Post-crash Fuel Leakage and Fire Safety Experiments for Hydrogen Vehicles

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ABSTRACT

Federal Motor Vehicle Safety Standards (FMVSS) for fuel system integrity set limits for fuel spillage during and after crashes to reduce the occurrence of deaths and injuries from fire. FMVSS 301 and 303 respectively specify post-crash limits for liquid fuels and compressed natural gas (CNG) [1, 2]. These limits have been used as a benchmark for setting leakage limits for hydrogen, based on energy equivalence, in industry standards and proposed or enacted international regulations [3, 4]. However the properties of hydrogen with regard to leak behavior and combustion are very different from those of liquid fuels or CNG. Gasoline will pool and dissipate slowly. CNG and hydrogen will rise and dissipate more rapidly. Hydrogen has a much wider range of flammability in air than most fuels, including CNG: 4% to 75% for hydrogen versus 5% to 15% for CNG. Therefore, a research program was developed and executed to assess the safety of the proposed allowable leak rate for hydrogen, through leak and ignition experiments in and around vehicles and vehicle compartment simulators.

INTRODUCTION

NHTSA has been involved in alternative fuel vehicle safety research and regulation going as far back as 1978. At that time, pursuant to the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976, NHTSA was charged with assisting the Department of Energy (DOE) in determining the applicability of the FMVSS's to electric and hybrid electric demonstration vehicles.

In the late 1980's and early 1990's additional legislation promoted the use of alternative fuels, including CNG. NHTSA responded to these initiatives by collecting information and conducting research which supported the promulgation of new standards setting crash integrity requirements for CNG vehicles, and life cycle strength, durability, and pressure relief requirements for high pressure natural gas storage cylinders (FMVSS 303, FMVSS 304).

The 2002 launch of the FreedomCAR and Hydrogen Fuel Initiative, a cooperative research partnership between government and industry to advance hydrogen fuel cell vehicle technology, led to initiation in 2006 of NHTSA's current, complementary effort to assess the safety of these unique fuel systems. Little real world data exists concerning the safety of hydrogen storage and high voltage fuel cell electrical systems. Therefore, NHTSA is conducting research to assess several aspects of hydrogen fuel system integrity and has initiated program tasks to develop data and test procedures in the following five areas:

- Safety of proposed fuel leakage limits for hydrogen fuel systems;
- Vulnerability of high-pressure hydrogen storage to impact loading;
- Cumulative expected/extended service life cycle testing of hydrogen storage cylinders;
- Electrical safety of high voltage fuel cell systems in crashes;
- Mitigation of explosion hazards posed by localized flame exposure on high-pressure composite storage cylinders.

This paper discusses the results of the first task listed above: The safety of the proposed allowable leak rate of hydrogen post-crash, which is based on energy equivalence to one ounce per minute of gasoline as specified in FMVSS 301, Fuel System Integrity or an equivalent amount of CNG as allowed in FMVSS 303, Fuel System Integrity of Natural Gas Vehicles.

This effort involved three series of experiments to assess the proposed allowable post-crash leak rate:

- Subtask A: Leak rate vs. concentration buildup in and around an intact automobile;
- Subtask B: Ignition and combustion tests in

an automobile compartment simulator (ACS) containing known concentrations of hydrogen;

- Subtask C: Full-scale leak, ignition and fire tests on intact and crashed automobiles

Because hydrogen fuel cell vehicles are currently in development, prohibitively expensive, and number only in the hundreds worldwide, none were available for the type of destructive testing required in this assessment. Therefore surrogates, in the form of an automobile compartment simulator, or late model conventional vehicles, were used to conduct the experiments.

A total of 88 tests were conducted in subtasks A, B, and C. Subtask A consisted of 15 tests: 14 were hydrogen accumulation tests in an intact vehicle and one was a sensor response test. Subtask B consisted of 19 tests in the ACS: 11 were accumulation tests and 8 were ignition tests. Subtask C consisted of 54 tests in intact, front, side and rear impacted vehicles that were obtained from other test programs: 39 of these tests were on accumulation, 8 were ignition tests, and 7 were sensor response time tests.

Battelle conducted this test program under contract DTNH22-08-D-00080.

DESCRIPTION OF EXPERIMENTS

Subtask A: Leak rate vs. concentration buildup in and around an intact automobile

A series of tests were conducted to simulate the effects of hydrogen leaks in and around a test vehicle in four locations: Under the vehicle, into the trunk, into the passenger compartment and under the hood. The reference leakage flow rate was 118 normal liters per minute (nlpm), which was derived from the energy equivalence of the allowable leakage rates in FMVSS 301 and 303. Subsequent tests utilized the traditional Bruceton "up-and-down method," at half and double the reference flow rate. The intent was to determine the role of flow rate in creating hazardous conditions. Hydrogen concentration data was recorded from initiation of the leak to either 60 minutes (per FMVSS 303) or until steady state concentration was achieved. Additionally in some tests the concentration decay time for the hydrogen remaining in the vehicle was also recorded. The decay time was a function of how rapidly hydrogen could escape through various routes in the vehicle compartment without an active or passive hydrogen venting system in place.

Test Facility, Instrumentation and Hardware

Tests were conducted at Battelle's High Energy Research Laboratory Area (HERLA) inside a 42-ft diameter blast containment chamber. The test vehicle was a 2008 Mitsubishi Lancer. Figure 1 shows the test vehicle in the blast chamber.

Figure 1. Mitsubishi Lancer in HERLA blast chamber for indoor testing of hydrogen leaks in and around a vehicle

The vehicle was equipped with an array of 12 hydrogen sensors positioned at specific locations as follows:

- 3 in the trunk compartment;
- 3 in the rear of the passenger compartment;
- 3 in the front of the passenger compartment;
- 3 in the engine compartment

The sensors were positioned at 10%, 50% and 90% of the vertical dimension of each compartment, along the vehicle center line, except in the case of the engine compartment, where a modified placement was necessary due to spatial constraints. Figures 2 and 3 show the positioning of the trunk and passenger front seat sensor suites.

Figure 2. Positioning of trunk sensors at 10%, 50%, and 90% heights

Figure 3. Positioning of front passenger compartment sensor suite at 10%, 50%, and 90% heights

<u>Hydrogen leak locations</u> The flow of hydrogen originated from specific locations into or underneath the vehicle as follows:

- 1 leak fed directly into the trunk
- 1 leak directly into the passenger compartment
- 1 leak straight up under the vehicle
- 1 leak straight down under the vehicle
- 1 leak at 45 degrees forward and down under the vehicle
- 1 leak at 45 degrees rearward and down under the vehicle
- 1 leak at 45 degrees forward and up toward the firewall

Figures 4, 5, and 6 photographically illustrate interior and exterior leak locations.

Figure 4. Hydrogen leak originating in the trunk

Figure 5. Hydrogen leak originating in floor of passenger compartment

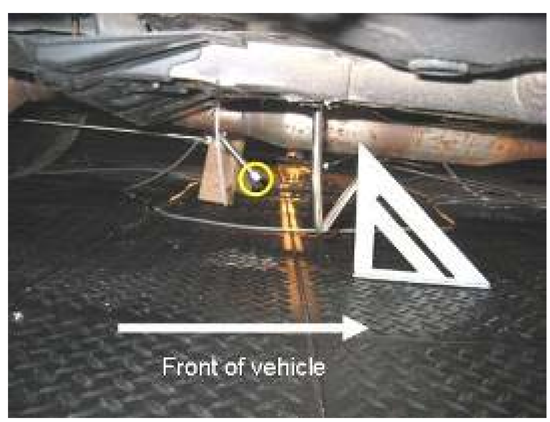

Figure 6. Hydrogen leak 45 degrees forward from the tank position underneath the vehicle

Test matrix The test matrix for the leak and accumulation tests is shown in Table1. Hydrogen concentration levels were monitored for 60 minutes or until steady-state was achieved. Tests 1 and 2 used a flow diffuser to provide less turbulence in the leak and limit mixing of the hydrogen with air. The remainder of the tests were conducted without the diffuser on the open end of the tubing, creating turbulence similar to a sheared fuel line.

Table 1
Test Matrix for Subtask A, Leak rate vs. concentration build-up in and around an intact vehicle

<table>
<tr><th colspan="2" rowspan="2">Leakage Location</th><th colspan="4">Flowrate of Hydrogen
(nlpm)</th><th rowspan="2">Duration
(min)</th></tr>
<tr><th>0</th><th>58</th><th>118</th><th>239</th></tr>
<tr><td colspan="2" rowspan="5">Trunk</td><td>--</td><td>--</td><td>Test 1*</td><td>--</td><td rowspan="9">60</td></tr>
<tr><td>Test 1 decay</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>--</td><td>--</td><td>Test 4</td><td>--</td></tr>
<tr><td>--</td><td>Test 11</td><td>--</td><td>--</td></tr>
<tr><td>--</td><td>--</td><td>--</td><td>Test 12</td></tr>
<tr><td colspan="2" rowspan="3">Passenger compartment</td><td>--</td><td>--</td><td>Test 5</td><td>--</td></tr>
<tr><td>Test 5 decay</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>--</td><td>--</td><td>Test 13</td><td>--</td></tr>
<tr><td rowspan="8">Under vehicle</td><td rowspan="4">Up</td><td>--</td><td>--</td><td>Test 2*</td><td>--</td></tr>
<tr><td>--</td><td>Test 8</td><td>--</td><td>--</td><td>30</td></tr>
<tr><td>--</td><td>--</td><td>Test 10</td><td>--</td><td rowspan="3">60</td></tr>
<tr><td>--</td><td>--</td><td>--</td><td>Test 9</td></tr>
<tr><td>down</td><td>--</td><td>--</td><td>Test 6</td><td>--</td></tr>
<tr><td>45° forward</td><td>--</td><td>--</td><td>Test 3</td><td>--</td><td rowspan="2">30</td></tr>
<tr><td>45° rearward</td><td>--</td><td>--</td><td>Test 7</td><td>--</td></tr>
<tr><td>engine</td><td>==</td><td>--</td><td>--</td><td>Test 14</td><td>60</td></tr>
</table>

*Test conducted with diffuser on end of tubing as opposed to tube being open-ended

Data recording and analysis As previously mentioned, hydrogen concentration data were recorded for three different leak rates at 12 positions in the Lancer. The purpose of the tests was to determine if, when, and how long the hydrogen concentration fell within the combustible regime of 4% to 75% hydrogen in air. The following graphs display spatial hydrogen concentration vs. time for representative tests. A yellow band highlights the flammability range of 4% to 75% hydrogen in air, and a darker yellow band denotes the stoichiometric concentration level of 28% to 32%. The data show that leak location dictated the extent to which hydrogen accumulated in the individual vehicle compartments. (Figures 7 and 8).

Leaks directly into the vehicle trunk or the passenger compartment resulted in combustible concentrations regardless of flowrate: 58, 118, or 239 nlpm. Figure 9 shows a comparison of the concentration levels attained in the trunk at various leak rates. The slowest leak rate of 58 nlpm resulted in a near-stoichiometric steady-state concentration in the top of the trunk, with the higher rate of 239 nlpm reaching the upper flammability limit throughout the trunk compartment.

The under-vehicle leaks did not result in any appreciable concentration levels inside the vehicle. The only under-vehicle leak to result in a combustible concentration was the one directed up toward the firewall at 239 nlpm. A peak concentration of under 10% hydrogen at the 10% sensor height location in the engine compartment occurred early in the test and over time fell below 4%.

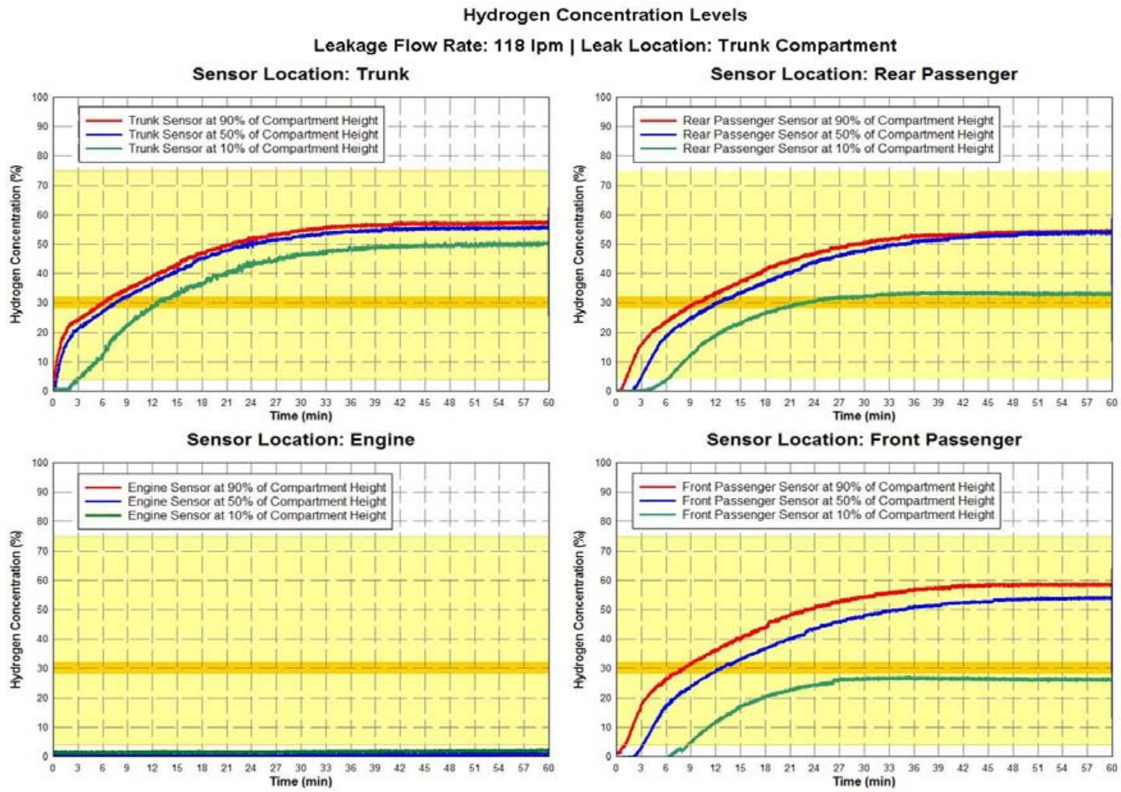

Figure 7. Test Number 4 - 118 nlpm into Lancer trunk compartment

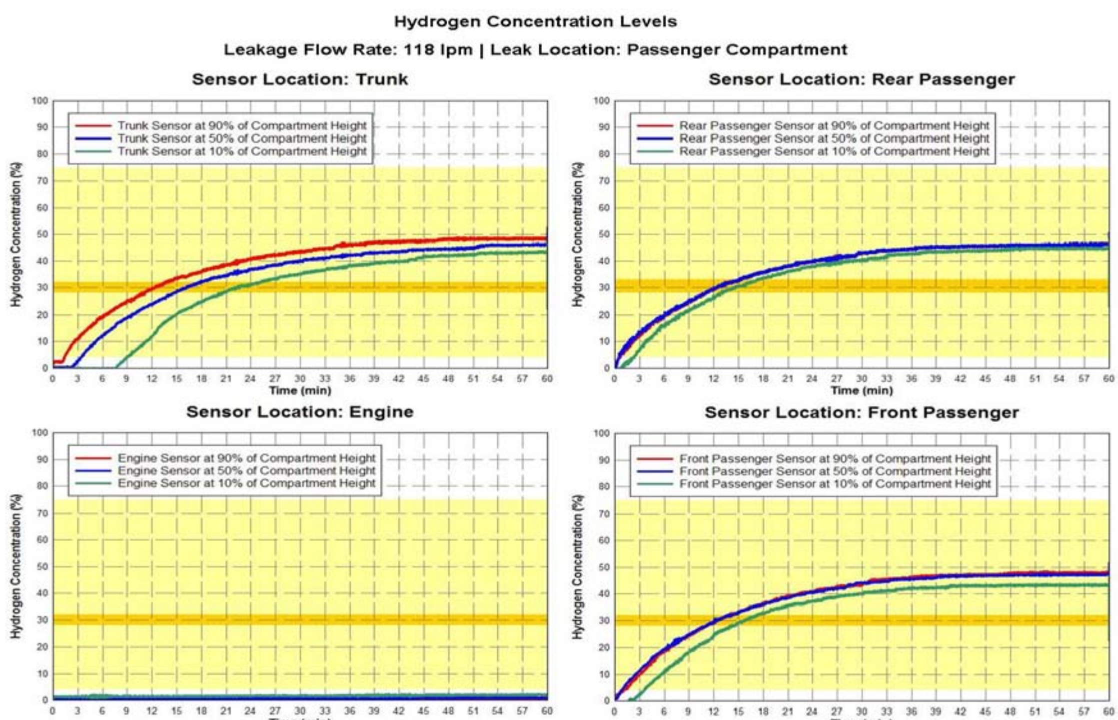

Figure 8. 118 Test Number 5 – 118 nlpm into Lancer passenger compartment

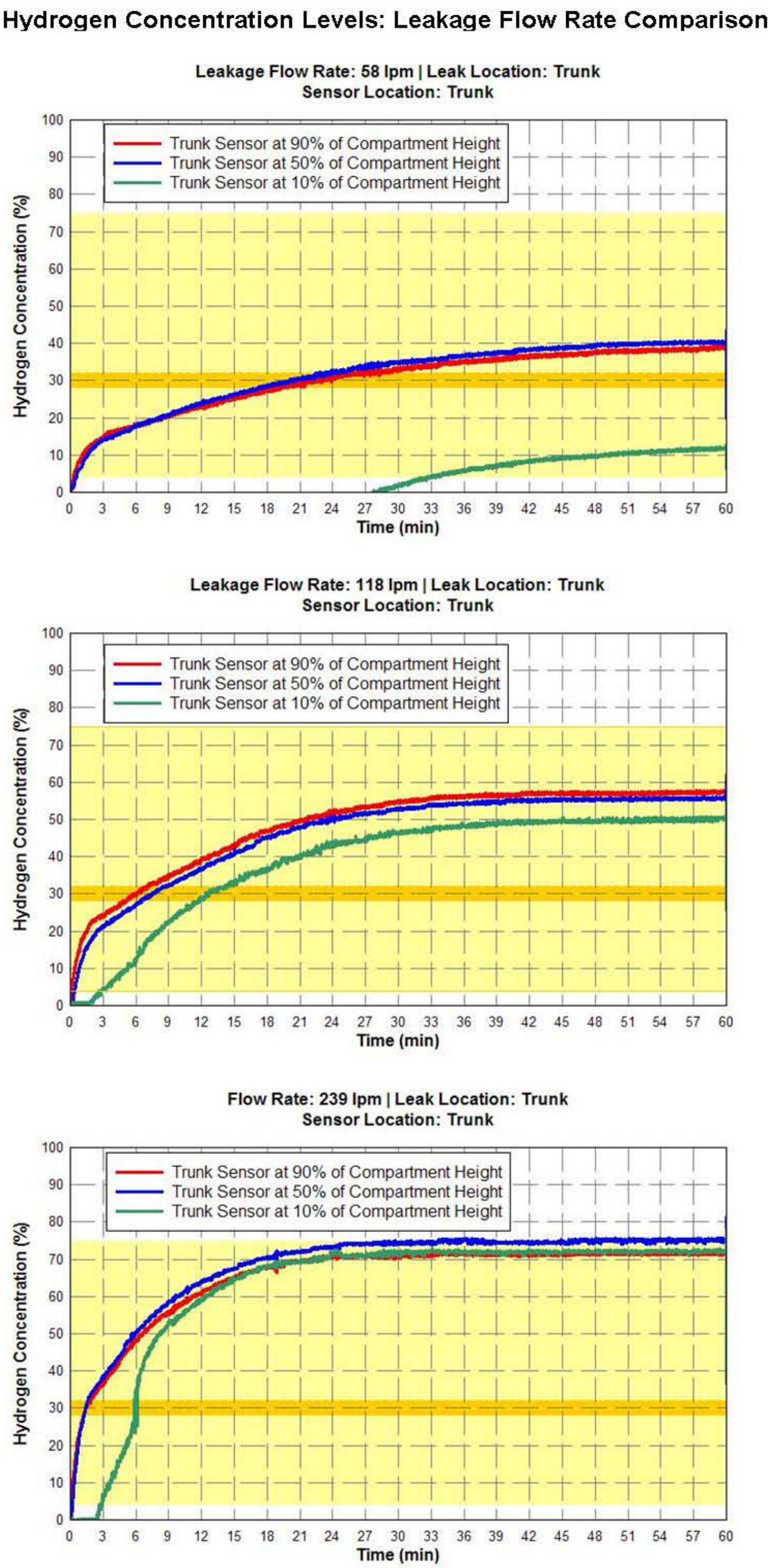

Figure 9. Hydrogen concentration levels: flow rate comparison

Post-leak decay The decay rate of hydrogen concentration following cessation of hydrogen flow was recorded for several tests. These data were used to assess how long a combustible mixture remained in the vehicle after the source leak was removed. Figure 10 shows the decay rate of hydrogen by compartment and stratification layer for an additional 60 minutes after the hydrogen injection test was complete. The data show that hydrogen is depleted from the lower regions first, most likely as a function of hydrogen moving up or out through various pathways as it is replaced by heavier air molecules. From the data presented, without ventilation the hydrogen concentration remains within the flammability range for the hour after the source of the leak was removed.

