SAFETY PRECAUTIONS AND ASSESSMENTS FOR CRASHES INVOLVING ELECTRIC VEHICLES

Michael Paine
David Paine
Australasian NCAP, Australia
James Ellway
Euro NCAP, Belgium
Craig Newland
Australian Automobile Association, Australia
Stuart Worden
New Zealand Land Transport, New Zealand

Paper Number 11-0107

ABSTRACT

Fully electric vehicles are being introduced to the passenger car market in addition to the already popular hybrid vehicles. There are existing and proposed standards for the design of these vehicles to reduce the risk of occupants and rescue personnel being exposed to hazards such as corrosive chemicals, toxic fumes, fire and electric shock in the event of a crash. Some manufacturers are understood to be working with rescue organisations to develop appropriate procedures for dealing with these crashes.

New Car Assessment Programs (NCAPs) have subjected several petrol-electric hybrid vehicles to the 64km/h frontal offset crash test, 50km/h barrier side impact test and the 29km/h side pole test. No problems with the electrical systems or batteries were encountered. These tests have generally involved vehicles with lead-acid or NiMH batteries. Lithium-ion batteries are becoming popular and these might introduce different hazards for crash-test and rescue personnel.

In October 2010 a research crash test of an electric car with a Lithium-ion battery was conducted by Australasian NCAP and Japan NCAP. Additionally, Euro NCAP has also assessed a number of vehicles powered by Li-ion batteries. This paper reviews the safety hazards and outcomes associated with those tests and provides draft advice for crash test and rescue organisations.

INTRODUCTION

The Australasian New Car Assessment Program (ANCAP), US Insurance Institute for Highway Safety (IIHS) and Euro NCAP have conducted 64km/h frontal offset crash tests since the mid 1990s. Japan NCAP and Korean NCAP also conduct this test. These organisations have also conducted 29km/h side pole tests on many vehicle models.

Almost all the tested vehicles have had conventional fuel systems (petrol or diesel). There have been several cases where there has been a fuel leak due to disruption of fuel lines or rupture of the fuel tank. Out of hundreds of crash tests ANCAP has experienced one minor fire, where an electrical short ignited some foam plastic insulation near the crushed radiator. Another post-crash hazard from conventional vehicles is leakage of battery acid.

Fully electric and electric hybrid vehicles potentially introduce new types of post-crash hazards. This paper reviews those potential hazards and provides advice for minimising risks. It is stressed, however, that experience with electric vehicles is limited and that this advice will need to be reviewed as more information becomes available. It is also acknowledged that vehicles manufacturers have put considerable resources into developing safe and reliable electrical systems for the current generation of electric vehicles. A serious incident involving a lithium-ion car battery is considered to be highly unlikely but it is important that crash test organisations and rescue organisations understand and are prepared for the potential hazards.

ELECTRIC VEHICLE TECHNOLOGY

Electrically-propelled automobiles have been in use for more than a century:

"Stored electricity finds its greatest usefulness in propelling cars and road vehicles, and it has been for this application, primarily, that the Edison storage battery has been developed. Mr Edison saw that there are two viewpoints: that of the electrical man with his instruments, his rules of efficient operation and reasonable life of the battery, his absolute knowledge that the same care should be given a vehicle battery that is given a valued horse or even a railroad locomotive; and that of the automobile driver, who simply wishes to go somewhere with his car, and who, when he arrives somewhere, wishes to go back. And in the long-promised storage battery the highly practical nature of Edison's work is once more exemplified in that he has held uncompromisingly to the automobilist's point of view." (Scientific American, January 1911)

However the popularity of electric vehicles soon declined when electric batteries could not match the price and energy density of petroleum-fuelled vehicles.

Electric hybrid vehicles were developed in response to environmental concerns and the desire to reduce fuel consumption for many modes of driving. Most current hybrid models have had Nickel-Metal Hydride (NiMH) storage batteries. Several of these models have been crash-tested by NCAP organisations and no problems associated with the electrical systems have been encountered. Furthermore, rescue organisations have developed procedures for dealing with crashes involving vehicles with NiMH batteries. Some procedures are model-specific and have been developed in consultation with vehicle manufacturers.

