

CRASHWORTHINESS TESTING OF ELECTRIC AND HYBRID VEHICLES

Sean O'Malley

David Zuby

Matthew Moore

Insurance Institute for Highway Safety

United States

Michael Paine

David Paine

Australasian New Car Assessment Program (ANCAP)

Australia

Paper Number 15-0318

ABSTRACT

Electric and hybrid vehicles are increasingly being offered as a means to provide personal transportation with less negative impact on the environment and lower operational cost. While still representing a small portion of fleets in industrialized countries, the availability of these types of vehicles is growing. Electric and hybrid vehicles comprised approximately 1 percent of new vehicle sales in the United States in 2004, and by 2013 this had grown to almost 4 percent. As a result, there is considerable interest in the crash safety of these vehicles and, in particular, potential hazards unique to their electrical drive systems such as electrocution, fire, and electrolyte spillage. This paper summarizes the crash test experience of electric/hybrid vehicle from the Australasian New Car Assessment Program (ANCAP) and Insurance Institute for Highway Safety (IIHS).

Since 2004, ANCAP and IIHS have subjected 42 hybrid and electric drivetrain vehicles to a variety of crashworthiness tests including both moderate and small overlap front crashes, side crashes, and roof strength tests. Crashworthiness results are summarized with special attention paid to the risk of electrical drive system hazards, and laboratory best practice related to electric vehicle testing is described.

The crashworthiness of hybrid and electric drive vehicles is typically similar to that of vehicles with internal combustion engines. IIHS has assigned eight good ratings, three acceptable ratings, and three poor ratings in frontal crash tests (both moderate and small overlap tests); 10 good ratings and one poor rating in side crash tests; and eight good ratings and one acceptable rating in roof strength tests. To date, ANCAP has assigned one 4-star rating and two 5-star ratings to electric vehicles in its evaluation program. Neither organization observed damage to the batteries or other portions of the electrical drive systems that indicated a potential risk.

Safety precautions and inspections of the electrical systems have evolved to include post-crash checks for isolation of high voltage from the chassis, leakage of volatile gases, and physical damage of the systems. In addition, vehicles are quarantined and observed after a test to ensure hidden damage does not result in fire risk developing over time.

Ten years of crash testing electric/hybrid vehicles by ANCAP and IIHS, covering a wide range of crash conditions, indicates the variation in crashworthiness performance of hybrid/electrical drive vehicles is comparable with the variation observed with conventionally powered vehicles. Neither ANCAP nor IIHS has observed problems associated with the electrical drive systems in tests of more than 40 hybrid and electrical vehicles. This observation suggests safety designers are providing good protection of the electrical drive systems in crashes represented by federal and consumer information tests.

While vehicles with high-voltage batteries present unique challenges to laboratory safety, ANCAP and IIHS experience suggests these potential hazards can be managed. Using appropriate tools and taking extra steps to ensure isolation of the battery from other parts of the vehicle has resulted in the successful execution of electric vehicle crash tests by both organizations without injury or other dangerous incident.

INTRODUCTION

Tougher fuel economy standards have spurred automakers to make design changes to their vehicle fleets to meet new regulations. Making vehicles lighter, installing smaller engines, using alternative fuels, and manufacturing hybrid and electric vehicles are some of the strategies for increasing fuel economy.

A vehicle is considered a hybrid if it has more than one power source to propel the vehicle, typically an internal combustion engine and electric motor. An electric vehicle is equipped with one or more electric motors to propel the vehicle. Both hybrid and electric vehicles have high-voltage battery packs, often referred to as Rechargeable Electric Storage Systems (RESS).

In 1999, the Honda Insight was the only hybrid electric vehicle (HEV) available in the United States, with 17 vehicles sold. In 2000, the Toyota Prius was introduced, with more than 5,500 vehicles sold. In 2004, the Honda Civic hybrid was introduced, with sales of 13,700 units. Beginning in 2004, there have been at least two new HEV models introduced each year, with 11 introduced in 2012. A total of 47,600 HEVs were sold in the United States in 2003. By 2013, that number had grown to almost 500,000 units (Figure 1). In 2013, there were 46 HEV models available in the U.S. market [1].

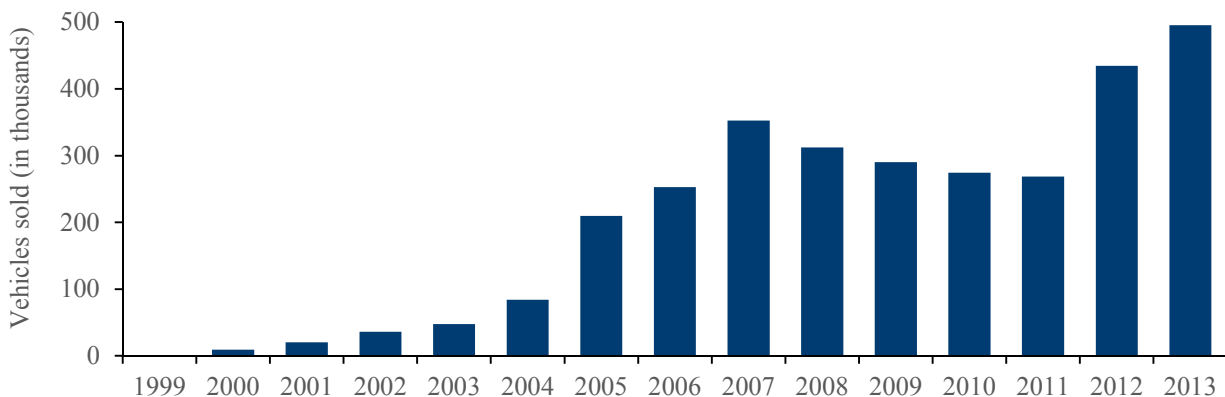


Figure 1. Hybrid and electric vehicle sales, United States.

The first mainstream plug-in electric vehicles (PEV) available in the United States were the Nissan Leaf and Chevrolet Volt, both introduced in December 2010, with sales of 19 and 326 units, respectively. Two additional PEV models were introduced in 2011, the Mitsubishi i-MiEV and Smart ED, with sales of 76 and 310 units, respectively. Nine PEVs were introduced in 2012, and six in 2013. By 2013, PEV sales totaled almost 100,000 units (Figure 2). There were 16 PEV models for sale in the United States in 2014 [1].

