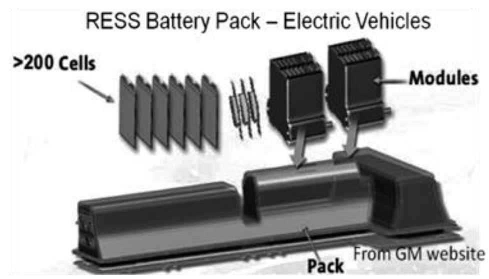
Safety Evaluation of Electric and Hybrid Vehicles

The numbers of electric and hybrid cars on US roads have increased significantly over the years, starting with the first introductions of Honda InSight (1999) and Toyota Prius (2000). As with all new technologies, any issues with these vehicles have received intense scrutiny[1,2], such as the case of fire in a Chevrolet Volt, which occurred in a vehicle that had been stored for several days after undergoing a crash test.

All hybrid & electric vehicles use high-voltage batteries ('rechargeable energy storage systems' or "RESS") to store energy that is used for propulsion when needed. Current energy storage technologies generally use Lithium-ion (Li) or Nickel-metal hydride (Ni-Mh) cells. A typical RESS consists of multiple cells connected together and the entire assembly surrounded by rigid structure. There are some unique challenges in assuring the safety of high voltage RESS units and these are discussed below.



'Functional Safety' and 'Safety in Accidents'

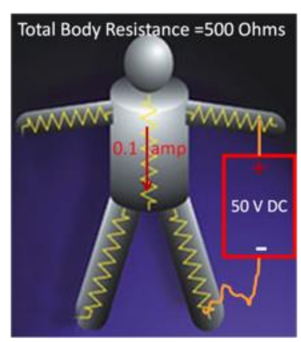
The overall safety of an automobile can be considered as being composed of (a) Functional safety, and (b) Safety of occupants (and others in proximity) in a crash or in accidents.

Functional safety consists of factors such as (i) safety during normal driving, (ii) safety during storage, (iii) safety while undergoing service and maintenance, and (iv) safe disposal of vehicle at end of life. The functional safety of hybrid and electric vehicles requires consideration of factors such as heat & thermal energy management, electrical system integrity, control system reliability, EMI shielding and charging system safety, etc., in addition to accounting for other factors associated with conventional vehicles. Test conditions for functional safety are specified by the vehicle manufacturer. Safety in accidents is evaluated by crash tests defined by the NHTSA and by the Insurance Institute for Highway Safety. Also, additional tests are conducted by some manufacturers to assess safety in crash scenarios which are likely but not included in the above.

Risk Factors associated with RESS-powered vehicles:

1. Electrical Shock & Injury: 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

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



---

[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.

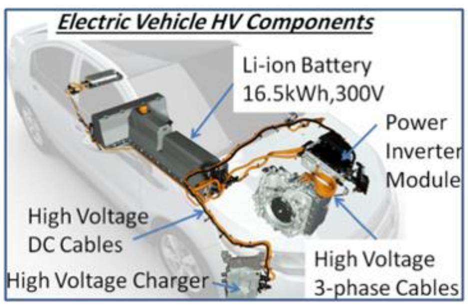
The sketch[3] is an example that a person with a body resistance of 500 Ohms contacting an electrical source of 50 volts will experience 100 milliamperes ('mA') of current.

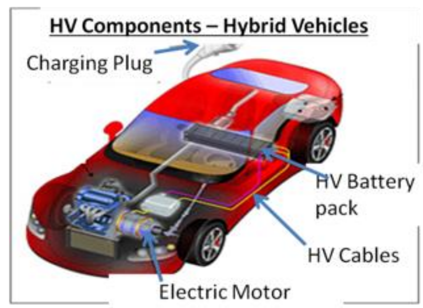
For reference, the International Electrotechnical Commission (IEC) uses 1000 Ohms as a typical value for adult human body resistance. The following are some guidelines[4] for the effect of direct current (DC), the ranges corresponding to females and males (or different body sizes) respectively.

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**

Generally, values higher than 50 volts DC are considered 'high voltage' and require adequate protection.

As examples, Chevrolet Volt specifies its RESS of lithium-ion batteries at 360 volts, whereas Tesla batteries are stated as 375 volts. 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 there are recommended practices (SAE J-1776) that specify that one or more of the following criteria 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.