More recently lithium-ion (Li-ion) batteries have been increasingly used for electrical storage – particularly in all-electric vehicles. Li-ion batteries are commonly used in laptop computers and they received somewhat negative reputation due to some fires associated with aircraft travel in the late 1990s.

The US Federal Aviation Authority investigated laptop computer fires in the early 2000s (Webster 2004). It points out that laptop batteries are composed of several cells and it is typical for one cell to ignite first. The aim is to extinguish the flames and prevent the other cells from igniting. The recommendation is to extinguish the flames with a Halon 1211 extinguisher then douse the computer with water. Smothering with ice or other covering should be avoided as this causes the heat to build up and ignite adjacent cells.

Figure 1. Frame from an FAA video "Extinguishing in-flight laptop computer fires"

Dousing with copious amounts water does appear to be successful in these cases but it does contravene the normal advice that water should not be used on lithium fires – since lithium can ignite when it contacts water.

LITHIUM-ION VEHICLE BATTERIES

Li-ion vehicle batteries are much more sophisticated than laptop computer batteries. There are numerous levels of automatically isolating stored electrical energy and they have inbuilt cooling systems to prevent heat build-up under most foreseeable circumstances.

Severe testing of Li-ion car batteries has been conducted:

Sandia National Laboratories' Battery Abuse Testing Laboratory, which has become the de facto automotive battery-testing shop in the U.S. The lab heats, shocks, punctures and crushes batteries to see how safe they would be in crashes and extreme operating conditions.

When lithium-ion cells first came to the laptop market, "the active materials were very energetic. There were some significant field failures," notes Chris Orendorff, the battery lab's team leader. The usual cause was thermal runaway, a chemical reaction that could start from excessive overheating, then potentially cause a cell to catch fire or explode. Although even extreme driving conditions are unlikely to trigger those problems, a crash could, and so could a sudden overcharge - for example, if lightning struck a charging port while a car was being recharged.

Small tweaks in chemistry can make a large difference in how well battery packs resist overheating or exploding. "Half a dozen different chemistries are still being considered as viable" in terms of performance and safety, Orendorff says. Sandia is seeing more designs with lithium iron phosphate cathodes, for example, because they stay cool and suffer little degradation over time. Additionally, batteries with anodes made from lithium titanate seem less likely to overheat even under hot driving conditions. Electrolytes containing different lithium salts are still being tested for greatest stability, too. Manufacturers are also testing a variety of mechanical safety features similar to measures developed to prevent thermal runaway in laptop lithium batteries. (direct quote from Fischetti 2010)

Orendorff (personal correspondence) further advises that Sandia has studied Li-ion batteries under various mechanical abuse conditions, including full battery crush (probably the most relevant to a crash scenario). The biggest concern with these systems is the uncertainty about the battery state-of-health after mechanical abuse. Sometimes connectors can be broken and communication is lost to a part of all of the battery with an unknown amount of energy remaining in the system. Handling and disposal become a significant concern.

Issues related to battery failure upon abuse would be evidence of venting, leaking electrolyte (carbonate solvents are highly flammable), thermal hazards (Sandia observed battery temperatures in excess of 1200 C for high order thermal runaway upon failure) and particulate hazards.

TÜV SÜD Automotive in Germany has also conducted impact testing of Li-ion car batteries. Figure 2 shows a test rig with a cylindrical impactor. Dr L Wech (personal correspondence) advises that the organisation carries out tests that simulate severe deformation of the battery pack in a crash. They use different geometrical forms of the impactor, different masses of the impactor and different impact velocities. Tests are performed in the open air. Staff are equipped with protective clothing and trained fire-fighting personnel are available. The temperature inside the battery is monitored during the tests and for a long time after the test.