Sales of PEV and HEV vehicles in the United States have increased annually, from 17 vehicles in 1999 to 592,231 vehicles in 2013, approximately 3.5 percent of all passenger vehicles sold. The sales volume of electric/hybrid vehicles in Australia is smaller (Figure 3), but the same upward trend is evident [2][3][4][5][6][7][8][9][10][11][12].

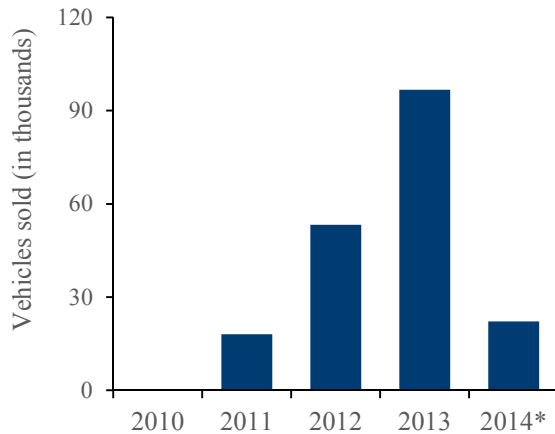


Figure 2. Plug-in electric vehicle sales, United States (*2014 sales, through first quarter).

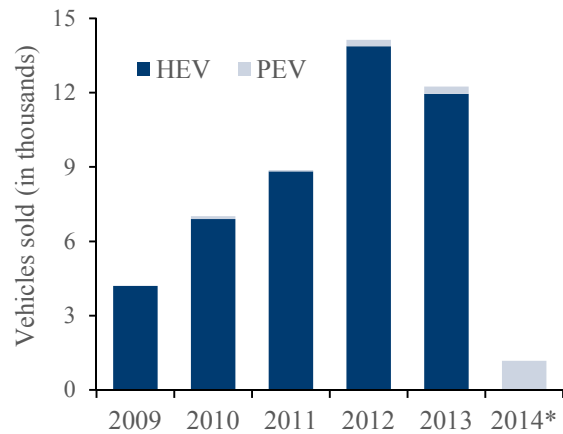


Figure 3. Plug-in electric and hybrid vehicle sales, Australia (*HEV sales not available).

Real-World Safety Concerns

Electric/hybrid vehicles have a number of safety concerns not associated with conventional vehicles including electrocution, explosion, electrolyte spillage, and/or fire. There have been numerous real-world examples of electric vehicles catching on fire after a crash and in the garages where they were being stored; in some cases, this may have been while the vehicle was being charged.

The most widely publicized fire incident involved a 2011 Chevrolet Volt after it was crash tested at MGA Research, in Burlington, Wisconsin, in June 2011. The Volt's lithium-ion battery caught on fire 3 weeks after being subjected to an 18 mi/h side pole test as part of the National Highway Traffic Safety Administration's (NHTSA) New Car Assessment Program (NCAP). The fire quickly spread to three adjacent vehicles. An extensive post-fire investigation later determined that a small amount of battery coolant penetrated the high-voltage battery case after the crash, causing the battery to short and eventually leading to a thermal runaway condition [13].

In 2012, 16 Fisker Karma electric vehicles caught fire and were destroyed at a port in New Jersey after Hurricane Sandy. It is believed that flooding caused a short circuit in one of the Karma's lithium-ion batteries, leading to a thermal runaway condition. The fire then spread, eventually igniting the 15 adjacent vehicles [14].

In 2013, two Tesla Model S sedans caught fire while being driven in the United States. The first, in Washington State, occurred after the car struck a metal object in the road. The second occurred after the car ran over a trailer hitch lying on the road in Tennessee. In both cases, road debris punctured the floor and battery pack, leading to battery failure and thermal runaway. Both drivers were able to pull over and exit the cars safely. Tesla said it would add underbody shielding to help protect the lithium-ion battery [15]. In 2014, a fire occurred when the driver, a car thief, crashed the car at high speed, tearing the vehicle in two. The battery pack was ejected and caught fire. The driver later died in the hospital from injuries sustained in the crash [16].

Real-World Safety

Due to the extra weight of RESS, hybrids are 10 percent heavier on average than their non-hybrid counterparts. Provided that the vehicle has good crashworthiness, this extra mass provides a slight safety advantage in some types of crashes, such as those involving other vehicles. A study by the Highway Loss Data Institute estimated the odds that a crash would result in injuries if people were riding in a hybrid vehicle versus the conventional version of the

same vehicle [17]. The analysis included more than 25 hybrid-conventional vehicle pairs, all 2003-11 models, with at least one collision claim and at least one related injury claim filed under personal injury protection (PIP) or medical payment (MedPay) coverage in 2002-10. Both PIP and MedPay are first-party insurance that cover the costs of injuries to drivers and their passengers in the insured vehicles. Figures 4 and 5 compare the injury odds of hybrids with their conventional counterparts under both types of insurance and show that the odds of injury are at least 25 percent lower in hybrids. The differences in injury odds may have been partly influenced by differences in how, when, and by whom hybrids are driven in comparison with their counterparts that are not completely captured by the covariates in the analysis. Nevertheless, these results indicate that electric drivetrains do not pose an overall increased risk of injury for their occupants.

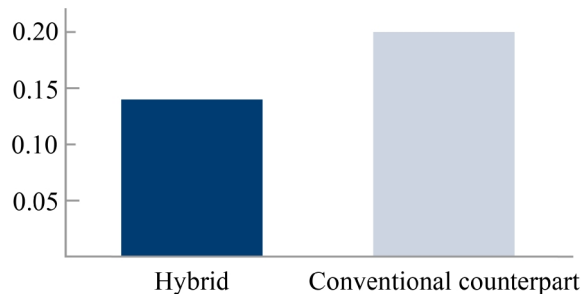


Figure 4. Estimated injury odds under collision and personal injury protection coverage.

