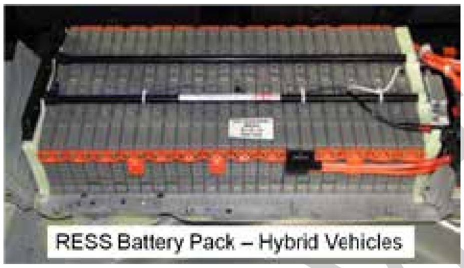
Safety Evaluation of Electric and Hybrid Vehicles

Hybrid cars have been on US roads for many years, starting with Honda InSight (1999) and Toyota Prius (2000) in mass production. Electric vehicles in mass production are more recent with the Chevrolet Volt and the Nissan Leaf introduction in 2010. Tesla and Fisker also produce electric cars in the high-price range and several other manufacturers are now also introducing such vehicles. A recent case of fire in an electric vehicle (Volt), that occurred several days after a crash test, was widely reported, signifying that risks associated with new technologies will receive intense scrutiny[1,2] even if these risks are less than the ones in the replaced technology.

As compared to conventional automobiles, hybrid & electric vehicles use high-voltage batteries (known as 'rechargeable energy storage systems' or "RESS") to store energy and then supply it as electric current when needed for operation. These batteries consist of multiple cells connected together inside a rigid enclosure. Electric vehicles (e.g. Volt, Leaf) have larger batteries that can propel the vehicle for significant distances whereas hybrid vehicles have smaller battery units. Current vehicles use either Lithium-ion (Li) cells or Nickel- metal hydride (Ni-Mh) cells.



Although some discussions in the media have been of the relative safety of these RESS-powered vehicles (as compared to their gasoline-powered counterparts), the appropriate question to ask in designing and evaluating these vehicles is whether all applicable safety standards are met and whether all steps have been taken to maximize occupants' safety in foreseeable situations. In this regard, the presence of high-voltage RESS units present several unique challenges. This note briefly discusses some of the issues.

'Functional Safety' and 'Safety in Accidents'

Risks are inherent in all systems that store energy, including conventional automobiles powered by liquid fuels or by compressed gas. Risks are also associated with any moving object because its motion gives it kinetic energy, which is a form of stored energy. For any new technology such as hybrid and electric vehicles, such risks need to be identified early and vehicle design and testing completed to assure maximum overall safety which is composed of
(a) Functional safety, and
(b) Safety of occupants (and others in proximity) in accidents.

Functional safety may be defined as consisting of (i) safety during normal operations, (ii) safety during service and maintenance, and (iii) safe disposal of vehicle at end of life. Safety during normal operation of these vehicles requires that, in addition to other aspects of conventional vehicles, one takes into account factors such as heat & thermal energy management, electrical system integrity, control system reliability, EMI shielding and charging system safety, etc. Test conditions for functional safety are specified by the

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[1] *"Chevy Volt & The Wrong-Headed Right",* http://www.forbes.com/sites/boblutz/2012/01/30/

[2] *"Chevrolet Volt Battery Incident Overview Report",* DOT HS 811, 573, National Highway Traffic Safety Administration, January 2012.

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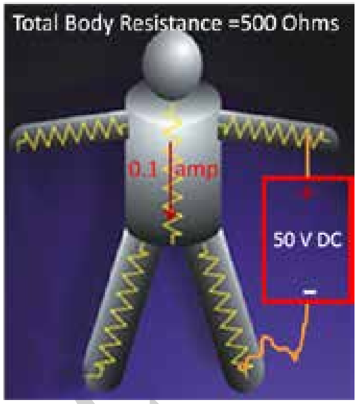
vehicle manufacturer. Safety in accidents is evaluated by crash tests defined by the NHTSA and by the Insurance Institute for Highway Safety, as well as by additional tests that may be conducted by manufacturers to represent likely accident scenarios.



<u>Some Risk Factors associated with RESS-powered vehicles</u>:

<u>1. Electrical Shock & Injury</u>: Thresholds for electrical injuries depend on many factors such as a person's body size, type & amount of current, time duration of contact, etc. The amount of current passing through a body is

$$Current\ (in\ amperes) = \frac{Voltage\ with\ respect\ to\ ground\ (volts)}{Resistance\ of\ the\ human\ body\ (Ohms)}$$

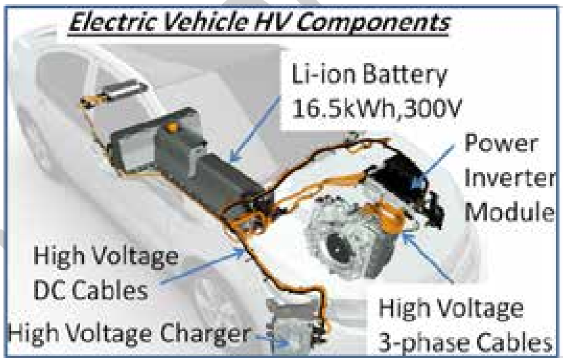
The sketch[3] is an example that a person with a body resistance of 500 Ohms contacting an electrical source of 50 volts will experience 100 milliamperes ('mA') of current.