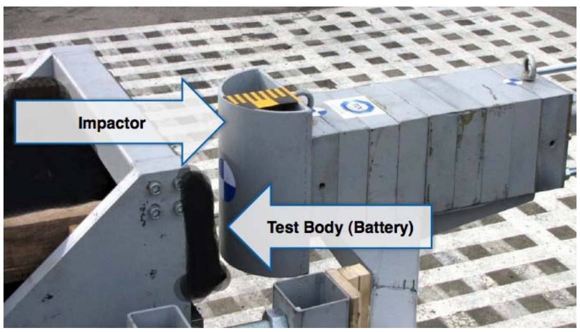

Figure 2. Li-ion battery impact test to be conducted by TÜV SÜD

CRASHES THAT MIGHT CHALLENGE BATTERY INTEGRITY

ANCAP and Euro NCAP have conducted 64km/h offset crash tests of the Mitsubishi i-MiEV electric car. No problems with the battery or high-voltage electrical system were encountered in either crash test and the automatic safety systems operated as designed. In the ANCAP tests (conducted at JARI in Japan) the peak vehicle body deceleration was 38g, measured at the base of the driver-side B-pillar. This deceleration is typical for a small car in this type of crash test (Paine 2009).

Euro NCAP also conducted a 29km/h pole test of the i-MiEV. Again no problems with the battery or high-voltage electrical system were encountered. However, Figure 7 illustrates that the vehicle body deformation came close to the exterior of the battery pack, which is mounted under the rear floor.

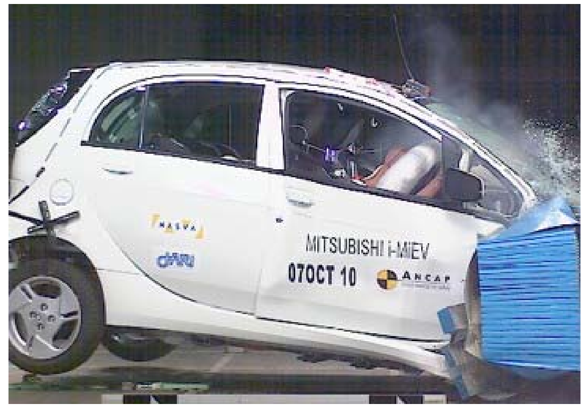

Figure 3. 64km/h offset crash test conducted by JARI for ANCAP

Figure 4. Post-crash electrical tests (ECE 2010)

Figure 5. Visual indicator of active high voltage used by JARI during the ANCAP crash test

The 29km/h pole impact test places severe demands on the vehicle structure. The majority of casualty crashes involving side impacts with narrow objects occur at impact speeds no more than this (Otte 2009). However, higher speed impacts do occur in real-world crashes and it is appropriate to consider the possible consequences of such a crash.

Figure 6. Overhead view at peak of 29km/h pole impact test of an i-MiEV (Euro NCAP)

Figure 7. Post-crash underside view of vehicle deformation. Battery pack is under the plastic panel at left (Euro NCAP)

ANCAP recently conducted a research crash test where a medium size (non-electric) sedan was subjected to a side pole crash test with the impact speed increased to 50km/h. A side pole test at 29k/h had already been conducted and so the vehicles could be compared. Figures 8-11 show the comparisons.

It is evident that there is substantially more intrusion in the 50km/h impact, including the rear floor area, compared with the 29km/h impact. Of course, no battery was present in this test and so no conclusion can be drawn about the likelihood of battery damage. However the test does suggest that further research should be conducted into this mode of crash with electric vehicles.

A50km/h side pole impact is a very severe crash and there is a high likelihood of occupant fatality (based on Otte 2009). The main concern with electric vehicles is the potential danger to rescuers and other road users.

Figure 8. ANCAP research crash test at 50km/h

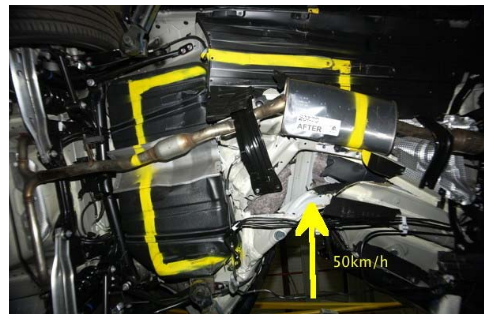

Figure 9. Underside of 50km/h vehicle. The yellow rectangle shows the approximate location of the rear floor area.