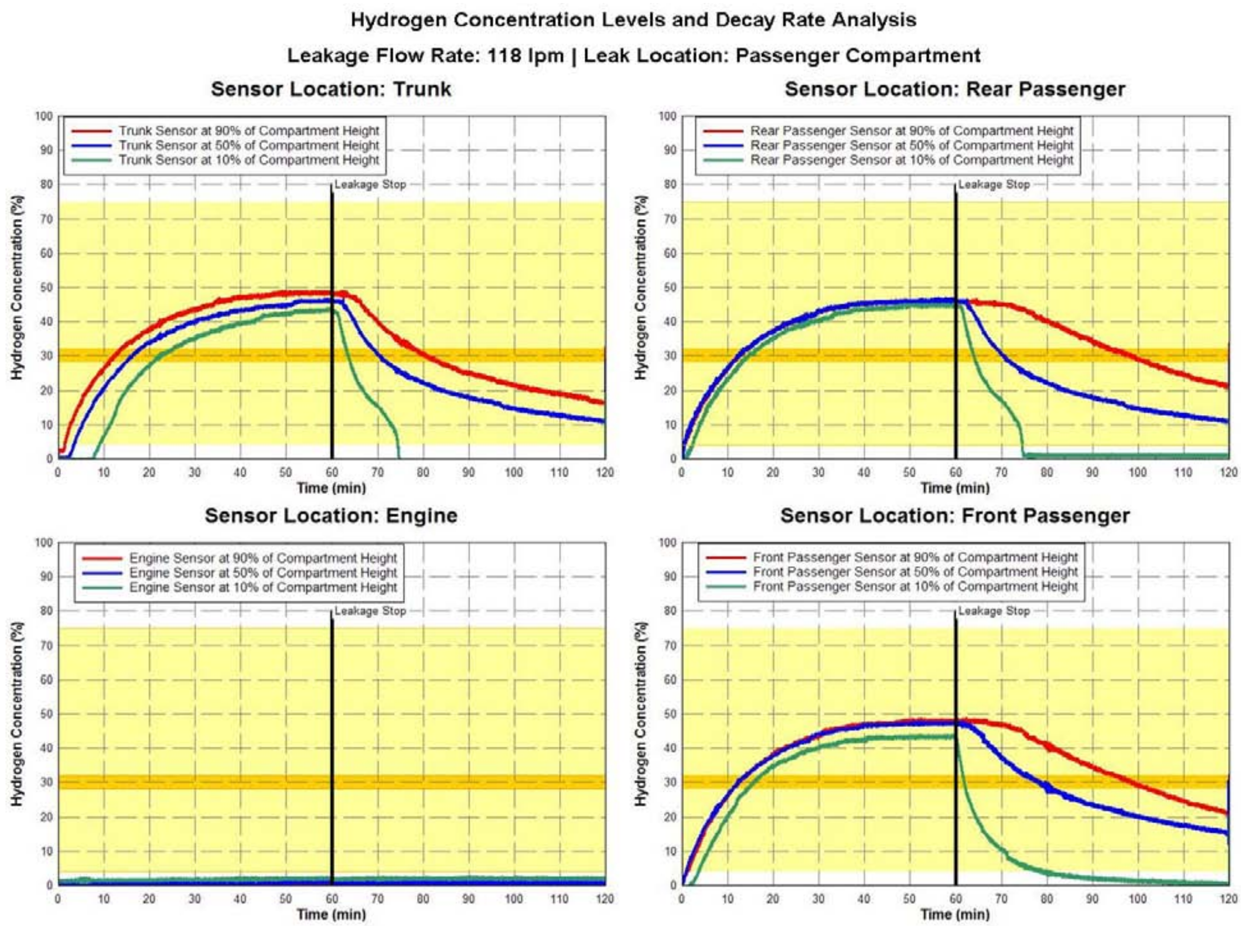

Figure 10. Hydrogen concentration rise and decay times

Subtask B: Ignition and combustion tests in an automobile compartment simulator (ACS) containing known concentrations of hydrogen

The scope of this task was to measure the heat flux and overpressure created subsequent to ignition, if combustible levels of hydrogen were to accumulate in the trunk or passenger compartment from a post-crash fuel system leak. These tests were conducted in an ACS that approximately reconstructed the geometry and volumes of the trunk and passenger compartment of the 2008 Mitsubishi Lancer test vehicle used in Subtask A. The purpose of the ACS was to allow multiple ignition tests that would not be possible in an automobile due to the resultant damage. The ACS was constructed with breakaway steel and Lexan panels that could be easily replaced to allow multiple ignition tests in a short period of time and using minimal resources. During the ignition tests, an instrumented manikin (Denton Hybrid III) was utilized to measure relevant burn (heat flux) and overpressure injury characteristics from the combustion of hydrogen mixtures.

Specific accumulation levels were selected for the ignition experiments representing just over the minimum flammability limit (5%), fuel-lean (15%), stoichiometric (30%), and fuel rich (60%) levels of hydrogen in air.

Test matrix Two types of tests were conducted in Subtask B. Accumulation calibration tests, and ignition tests. The accumulation tests focused on obtaining a representative leakage rate between the trunk and passenger compartment of the ACS that approximated the flow characteristics of the leak tests in the Mitsubishi Lancer in Subtask A. For the purposes of this paper, only the ignition tests will be discussed. Table 2 shows the test matrix for the Subtask B ignition tests.

Table 2
ACS Ignition Tests

Ignition Tests			
Leakage Location	**Test #**	**Hydrogen Concentration (%)**	**Leak Duration (min:sec)**
Trunk	32	5	1:30
	33	15	4:30
	34	60	24:30
Passenger compartment	24	15	5:00
	25	15	4:30
	26	30	20:00
	28	60	24:30
	29	5	1:30

Data recording and analysis For the hydrogen accumulation calibration tests, a suite of sensors, similar to those used in the Mitsubishi Lancer in Subtask A, were installed at the 10%, 50% and 90% height locations of the trunk and passenger compartment. A series of calibration tests were conducted to determine the time at which the target concentrations of hydrogen were achieved. For the ignition tests, only the 50% sensors were left in place to avoid damaging the entire arrays.

Overpressure transducers were mounted on a test stand outside the ACS and on the manikin at the right ear, mouth, and left chest. Heat flux sensors were mounted at several discrete positions on the manikin as shown in Table 3 and Figure 11.

Table 3
Manikin Heat Flux Sensors

Right eye (A)	Left outer wrist (I)
Right cheek (B)	Right palm (J)
Left cheek (C)	Left backside hand (K)
Right shoulder (D)	Right hand between fingers (L)
Right underarm (E)	Left hand between fingers (M)
Left underarm (F)	Groin (N)
Right inner elbow (G)	Right back knee (O)
Right inner wrist (H)	

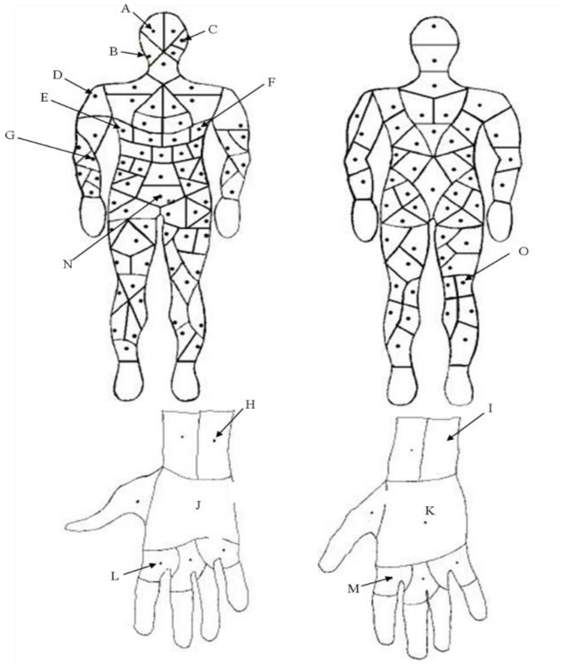

Figure 11. Heat flux sensor locations on manikin

A heat flux sensor was also mounted on the test stand outside the vehicle, just forward of the B-pillar, to measure thermal exposure experienced by anyone, such as first responders, approaching the outside of the vehicle.

The heat flux measurements were processed using the BURNSIM computer model to predict potential burn injury [5]. BURNSIM uses heat flux data to compute the tissue temperature as a function of exposure time and depth. The model determines the burn depth, and by extension, the degree of injury.

Hydrogen ignition tests Calibration tests in the Lancer and in the ACS showed stratification, inversion, and a lack of uniform mixing of hydrogen. Ignition time was selected based on calibration curves when the sensor at the 50% height reached the target concentration level. Results from representative tests are discussed below.

Test 29: 5% ignition, passenger compartment Leak The ASC panels were held in place with magnets. All exterior panel seams were taped with duct tape, and hydrogen sensors were positioned at the 50% trunk and front seat passenger compartment levels. The ignition source was located on the dashboard. The right underarm, back knee, left outer wrist, and left cheek heat flux sensors were not used in this test. The setup for test 29 is shown in Figure 12.

Figure 12. Test 29 ACS setup

Heat flux sensors in the right eye, right check, right shoulder, right inner elbow, left underarm, right inner wrist, right hand between fingers, left hand between fingers, and left hand backside positions registered thermal levels that could result in first- or second-degree burns. The heat flux sensor on the test stand outside the ACS did not detect any significant radiant energy. No detectable overpressure was observed. No luminous combustion was observed using high-speed imagery. The panels remained attached to the ACS, but displayed slight bulging.

<u>Test 33: 15% ignition, trunk leak</u> In this test heat flux sensors located in the right back knee, right underarm, left cheek, right inner wrist, and left outer wrist were not used. Figure 13 shows the concentrations recorded in the Lancer and ACS calibration tests, and in the ignition test.

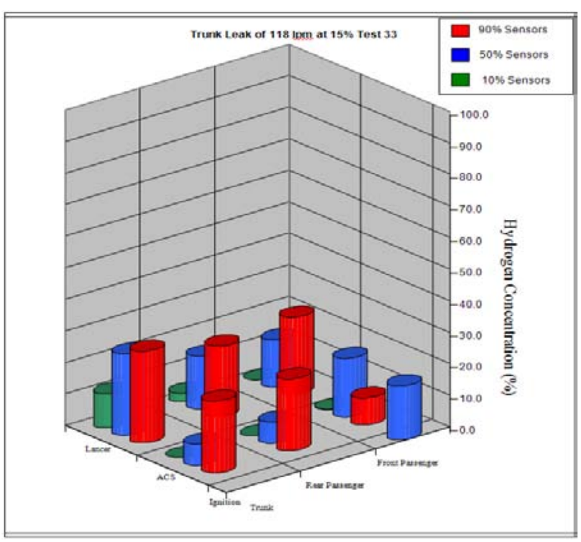

Figure 13. Calibration and ignition at 15% hydrogen in air

Sensors in the right eye, right cheek, right shoulder, right inner elbow, groin, left underarm, right hand palm, right hand between fingers, and left hand between fingers, detected heat fluxes that could cause second-degree burns. No overpressure was measured by the pressure transducers. High speed stills in Figure 14 show some luminosity during combustion. The slight overpressure from combustion caused panels to separate from the ACS framework.

Figure 14. High speed stills showing combustion in Test 33.

<u>Test 26: 30% ignition, passenger compartment leak</u> This test was expected to be the worst case, as the ignition target was the stoichiometric concentration of hydrogen in air. The BURNSIM injury predictions are provide in Table 4. The highest temperature occurred at the left outer wrist, with the most severe depth occurring at the right palm. The heat flux recorded at the test stand also could pose serious burn injury potential to other persons at this location.

Table 4
BURNSIM data for Test 26 (30% hydrogen)

Sensor Location	Degree of Burn	Maximum Temperature (°C)	Burn Threshold Depth (µm)
Right Eye	1st	146	111
Left Cheek	1st	100	35
Right Cheek	2nd	113	364
Right Shoulder	1st	76	113
Right Inner Elbow	2nd	215	1240
Right Underarm	2nd	180	431
Right Back Knee	2nd	122	195
Right Inner Wrist	2nd	251	857
Right Hand Palm	2nd	187	1317
Right Hand between Fingers	2nd	238	252
Left Outer Wrist	2nd	267	696
Left Hand Backside	2nd	174	1281
Left Hand between Fingers	2nd	187	132
Test Stand	1st	133	175

Significant overpressure was generated inside the passenger compartment during combustion, apparently a transition from deflagration to detonation. Low pressures are evident at about 15 msec and rapidly transition to about 80 psi at about 22 msec. Assuming that time zero is defined as the time at which the spark is applied (zero induction time) and that the shock front was measured at the window (37 in. away on the test stand), the approximate velocity of the combustion is ≈ 2400 ft/sec, about twice (Mach 2) the speed of sound. The three separate shocks observed at the test stand location can be rapid, separate detonations of the front, rear, and then trunk compartment volumes. Figure 15 is an overpressure composite. The consequence of this overpressure exposure is probably lethal to passengers [6].

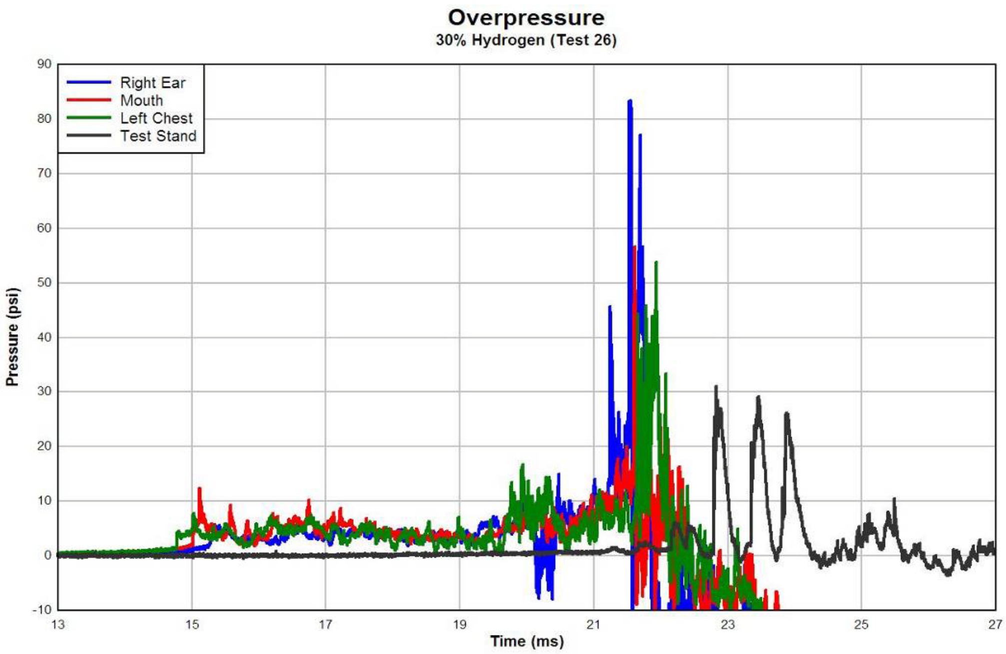

Figure 15. Test 26: pressure vs. time, 30% hydrogen in ACS

Figure 16 shows the ignition event in Test 26.