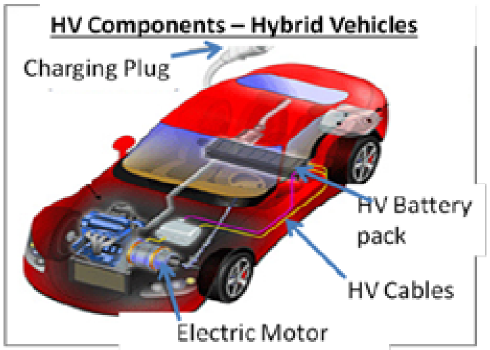
For reference, the International Electrotechnical Commission (IEC) uses 1000 Ohms as a typical value for adult human body resistance. The following are some guidelines[4] for the effect of direct current (DC), the ranges corresponding to females and males (or different body sizes) respectively.

BODILY EFFECT	DIRECT CURRENT
Threshold of perception	~3-5 mA
Pain, voluntary muscle control maintained	~40-60 mA
Unable to let go of wires	~51-76 mA
Severe pain, difficulty breathing	~60-90 mA
Possible heart fibrillation after 3 seconds	~500 mA

A different set of guidelines exist for alternating current (AC). Generally, any value higher than 50 volts DC is considered to be 'high voltage' and needs adequate protection.

Chevrolet Volt specifies its RESS as lithium-ion batteries at 300 volts, whereas Toyota Prius batteries are stated as 346 volts (MY 2010) or 207 volts (MY 2012). In addition to the batteries, all components connected to the batteries directly or indirectly are also considered to be part of the high-voltage system (shown in the sketches above). In such vehicles, it is necessary to assure that those likely to come in contact with the automobile during normal operations or in accidents are adequately protected from all high- voltage parts. There are no US regulations[5] that explicitly address this issue of electrical safety but





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[3] methoden_messprinzip_01.jpg from http://www.data-input.de/_site/german/methode/

[4] Backstrom & Dini, "Firefighter Safety and Photovoltaic Installations Research Project", November 2011, Underwriters Laboratories

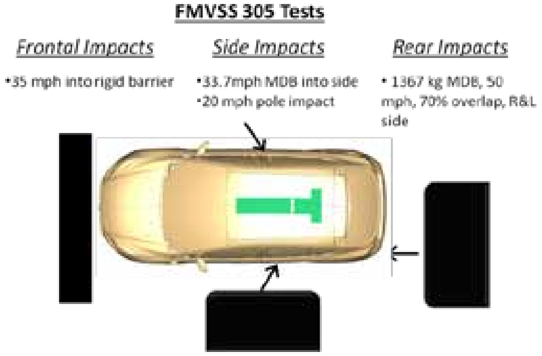
there are recommended practices (SAE J-1776) that specify that one or more of the following criteria need to be met after any crash test:

- Voltage at specified locations on electrical bus < 60V DC or <30V AC;
- Electrical energy < 0.2 Joules ;
- Isolation between high-voltage bus and conducting structure > 500 Ohms/volt; or > 100 Ohms/volt for DC-only buses not connected to electrical grids.

The above are post-crash criteria and may not govern functional safety for RESS-powered vehicles. Such tests and measurement requirements for functional safety need to be defined by each manufacturer.

<u>**2. Post-crash fire**</u>**:** Risk of fire arises if flammable fluids come in contact with a vehicle's hot parts (e.g. in the engine compartment) or if sparks resulting from an accident ignite such material. Since high-voltage batteries generate significant amount of heat while operating, it is possible that they (and their enclosures) may become hot surfaces, in addition to the 'usual' hot parts in a conventional car (e.g. those in the engine compartment, the exhaust system, etc). Therefore, the batteries and enclosures need to be isolated from all flammable items during normal operation and this isolation needs to be maintained in and after accidents as well. It is also desirable to ensure that electrolytes in the battery cells do not leak by any significant amount since these may also be flammable and be sources of fire.

Another concern in crash safety of RESS-powered vehicle is the probability of spark generation due to electrical short-circuits or 'arcing'. Such electrical faults may be caused due to various reasons. For example, if the battery is deformed severely during a crash, electrodes of one cell may contact electrodes of another cell, leading to sparking. As another example, leakage of fluids from damaged cells may also create short-circuits between cells' electrodes.