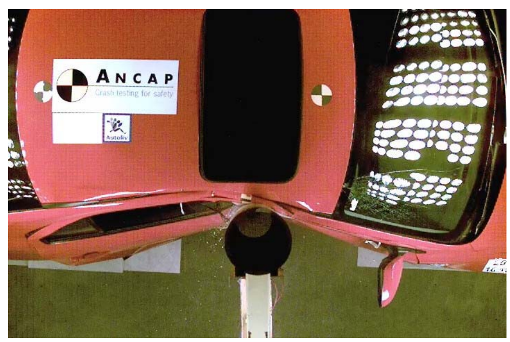

Figure 10. Same model in 29km/h impact

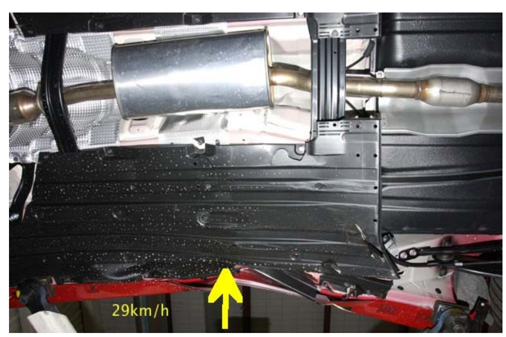

Figure 11. Underside of 29km/h vehicle. Rear is to the right.

In a multi-vehicle crash the other issue to consider is the risk of the other vehicle catching fire and the fire spreading to the electric vehicle. Digges (2009) reports that in 1% of vehicle fatalities in the USA fire is recorded as the most harmful event. Fires are recorded in 0.2% of NASS cases (weighted). A provisional assessment is therefore that the probability of an electric vehicle with an Li-ion battery colliding with a conventional vehicle that catches fire is extremely low.

POST-CRASH PROCEDURES

The Appendix sets out possible procedures for dealing with crashes involving vehicles with Li-ion batteries. This is based on a review of available documentation from manufacturers and emergency rescue organisations. It was found that information was somewhat sketchy and was sometimes contradictory. Some examples are given below.

Vehicle manufacturer A: "In case of vehicle fire, inform fire department immediately and start extinguishing the fire if possible.

1) By fire extinguisher. Use the type of fire extinguisher which is suitable for flammable liquid or electrical equipment fires.

2) By water. NEVER EXTINGUSH BY SMALL VOLUME OF WATER. It is quite dangerous. This is only possible if you can use a large volume of water (e.g. from fire-hydrant), otherwise wait for fire department to arrive on the scene."

Vehicle manufacturer B: "In case of vehicle fire, contact the fire department immediately and extinguish the fire if possible... In case of extinguishing fire with water, large amounts of water from a fire hydrant (if possible) must be used. DO NOT extinguish fire with a small amount of water. Small amounts of water will make toxic gas produced by a chemical between the Li-ion battery electrolyte and water. In the event of small fire, a Type BC fire extinguisher may be used for an electrical fire caused by wiring harness, electrical components, etc. or oil fire"

A manual for vehicle rescuers: "*Do not use water* or foam to extinguish lithium-ion battery fires. Extinguish lithium-ion battery fires with dry sand, sodium chloride powder, graphite powder, or copper powder. *Copious amounts of water and/or foam can be used* on electric vehicle fires with no danger to response personnel of electrical shock. Cleanup lithium-ion electrolyte spills with dry sand or other noncombustible material and place into container for disposal."

CONCLUSIONS

Further research should be conducted into the robustness of Li-ion batteries in a crash situation. In particular, investigation should consider the types and severities of crash that can be expected to place severe demands on in the in-built safety systems of electric vehicles and their batteries.

Further research is also needed to develop appropriate and consistent post-crash procedures for dealing with electric vehicles, including fires. A draft for such procedures is provided in the Appendix.