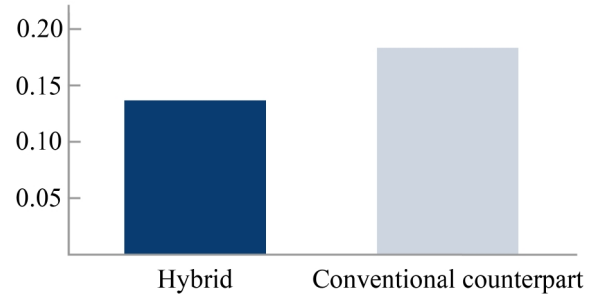


Figure 5. Estimated injury odds under collision and medical payment coverage.

Additionally, IIHS conducted a study of fatal vehicle crashes associated with a fire for model year 2009-14 vehicles [18]. The rate of fire incidences for electric and hybrid vehicles was comparable with those for conventionally powered vehicles.

ELECTRIC/HYBRID VEHICLE TESTS

Battery Testing Standards

There are numerous standards that address the safety of batteries and RESS at the component level such as the Society of Automotive Engineers (SAE J2464, J2929, and J2380), United Nations Economic Commission for Europe (ECE R.100), and draft Global Technical Regulation No.13 for RESS [19-20]. All prescribe tests that simulate various environmental, mechanical, and electrical conditions that batteries and RESS can be subjected to in the automotive environment including:

- Vibration
- Thermal shock and cycling
- Mechanical impact, integrity, and shock
- Fire resistance
- External short circuit protection
- Over- and under-charge protection
- Over-temperature protection

Generally, the standards specify that the battery or RESS shall not leak electrolyte, rupture, catch fire, or explode when subjected to the conditions of each test. The isolation resistance is measured between the positive and negative terminals and the battery case/ground to ensure the internal integrity of the battery or RESS has not been compromised. The isolation resistance should exceed 100 Ω/V , following procedures described in the standards.

In the United States, Federal Motor Vehicle Safety Standard (FMVSS) No. 305 [21] addresses the crash safety of RESS through full-vehicle crash tests. Specifically, FMVSS 305 requires that following regulatory compliance frontal barrier, rear moving barrier, and side moving deformable barrier crash tests:

- RESS shall remain attached and secured in the vehicle, with no intrusion into the occupant compartment
- Electrical isolation of the RESS must be no less than 500 Ω/V
- Any electrolyte spillage shall not enter the occupant compartment nor exceed 5 liters outside the occupant compartment.

FMVSS 305 does not impose separate requirements for RESS internal integrity, as this is covered by the aforementioned standards.

Laboratory Vehicle Tests

The Insurance Institute for Highway Safety (IIHS) and Australasian New Car Assessment Program (ANCAP) have crash tested 42 hybrid and/or electric vehicles in various test scenarios. IIHS performs vehicle crashworthiness evaluations using the following tests:

1. Moderate overlap front crash test (64 km/h, 40 percent overlap on driver side, into deformable barrier)
2. Small overlap front crash test (64 km/h, 25 percent overlap on driver side, into rigid barrier with radius on the right edge)
3. Side crash test (50 km/h, deformable mobile barrier into driver side)
4. Roof strength (quasi-static loading on either driver or passenger side of vehicle)

Ratings of good, acceptable, marginal, or poor are awarded to the vehicle in each test mode. The crash test ratings are based not only on measurements made by sensors in the test dummy but also analysis of the dummy's observable motion and measurements of safety cage deformation. The roof crush test is evaluated by measures of crushing force and displacement of the crushing platen [22].

ANCAP performs similar tests as part of its 'Star' rating evaluation program that include:

1. 40 percent frontal offset test (64 km/h on driver side)
2. Side impact test (50 km/h, mobile deformable barrier crashing into driver side of vehicle)
3. Pole side impact test (29 km/h, driver side of vehicle into rigid pole)

The IIHS and ANCAP side impact tests differ in that the deformable barrier used in the IIHS side test has a mass of 1,500 kg and is shaped like an SUV, whereas the ANCAP side impact barrier is shaped like passenger car with a mass of 950 kg.

The results of the three vehicle crash test scenarios above contribute to the ANCAP overall star ratings, which range from 1 to 5 stars. In addition to the vehicle crash tests, ANCAP performs a pedestrian protection assessment, a whiplash protection assessment, and reviews the inclusion of safety assist technology on the vehicle in order to derive the ANCAP overall star rating for the vehicle. The ANCAP rating covers three vehicle safety areas: occupant protection, pedestrian protection, and safety assist technology [23].

Figures 6-9 compare the ratings of plug-in electric (PEV) and hybrid electric (HEV) vehicles with the ratings of conventional vehicles in the same vehicle classes and model years. The electric/hybrid vehicles have a higher proportion of good IIHS ratings in the moderate overlap front test, side impact test, and roof strength test than conventionally powered vehicles from the same vehicle classes and model years. In addition, several HEVs and PEVs have been awarded IIHS *Top Safety Pick* awards, indicating they have the highest level of overall safety according to IIHS guidelines (Table 1).

Moderate overlap - All Moderate overlap - PEV/HEV

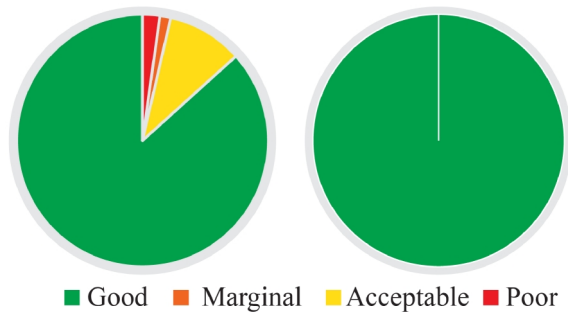


Figure 6. IIHS moderate overlap test ratings.

Small overlap - All Small overlap - PEV/HEV

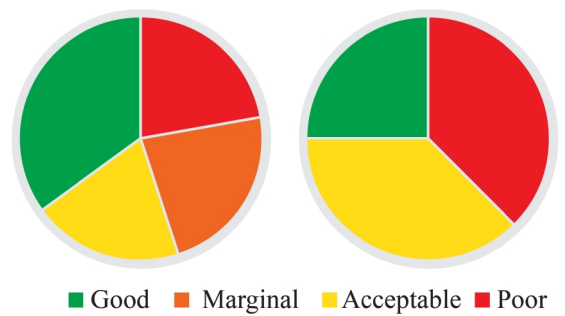


Figure 7. IIHS small overlap test ratings.