Currently, FMVSS 305 governs the evaluation of post-crash fire safety in hybrid and electric vehicles in the US. It sets post-crash-test criteria for minimum values of electrical isolation and for maximum permissible leakage from batteries. These criteria have to be met in the FMVSS tests, including FMVSS 208 (front barrier impacts), FMVSS 214 (moving deformable barrier impact into the side of the automobile) and FMVSS 301 (moving deformable barrier impacting the rear of the vehicle and overlapping 70% of its width). The tested vehicle undergoes a 360-degree rollover and measurements taken afterwards must meet the following:

- no visible electrolyte spillage in passenger compartment and no more than 5 liters overall;
- battery modules must remain in the original location, with no intrusion into the passenger compartment;
- electrical isolation must be at least at 500 Ohms/Volt (measured between the battery and the conducting structure of the automobile).

Although FMVSS 305 only requires that the above be met in the federally mandated (FMVSS) crash tests, many manufacturers conduct such evaluations in other crash conditions as well. NHTSA also makes these

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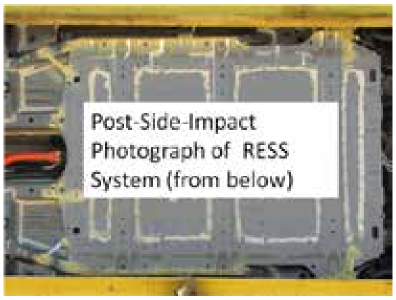
[5] European countries have such regulations as part of ECE R94, etc. for crash safety of RESS-powered vehicles.



measurements as part of its New Car Assessment Program and reports results from them on its website.

3. Post-crash Rescue: It is widely regarded that trauma from serious automobile crashes is a time-dependent disease and survival probabilities and injury outcome for injured occupants depend on the time elapsed from the accident to the proper emergency care at an appropriate trauma facility. It is therefore highly desirable to keep this elapsed time as short as possible. The term 'golden hour' [6] is often used as a guideline that victims with serious injuries have the best possible outcome if they receive appropriate trauma care in less than one hour. Since

$$
\begin{aligned}
\textit{Total elapsed time} &= \textit{Time taken to notify emergency services}\\
&+ \textit{Response time of emergency services}\\
&+ \textit{Time to extricate occupants from vehicle}\\
&+ \textit{Time to transport to trauma facility},
\end{aligned}
$$

each of the above components should be minimized so as to reduce the total time elapsed before getting appropriate care. In the above equation, the *'time to extricate occupants from vehicle'* depends to a significant extent on several aspects of vehicle design, in addition to the type and the severity of the crash. In case of serious damage to a vehicle, extrication of its occupants may require emergency responders to cut and remove parts of the automobile. When there are high-voltage systems present in the vehicle, such cut-and-remove operations may pose unacceptable risks[7] for emergency responders. This in turn can affect the extrication process if the emergency responders need to spend time to figure out the location of the high-voltage components before cutting.

This factor has received significant attention from government and from advisory agencies. No regulations on this issue exist in the US yet but NHTSA has issued interim guidance documents[8] for emergency responders as well as for tow truck operators and for consumers. The Society of Automotive Engineers (SAE) has also developed "Hybrid and EV First and Second Responder Recommended Practice" (SAE J-2990). Most automakers publish specific instructions[9] for first responders as part of their service manuals for RESS-powered vehicles and many provide training as well.

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[6] Calland, "Extrication of the seriously injured road crash victim", Emergency Medicine Journal, vol. 22, 2005

[7] USA Today, "Cars safer for passengers but not first responders", August 8, 2012

[8] NHTSA report DOT HS 811 574, "Interim Guidance for Electric and Hybrid-electric Vehicles Equipped with High Voltage Batteries", January 2012.

[9] Chevrolet Volt First Responders' Guide, https://www.gmstc.com/WebTreeDocuments/download.asp?lID=9&nID=584

While such published instructions are helpful, they are not yet universally known. Therefore, it also becomes desirable that appropriate labels be placed inside the vehicle on the high-voltage parts to help guide extrication process. Another desirable feature for RESS-powered automobiles is that manual disconnect capability be provided for the high-voltage parts and that this be easily accessible and quickly identifiable by first responders as well as by service providers.

Outlook: The numbers of hybrid and electric vehicles are likely to continue to grow in the coming years. As this technology develops further, storage batteries (RESS) are likely to become more efficient and have increased storage capacity, leading to longer operational range and lower per-unit cost for these vehicles. With growing numbers and more exposure (more miles travelled), it is also likely that new issues related to functional safety and crashworthiness of RESS-powered automobiles will continue to emerge. This is of interest from the viewpoint of product liability as well and will require that performance evaluation of these vehicles consider all parts of the vehicle including the electrical and electronics/control systems.

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