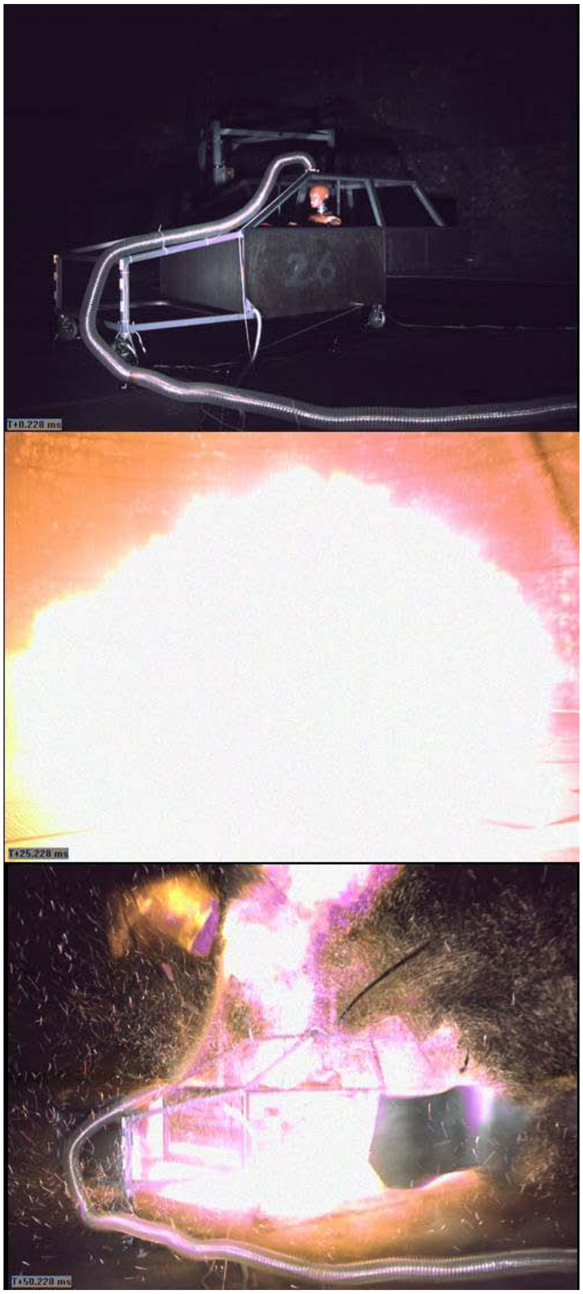

Figure 16. High-speed stills showing detonation and separation of ACS panels in Test 26

Test 34 : 60% ignition, trunk leak This test represented a fuel rich environment closer to the upper flammability limit of 75% hydrogen in air. BURNSIM data predicted second degree burns on the manikin and at the test stand outside the ACS. A small overpressure resulted from combustion of this test of just over 1 psi, the physiological consequence of which is 20% probability of eardrum rupture [7]. Figure 17 shows stills from the comparatively long duration fireball and separation of the panels from the ACS in this test.

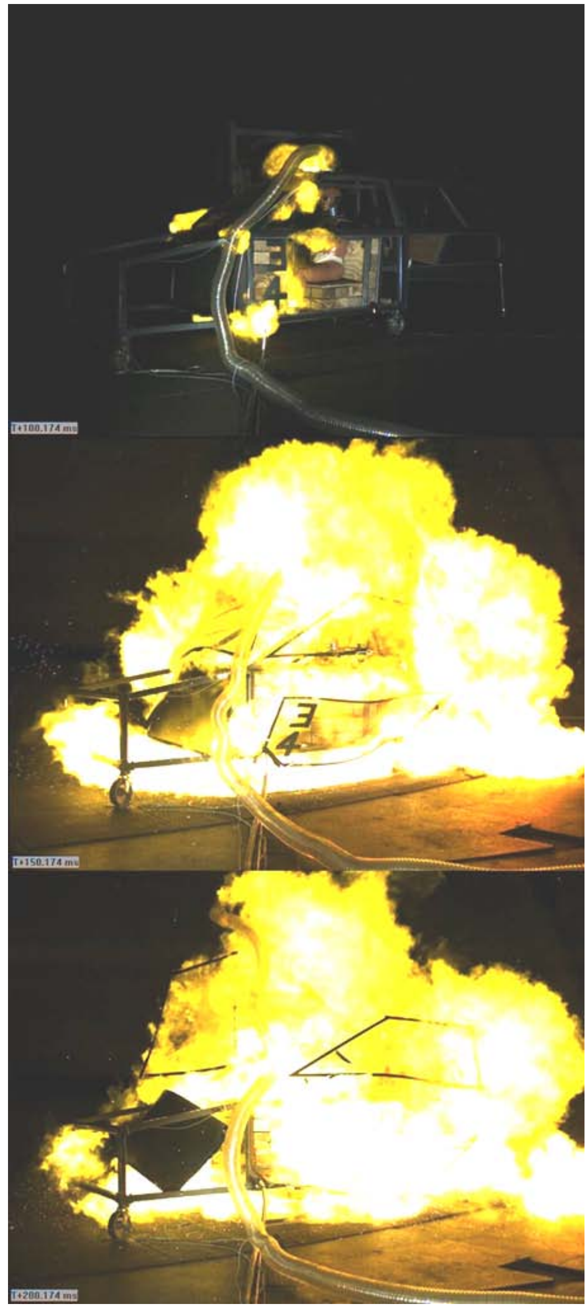

Figure 17. High speed stills showing combustion and panel separation in Test 34

Subtask C: Full-scale leak, ignition and fire tests on intact and crashed automobiles

The objective of this task was to quantify the effects of crash damage on hydrogen accumulation and combustion characteristics for three leak parameters—location, rate, and duration. These tests were conducted on four vehicles: intact and front-impacted 2008 Mitsubishi Lancers; side-impacted 2009 Mazda6 Sedan; and rear-impacted 2008 Ford Taurus. These test vehicles were transferred from NHTSA's Compliance and New Car Assessment crash test programs. The test vehicles are shown in Figure 18.

Figure 18. Test vehicles for accumulation and ignition experiments

<u>Test matrix</u> Thirty-nine leak-accumulation tests were conducted at seven leak rates ranging from 3 to 236 nlpm over 60 minutes, and originating from the trunk, rear-passenger compartment, or under the vehicle, as in Subtask A. Vehicles were equipped with the same array of 12 hydrogen sensors as in Subtask A. In some of the tests employing a lower leak rate (<59 nlpm) additional sensors were added at the top (100%) vertical height of the trunk and passenger compartments.

Altogether, eight ignition tests were conducted on the intact, front, rear and side-impacted vehicles. Vehicles were equipped with the same sensors including the instrumented manikin and exterior test fixture measuring heat flux and overpressure, as the ACS test article in Subtask B.

<u>Observations from accumulation tests</u> Front-crashed vehicle: (1) leaks as low as 30 nlpm in the trunk or passenger compartment resulted in detectable flammable levels in the other compartment; (2) leaks as high as 236 nlpm underneath the vehicle did not result in detectable accumulation inside the vehicle; and (3) low leak rates resulted in random (inversions; pockets), but sometimes detectably flammable, levels of hydrogen.

Figure 19 shows an example of these characteristics of a slow leak rate.

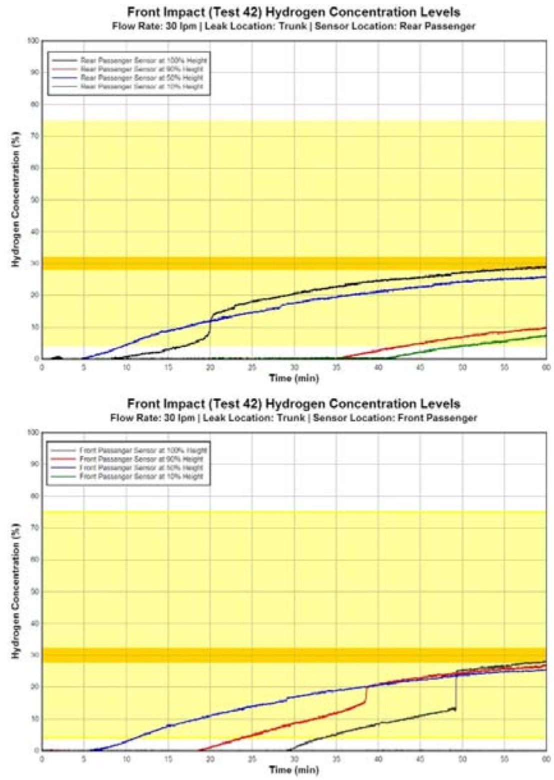

Figure 19. Inversions of slow leak (30 nlpm)

Side-crashed vehicle: (1) leaks ≥59 nlpm in the passenger compartment resulted in detectable flammable levels, but leaks as high as 236 nlpm in the trunk did not result in detectable flammable atmospheres in the passenger compartment; (2) leaks underneath the vehicle as high as 236 nlpm did not result in detectable accumulation inside the vehicle; and (3) even with high leak rates, accumulations sometimes appeared random and elusive with respect to migrating to the highest locations.

Rear-crashed vehicle: (1) leaks as low as 30 nlpm in the rear-passenger compartment resulted in low but detectable flammable levels; (2) leaks as high as 236 nlpm underneath the vehicle did not result in detectable accumulation inside; and (3) leaks originating in passenger and trunk compartments resulted in random accumulations, all of which were flammable.

Overall observations from Subtask C hydrogen accumulation tests were: (1) at low leak rates (≤60 nlpm), hydrogen did not mix well in air, resulting in its concentrations being random, exhibiting characteristics similar to a lava lamp in which slow motion causes media of different densities to remain unmixed, pocketing locally, varying and moving in random fashion, and inverting where higher-sensor locations register lower concentrations than do lower-sensors locations, or being absent at highest locations; (2) at high leak rates (≥118 nlpm), hydrogen mixes more homogenously, resulting in more stratified levels, increasing more uniformly throughout the vehicle, being detectable nearest the leak source first, generally seeking higher elevations, and reaching more uniform and steady-state concentrations with time; and (3) door, window, and frame seals in front or rear-impacted vehicles were not compromised to the extent of allowing hydrogen from leaks underneath to accumulate inside the vehicle. Such flow, mixing, and stratification behavior has been predicted by computational fluid dynamic modeling by Breitung [8].

<u>Observations for ignition tests</u> Two types of ignition tests were conducted: (1) at the in-going potential standard leak rate of 118 nlpm for a duration of 1.5 min, which introduced a just-flammable ~5% hydrogen inside the car if distributed evenly; and (2) at the lowest leak rate experimentally possible (3 nlpm) over 60 min, which could result in accumulated hydrogen (~5%) that might be ignited by sparking at the top of the passenger compartment (leaking 3 nlpm for 60 min was near-equivalent to the volume of hydrogen leaking at 118 nlpm for 1.5 min).

Fire effects varied in terms of peak thermal flux, overpressure, and internal vehicular damage. Aftereffects ranged from window fogging (condensation from hydrogen combustion) to structural damage (deformed doors, broken windows) to second-degree burns and eardrum rupture [9].

One additional significant finding was a propensity for secondary fire after sparking and hydrogen ignition, which was replicated. These secondary fires, that consumed flammable material inside the vehicles, occurred in the intact and front and side-impacted cars. The origin of these secondary fires, that erupted within minutes after initial sparking and severely damaged the vehicles, appeared to be flammable material inside the trunk (spare tire) or cabin (headliner).

<u>Representative test results for ignition tests</u> Table 5 shows the results for the eight ignition tests that were conducted on the intact and crashed vehicles.

Table 5
Matrix and critical data from Task C ignition tests

Task 2c Vehicle Ignition Tests					
Vehicle	**Leak Rate (nlpm)**	**Leak Duration (min)**	**Test #**	**Ignition?**	**Secondary Fire?**
Front Impact	**118**	**1.5**	**68**	**Yes**	***<u>Yes</u>***
Intact	3	60	82	No	No
	6	**60**	**83**	**Yes**	***<u>Yes</u>***
Rear Impact	6	60	84	No	No
	12	60	85	No	No
	24	**60**	**86**	**Yes**	**No**
	48	60	87	Yes	No
Side Impact	**60**	**60**	**88**	**Yes**	***<u>Yes</u>***

Test 68 was the first test in the series. The leak was located in the trunk and flowed at a rate of 118 nlpm for 90 sec. The total hydrogen volume delivered was 177 liters into 3,012 liters, or ≈ 5% of the trunk and passenger compartment volumes. A hydrogen sensor was located at 50% height in both the front-passenger and trunk compartments. The ignition source was a spark plug (100 J), located a few inches between the leak in the trunk and the 50% sensor location.

Although neither hydrogen sensor detected a flammable hydrogen concentration, sparking resulted in a combustion event more damaging than expected based on Subtask B testing.

The graph of the concentration vs. time history from the hydrogen accumulation test 34 at 118 nlpm (Figure 20 below) may provide some insight into why the sensors did not detect hydrogen in the ignition test.

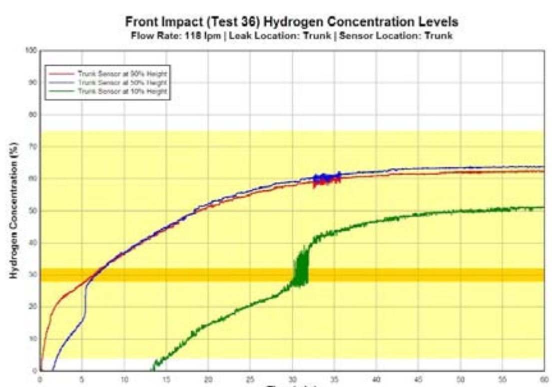

Figure 20. Test 34: 118 nlpm trunk leak (Subtask A)

Note that at 90 seconds, the trunk sensors detect 0 to 20% hydrogen depending on whether the sensor is at the 10%, 50%, or 90% compartment height location. Therefore, though this leak rate provided 5% by volume, the concentrations were highly variable at the time of ignition, and locally probably closer to 20%.

The increased confinement of the vehicle, albeit after impacted (front), when compared to that of the ACS that was sealed with magnets and tape, appears to have held pressure generated longer after ignition and allowed it to build to significantly higher levels. The resulting overpressure inside the vehicle peaked at approximately 9 psi, significantly higher than that generated in the ACS ignition test under the same flow conditions. In contrast, the heat flux was similar for tests in both subtasks.

The hydrogen accumulation tests showed that a leak rate of 118 nlpm into the trunk and passenger compartments of intact and crashed vehicles over the course of an hour can result in the presence of flammable concentrations inside the vehicle in as little at 90 seconds. Therefore, the remainder of the vehicle ignition tests in Subtask C sought to determine the minimum leak rate that could result in a flammable concentration over the course of an hour.

Table 5 shows that test number 82, with a leak rate of 3 nlpm for 60 minutes did not result in ignition, but test 83, with a leak rate of 6 nlpm did. Moreover, in three of the vehicle ignition tests, secondary fires broke out due to ignition of interior components. Figures 21, 22, and 23, show the time line of the secondary fires that broke out in tests 68, 83 and 88. These fires originated in the spare tire compartment (86 and 88), and the headliner (test 83).

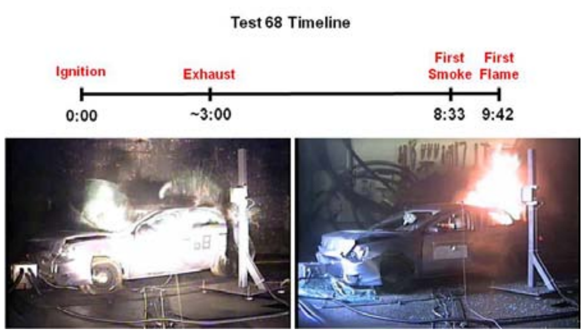

Figure 21. Test 68: Secondary fire observed at ≈ 10 minutes

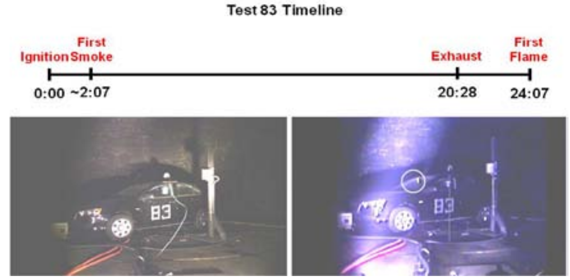

Figure 22. Test 83: Secondary fire observed at ≈ 24 minutes

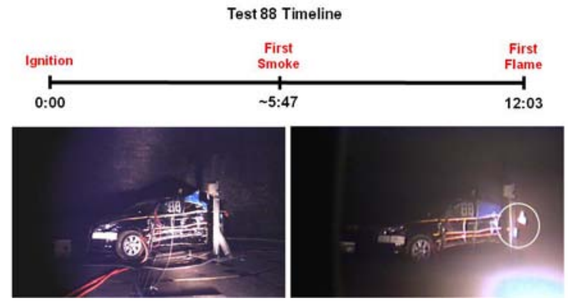

Figure 23. Test 88: Secondary fire observed at≈ 12 minutes

CONCLUSIONS

The tests conducted in this program were simulations utilizing conventional vehicles and vehicle compartment simulators, into which the proposed allowable energy equivalent of hydrogen was purposefully introduced, into or around the vehicle. The hydrogen was purposely ignited to determine whether the outcome presented a hazardous condition. The study is not indicative of how a hydrogen fuel system would perform in a crash. However it does show what consequences could be expected, should various volumes or concentrations of hydrogen accumulate within a vehicle in the presence of an ignition source.

With regard to the objective of determining the safety of the proposed minimum allowable post-crash leak rate, data indicate that leak rate is not the most important metric, but instead the volume of hydrogen leaked into the automobile compartments to accumulate locally to 5%, or to a level exceeding the lower flammability limit of 4%. It appears to be unimportant if this lower flammability limit is reached via a low leak after long duration (up to 60 minutes) or a higher leak rate over a very short duration.

Fire effects varied in terms of peak thermal flux, overpressure, and vehicle damage. Subtask A revealed that hydrogen can remain in an enclosed compartment for a significant amount of time even after cessation of a leak. Higher leak rates can reach steady state concentrations at or above the upper flammability limit where, in the absence of ignition, asphyxiation could also become a concern. Lower leak rates can reach steady state near the stoichiometric level where detonation can occur.

Subtask B provided data on the combustion effects of lean, stoichiometric, and fuel rich concentrations of hydrogen. However, the magnetic and taped seals on the ACS allowed the panels to bulge and break away, which likely mitigated the overpressure effects seen in the actual vehicle tests in Subtask C, which all utilized only 5% by total volume of hydrogen. Also, the ACS did not contain any combustible materials like the real vehicles.

There was a propensity in the Subtask C tests for secondary fire after the initial hydrogen ignition. These secondary fires consumed flammable material inside the vehicles and occurred in both the intact, front-impacted, and side-impacted automobiles.

The research shows that based on these test results:

- All accumulation of hydrogen within passenger compartments should be avoided.
- More than one sensor in vehicle compartments may be required for alarm purposes.
- Vehicle devices that vent passenger compartments upon impact are warranted.
- Flammability tests on fabrics exposed to hydrogen or hydrogen flames may have merit.

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CRASH SAFETY OF HYBRID- AND BATTERY ELECTRIC VEHICLES

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ABSTRACT

Besides the suitability for daily use, sufficient cruising range, rapid battery charging times and an area-wide service infrastructure, the crash safety performance will also play a key role for the consumer' s acceptance of electric vehicles. In particular, the electric energy storages and high voltage systems are very challenging to the crash safety performance.