Side impact - All Side impact - PEV/HEV

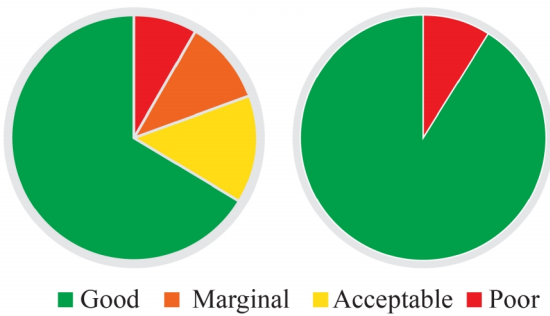


Figure 8. IIHS side impact test ratings.

Roof crush - All Roof crush - PEV/HEV

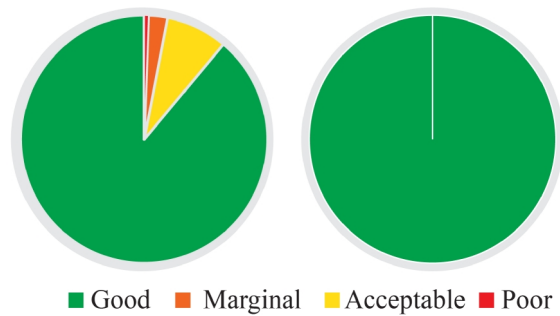


Figure 9. IIHS roof crush test ratings.

Table1
Top Safety Pick awards for PEV/HEV tested by IIHS.

	2009	2010	2011	2012	2013	2014	2015
Chevrolet Volt			x	x	x	x	x
Ford C-Max Hybrid						x	x
Honda CRZ				x	x		
Honda Insight				x	x		
Lexus CT200h			x	x	x		x
Nissan Leaf			x	x			
Toyota Prius	x		x	x	x	x	x
Toyota Prius C				x			
Toyota Prius V				x	x		x

Three IIHS small overlap crash tests of electric/hybrid vehicles resulted in poor structural ratings, and six IIHS side impact tests resulted in acceptable structural ratings. However, the area surrounding the vehicle's high-voltage battery (RESS) was intact in all cases, with no electrical safety issues (Figures 10-12). Moreover, of the 12 HEV/PEV models tested since IIHS incorporated a 2-week post-test observation period, none have caught fire like the Chevrolet Volt tested by NHTSA.

For the ANCAP tests, only the 2010 Mitsubishi i-MiEV scored lower than the maximum 5 star ANCAP rating, with a final rating of 4 stars. The rating was influenced by occupant injury risk, rather than structural performance of the vehicle, and no crashworthiness deficiencies related to electrical safety were identified as part of the usual assessment.



Figure 10. RESS location in 2013 Toyota Prius C after IIHS small overlap test, side view.



Figure 11. RESS location in 2014 Nissan Leaf after IIHS small overlap test, bottom view.

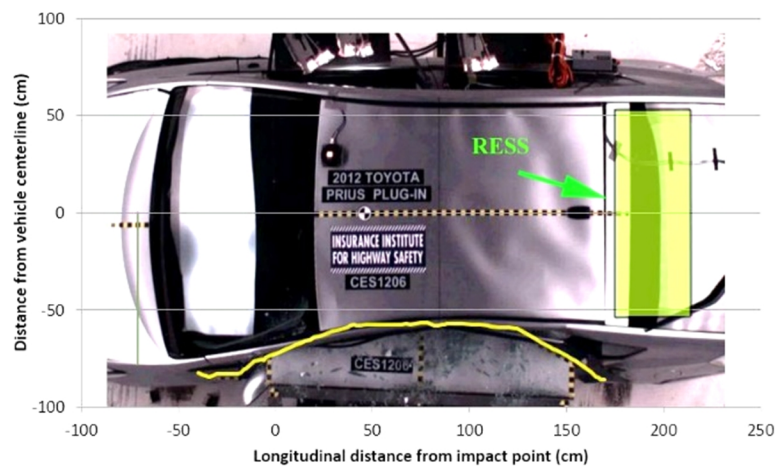


Figure 12. RESS location in 2012 Toyota Prius Plug-In during IIHS small overlap test, overhead view with intrusion chart.

Laboratory Safety for HEV/PEV Crash Testing

HEV/PEV crash test procedures utilized by IIHS and ANCAP have evolved since these vehicles were first introduced in the mass market. There are no specific SAE or other guidelines on crash testing such vehicles; instead, IIHS and ANCAP have evaluated the best practices utilized by automakers and other testing organizations and developed them into a single procedure. It is anticipated that these procedures will continue to evolve as new types of HEV/PEVs enter the market. This section describes the procedures adopted to evaluate the crashworthiness of HEV/PEV vehicles.

Test procedures include monitoring the battery temperature, electrical isolation of the RESS from the vehicle chassis, and verifying that automatic battery disconnection from the drive circuit has occurred after a crash. In addition, as fires caused by RESS damage may occur, a fire management plan has been implemented. Finally, proper discharging and disposal procedures are followed before discarding the vehicle.

Laboratory safety when working on vehicles that include a high-voltage RESS requires the use of protective gear and tools designed for high-voltage work. Eye protection (safety goggles) and insulated gloves and boots should be worn by personnel working with an HEV/PEV RESS. In addition, hand tools should be adequately insulated and, where applicable, include cross-guards to prevent hands from slipping on to any uninsulated part (Figure 13). Finally, high-voltage tool kits should include an insulated pole with a hook or loop that can be used by a second person to pull away a technician who may come in contact with the high-voltage source despite precautions (Figure 14). High-voltage work kits are available from major tool suppliers.