In the case of crash test organisations, there are several extra pre-crash arrangements that should be put into place in preparation for an electric vehicle crash test (also set out in the Appendix). Based on this initial research, consideration should be given to having available special fire-fighting equipment, as well as thermal imaging equipment, to remotely check for hot-spots around key vehicle components, and a gas monitor to check for flammable or toxic gases) near the crashed vehicle.

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APPENDIX - DRAFT PROCEDURES FOR CRASHES INVOLVING ELECTRIC VEHICLE WITH LITHIUM-ION BATTERIES

Caution: There are inconsistencies in the referenced advice for dealing with fires that involve lithium-ion batteries. Further research is necessary to resolve these inconsistencies. The following procedures are provided as a basis for development of an international procedure for this purpose and are not intended to be applied in real-world situations in their current form.

PRE-CRASH PREPARATIONS

1) Train staff in use of a (recommended) thermal imaging equipment to locate hot spots in the vehicle after the crash

2) Train staff in use of a (recommended) gas monitor unit for detecting flammable and toxic gases

3) Conduct a trial run of manufacturer's rescue manual, including operation of the (manual) battery isolation switch, backup procedures (if any) if the isolation switch is not operable (e.g. due to crash damage), identification of high voltage components, identification of battery fluid leaks and external battery damage and, if available, procedures to safely discharge the battery (which should be fully charged for the crash test)

4) Measure the electrical resistance at key points, in accordance with ECE/TRANS/WP .29/2010/122 (the same points are also measured after the test, when the vehicle has been declared safe for post-crash assessment). Also fit an external indicator in a prominent exterior location (such as the C-pillar) to show when the high voltage circuit is active.

5) Assess evacuation routes for all personnel who will attend the crash test. From every observation area there must be an evacuation route that does not involve approaching the crash test area. Also determine evacuation assembly points and head-count procedures.

6) Train appropriate staff in fire fighting procedures and ensure there is suitable fire-fighting equipment, including high volume water hoses that will reach the crash test area and protective clothing/equipment.

