the basic mechanical design requirements for a robust and reliable battery packaging system.


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## 1. Introduction

Lithium-ion (Li-ion) batteries have become the preferred on-board power source for a pure electric vehicle (EV) due to their high power, high energy density and long cycle life [1]. However, they are also considered sensitive to variations in factors, such as ambient temperature, vibration and pressure. Control of battery temperature and the environment in which a battery pack operates is required to maximise its energy capacity. It has been suggested that the battery temperature must be maintained below 50 °C for safe operation [2,3]. 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 Hz to 20 Hz, and the vehicle chassis system from 20 Hz to 40 Hz [4–6]. 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 [2,7–9].

Such irregular behaviours were the marked characteristics of Li-ion battery packs during the initial development phase of EVs. On several occasions, they compelled the original equipment manufacturers (OEMs) to withdraw their products from the market. In 2002, EV Global Motors Company received reports of five cases of Li-ion batteries overheating in their electric bicycles. In three of those cases, the battery packs caught fire. Subsequently, they announced the recall of 2000 Li-ion battery packs through the U.S. Consumer Product Safety Commission [10]. General Motors also called back approximately 8000 units of the Chevrolet Volt sold in the U.S. after incidents of GM Chevrolet Volt's Li-ion battery pack catching fire during the National Highway Traffic Safety Administration crash-safety tests were reported in 2011 [11]. More recently, an explosion of a Li-ion battery pack in GM's test facility in Michigan caused five workers to seek immediate medical help [12,13]. Tesla Motors also received negative publicity on account of road debris penetrating the battery packs in Tesla Model S and causing fire [14,15].

Though continual improvements in the safety of large battery packs for EVs are being made, both the general consumer and the OEMS remain apprehensive about accidents during normal use and unintended abuse of EVs [1,16]. Strict regulations governing the safety of Li-ion battery cells have therefore been stipulated. Table 1 lists various SAE standards relevant to packaging design and performance testing of automotive battery packs [17]. Large scale electrification of private and public transportation sectors however does not seem possible until the behaviour of Li-ion battery packs is properly understood and questions pertaining to their reliability are answered [18,19]. It is of utmost importance to investigate the design features that can enhance the safety and reliability of a Li-ion battery pack. The significance of this research is accentuated by the fact that the international standard SAE J1797 – Recommended Practice for Packaging of Electric Vehicle Battery Modules is only applicable to lead-acid, nickel cadmium and nickel metal-hydride battery packaging design and not to Li-ion battery packs [20].

It has been reported that among several factors affecting the reliability of Li-ion battery packs, a number of these can arise during the manufacturing process. The most important are chemical factors such as impurities and concentrations, and joining procedures, i.e. material processing and cell closures, either hermetic or crimp [21]. Another report maintains that in the long term environmental conditions where a battery pack operates, such as ambient temperature, pressure, mechanical and thermal shock, mechanical vibration, have a major impact on battery reliability. This report goes on to provide some general battery assembly guidelines [22]. A different study points out that the performance of Li-ion battery packs in EVs strongly depends upon typically uncontrolled ambient operating conditions and therefore cannot be assessed based on laboratory experiments [23]. A more recent work on the other hand suggests that the battery cell temperature also affects the reliability and cycle life of Li-ion battery packs [24].

Despite the fact that different groups hold different opinions about the factors that lead to the unpredictable behaviour of Li-ion battery packs, most of the published work is concentrated towards developing stable electrolytes, new and safe electrode materials, and thermal management solutions for Li-ion batteries. An area that has often been overlooked is the contribution of a robust mechanical design of a battery pack enclosure towards its reliability. Conventional safety devices incorporated in commercial Li-ion batteries were reviewed by a group of researchers, but their work was limited to single cells [25]. In this paper, we review safety features incorporated in large battery packs in EVs.

A robust and reliable battery packaging design needs to address several design issues pertaining to thermal runaway, vibration isolation and crash safety at cell level as well as at modular level. At each of these levels there is a need to restrict relative motion between battery cells in order to eliminate potential failures of the battery pack. Strategic placement of the battery pack in an EV can also increase the effectiveness of battery packaging design to address

**Table 1**
SAE standards governing mechanical design of automotive battery packs.

| 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 utilise 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 |