Safely preparing an HEV/PEV for an IIHS crash test requires gathering information about the electric drive system from the test vehicle manufacturer and having a detailed checklist of procedures to follow (Appendix A). The following information can facilitate safe installation of monitoring systems and post-crash disposal of the tested vehicle:

- Location of the manual service disconnect (MSD)
- Locations of the RESS and high-voltage wiring
- Recommended connection locations for monitoring RESS isolation
- Instructions for charging/discharging the RESS
- Information about the chemical properties of the battery coolant
- Information about the color and location of the battery coolant
- Copy of the Material Safety Data Sheet for the battery or its components
- Information about hazards unique to the test vehicle's particular RESS



Figure 13. Assortment of high-voltage tools.

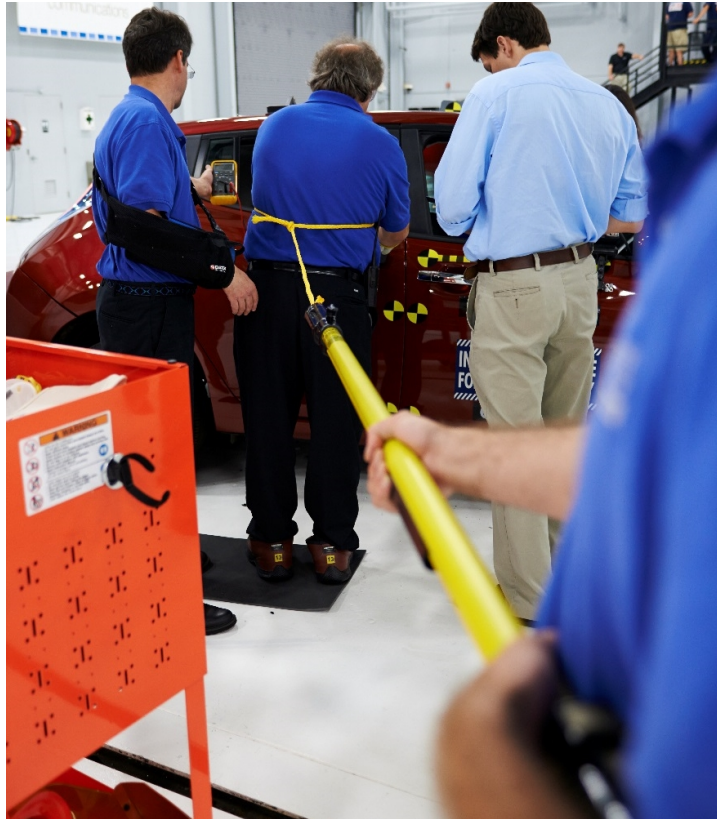


Figure 14. Insulated pole, shown attached to technician measuring high-voltage battery isolation.

Preparation of an HEV/PEV for a crash test begins with using the MSD to isolate the RESS from the vehicle chassis while test equipment is installed and pre-crash measurements are taken. Locations of the MSD are not standardized and vary considerably (Table 2 and Figures 15-16).

Table2.
Examples of locations for manual service disconnects on HEV/PEV.

Model(s)	Location	Notes
Chevrolet Volt	Rear of center console	Accessed through panel inside console
Ford C-Max	Behind and under left rear seat	Rear seat must be folded fully forward
Lexus CT 200h (also Toyota Prius and Prius V)	Rear cargo area	Remove spare tire cover and foam tool bin
Mitsubishi i-MiEV	Under rear of front passenger seat	Move front passenger seat fully forward
Nissan Leaf	Center tunnel in rear seating area	Remove bolted cover
Toyota Prius C	Under rear seat cushion	Remove cushion and access panel
Toyota Prius V	Within center console	Remove center console fascia then remove plastic MSD cover

A clear means of identifying the MSD status should be adopted so that all personnel can know when the vehicle is safe to work on. For example, IIHS practice is to secure the MSD key/plug to the roof of the test vehicle with orange tape (Figure 17). Personnel should consider the RESS to be connected to the drive system if this indicator is absent.



Figure 15. Manual service disconnect in Lexus CT200h, shown in cutaway.



Figure 16. Manual service disconnect in Chevrolet Volt, shown in cutaway.

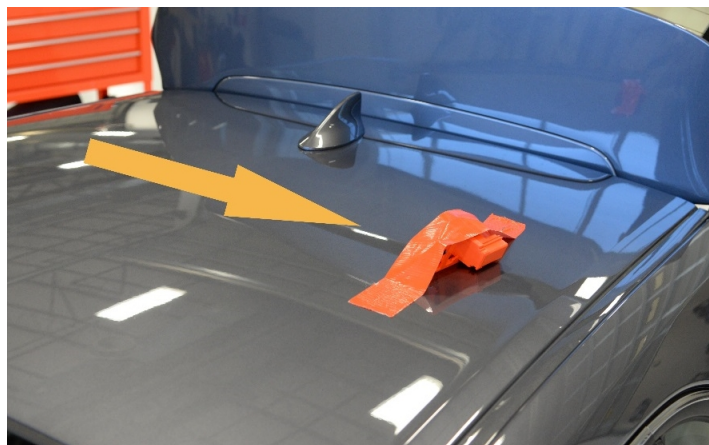


Figure 17. MSD taped to roof of Lexus CT200h while work is conducted to battery system.

For IIHS tests, a monitoring circuit, as described in FMVSS 305, is installed across the positive and negative leads on the drive side of the MSD. This attachment allows the post-crash measurements to ascertain whether the crash-initiated disconnection of the RESS from the drive system has occurred. The IIHS box that contains this circuit also contains circuitry to monitor a thermocouple that is attached to the RESS housing to help identify the potential for post-crash fire events. Figure 18 shows the schematic diagram of the IIHS RESS monitor. Figure 19 illustrates how test probe terminals are protected from accidental contact by technicians and test witnesses. Care should be taken not to interfere with the RESS or high-voltage wiring when installing other test equipment (e.g., data acquisition system, cameras, and related power supplies).

The first check after a crash test is to confirm isolation of the high-voltage power source from the vehicle chassis. This is done by measuring the voltage between the various test points on the monitor. If a non-zero potential is measured, then the isolation resistance is calculated by switching in the known resistors and using the re-measured voltages in the formulas shown in Figure 18.