7) Develop and implement a plan for containment of leaked hazardous fluid

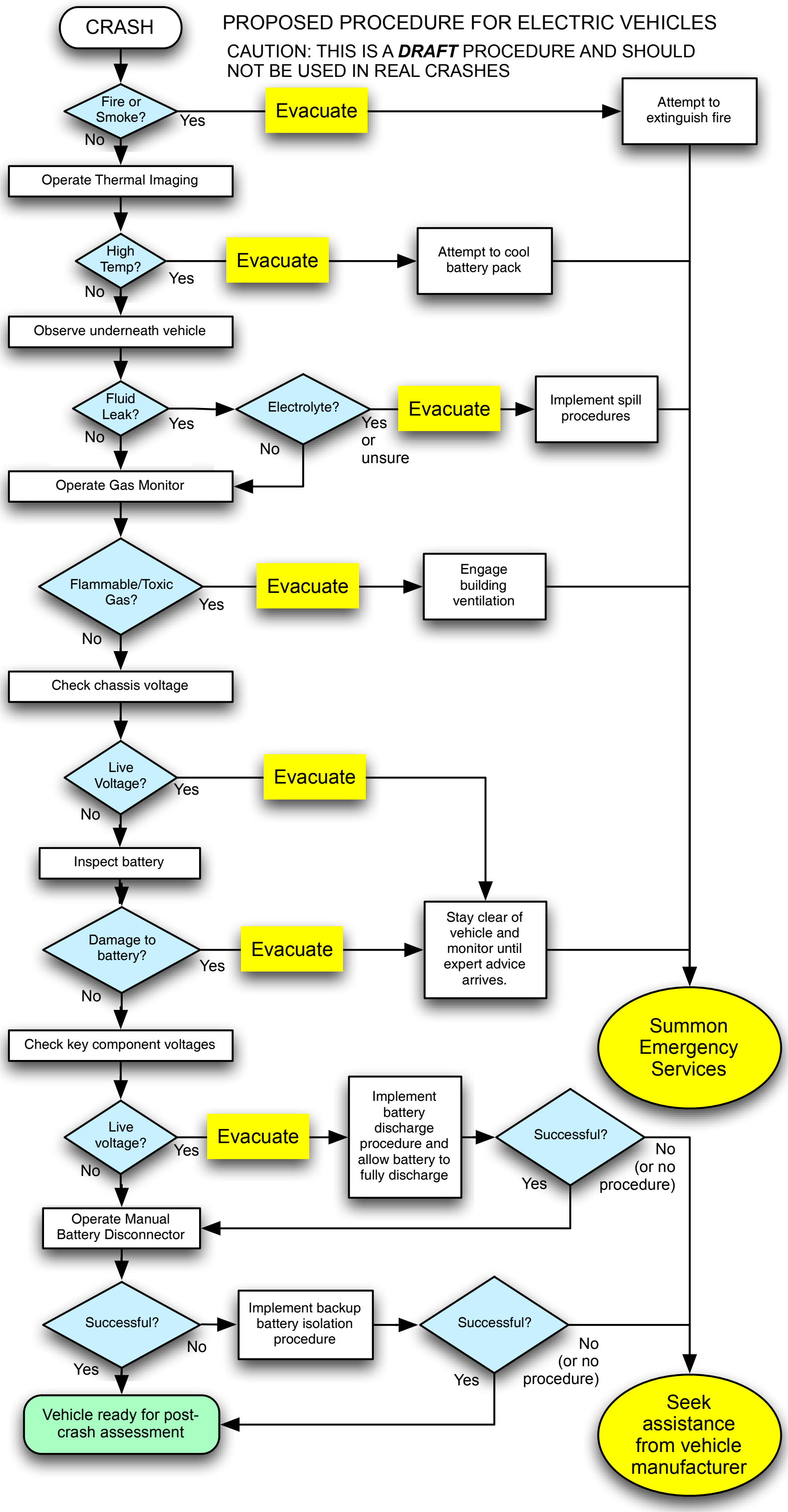
8) Notify local emergency services of the proposed crash test date and time and provide them with necessary information, including the circumstances under which they might be summoned (see flow chart). Where possible, emergency service personnel should attend the crash test (this can be useful experience for these personnel).

9) Notify the vehicle manufacturer and determine a contact person with appropriate technical knowledge who will be available (preferably in person) at the time of the crash test

10) Prior to the crash test inform all observers about the potential hazards (fire, smoke, toxic gases, hazardous liquids), the signal for evacuation, the evacuation routes and the assembly points

POST-CRASH PROCEDURES

The draft flow diagram overleaf indicates the step to be taken to ensure that it is safe to conduct a post-crash inspection of the vehicle.


CRASH
PROPOSED PROCEDURE FOR ELECTRIC VEHICLES
CAUTION: THIS IS A ***DRAFT*** PROCEDURE AND SHOULD NOT BE USED IN REAL CRASHES
Fire or Smoke?
Yes
No
Evacuate
Attempt to extinguish fire
Operate Thermal Imaging
High Temp?
Yes
No
Evacuate
Attempt to cool battery pack
Observe underneath vehicle
Fluid Leak?
Yes
No
Electrolyte?
Yes or unsure
No
Evacuate
Implement spill procedures
Operate Gas Monitor
Flammable/Toxic Gas?
Yes
No
Evacuate
Engage building ventilation
Check chassis voltage
Live Voltage?
Yes
No
Evacuate
Inspect battery
Damage to battery?
Yes
No
Evacuate
Stay clear of vehicle and monitor until expert advice arrives.
Summon Emergency Services
Check key component voltages
Live voltage?
Yes
No
Evacuate
Implement battery discharge procedure and allow battery to fully discharge
Successful?
Yes
No (or no procedure)
Operate Manual Battery Disconnector
Successful?
Yes
No
Implement backup battery isolation procedure
Successful?
Yes
No (or no procedure)
Vehicle ready for post-crash assessment
Seek assistance from vehicle manufacturer