2. Post-crash fire: Such risks arise if flammable materials come in contact with a vehicle's hot parts or if sparks resulting from an accident ignite such material. In addition to the 'usual' hot parts in a conventional car, the batteries may themselves become hot surfaces during operation. Therefore, such batteries need to be properly isolated during operation. Safe levels of such isolation also need to be maintained during and after accidents as well and it is also necessary to ensure that any flammable electrolytes in the battery cells do not leak by any significant amount.

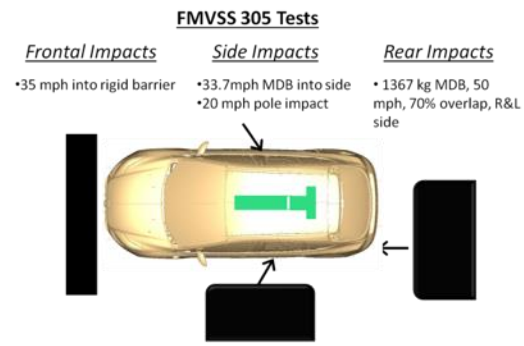
[3] methoden_messprinzip_01.jpg from http://www.data-input.de/_site/german/methode/

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

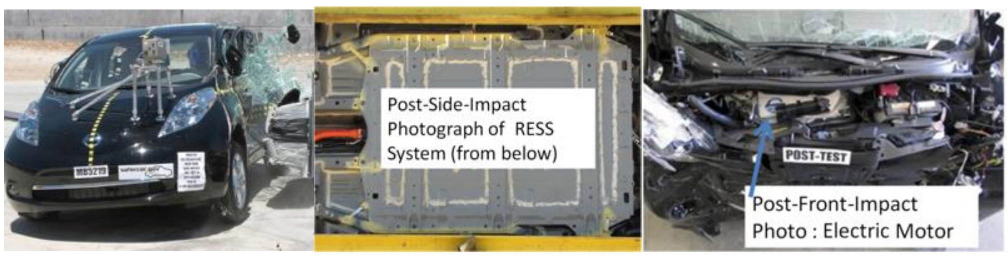
[5] European countries have such regulations as part of ECE R94, etc. for crash safety of RESS-powered vehicles.

Another safety-related concern in RESS-powered vehicle is the probability of spark generation, such as due to electrical short-circuits or 'arcing'. These electrical faults may occur for various reasons, e.g., if the battery is deformed severely during a crash, the 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 criteria for minimum values of electrical isolation and for maximum permissible leakage from batteries post-crash in 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).



NHTSA also records these measurements as part of its New Car Assessment Program and reports them on



its website as part of its New Car Assessment Program.

3. Post-crash Rescue: It is widely regarded that trauma is a 'time-dependent disease' and survival probabilities and injury outcome depend greatly on the 'time elapsed' from the moment of accident to the moment when proper care is given at an appropriate facility. It is thus highly desirable that this elapsed time be as short as possible and the term 'golden hour' [6] is often used as a guideline to be met for victims with serious injuries. Since

Total elapsed time = Time taken to notify emergency services
+ Response time of emergency services
+ Time to extricate occupants from vehicle
+ Time to transport to trauma facility;

it is necessary that each of the above components be minimized in order to reduce the total 'time elapsed' for getting appropriate care. In the above formula, the *'time to extricate occupants from vehicle'* depends to a significant extent on several aspects of vehicle design, as well as on the type and the severity of the crash. In cases of serious damage to a vehicle, extrication of its occupants may require emergency responders to cut and remove parts of the automobile. When RESS batteries are present in the vehicle, such cut-and-remove operations may pose unacceptable risks[7] for emergency responders. This can prolong the extrication process if emergency responders need to spend extra time to figure out the location of the high-voltage components before cutting into the vehicle's body.

[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

.

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. Wider availability of smartphone- and web-based information for each vehicle is highly desirable as a safety-enhancement measure. Additionally, the placement of appropriate labels inside the vehicle on the high- voltage parts will further help quicken the extrication process.

Another desirable feature for RESS-powered automobiles is that manual disconnect capability be provided for high-voltage parts and that this be easily accessible and quickly identifiable by first responders as well as by service providers.

<u>SUMMARY:</u> The number of hybrid and electric vehicles is likely to continue to grow in the coming years and their RESS batteries are likely to have increased storage capacity and it is likely that new safety-related issues for such automobiles will continue to emerge.

---

[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