An isolation resistance of more than 500 Ω/V is considered safe and would represent compliance with FMVSS 305 following regulatory tests. This measurement confirms the high-voltage battery is isolated from the vehicle body. Simultaneously and from a distance, other laboratory personnel visually check for signs of smoke or coolant leakage. Once electrical isolation of the RESS is established, collection of any leaking coolant may begin. Temperature of the RESS housing is monitored throughout post-crash procedures. As an extra precaution, the MSD should be removed as soon as it is accessible to test personnel.

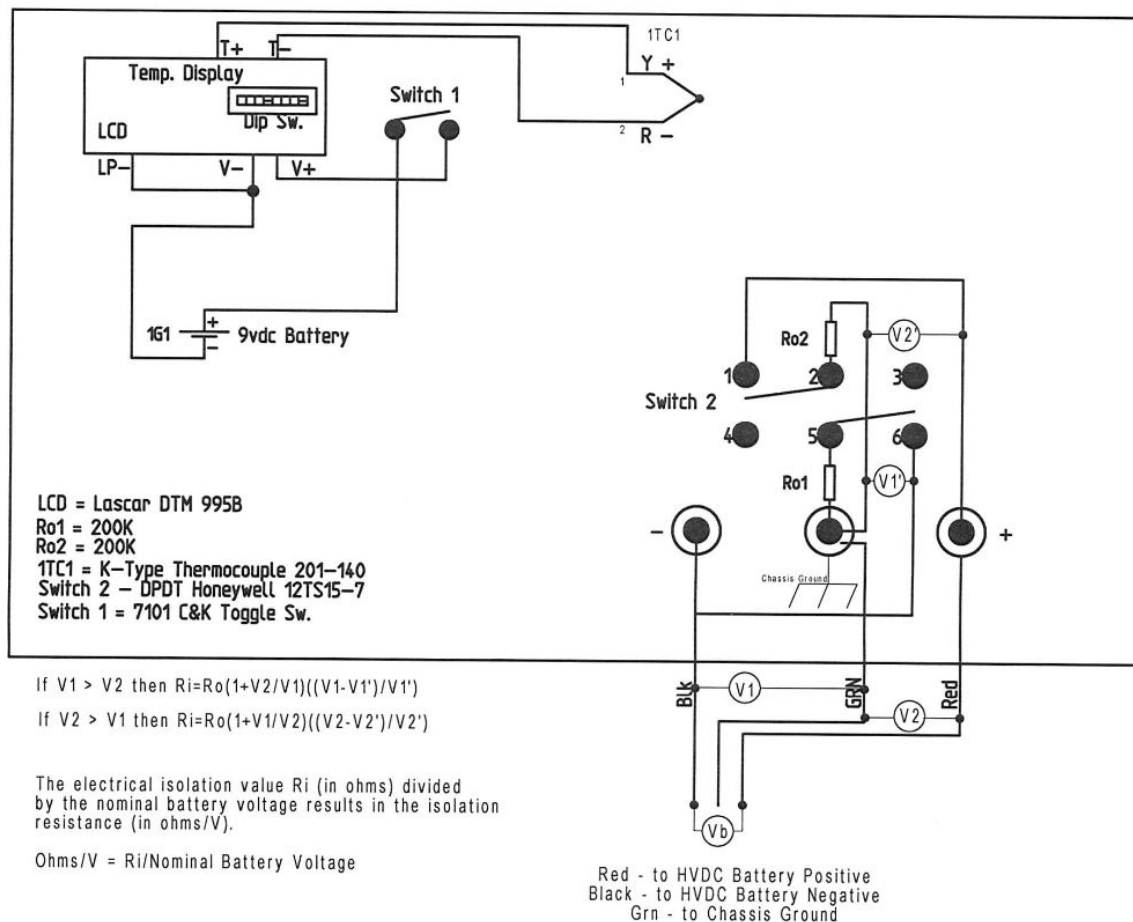


Figure 18. Schematic of IIHS '305' box, including thermocouple circuit and isolation resistance formula.



Figure 19. IIHS '305' box, showing thermocouple readout, resistor switch, and terminal cover.

In the event of any sign of fire or rising temperatures at the RESS housing, the vehicle should immediately be moved out of the laboratory if it is safe to do so. This can be managed with a lift truck equipped with insulating material on its forks to shield both the lift and its operator from potential electric shock. Fire extinguishing operations should commence immediately. Extinguishing fires associated with both nickel metal hydride (Ni-MH) and lithium-ion (Li-Ion) batteries typically involves applying copious amounts of water, although there is conflicting advice amongst some manufacturers regarding how to best handle a fire event; for example, instructions for the Toyota Prius C and Prius V are to let the battery burn itself out [24]. Regardless, as an additional precaution, it is good practice to arrange for the local fire department to be present during crash tests of HEV/PEV, especially those with Li-Ion batteries.

Another hazard associated with damage to high-voltage batteries is the possible release of carbon monoxide, hydrogen fluoride, and other harmful gases. Gas detection equipment can be used to check for their presence after a test, but this equipment is very expensive and the release of gases is unlikely in tests conducted by IIHS and ANCAP. The potential hazard may be managed by moving the vehicle to a well-ventilated area. A release of gas typically indicates a serious problem within the RESS.

Since the post-crash fire from the Chevrolet Volt test was reported by news media, IIHS has included an additional precaution and evaluation of this potential risk. Tested HEV/PEVs are stored for a period of 2 weeks in a metal storage shed located remote from the test laboratory (Figure 20). This minimizes the risk of collateral damage in the unlikely event of a fire. After this observation period, the vehicle's high-voltage battery is discharged per the manufacturer's recommended procedure.



Figure 20. Electric/hybrid vehicle post-test storage.

CONCLUSIONS

Neither ANCAP nor IIHS crashworthiness testing has identified safety-related issues associated with the high-voltage RESS of electric and hybrid vehicles. In fact, test results suggest that, as a class, these vehicles are more crashworthy than their conventionally powered counterparts. However, the number of crash tests of vehicles with electric drive systems is small compared with ANCAP and IIHS experience with conventional vehicles, and there are crash test scenarios not covered by the crash tests conducted by ANCAP and IIHS. For example, higher speed narrow object impacts may intrude into the battery compartment. As the availability of these vehicles increases, it seems likely that crash testing may uncover problems unique to these vehicles.