Already in the Mercedes-Benz S 400 HYBRID in 2009, worldwide the first series-production vehicle with a Lithium-Ion battery, a seven-stage safety concept has been implemented. It has an extremely high performance in terms of functional and operational safety during normal driving and an outstanding crash performance in any real world accidents. Similarly, an intrinsically safe packaging concept has been implemented in all other Mercedes-Benz Hybrid- and Battery Electric Vehicles, such as the ML 450 HYBRID, the A-Class E-Cell, the B-Class F-Cell, and the Smart Electric Drive. All safety relevant components of the high-voltage system have been integrated and protected in a safe manner. This is particularly true for the high voltage battery. The HV-system has been isolated and protected against any contacts, and it will be shut-off in any accident. In the future Mercedes-Benz hybrid- and electric vehicles, this safety concept will be enhanced consistently, by utilizing the Mercedes-Benz safety philosophy of "Real Life Safety". Its key elements are:

- A foolproof strategy to cut-off the high voltage in accidents will prevent any electric shocks.

- A concept of protection zones defines the accident-proof placement of all the safety relevant high voltage components along with the highest possible structural safety.

- Mechanical requirements for HV-components ensure the electric insulation and shock-proof protection.

- An integrated safety concept shall prevent any critical damages to the high voltage battery in case of high crash loadings.

This paper illustrates Daimler's concept for crash safety of hybrid- and electric vehicles.

INTRODUCTION

Driven by severe fuel economy and CO_2 emission regulations, the automobile industry experiences a fundamental change. Undoubtedly, hybrid and battery electric vehicles will play a major role in the future individual traffic, with the focus on the suitability for daily use, sufficient cruising range, and energy charging time, at reasonable cost. The key to achieve these goals will be the energy storage technology, with Lithium-ion batteries as a future base. Since these new high voltage systems involve some major challenges with regard to functional safety and operating safety, foolproofness and crash safety, an equally important criterion for the acceptance of alternatively driven vehicles by the general public will be the same high safety standards as established for conventional vehicles.

Some basic requirements to the integrity of the high voltage system, such as the protection against electric shocks and the avoidance of fire or explosion of energy storages after a crash have already been addressed in the existing and currently discussed safety standards for alternative vehicles with high voltage systems (i.e. FMVSS 305, ECE R94/95, GB/T 18384, Attachment 111). This has been the base for the development of the Mercedes-Benz S 400 HYBRID, which has been launched in 2009 as the world wide first series vehicle with a Lithium-ion battery. As a result, the following seven-stage safety concept has been implemented:

1. Color-code and contact protection for all high voltage wiring with amply insulation and special plugs,

2. High-strength steel housing for the lithium-ion battery located well protected in the extremely stiff zone before the fire wall,

3. The battery cells are bedded in a shock absorbing gel, with a separate cooling circuit and a blow-off vent with burst disk,

4. Multiple safety interlock to automatically separate battery terminals,

5. Continuous short circuit and malfunction monitoring,

6. Active discharging of the high voltage system in the event of faults or fire,

7. Pyrotechnical tripping of the voltage system in the event of an accident.

Based on the Mercedes-Benz "Real World Safety" philosophy, this concept will be enhanced consistently in the future Mercedes-Benz hybrid and battery electric vehicles. The key goals will be:

- A high structural safety, based on protection zones for all high voltage components, surrounded by deformation zones to manage the crash energy and specifically programmed to the vehicle concept, while implementing intelligent light weight design.

- An intelligent integration concept for the high voltage battery to prevent critical damages even if directly impacted during a crash.

- The implementing of high requirements to the mechanical stability of all high voltage components, combined with an ultimate shock-proof protection by cut-off and discharge during any accidents.

- The consistent protection of other road users (compatibility) along with an enhanced implementation of the new driver assistance and crash avoidance systems.

Vehicle	S 400 HYBRID	ML 450 HYBRID	B-Class F-CELL	A-Class E-CELL	Smart ED
					
Type	(Mild-) Hybrid	(Full-) Hybrid	Fuel Cell Vehicle (FCV)	Battery Electric Vehicle (BEV)	Battery Electric Vehicle (BEV)
Vehicle Concept					
Battery Location	Front	Rear Axle	Rear Axle	Floor	Floor

Figure 1. Mercedes-Benz hybrid and electric vehicles.

Figure 1 shows an overview of the actual Mercedes-Benz alternative propulsion vehicles. The traction battery of the A-class E-CELL and the Smart Electric Drive is integrated on the floor of the passenger cell. In the F-CELL B-class, the hydrogen tank and the fuel cell stack are located on the floor, while the small HV-battery is well protected on the vehicle's rear axle. While the mild hybrid battery of the S 400 HYBRID is located behind the right wheel arch, the full hybrid battery of the ML 450 HYBRID is placed on the rear axle. All these integration concepts implement the highest possible crash protection in all accident types.

HIGH VOLTAGE CUTT-OFF IN THE EVENT OF AN ACCIDENT

The power train of both hybrid and electric vehicles utilizes high voltages up to several hundreds of volts, for which severe safety regulations have been legislated appropriately. Voltages above 30 V a.c. and 60 V d.c. respectively are in class B voltage, which requires already enhanced protection against electric shock. Nevertheless, the high voltage will be cut-off from the battery and discharged in Mercedes vehicles in any serious accidents, in order to reliably avoid any risks of electrical shocks even at very high vehicle damages [1]. By opening the battery contactors, the high voltage must be reduced below 60 V d.c. and 30 V a.c. accordingly in less than 5 seconds. High voltage sub-systems with extremely high energies in the link will be discharged actively by a short circuit. Generally, this HV-deactivation is linked to the crash detection sensors for frontal / lateral / rear crash and rollover, and the subsequent activation of the restraint system. Two different switch-off strategies have been implemented (Figure 2):

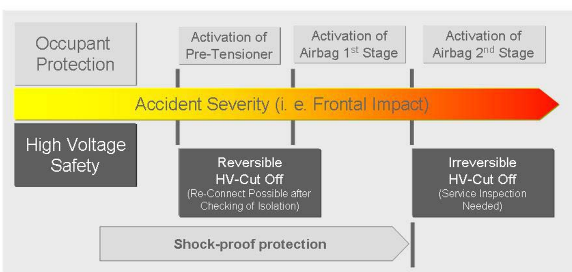

Figure 2. High-voltage cut-off in a crash.

1. In minor severe accidents, i.e. frontal collisions with activation of the seat belt pretensioners or the 1st stage of airbags, the high-voltage system will be shut-down reversibly. After the self diagnosis has not detected any insulation faults, the HV-system will be re-activated, and the engine of vehicles still drivable can be re-started.

2. In any severe accidents (i.e. airbags fully fired in frontal crash), the HV-system will be cut-off irreversibly. In this case, a re-start of the engine will only be possible after a diagnosis or repair has been conducted at an authorized service station.

CRASH PROTECTION ZONES FOR HV-COMPONENTS

Extremely important for the safety performance of battery electric and hybrid vehicles in any real world accidents is the well protected placement of all safety relevant components. This is particularly true for the high voltage battery which must not be damaged even in very severe accidents resulting in any crucial cell damages or a loss of protection against contact. In order to define the protection zones for the best possible integration of energy storages, a specific study was conducted [2] by analyzing the damages of approx. 9000 vehicles involved in severe real world accidents, using the German In-Depth Accident Study (GIDAS) data base [3]. For each vehicle, the deformations in the lower vehicle (floor) level were plotted in a standardized 2-D grid. By consolidating the resulting deformation matrix with the accident frequency and severity, the probability of the deformation of each vehicle cell in any crash type can be evaluated accordingly. Figure 3 compares the resulting deformation matrix of a station wagon with the vehicle intrusions in the standard crash tests.

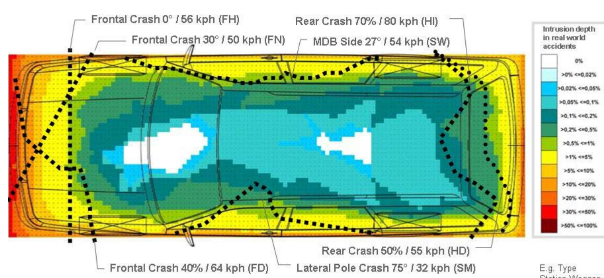

Figure 3. Comparison of vehicle intrusions in real world accidents and crash tests.

Based on this deformation probability matrix, three deformation zones have been specified for the safe location of high voltage components (Figure 4):

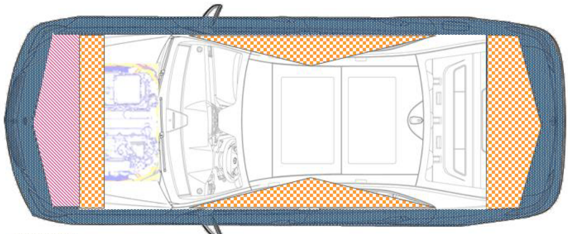

Figure 4. High voltage safety protection zone concept.

Protection Zone 1: The outside deformation area which is already damaged in minor collisions without any activation of the restraint system is a keep-off zone for any HV-components. If (for whatever reason) the location of a HV component in this area were unavoidable, it must be well protected against any damages in minor or serious accidents, and the high voltage wiring must be coated additionally.

Protection Zone 2: Areas deformed in medium severe frontal collisions characterized by firing the belt pretensioner or the 1st stage of the airbag require enhanced protection against contact according to class IPXXB with a test finger of a diameter of 12 mm (Figure 5).

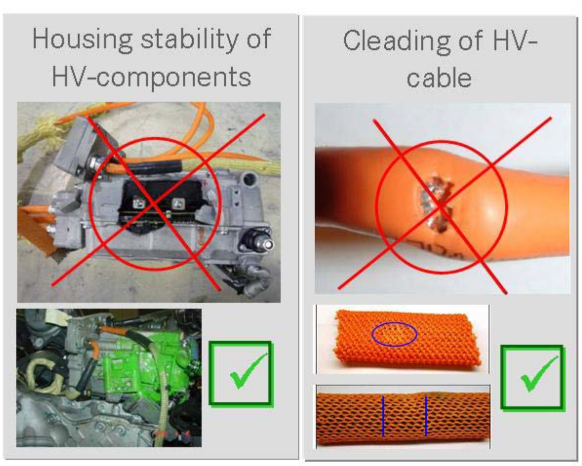

Figure 5. Contact protection of HV-components

Protection Zone 3: The preferred zones for the location of high voltage systems are not damaged in the standard crash tests, and only with a probability of less than 2 % in real world accidents. Areas deformed in the standard crash tests should be avoided.

THE CRASH SAFETY OF HIGH VOLTAGE BATTERIES

The current safety standards of high voltage batteries address the chemical and thermal performance of battery cells during mechanical loads, i.e. pressure forces and intrusion. Due to the high loads, the cells will be damaged typically, with the result of electrolyte leakage. Undisputed the fact that these cell tests are crucial for the design of HV-batteries, they do not represent the typical loads to the battery during crash or even in severe real world accidents [4, 5, 6]:

- Crash simulations indicate that the maximum loads applied to the battery rarely exceed 200 kN. The key reason for this phenomenon are the indirect, multiple and distributed load paths of the crash propagation: i.e. the battery protecting cage and the surrounding vehicle structure may absorb energy, the battery may move and dodge, the battery mounting and housing may be deformable, and other compliances and reinforcements may cushion the peak loads to the battery.

- The forces specified in the current battery standards (i.e. SAE J2464), i.e. the thousand fold of the battery weight is not high enough to achieve the 50 % battery crush (of the battery dimension) targeted; even the small 20 kg battery of a mild hybrid vehicle battery will be crushed only by approx 11 % with a static load of 200 kN.

- Another crucial difference of crash loads versus quasi-static tests is the time scale: due to the very short period of the whole crush of approx 100 ms (the blink of the eye) peak loads are applied only for milliseconds. Same as any component, the battery withstands much higher short-period dynamical forces than the maximum static loads.

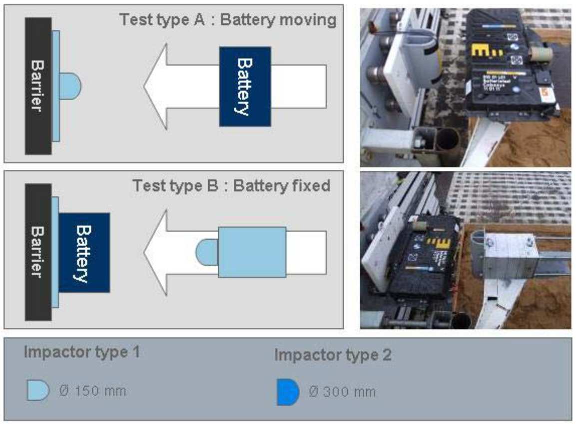

Figure 6. Test set-up of dynamic battery impact.

In order to assess the safety performance of HV batteries in severe crashes more realistically, Mercedes-Benz has conducted a comprehensive series of dynamical crash tests with all types and sizes of HV-batteries currently used in the current Mercedes-Benz hybrid and electric vehicles (Figure 6). In order to implement the highly dynamical crash loads as realistically as possible, the loads were applied in dynamic impact tests simulating all the dynamic and acceleration effects and resulting inertial forces. The load profiles were derived from both the relevant vehicle crash for each battery type, and from the maximum loads achieved in quasi-static battery tests. If the battery was impacted in the crash, the deformation energy was evaluated by crash simulation, and the equivalent kinetic energy was applied in the dynamic base test. If the battery was not impacted, similar loads as in the standard quasi-static battery tests were applied with respect to battery intrusion and maximum force. For reasons of comparability, similar energies of 3-6 kJ were applied in all base tests. In further tests, the crash energy was increased significantly (between 1.5 to three times). The test program with the load specification is shown in Figure 7.

Battery Type	Mild-Hybrid (Li-ion)	F-CELL (Li-ion)	Full-Hybrid (NiMH)	BEV (Li-ion)
Battery Data	0,8 kWh, 24 kg	1,4 kWh, 48 kg	2,4 kWh, 83 kg	14 kWh, 1 48 kg
Test # 1	B1 3,5 kJ	A1 3 kJ	A1, A2 5kJ	A2 6kJ
Test # 2 (≥ 50% Load increasing)	B1 5,6 kJ	B1 9 kJ	B1 9 kJ	A2 9kJ

Figure 7. Dynamic battery test series .

The results (Figure 8) are discussed in detail in the ESV-paper "Crash Safety Aspects of HV Batteries for Vehicles" [7]. Despite the extremely high loads and the resulting major battery intrusions above the values measured in the relevant crash tests, no thermal or electric reactions occurred, and the shock-proof protection was ensured. No short circuits, no electrolyte leakages, no fire or even explosion occurred in all tests. Given the very realistic test method along with the loads applied being much higher than in very severe accidents, an extremely high crash safety performance could be demonstrated for all batteries.

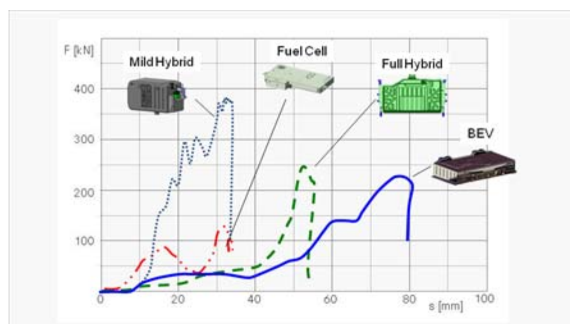

Figure 8. Crash characteristics of traction batteries.

It is also obvious from the test results that the current test standards for high voltage batteries, based on quasi-static tests, do not reflect the mechanical loads experienced in the dynamic crash tests conducted. This is true for the specification of a minimum crush of the battery package, and it is even more for the correlation of the maximum load to the battery weight. As a result, these standards must be modified appropriately.

INTEGRATED SAFETY CONCEPT FOR HV-BATTERIES

Although it must be the ultimate goal to locate the HV-battery in a well protected zone as described above, this will not always be feasible in all vehicles, and under all circumstances. This is particularly true in small electric vehicles with traction batteries of the dimension of approx 1200 x 500 x 200 mm, or if more than one battery will be needed to achieve a satisfactory cruising range. On the other hand, the dynamic crash tests described above have proven that HV-batteries can withstand very high crash impacts without any severe damages. And severe crash tests with different vehicle sizes, different battery types and sizes, different battery integration concepts and locations have shown that an equally high crash safety performance can be achieved by implementing an intelligent safety integration concept which takes into account the following relevant criteria:

- The safety performance of the battery materials, the chemistry of the cells in particular, i.e. the electrolyte and material of the anode and cathode.

- The battery stability, in particular the enclosure material, interior expansion space and deformation zones, appropriate arrangement of the connectors of the electronics and of the cooling ports.

- The battery protection, i.e. a stiff cage around the battery, reinforcements in the surrounding vehicle structure.

- The battery integration, such as a programmed compliance in the mounting, clearances for battery movement, no block building, staggered arrays.

- The safety performance of the battery in the crash tests, i.e. battery impact, maximum crash loads, battery intrusion or damage.

- The ultimate mechanical loads to the battery in the static and dynamic battery tests, i.e. enclosure cracks, electrolyte leakages, short circuits, fire explosion.

CONCEPT OF STRUCTURAL INTEGRITY AND CRASH COMPATIBILITY

Due to the changes in the power train and energy storages, the packaging of the traction battery in particular, alternatively driven vehicles are exposed to major challenges in the crash performance such as the stability of the vehicle structure and the related occupant protection. This is particularly true for the compatibility in a collision with other road users such as a (smaller / bigger) car, a cyclist or pedestrian. In addition to the compatibility features of conventional vehicles, the mass ratio, the structural stiffness ratio and the geometric suitability, some additional challenges have to be addressed. One specific focus is on the avoidance of collisions with pedestrians and cyclists due to the missing engine noise of electric drives, where even a new regulation is under discussion. Another aspect is the hazard to 3rd parties, rescue people in particular, due to damages of the high voltage system in an accident, and the potentially resulting electric shock, electrolyte leakage, vehicle fire or even explosion. As a result, the enhanced implementation of the new crash avoidance technologies will play a major role in improving the safety performance of alternative vehicles.

In the actual vehicle population, a maximum mass ratio of 1:2, and the resulting inverse ratio for the velocity change of the two vehicles in the collision, can be managed in today's advanced occupant protection system. With future alternative vehicles in the exposure, this ratio may potentially increase up to 4:1 since on the one hand, the weight of small electric vehicles must be reduced significantly in order to increase their cruising range. Oh the other hand, the weight of hybrid cars such as big limousines or SUV will increase due to the additional traction battery and electric drive. The management of the resulting delta V's in car-to-car collisions through the restraint system, in order to achieve tolerable occupant loadings, will be a major challenge.

With regard to the structural and geometrical compatibility of hybrid and electric vehicles, a particularly important aspect will be the well protected integration of the high voltage systems in vehicle areas which will not be damaged in any severe accidents. Another focus is the energy absorbing crush zones which must be programmed specifically to the packaging concept of the vehicle's key components. Table 1 shows the impact of the different alternative vehicle concept on the crash performance.