Crash testing has been executed safely through careful attention to the unique hazards associated with high-voltage batteries. However, new types of electric powertrains (e.g., fuel-cells) are being introduced into the market, so laboratory safety practice will need to evolve. Current electric/hybrid safety procedures may be a good starting point when developing them.

Additional information regarding the safety precautions used when testing electric/hybrid vehicles can be found in “Safety Precautions and Assessments for Crashes Involving Electric Vehicles” [24].

REFERENCES

- [1] U.S. Department of Energy. 2014. Alternative fuels data center. Available: <http://www.afdc.energy.gov/data/>. Accessed: 2 Mar 2015. Washington, DC.
- [2] Pontes, J. 2014. EV sales; Australia December 2013. EV-Sales.blogspot.ca, Jan 18. Available: <http://www.ev-sales.blogspot.ca/2014/01/australia-december-2013.html>. Accessed: 2 Mar 2015.
- [3] Pontes, J. 2015. EV sales; Australia full year 2014 (updated). EV-Sales.blogspot.ca, Jan 15. Available: <http://ev-sales.blogspot.com.br/2015/01/australia-full-year-2014.html>. Accessed: 2 Mar 2015.
- [4] Dowling J. 2011. Mitsubishi electric car back in stock. Carsales.com.au. Available: <http://www.carsales.com.au/news/2011/small-passenger/mitsubishi/mitsubishi-electric-car-back-in-stock-26567>. Accessed: 2 Mar 2015. Victoria, Australia.
- [5] Pontes, J. 2013. EV sales; Australia full year 2012. EV-Sales.blogspot.ca, Jan 5. Available: <http://www.ev-sales.blogspot.ca/2013/01/australia-full-year-2012.html>. Accessed: 2 Mar 2015.
- [6] Ottley S. 2013. Hybrid car sales make up 1 per cent of vehicle sales. *The Sydney Morning Herald*, Nov 30. Available: <http://www.smh.com.au/national/hybrid-car-sales-make-up-1-per-cent-of-vehicle-sales-20131129-2ygw9.html>. Accessed: 2 Mar 2015.
- [7] Nicholson T. 2014. Toyota hits new hybrid high. GoAuto.com.au, Mar 27. Available: <http://www.goauto.com.au/mellor/mellor.nsf/story2/A19B001FC141478ECA257CA800178264>. Accessed: 2 Mar 2015.
- [8] Bober I. 2014. Hybrid sales flopped in 2013. *Practical Motoring*, Jan 21. Available: <http://practicalmotoring.com.au/car-news/hybrid-sales-flopped-2013/>. Accessed: 2 Mar 2015. New South Wales, Australia: Practical Motoring.
- [9] Pettendy M. 2014. New Mazda2 to plug in. Motoring.com.au, Jun 30. Available: <http://www.motoring.com.au/news/2014/small-passenger/mazda/2/new-mazda2-to-plug-in-44423>. Accessed: 2 Mar 2015. Victoria, Australia.

- [10] TMR Team. 2013. Toyota's greenest Camry surpasses Prius in Australian hybrid sales. *The Motor Report*, Apr 10. Available: <http://www.themotorreport.com.au/56320/toyotas-greenest-camry-surpasses-prius-in-australian-hybrid-sales>. Accessed: 2 Mar 2015.
- [11] Martin S. 2012. Cool and green hybrid car sales surge to Australian record. *News.com.au*, Aug 2. Available: <http://www.news.com.au/finance/cool-and-green-hybrid-car-sales-surge-to-australian-record/story-e6frfm1i-1226441599395>. Accessed: 2 Mar 2015. New South Wales, Australia.
- [12] Australian Business Journal. 2015. Drivers going green as hybrid cars sales soar. *TheAuBJ*, Aug 2. Available: <http://www.australianbusinessjournal.com.au/drivers-go-green-as-sales-of-hybrid-cars-soar/>. Accessed: 2 Mar 2015. Victoria, Australia.
- [13] Crawley J. 2012. Probe of Chevy Volt fires closed. *Reuters*, Jan 20. Available: <http://www.reuters.com/article/2012/01/21/us-gm-volt-idUSTRE80J20X20120121>. Accessed: 2 Mar 2015.
- [14] Lienert A. 2012. Fisker reveals cause of Karma fires during Hurricane Sandy. *Edmonds.com*, Nov 6. Available: <http://www.edmunds.com/car-news/fisker-reveals-cause-of-karma-fires-during-hurricane-sandy.html>. Accessed: 2 Mar 2015.
- [15] Ivory D. 2014. Federal safety agency ends its investigation of Tesla fires. *The New York Times*, Mar 28. Available: <http://www.nytimes.com/2014/03/29/business/safety-agency-ends-investigation-of-tesla-fires.html>. Accessed: 2 Mar 2015.
- [16] Burke K. 2014. Driver of stolen Tesla that crashed, split in 2, dies. *Automotive News*, Jul 10. Available: <http://www.autonews.com/article/20140710/OEM11/140719991/driver-of-stolen-tesla-that-crashed-split-in-2-dies>. Accessed: 2 Mar 2015. Detroit, MI: Crain Communications Inc.
- [17] Highway Loss Data Institute. 2011. Injury odds and vehicle weight comparison of hybrids and conventional counterparts. *HLDI Bulletin* 28(10). Arlington, VA.
- [18] National Highway Traffic Safety Administrations. 2015. Fatality Analysis Report System. Available: <http://www.nhtsa.gov/FARS>. FARS data, February. Washington, DC: U.S. Department of Transportation.
- [19] Society of Automotive Engineers. 2014. Safe handling of high-voltage battery systems. Classroom training, Course ID C1019. Available: <http://training.sae.org/seminars/c1019/>. Accessed: 2 Mar 2015. Warrendale, PA.
- [20] Society of Automotive Engineers. 2015. Impact and Rollover Test Procedures Standards Committee meetings. Available: <http://www.sae.org/works/committeeHome.do?comfID=TEVSSTS1>. Accessed: 2 Mar 2015. Warrendale, PA.
- [21] Office of the Federal Register. 2011. *Code of Federal Regulations*; Title 49 Transportation, Part 571 Federal Motor Vehicle Safety Standards, Standard No. 305 Electric-powered vehicles: electrolyte spillage and electrical shock protection. Washington, DC: National Archives and Records Administration.
- [22] Insurance Institute for Highway Safety. 2015. About our tests. Available: <http://www.iihs.org/iihs/ratings/ratings-info/frontal-crash-tests>. Accessed: 2 Mar 2015. Arlington, VA.
- [23] Australasian New Car Assessment Program. 2015. ANCAP safety ratings explained. Available: <http://www.ancap.com.au/safety-ratings-explained>. Accessed: 2 March 2015. Manuka, Australia.
- [24] Paine M, Paine D, Ellway J, Newland C, Worden S. 2011. Safety precautions and assessments for crashes involving electric vehicles. Paper no. 11-0107. *Proceedings of the 11th International Technical Conference on Experimental Safety Vehicles*. Washington, DC: National Highway Traffic Safety Administration.