Table 1.
Impact of alternative propulsion concepts on crash performance

Drive	Key Aggregates	Crush *	Crash Safety Performance *
Hybrid: Mild oder Plug-in	Big Combustion Engine Small Electric Motor Small HV-Battery Big Fuel Tank Small 12 V Batterie	FRONT: Similar SIDE: Similar REAR: Slightly Reduced	CRASH PULSE: Adverse COMPATIBILITY: Adverse INTRUSION: Similar
E-Cell BEV	Big Electric Motor Big HV-Battery Plug-in	FRONT: Higher SIDE: Less REAR: Slightly Reduced	CRASH PULSE: Favorable KOMPATIBILITÄT: Favorable INTRUSION: Less in Side Impact
E-Cell Plus Range Extender	Big Electric Motor Medium HV-Battery Small Engine Small Fuel Tank Plug-in	FRONT: Similar SIDE: Similar REAR: Slightly Reduced	CRUSH PULSE: Favorable COMPATIBILITY: Favorable INTRUSION: Less in Side Impact
Fuel Cell	Electric Motor Stack Oxygen Tank Medium HV-Battery	FRONT: Similar SIDE: Similar REAR: Reduced	CRUSH PULSE: Favorable COMPATIBILITY: Favorable INTRUSION: Less in Side & Rear Impact

* Compared to conventional vehicle

The elimination of the conventional combustion engine in battery electric vehicles will enable new crush zones in the vehicle front. On the other hand, the integration of the relatively big and sensitive traction battery will require very stiff areas which must not be deformed in a crash in order to protect the battery. An obvious area for the battery is the vehicle floor, thus killing two birds with one stone: Since the passenger cell must be designed extremely stiff for the occupant protection in order to prevent any major intrusions ("safety cage"), a stiff vehicle floor along with very solid rocker panels will also enable a very high protection of the battery from any damages in severe crashes. In electric vehicles with a small combustion engine as a range extender must take into account the packaging of the engine and the fuel tank in the vehicle rear. Accordingly, the stack and the hydrogen tank of fuel cell vehicles will be placed on the vehicle floor, while the relatively small high voltage battery as an energy buffer will be located well protected above the rear axle.

The BlueZERO concept for the future alternatively driven Mercedes vehicle generations will be based on a flexible modular safety packaging concept, as shown in Figure 9. The sandwich floor already realized in the A- and B-class will house the different energy storages as needed, and the space above the rear axle may be used for any additional components which must be protected in vehicle crashes. As a result, all variants of battery electric vehicles, even a gas fueled engine fueled can be implemented on this platform.

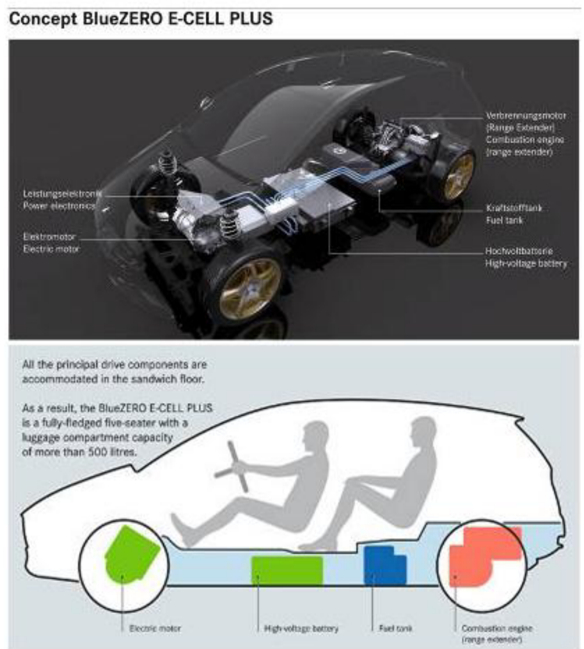

Figure 9. Concept BlueZERO.

OPPORTUNITIES FOR ENHANCED CRASH AND OCCUPANT PROTECTION IN HYBRID AND ELECTRIC VEHICLES

A major roadblock for the consumer acceptance of electric vehicles is their still very limited cruising range. As a result, by utilizing the formula "Less Weight = Less Energy Consumption = Smaller Traction Battery = Lower Vehicle Cost", consistent light weight design will be a key to the success of electric vehicles in the market. Due to the high cost of HV batteries (i.e. 1000 € for a 100 kg battery), an additional 10-15 € could be spent for each kg vehicle weight reduction without a significant increase of the vehicle cost [8]. This may push a break-through of light-weight design in electric vehicles, enabling new materials and technologies which have been too expensive for conventional vehicles, even exotic carbon fibers (Figure 10).

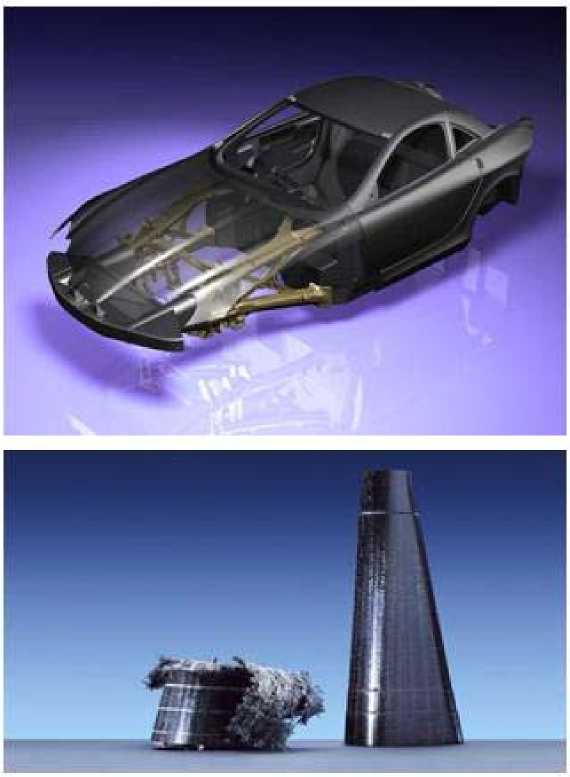

Figure 10. Vehicle body with carbon elements.

Since the traction battery may amount for up to 20 % of the total vehicle weight, a specific focus should be on weight reduction measures, such as utilizing the vehicle floor itself to house the battery.

Given the partially more difficult crash performance of alternative vehicles, another important aspect to enhance the safety performance will be the consistent implementation of the new crash avoidance and driver assistance systems. This is particularly true for the Mercedes-Benz PRE-SAFE systems which can be significantly improved by utilizing the high electric power available from the high voltage batteries. One example is the motorized seat belt which, with the current 12 V power supply, is limited in both the pretension times of minimum 100 ms, and the belt-to-occupant retraction force of maximum 200 N. With the power of 400 V, this performance data could be easily increased to less than 10 ms and up to 800 N. This would not only allow to use motorized seat belts also in the event of a crash and thus to eliminate the pyrotechnical seat belt pretensioners, but also to pull an occupant “out- of-position” back into the seat backrest. This would be a major benefit in many real world accidents where the occupants are no longer in the ideal back position due to a forward movement by emergency braking, vehicle spinning or minor impacts preceding the most severe crash.

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SAFETY PRECAUTIONS AND ASSESSMENTS FOR CRASHES INVOLVING ELECTRIC VEHICLES

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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.

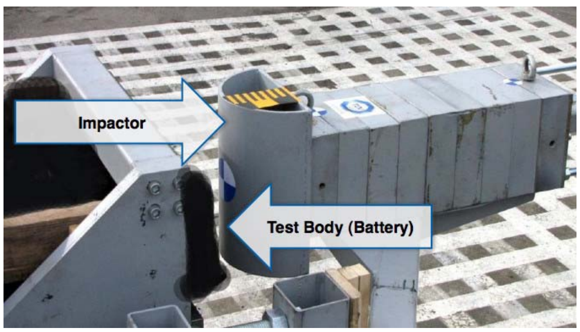

Figure 2. Li-ion battery impact test to be conducted by TÜV SÜD

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.

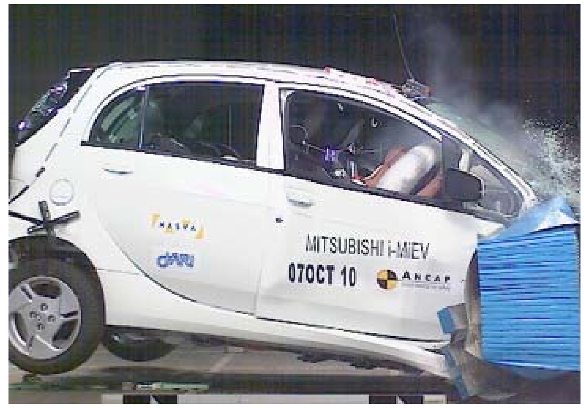

Figure 3. 64km/h offset crash test conducted by JARI for ANCAP

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

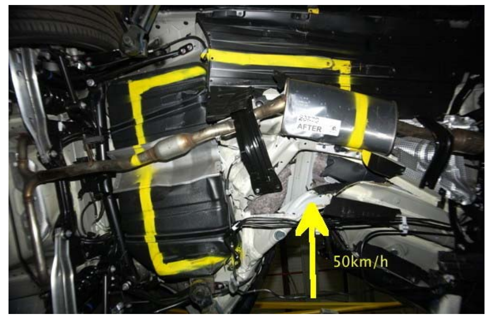

Figure 9. Underside of 50km/h vehicle. The yellow rectangle shows the approximate location of the rear floor area.

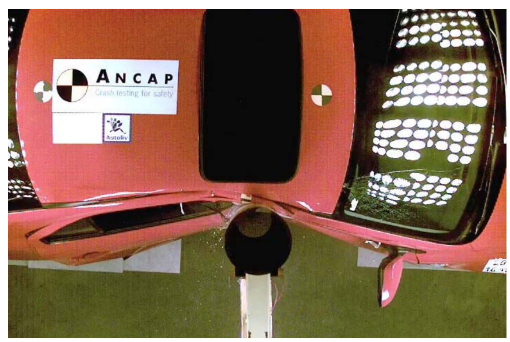

Figure 10. Same model in 29km/h impact

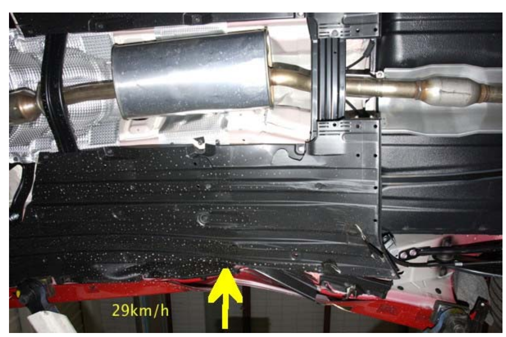

Figure 11. Underside of 29km/h vehicle. Rear is to the right.

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

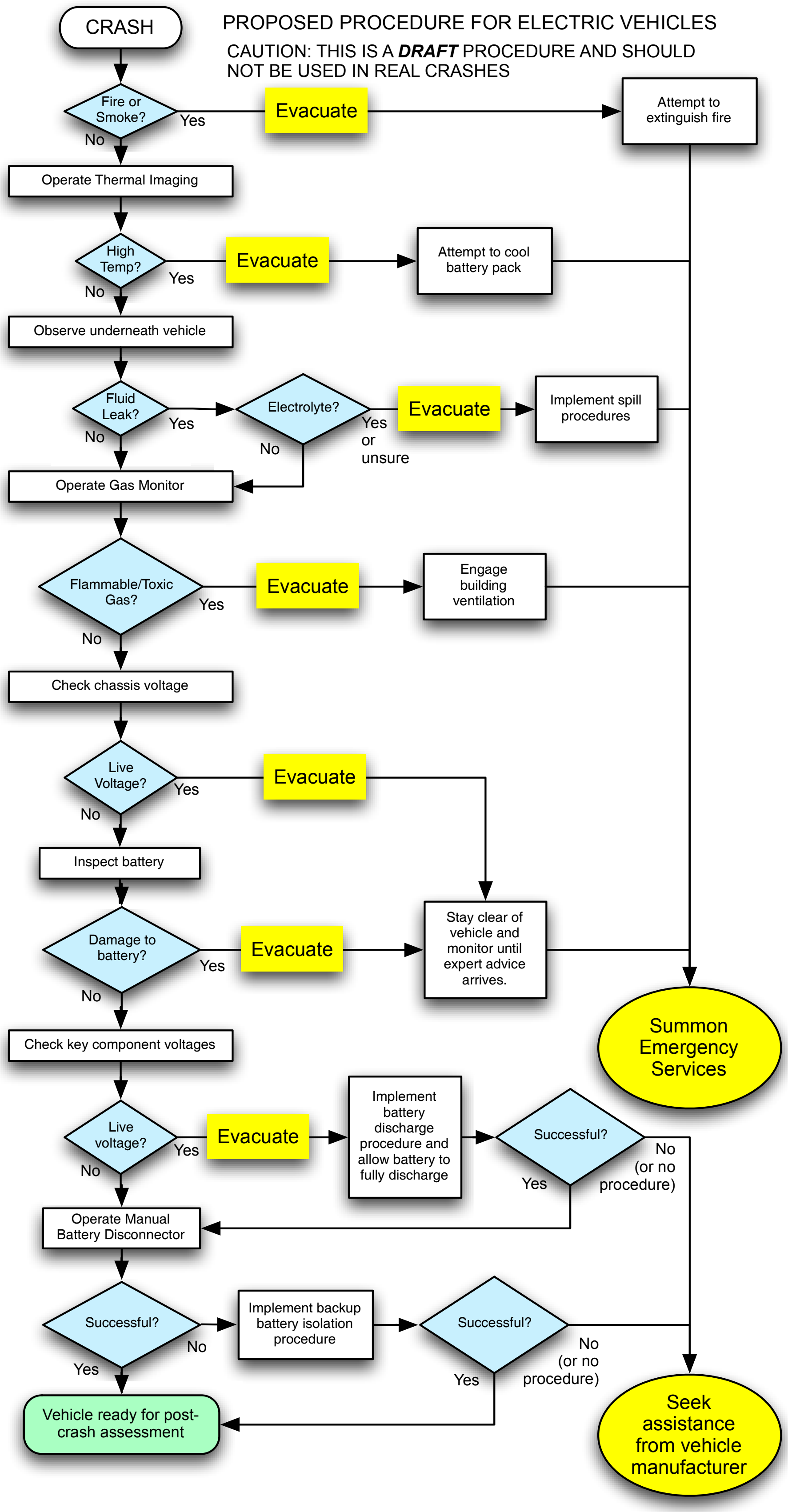
8) Notify local emergency services of the proposed crash test date and time and provide them with necessary information, including the circumstances under which they might be summoned (see flow chart). Where possible, emergency service personnel should attend the crash test (this can be useful experience 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?
No (or no procedure)
Yes
Operate Manual Battery Disconnector
Successful?
No
Yes
Implement backup battery isolation procedure
Successful?
No (or no procedure)
Yes
Vehicle ready for post-crash assessment
Seek assistance from vehicle manufacturer

INJURY MITIGATION TECHNOLOGY APPLICATIONS AND THE RELATIONSHIPS TO VEHICLE MASS, PRICE, AND FUEL ECONOMY

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Paper Number 11-0114

ABSTRACT

Managing the vehicle level trade-offs between motor vehicle safety performance consequent to the application of new injury control technologies and the potential increasing mass effects consequent to application of those technologies on the one hand, and the needs and desires for increased fuel economy through reduction in vehicle mass on the other hand, is a complex and vexing challenge. Historically, most studies of vehicle safety performance and fuel economy have focused upon the collision injury performance of vehicles as a function of vehicle mass. This study examines the connection from a somewhat different perspective by examining vehicle level attribute data (price, mass, and fuel economy) from both public and commercial sources for changes that register at a make/model level in the model years in which newly emerging safety technologies have been made standard.

The installation of injury mitigation technologies over the period 1998 through 2010 has been studied at the make/model/model year level for base or near-base model vehicles sold in the United States. The introduction and application of 28 safety technologies has been collected from multiple automotive reporting services (including: edmunds.com, Ward's Automotive, msn.com, iihs.org, and safercar.gov). A census of technology presence has been tabulated by: technology, manufacturer, make, model, model year, body style, and technology presence as standard or optional equipment. Corresponding base vehicle price, mass and fuel economy data have also been tabulated using publicly available sources for such vehicle level attribute data. Unique vehicle make/model combinations were paired for model years immediately prior to the installation of a new emerging safety technology and the model year of first standard installation of the particular technology. This also includes models for which a technology was optional and then became standard equipment. Changes in the vehicle level mass, price, and fuel economy were calculated and tabulated for multiple specific technologies and the change results are presented herein.

INTRODUCTION

A considerable variety of factors influence the safety content of vehicles. These include regulatory activity, customer demands, safety initiatives by individual manufacturers, manufacturers' competitiveness and safety concerns, etc. New technologies usually cannot be simply added into an existing vehicle architecture without extensive re-engineering of multiple vehicle level systems and sometimes major reconfiguration of manufacturing facilities for components and vehicle assemblies. Market acceptance, affordability, supply chain capacity and capability, indeterminate safety technology effectiveness, and uncertainties over possible unintended consequences are all factors that limit the rapidity of injury mitigation technology insertion into the stream of commerce. Consequently, injury mitigation technologies tend to propagate in a consistent pattern with a low initial penetration rate, often appearing as optional features and then gradually becoming standard features on a greater proportion of the new vehicle fleet in successive years. This pattern was characterized and reported upon in Lange, et al. [1] for a multiple injury control technologies.

SAFETY TECHNOLOGIES

Safety or injury mitigation technologies were selected based on their suitability to the analysis. Technologies with limited data sets were avoided. The technologies included in this study are:

- Anti-Lock Brakes (ABS) - on all four wheels.
- Dynamic Head Restraints - includes all systems of varying complexity that move the head restraint in response to a collision.
- Energy Management Feature - refers to seat belt load limiting devices.
- Head Airbag - includes all types of airbags for side impact head protection.
- Pretensioners - seat belt devices that apply tension to safety belt webbing and take up belt slack early in a collision to couple the occupant to the vehicle center of mass early in a crash to lengthen the ride down time for energy absorption.
- Side Airbag - includes all varieties of side impact airbags and deployment locations.
- Stability Control - computer controlled system to prevent the loss of or restore control over a vehicle by way of sensors and application of brakes, steering, and other vehicle systems.
- Tire Pressure Monitoring System (TPMS) - monitors all four tires and indicates when a default low pressure is reached, audibly and/or visually.

PRICE, MASS, AND FUEL ECONOMY

Vehicle price, mass, and fuel economy were obtained from electronic versions of Ward's Automotive Yearbooks. The data includes multiple variants and trim levels for vehicles sold in the U.S. Safety features specified in the Ward's data were matched with the price, mass, and fuel economy data. Data regarding some of the injury mitigation technologies in this study were only available from NHTSA's Safercar database. This resource includes both crash testing data as well as manufacturer submitted survey data for multiple injury mitigation technologies that are of interest to the National Highway Traffic Safety Administration (NHTSA). Some data was collected from motor vehicle manufacturers' websites and the websites of Edmunds and MSN Autos.