Appendix A – Electric Vehicle Supplemental Checklist (IIHS)

INSURANCE INSTITUTE FOR HIGHWAY SAFETY VEHICLE RESEARCH CENTER		CHECKLIST	Page: 1 of 2	Electric Vehicle Supplement	COORDINATOR
Safety Measures and Tasks				CENXXXX	
This checklist covers safety related tasks and pre and post-crash measurements.		Vehicle:			
!! HIGH VOLTAGE SYSTEMS ARE NEVER SAFE, THEY CAN ONLY BE CONSIDERED SAFER !!		VIN:			
Initial	Date	Checklist Items			
Pre-Test (before vehicle prep)					
		Type of propulsion battery (e.g. Li-Ion, NiMH, etc.) _____.			
		Manufacturer instructions for installing '305' isolation box received and satisfactory			
		Copy/Paste 'Battery Isolation Worksheet' (Crashworthiness/ <u>ElectricVehicleInformation</u>) into test Data folder			
		Nominal HV battery voltage _____ V & resistor needed for '305' box (at least 500 times nominal battery voltage) _____ Ω			
		Verify propulsion battery is at full state of charge, per readout (varies by car; all but one 'bar' is typically sufficient)			
		Color of HV battery coolant (for leak detection, post-crash)			
Pre-Test Prep (Vehicle) !!! Appropriate Personal Protective Equipment to be worn at ALL TIMES !!					
		Remove positive cable from battery (12v) and then the HV service disconnect (MSD)			
		Tape MSD to roof of vehicle with orange tape !! MSD is to be taped to roof of vehicle whenever it is not installed in the HV battery!!			
		Install '305' box, per manufacturer instructions OR request OEM to install if installation is deemed too hazardous (Caution; the 305 box is now essentially part of the HV system)			
		Install thermocouple on battery (or as close as possible to actual battery housing)			
		Photograph wiring hook-up and routing			
		Check voltage of + and – terminal to vehicle body; both should be zero. If not, STOP and contact manufacturer!			
		Install service disconnect			
		Check battery isolation, using Battery Isolation Worksheet. If results are more than 500 Ω /V, remove service disconnect & tape to roof and continue.....			
		Remove accelerator cable/connector			
		Fabricate a locking plate to hold transmission in 'Neutral' during crash			
		Verify area surrounding HV battery is clear of metal shavings, tools, loose cables, etc.			
		Schedule Fire Department to be on hand during test if vehicle contains Li-Ion battery			
		Verify all HV safety equipment is in Crash Hall and easily accessible, the emergency egress path for vehicle is clear, and forklift present (with fork isolators attached)			

INSURANCE INSTITUTE FOR HIGHWAY SAFETY VEHICLE RESEARCH CENTER		CHECKLIST	Page: 2 of 2	Electric Vehicle Supplement	COORDINATOR
Safety Measures and Tasks				CEN1453	
This checklist covers safety related tasks and pre and post-crash measurements.		Vehicle:			
!! HIGH VOLTAGE SYSTEMS ARE NEVER SAFE, THEY CAN ONLY BE CONSIDERED SAFER !!		VIN:			
Initial	Date	Checklist Items			
Pre-Test (Shed)		!!! Appropriate Personal Protective Equipment to be worn at ALL TIMES !!			
		Prior to Final Checklist, install the service disconnect			
		Record battery isolation, using Battery Isolation Worksheet in Excel (Pre-test). If results are more than 500 Ω/V , continue with final checklist			
Post-Test (Crash Hall)		***Perform Steps Prior to Human Contact With Vehicle***			
		INFORM PEOPLE ON FLOOR TO NOT TOUCH THE VEHICLE UNTIL THE ALL CLEAR IS GIVEN!!			
		Verify there is no toxic gas venting – visual			
		Verify there is no smoke or fire coming from battery			
		Verify there is no battery coolant leakage			
		Record battery temperature (thermocouple reading) _____ °F. Continue to monitor for increase using thermal imager and by monitoring temperature readout			
		Check battery isolation, using Battery Isolation Worksheet in Excel (Post-test). ☐ Greater than 500 Ω/V , continue.... ☐ Less than 500 Ω/V means a potential isolation loss; quarantine vehicle and continue to monitor.....			
		Continue to monitor battery temperature and isolation for 5 minutes. If stable 			
		Continue with typical post-crash analysis			
		Remove service disconnect if possible & tape to roof			
		DO NOT LEAVE VEHICLE IN BUILDING UNATTENDED AT ANY TIME!			
Post-Test (Photo Studio)		!! Appropriate Personal Protective Equipment to be worn at ALL TIMES !!			
		Remove service disconnect as soon as possible & tape to roof			
		Remove '305' box			
		If vehicle has Li-Ion propulsion battery, have observer present when the vehicle is in the building. Move vehicle to secure area outside at end of day (DO NOT LEAVE IN BUILDING UNATTENDED AT ANY TIME!). Vehicle will be quarantined in secure area, with fully charged battery, for at least 2 weeks before allowing manufacturer to discharge it			
		If vehicle propulsion battery is not Li-Ion, the battery should be discharged by manufacturer ASAP and before vehicle is sold for scrap (alternatively, the OE's can take possession of the battery)			