Although data is available for pickup trucks as well as other light duty vehicles, pickup trucks are excluded from this analysis as variation in body style and bed length confounds the selection of consistent year on year vehicle model level pairings that are necessary for the analyses discussed herein.

CALCULATIONS

After matching mass, fuel economy, and price to a specific injury mitigation technology, an analysis was performed to match closely related trim levels in successive years in which the technology became standard in the second year. Often, it was preferable to use pairings where a technology was optional one year and standard in the next. The key vehicle parameters are based on the optional technology not being present, so it is a good indicator of the association between the technology's presence and change in the key parameters of this study. When patterns of insertion were unclear or there was doubt over the sampling, the vehicle model was excluded from these analyses. Thirty to sixty matched vehicle pairs resulted per application for each technology from which fleet wide changes in the key parameters of vehicle mass, fuel economy and price were calculated.

The engine size and drive configuration were closely controlled to minimize influence on increases in price, mass, and fuel economy. These are typically the most influential factors in changes in all three of these characteristics, and can have a significant impact on all three in the same model year. While some trim levels changed in name each year, the closest applicable trim level was applied in the subsequent year from a price standpoint as required. Occasionally, a one year jump in model years was acceptable if the correlation was better between the trim levels. Manufacturers also will skip a model year on occasion, for example, continuing to sell a 2007 model year vehicle into 2008 and then introducing the 2009 model year vehicle at the end of 2008 with no production of a 2008 model year vehicle.

Differences for each matched vehicle pair were calculated and have been plotted for each vehicle characteristic and each injury mitigation technology. Distributions by technology were plotted for each characteristic using boxplots. The lower and upper limit values of a box represent respectively the 25th and 75th percentile points for the parametric distribution. Points plotting above or below the vertical lines extending from the boxes are outliers, i.e., changes unusually high or low with respect to the collected data sample. Statistics for the distribution of the change in price, mass, and fuel economy corresponding to each of the injury mitigation technologies studied were calculated and reported. Statistics calculated are: mean, standard deviation, minimum, first quartile (25th percentile), median, third quartile (75th percentile), and maximum.

As many different factors that are not considered in this analysis can affect major changes in the vehicle parameters we studied, it is unlikely that extreme difference values for any of the characteristics are due solely to the addition of the particular technology. Quartile values and the interquartile range (distance between the first and third quartiles) may be more likely to provide insight into the potential effects of technology additions.

Curb Weight

For the entire data set, the average curb weight was calculated for each model year. The results are summarized in Table 1 and graphically illustrated in Figure 1. The trend indicates an increase in the fleet average curb weight from 3,339 lb with a standard deviation of 763.5 lb in 1996, to 3,989.3 lb with a standard deviation of 881.9 lb in 2010.

For the injury mitigation technologies studied, the average curb weight differences ranged from 33.9 lb for dynamic head restraints to 72.2 lb for side air bags. The first quartile for most technologies was 0 or slightly less than zero. This small difference from a zero value would indicate that in general, addition of most of these injury mitigation technologies had a small adverse effect on vehicle mass consequent to the addition of the technologies. The smallest interquartile range is for tire pressure monitors (0,10), a technology with little mass effect. The results are summarized in Figure 2 and Table 2.

Manufacturer's Suggested Retail Price (MSRP)

The MSRP for the data set was calculated for each model year and summarized in Figure 3 and Table 3. MSRP increases steadily from $25,536 with a standard deviation of $15,835 in 1996, to $38,015 with a standard deviation of $22,468 in 2010.

For the safety technologies studied, average MSRP differences ranged from $320 for stability control additions to $1,174 for ABS additions. However, the amount of variation in differences is large for each technology, exceeding $1000 in every case. Further work needs to be done to understand actual price effects due to specific additions of single technologies. In many cases, multiple safety technologies and other features may be introduced in a single mode year change and the price changes may not reflect the true costs or affordability effects of the addition of an injury control technology on an individual basis. The results are summarized in Figure 4 and Table 4.

Fuel Economy

The average city and highway fuel economy for the data set was calculated for each model year and summarized in Figure 5 and Table 5. It should be noted that the drop in fuel economy seen in 2008 is attributable to the Environmental Protection Agency's revised testing standards that lowered average fuel economy and were intended to more closely reflect real world driving conditions. Fuel economy on average decreased for both city and highway driving during the time period of the study. The fleet average city cycle fuel economy in 1996 was 21.30 mpg with a standard deviation of 5.72 mpg; that value changed to 18.99 mpg with a standard deviation of 5.67 mpg in 2010. In the highway cycle, average fuel economy was 27.46 mpg with a standard deviation of 6.45 mpg; that value changed to 25.27 mpg with a standard deviation of 5.80 mpg in 2010.

For the injury mitigation technologies studied, neither set of differences between city and highway cycle fuel economy provide clear trends or significant positive or negative effects. Values for each injury control technology are generally spread across positive and negative values and interquartile ranges are generally centered around zero. The results are summarized in Figures 6 (city cycle) and 7 (highway cycle) and Tables 6 (city cycle) , and 7 (highway cycle).

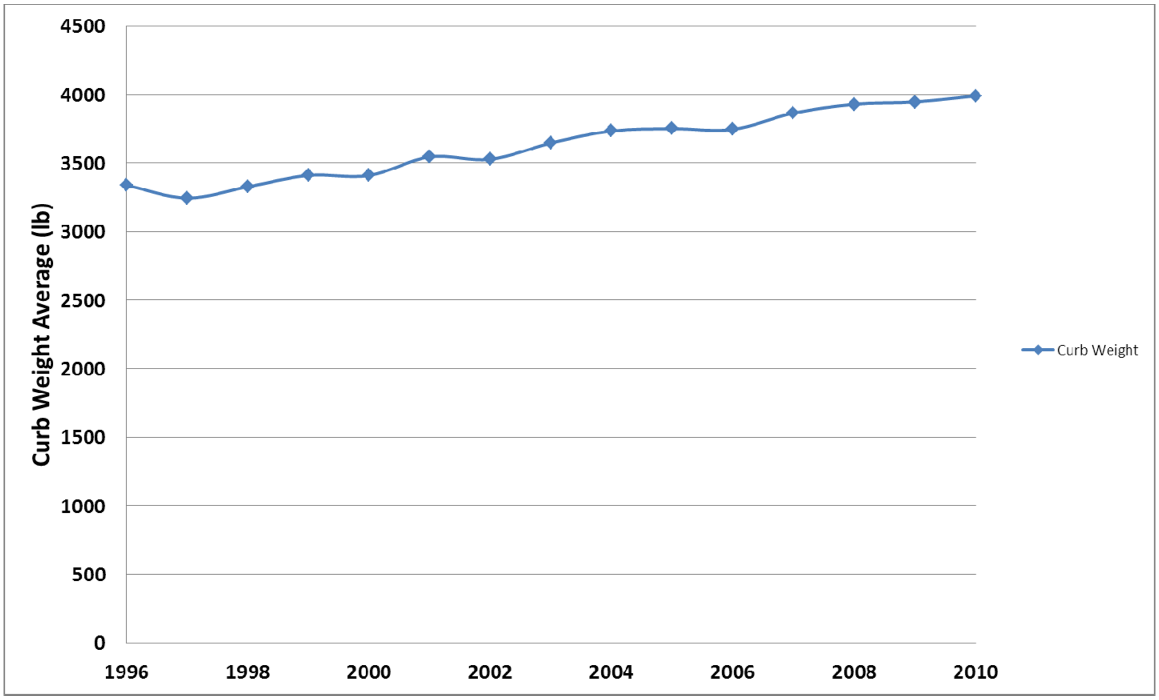

Figure 1. Curb weight average for data set by model year.

Table 1.
Summary of curb weight data by model year

Year	Curb Weight Average (lb)	Standard Deviation	Weight Delta (lb)
1996	3339.0	763.5	[redacted]
1997	3245.2	696.1	-93.8
1998	3327.7	753.7	82.6
1999	3410.9	746.9	83.2
2000	3410.1	759.9	-0.8
2001	3545.9	826.5	135.8
2002	3527.8	734.6	-18.1
2003	3646.7	792.1	118.9
2004	3734.9	852.1	88.2
2005	3751.6	822.3	16.7
2006	3746.3	795.3	-5.2
2007	3865.0	780.1	118.7
2008	3929.9	847.2	64.9
2009	3945.9	864.1	16.0
2010	3989.3	881.9	43.4

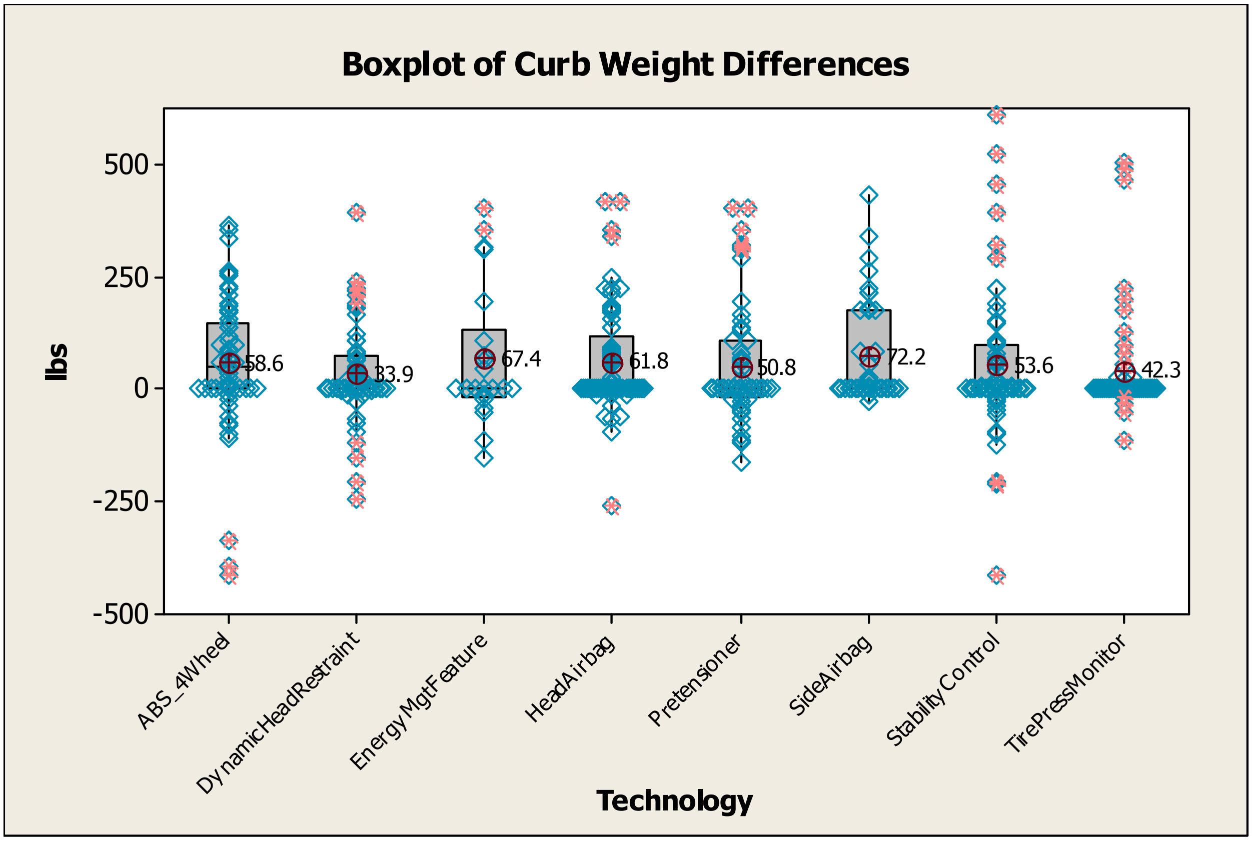

Figure 2. Boxplot of curb weight differences.

Table 2.
Statistical summary of curb weight differences by technology

Technology	Count	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
ABS_4Wheel	63	58.6	147.1	-415	0	50	148.0	362
DynamicHeadRestraint	61	33.9	104.7	-246	0	0	74.5	394
EnergyMgtFeature	22	67.4	152.6	-152	-15.3	0	131.3	405
HeadAirbag	73	61.8	117.8	-259	0	0	117.0	419
Pretensioner	54	50.8	135.0	-163	-19	0	110.0	405
SideAirbag	41	72.2	115.3	-25	0	0	176.5	433
StabilityControl	65	53.5	162.9	-415	0	0	100.5	612
TirePressMonitor	54	42.3	122.1	-115	0	0	10.3	505

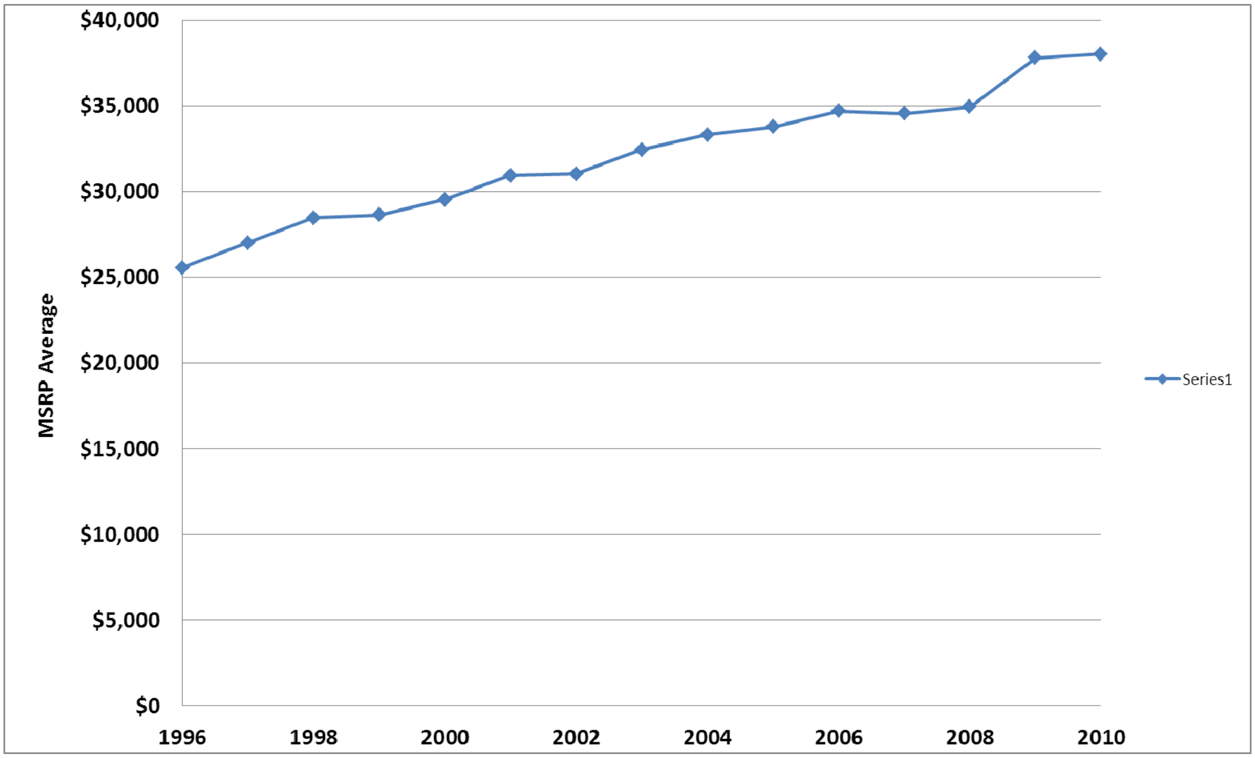

Figure 3. MSRP average by model year for data set.

Table 3.
Summary of MSRP data by model year

Year	Average MSRP	Standard Deviation	Price Delta
1996	$25,536	$15,835	
1997	$26,994	$16,119	$1,458
1998	$28,446	$16,475	$1,452
1999	$28,628	$15,877	$182
2000	$29,521	$15,063	$893
2001	$30,933	$17,029	$1,413
2002	$31,014	$16,932	$80
2003	$32,417	$16,562	$1,403
2004	$33,306	$17,767	$889
2005	$33,751	$18,599	$446
2006	$34,688	$20,045	$937
2007	$34,526	$20,307	-$163
2008	$34,912	$19,899	$386
2009	$37,782	$23,628	$2,871
2010	$38,015	$22,468	$232

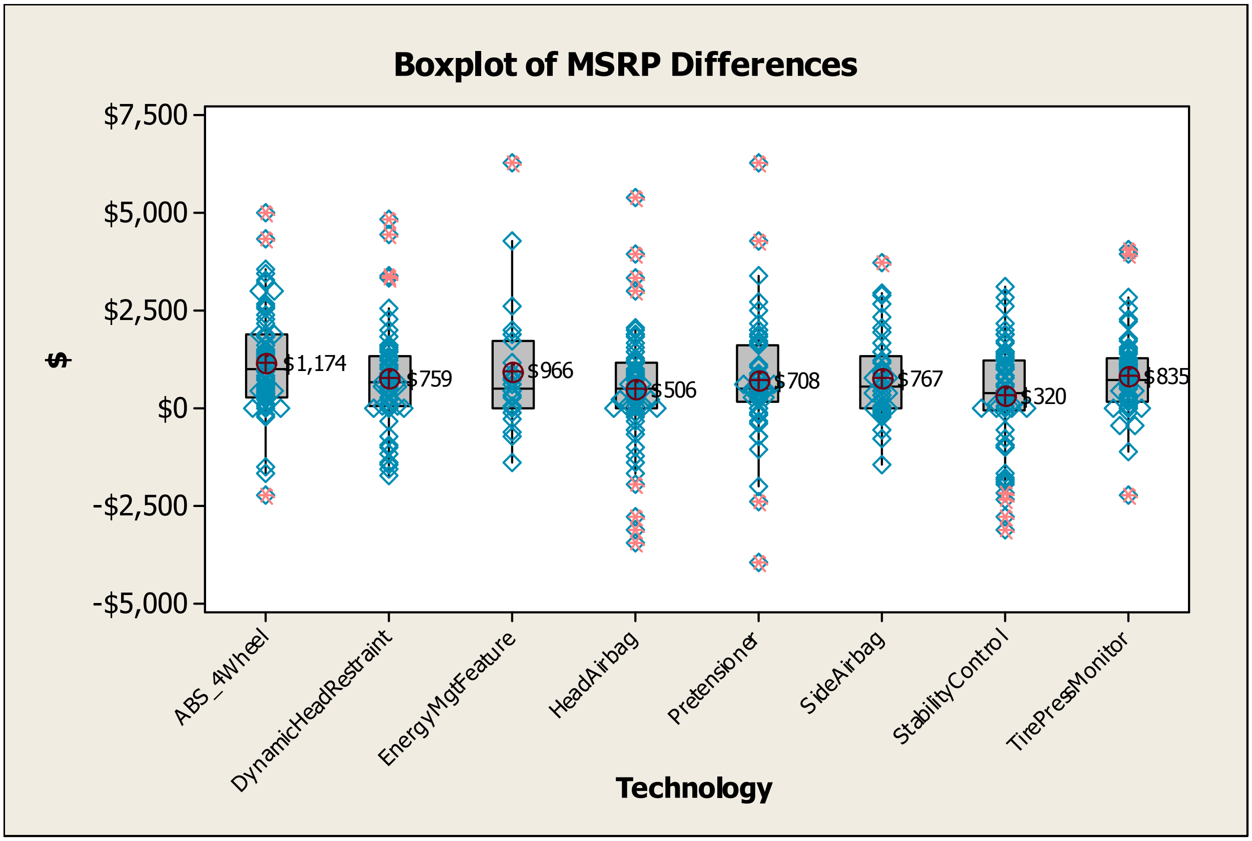

Figure 4. Boxplot of MSRP differences.

Table 4.
Statistical summary of MSRP differences by technology

Technology	Count	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
ABS_4Wheel	63	$1,174	$1,350	-$2,220	$290	$1,015	$1,900	$5,000
DynamicHeadRestraint	61	$759	$1,275	-$1,735	$43	$675	$1,306	$4,880
EnergyMgtFeature	22	$966	$1,717	-$1,390	-$25	$520	$1,750	$6,290
HeadAirbag	73	$505	$1,391	-$3,485	$0	$495	$1,178	$5,430
Pretensioner	54	$708	$1,538	-$4,000	$155	$500	$1,593	$6,290
SideAirbag	41	$767	$1,083	-$1,460	$3	$530	$1,320	$3,755
StabilityControl	65	$320	$1,355	-$3,160	-$85	$380	$1,238	$3,110
TirePressMonitor	54	$835	$1,079	-$2,230	$169	$743	$1,281	$4,090

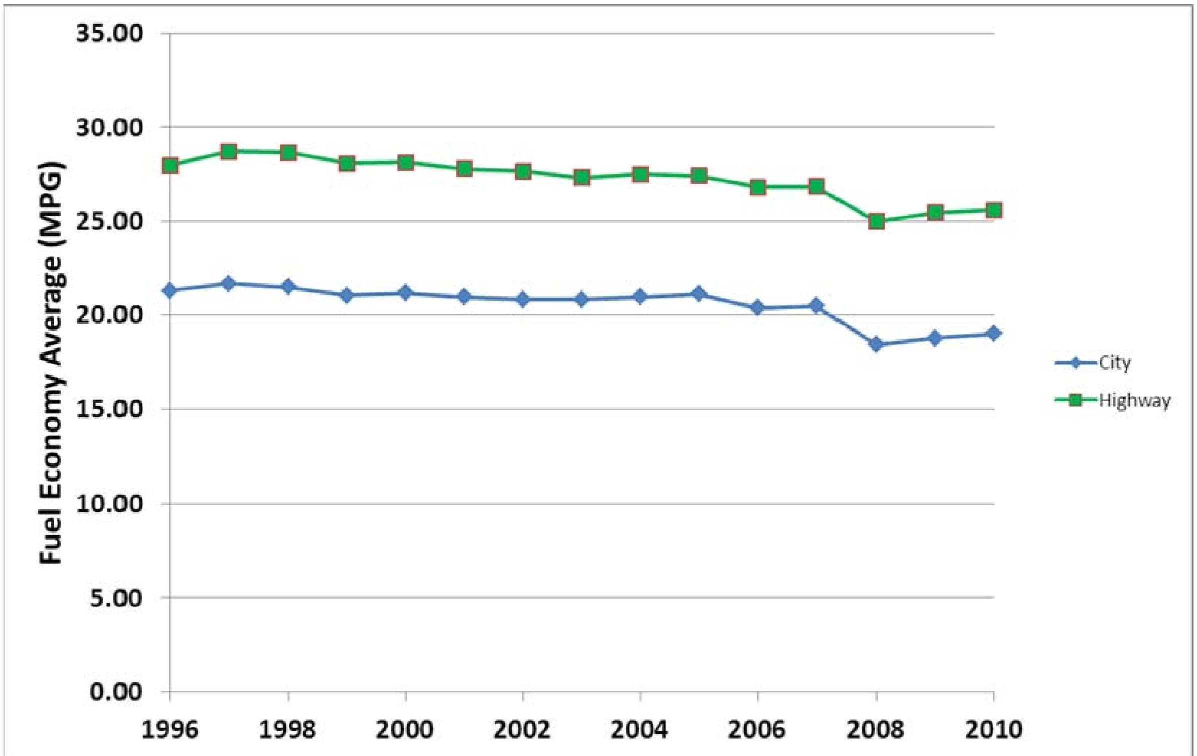

Figure 5. Fuel economy average by model year for data set.

Table 5.
Summary of fuel economy data

Year	Avg. City Fuel Ecomony (MPG)	Standard Deviation	City Fuel Economy Delta (MPG)	Avg. Highway Fuel Ecomony (MPG)	Standard Deviation	Highway Fuel Economy Delta (MPG)
1996	21.30	5.72		27.96	6.45	
1997	21.66	5.85	0.36	28.69	6.59	0.72
1998	21.48	5.61	-0.18	28.64	6.54	-0.05
1999	21.02	5.25	-0.45	28.06	5.93	-0.58
2000	21.15	5.98	0.13	28.13	6.71	0.07
2001	20.94	5.88	-0.22	27.78	6.34	-0.34
2002	20.80	5.90	-0.13	27.65	6.43	-0.13
2003	20.82	6.35	0.02	27.29	6.54	-0.36
2004	20.94	6.89	0.12	27.48	6.93	0.19
2005	21.10	6.86	0.16	27.40	6.70	-0.08
2006	20.36	6.45	-0.75	26.80	6.14	-0.60
2007	20.47	5.78	0.11	26.81	5.54	0.02
2008	18.40	5.21	-2.07	24.96	5.11	-1.85
2009	18.75	5.12	0.35	25.45	5.47	0.49
2010	18.99	5.67	0.24	25.57	5.80	0.13

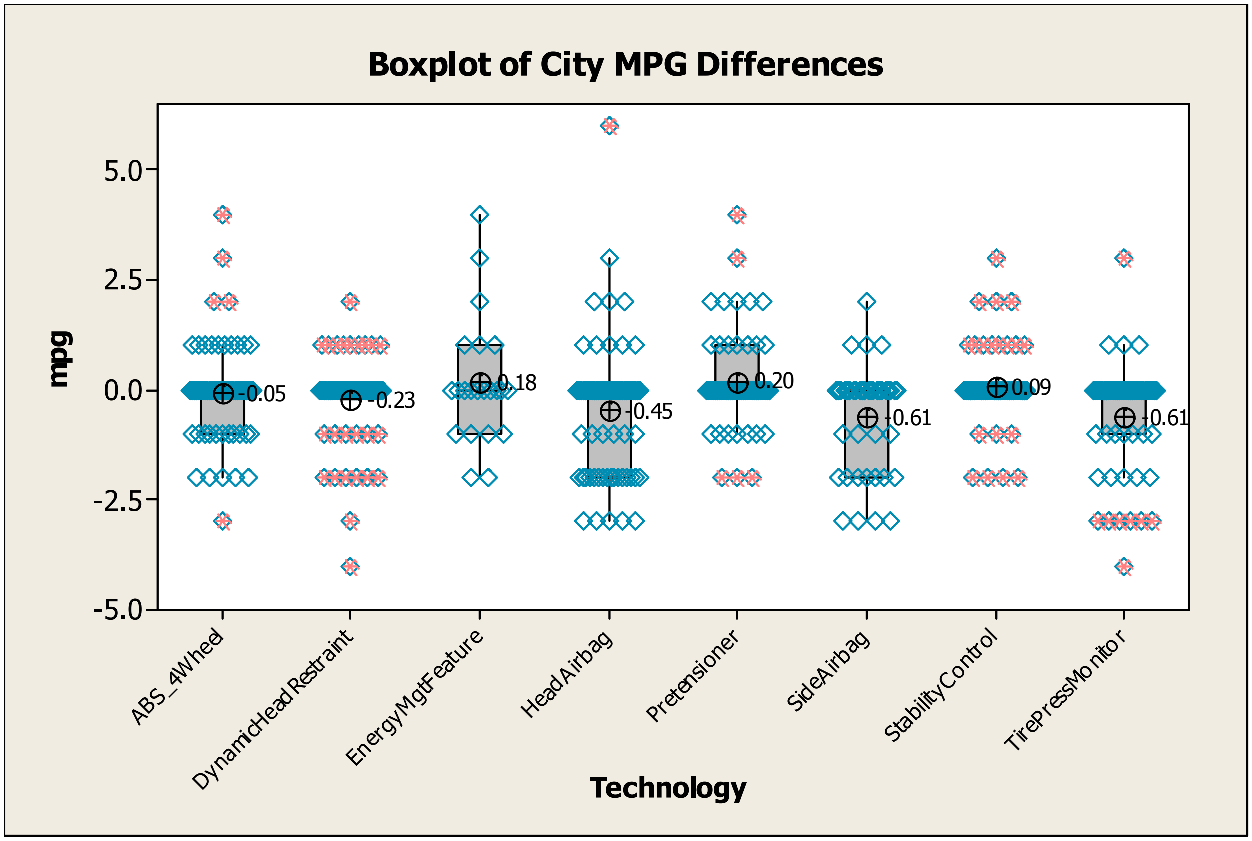

Figure 6. Boxplot of city fuel economy differences.

Table 6.
Statistical summary of city fuel economy differences by technology

Technology	Count	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
ABS_4Wheel	63	-0.048	1.156	-3	-1	0	0	4
DynamicHeadRestraint	61	-0.230	1.039	-4	0	0	0	2
EnergyMgtFeature	22	-0.182	1.435	-2	-1	0	1	4
HeadAirbag	73	-0.452	1.500	-3	-2	0	0	6
Pretensioner	54	0.204	1.139	-2	0	0	1	4
SideAirbag	41	-0.610	1.222	-3	-2	0	0	2
StabilityControl	65	0.092	0.861	-2	0	0	0	3
TirePressMonitor	54	-0.611	1.295	-4	-1	0	0	3

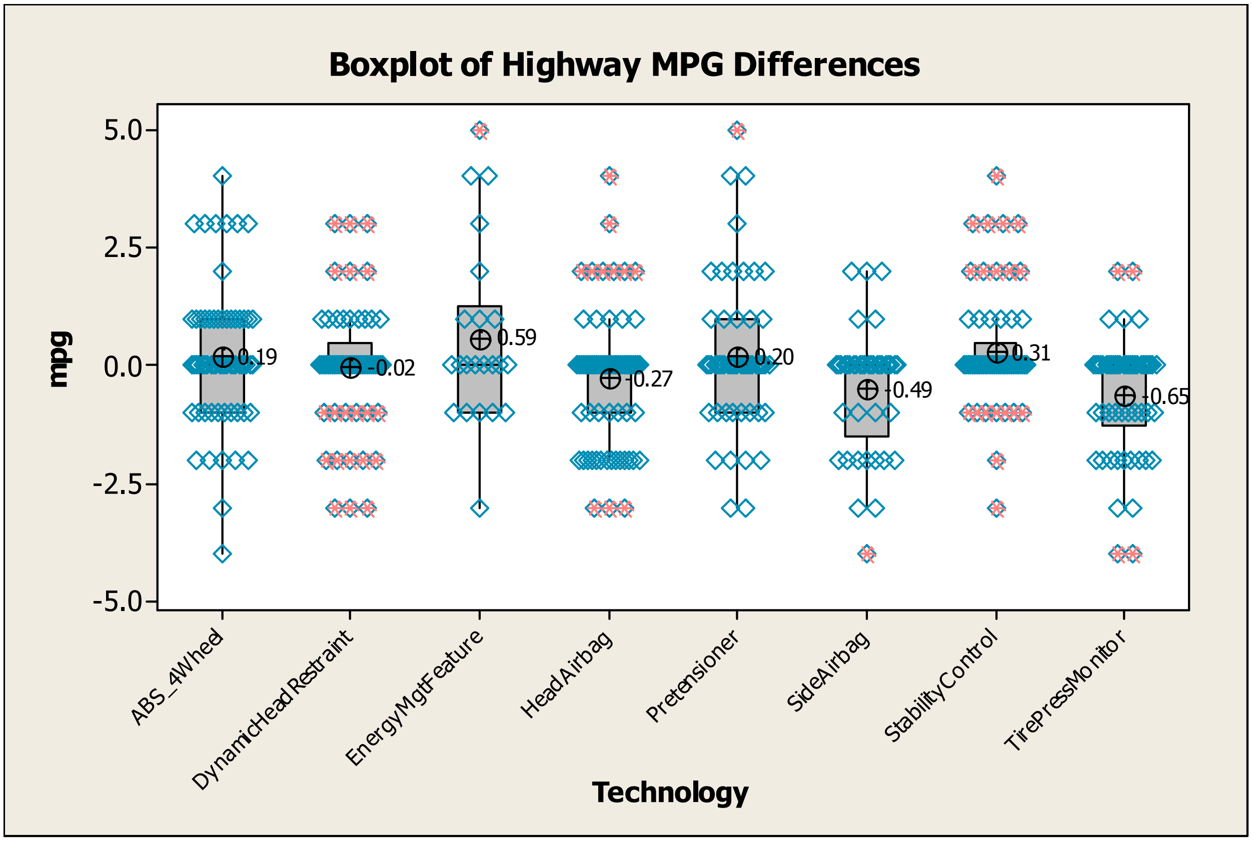

Figure 7. Boxplot of highway fuel economy differences.

Table 7.
Statistical summary of highway fuel economy differences by technology

Technology	Count	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
ABS_4Wheel	63	0.190	1.512	-4	-1	0	1	4
DynamicHeadRestraint	61	-0.016	1.297	-3	0	0	0.50	3
EnergyMgtFeature	22	0.591	1.943	-3	-1	0	1.25	5
HeadAirbag	73	-0.274	1.387	-3	-1	0	0	4
Pretensioner	54	0.204	1.595	-3	-1	0	1	5
SideAirbag	41	-0.488	1.325	-4	-1.50	0	0	2
StabilityControl	65	0.308	1.198	-3	0	0	0.50	4
TirePressMonitor	54	-0.648	1.261	-4	-1.25	0	0	2

DISCUSSION

In general, application of emerging injury mitigation technology seems not to have had significant disruptive effects on any of the three vehicle level parameters: mass, price, or fuel economy.
The modest impacts addition of injury mitigation technologies may have effected throughout the

decade 1999 to 2009 on vehicle level price, mass, and fuel economy suggest that as manufacturers added the material cost and mass associated with safety technologies to base vehicles, other system level or architectural level changes may have been effected simultaneously so as to offset or compensate for the vehicle level cost and mass increases associated with the added safety equipment. Manufacturers have as well as possible attempted to integrate advanced, emerging, and new injury control technologies into vehicles without changing the market placement, affordability, or competitiveness of vehicles at the make/model level. This strategy of balancing vehicle level content and attributes to compensate for the added mass, fuel economy, and cost effects of emerging safety technologies may become more difficult to manage as fuel economy standards become more demanding. In the future, fuel economy standards will serve as a prime driver for major architectural revisions in vehicle size and mass and will demand relatively larger proportions of available research and engineering resources.

There are obvious limitations inherent in this type of analysis. While the general size of vehicles can be characterized, structural changes that result in vehicles with higher mass 'density' are difficult to characterize. A current vehicle's structure, controlling for external dimensions and materials would in most cases weigh much more than a vehicle of a decade ago, due to the greater injury control content and improved structures to manage a greater variety of collision load cases as well as address the structural needs and dynamic response of the rest of the vehicle.

Further, it is not possible to reconstruct the thousands of design decisions made by engineers developing each portfolio entry for each motor vehicle manufacturer. The study of association between certain injury mitigation features and mass, price and fuel economy is not meant to imply that addition of a technology caused a particular resulting increase or decrease. Rather, this study reports at a gross vehicle level the relationships registered over time, over the new vehicle fleet. Analyzing any feature with a myopic viewpoint that only considers the price or mass of the feature's components is erroneous. It is impossible to extract the true extent of the mass and price of a new injury mitigation technology as multiple elements of the vehicle structure, electronics, package, etc. would have undergone thoughtful consideration and incurred expenditure to enable the use of that feature.

CONCLUSIONS

Overall, there is little association between the addition of new safety technologies and changes in overall vehicle mass, price, and fuel economy. The addition of individual injury control technologies appears to have been largely offset by operational efficiencies or through applications of advanced designs and weight savings harvested elsewhere in the vehicle. Compared to the overall trends seen in the dataset of increasing curb weight, increasing price, and decreasing fuel economy, the individual safety technologies do not strongly correlate as contributors to these overall vehicle parameters.

REFERENCE

[1] Lange, R.L, Pearce, H.M., Jacuzzi, E.A. 2011. "Installation Patterns for Emerging Injury Mitigation Technologies, 1998 Through 2010." 21st Enhanced Safety of Vehicles Conference, Washington, DC.

CRASH SAFETY ASPECTS OF HV BATTERIES FOR VEHICLES

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ABSTRACT

Undisputed, the current safety standards for high voltage batteries address the chemical and thermal performance of battery cells during mechanical loads, i.e. pressure forces and intrusion. However, they do not represent the typical loads to the battery in vehicle crashes:
- The battery intrusions specified in the standards, namely 50 % of the battery dimension, cannot be achieved with the typical battery on standard compression machines due to the high forces needed.
- The maximum forces specified in the standards, namely the thousandfold of the battery weight, are unrealistically high even for small batteries in mild hybrid vehicles (i.e. the 24 kg battery of the Mercedes-Benz S 400 HYBRID). The loads applied to the battery rarely exceed 200 kN.
Even with 240 kN applied to the battery package, the battery intrusion achieved is only approx 11 %, which is well below the targeted 50 %.
There are two main differences between the loads applied to the battery in a vehicle crash versus the quasi-static battery tests: 1. Due to the crash propagation, the load is applied indirectly by the surrounding structure and components via multiple and distributed load paths; 2. Due to the short period of the peak loads, the battery can withstand much higher dynamical forces than the maximum static loads.

In order to assess the safety performance of HV batteries in severe crashes more realistically, a comprehensive series of dynamical impact tests was conducted with all types and sizes of HV-batteries used in the current Mercedes-Benz hybrid and electric vehicles. The load profiles were derived from both, the relevant vehicle crashes, and the quasi-static battery standards, applying even higher loads and battery intrusions. The tests were conducted at the crash test facility of the TÜV SÜD, utilizing two different test methods:

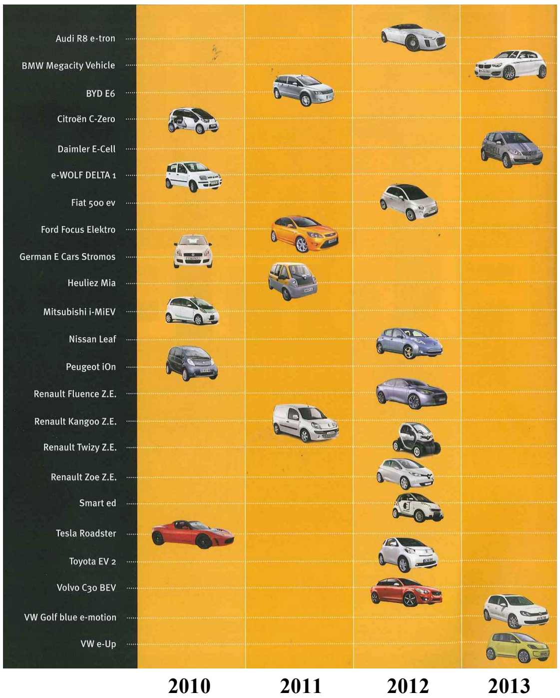
a) The moving battery hitting an impactor attached to the rigid barrier;
b) The moving impactor hitting the battery attached to the rigid barrier.

Despite the high loads and the resulting major battery intrusions, no thermal or electric reactions occurred, neither short circuits, nor electrolyte leakages, nor fire or explosion. The shock-proof protection was ensured in all tests. Given the very realistic test method along with the high loads applied, a very high crash safety performance could be demonstrated for all the batteries. Furthermore, the tests confirmed that there are major differences in the load characteristic between the quasi-static battery test standards, and the dynamic crash loads. As a result, more realistic component tests for traction batteries must be specified as soon as possible.

INTRODUCTION

Driven by severe fuel economy and CO_2 emission regulations, there is no doubt that hybrid and battery electric vehicles will play a major role in the future individual traffic. It goes without saying that the consumers expect an equally high safety standard for alternatively driven vehicles as established for conventional cars. While many car lines already offer a hybrid version, the availability of battery electric vehicles (BEV) is still restricted to small series, or special vehicles, and the number of purchasable electric car models (Table 1) is still limited [1]. While currently only approx. 40,000 hybrid and electric vehicles are currently licensed in Germany, of which only 2,300 are BEV's [2], this number is expected to increase to up to 1 Mio by 2020 [3]. All major OEMs have announced new electric cars in the near future.

Table 1.
List of BEV purchasable in Germany [1].



A roadblock for the acceptance of electric vehicles is their still limited cruising range. The key to success is intrinsically tied to the energy storage technology, Lithium-ion high-voltage batteries (HV) obviously being the base for the near future hybrid and electric vehicles. As any energy storage, also HV-batteries implicate some challenges to both the functional safety and the crash safety, which must be addressed appropriately. As discussed in the ESV-paper “Crash Safety of Hybrid- and Battery Electric Vehicles” [4], the crash performance of hybrid and electric vehicles is mainly affected by two key factors: 1. the crash performance of the battery itself, and 2. the crash protected integration of all the HV components in the vehicle. While the protection zones for the best possible integration of energy storages were evaluated in another study [5] by analyzing the damages of approx. 9,000 vehicles involved in severe real world accidents (Figure 1), the focus of this paper is on the crash safety performance of the HV batteries.

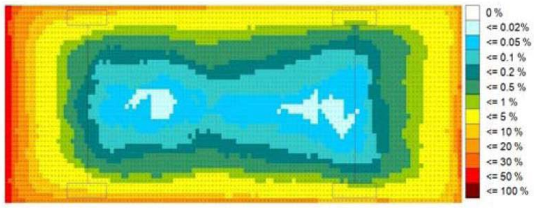


Figure 1. Deformation probability in severe real world accidents (passenger cars, top view, vehicle front on the left).

MOTIVATION

The current safety standards of high voltage batteries address the chemical and thermal performance of individual battery cells and its composites during mechanical loads, i.e. pressure forces and intrusion / deformation. Typically, due to the high loads, the cells will be destroyed with the result of electrolyte leakage. The break out of a fire depends on the temperature level generated during the test, or any extraneous ignition. Although these tests are very useful in evaluating the safety performance of battery cells, there are many arguments that these tests do not represent the typical loads to traction batteries in crash tests or in severe real world accidents.

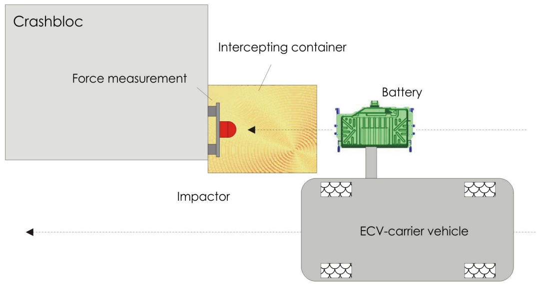
Already the implementation of the test requirements encounters some major difficulties. Generally, the traction battery is packaged in the vehicle as a module with a housing including the electronics, the cooling system and other elements. Due to the high deformation resistance of such a battery module, the battery intrusions specified in the current test standards, namely 50 % of the battery dimension, could only be achieved with extremely powerful test benches. Moreover, the maximum forces specified in the current standards (i.e. SAE J2464), namely the thousandfold of the battery weight, are not high enough to achieve the targeted intrusion: i.e. only 11 % deformation of the battery housing could be achieved (~ 24 mm) by applying the thousandfold of the small 24 kg battery with 0.8 kWh of the Mercedes-Benz S 400 HYBRID [6,7,8]. Due to the structural design of the battery, no battery cells will be impacted at such minor intrusions. Applying this requirement to the battery of full hybrid vehicles with 1,5-3 kWh, or to the battery of electric vehicles with 15-35 kWh, resulting in battery weights of 50 to 200 kg, the minimal load would be 500 to 2000 kN, which is totally unrealistic compared to the loads applied even in the crash tests: In crash simulations the maximum loads rarely exceed 200 kN.

There are two main differences between the loads applied to the battery in vehicle crashes versus the quasi-static battery tests:
1. The crash load is propagated to the battery by the surrounding structure and components via multiple and distributed load paths, thus being applied only indirectly, i.e. the battery may move or dodge, the battery mounting and housing may be designed deformable, the battery protecting cage and the surrounding vehicle structure may absorb energy, and many other compliances and reinforcements may cushion the peak loads to the battery.
2. Another crucial difference of crash loads versus quasi-static tests is the time scale: due to the very short period of the whole crash of approx 100 ms (the blink of the eye) peak loads are applied only for milliseconds. Same as any component, the battery can withstands much higher short-period dynamical forces than the maximum static loads. On the other hand, due to the high peak values of the vehicle acceleration during the crash – up to 80 G's – high inertial forces will be generated in the battery interior, and must be taken into account in the mechanical design of the battery.

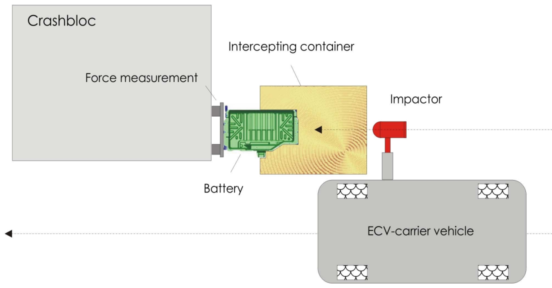
In order to evaluate the safety performance of traction batteries in vehicle crashes realistically, the parameters of the corresponding component tests must be defined appropriately. In particular, misconstrue of the battery due to an unrealistically high mechanical stability required, and the resulting in unnecessary high costs must be avoided. Therefore, a comprehensive series of dynamical crash tests with all types and sizes of HV-batteries used in the actual Mercedes-Benz hybrid and electric vehicles has been conducted.

TEST METHOD

The tests were conducted at the crash test facility of the TÜV SÜD, utilizing an impactor with variable mass and geometry hitting the battery. In order to cover a wide range of impact energy, speed, mass and geometry, two different test methods were applied (Figure 2):
a) The moving battery was hitting an impactor attached to the rigid barrier;
b) The moving impactor was hitting the battery fixed to the barrier.



a) Impactor fixed to the barrier, battery moving



b) Battery fixed to the barrier, impactor moving

Figure 2. Impact test configurations.

The set-up (a) was mainly used for larger batteries. For smaller batteries, the test method was inversed (b) when the targeted kinetic energy could not be achieved with the limited impact speed. In these cases, the batteries were fixed to the barrier and impacted with 40 kph by the energy equivalent mass. In these cases, the high inertial forces resulting from the battery acceleration could not be simulated, unfortunately. In either case, the moving part was mounted to the support shaft of a truck approaching the barrier with the selected test speed. Shortly before the impact, the moving mass was decoupled from the support shaft and flying free against the barrier, while the truck was passing the barrier on the side.

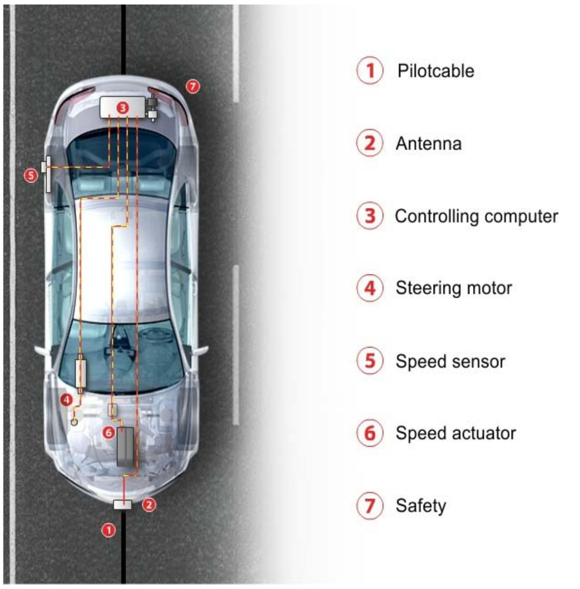


Figure 3. Electronically controlled vehicle system (EVC).

The truck was controlled by the Electronically Controlled Vehicle system (EVC). It was developed by TÜV SÜD to enable most realistic and reproducible crash tests for all vehicle sizes, from small cars up to big trucks, in any possible configuration [9, 10]. EVC (Figure 3) guarantees an accurate control of a driverless vehicle with respect to speed and course. With a wire on the road defining the driving course, and an antenna in the front bumper, the control unit in the vehicle enables autonomous acceleration, braking and steering. Any corrections to the direction are calculated continuously and applied to the steering by an electric motor. Similarly, the vehicle speed is controlled by automatically adjusting the throttle. Shortly before the crash, the control elements can be decoupled, and the vehicle can be stopped at any time by an independent radio signal.

This test configuration (Figure 4) allows impact speeds up to 55 kph, impact masses up to 500 kg, resulting in maximum impact energy of 60 kJ, using different impactor geometries as illustrated in Figure 5, i.e. half cylinder, hemisphere or wedge.

Figure 4. Test build-up for dynamic battery impact.

The impact loads were monitored with load cells on the barrier, and the intrusions to the battery were measured as well. The batteries were monitored for 48 hours after the tests.

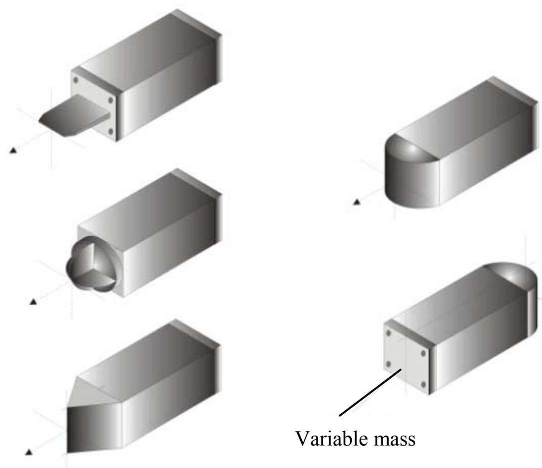


Figure 5. Impactor geometries.

TEST SAMPLES AND DYNAMIC LOAD PROFILES

Figure 6. Batteries of actual Mercedes-Benz hybrid and electric vehicles.

Figure 6 shows the batteries used in the actual Mercedes-Benz hybrid and electric vehicles.

A Lithium-Ion 0,8 kWh mild hybrid battery (24 kg) in the S 400 HYBRID, a NiMH 2,4 kWh full hybrid battery (83 kg) in the ML 450 HYBRID, a 1,4 kWh Li-Ion battery (48 kg) in the B-Class F-CELL, and a 14 kWh Li-Ion battery (148 kg) in the Smart ELECTRIC DRIVE. 2-3 samples of each battery were available for the dynamic crash tests.

In all Mercedes-Benz hybrid and electric vehicles, the traction battery is well protected against any critical loads or damages in vehicle accidents. This is true for the battery located in front of the compliant firewall of the S 400 HYBRID, for the battery placed above the stiff rear axle of the ML 450 HYBRID or of the B-class F-CELL and for the battery of the Smart ED located on the vehicle floor between the solid side rocker panels.

Battery Type	Mild-Hybrid (Li-ion)	F-CELL (Li-ion)	Full-Hybrid (NiMH)	BEV (Li-ion)
Battery Data	0,8 kWh, 24 kg	1,4 kWh, 48 kg	2,4 kWh, 83 kg	14 kWh, 148 kg
Test Type # 1	B (Battery fixed)	A (Battery moving)	A	A
Test data # 1	m=280 kg v= 18 km/h E=3,5 kJ	v=40 km/h E=3 kJ	v=40 km/h E=5 kJ	v=32 km/h E=6 kJ
Test Type # 2	B	B	B	A
(Test data # 2	m=300 kg, v= 22 km/h E=5,6 kJ	m=200 kg, v=35 km/h E=9 kJ	m= 200 kg, v=35 km/h E=9 kJ	v=40 km/h E=9 kJ

Figure 7. Dynamic battery impact test parameters.

The parameters of the dynamic battery tests (Figure 7) were based on the maximum loads (both force and intrusion) achieved in the quasi-static battery tests and in addition, the load paths in the relevant crash tests were evaluated utilizing crash simulation. For reasons of comparability, similar load cases were applied to all batteries. In the base test, a kinetic energy of 3-6 kJ was applied according to the force-deflection characteristics of the quasi-static tests. Although this energy is above and beyond the loads experienced in the vehicle crash tests, the energy was significantly increased (between 1.5 and 3 times) in a further test. While a half cylinder with 300 mm diameter was used for the larger batteries, a smaller diameter of 150 mm was used for the smaller batteries in order to take into account the smaller battery dimensions.

TEST RESULTS

Mild-Hybrid Battery (Li-Ion)

In the quasi-static test with a cylinder of 150 mm diameter, 24 mm intrusion was achieved at 270 kN maximum load. In order to apply the equivalent energy of 3.5 kJ to the small 24 kg battery in the dynamic impact, the battery attached to the barrier was impacted with 280 kg mass at 18 kph. Similar to the static test, a maximum deformation of 25 mm was achieved at a maximum force of 300 kN. While an almost linear load characteristic was measured in the static test, the slope of the dynamic load is flat up to 10 mm, increasing progressively with higher intrusion. In the 2nd tests, the energy was increased by 50 %, which is equivalent to 300 kg impactor mass and 22 kph, resulting in 35 mm intrusion at 380 kN (Figure 8). Same as in the static tests, the battery enclosure did not break despite the high deformation, and no thermal reactions or electrolyte leakages occurred. The battery state of charge (SOC) was 80 % in both tests, and the shock-proof protection was fully ensured. Since the battery cells are mounted individually in the housing, no damages are expected even at very high inertial forces during battery acceleration. Although the crash energies applied in the tests are far above the loads expected even in very severe real world accidents, the crash safety performance of the battery is excellent, mainly to the extremely stiff high quality steel cage.

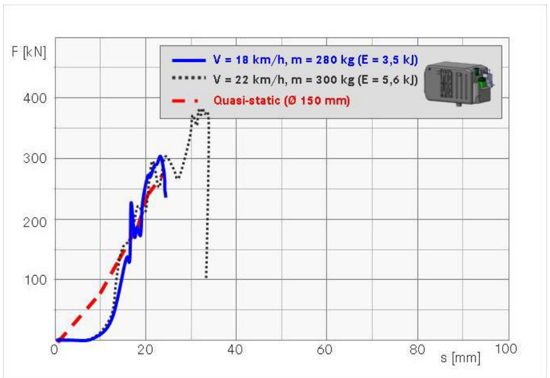


Figure 8. Load characteristics of the mild-hybrid Li-ion battery.

F-CELL Battery (Li-Ion)

Again, the parameters of the dynamic impact were based on a quasi-static test with a cylinder of 300 mm diameter. According to 90 mm intrusion at 60 kN, 3 kJ kinetic energy was applied with 40 kph battery impact speed. Interestingly, only one third (35 mm) intrusion was achieved at the double peak load (130 kN) versus the quasi-static test, the dynamic load characteristic significantly deviating from the linear slope. Since no thermal or chemical reaction occurred in a quasi-static test with 90 mm intrusion, the kinetic energy was tripled to 9 kJ in the 2nd test, by impacting the battery attached to the barrier with 200 kg at 35 kph. Despite 110 mm intrusion 150 kN peak, still no electric or thermal reactions could be measured (Figure. 9). The battery SOC was 90 %, and the shock-proof protection was ensured.

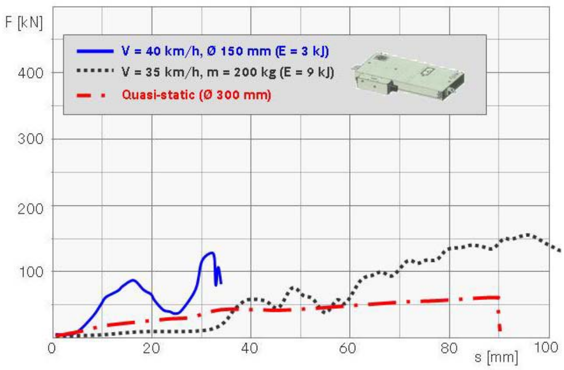


Figure 9. Load characteristics of the F-CELL Li-ion battery.

Full-Hybrid Battery (NiMH)

In the quasi-static test, the battery failed at 90 mm intrusion at 180 kN due to the contact between conduction parts in the electronics, resulting in short circuits and spark generation. In the energy equivalent dynamic test, the battery was impacted by a half cylinder with 40 kph, with a diameter of 150 mm in the 1st test, and 300 mm in the 2nd test. Despite the higher dynamic forces (200 and 250 kN), the resulting battery intrusions (50 and 55 mm respectively) were significantly lower than in the static test (Figure 10). Due to rotary motions during the impact, only approx. 2/3 of the kinetic energy was transferred in deformation energy. This could be the reason why, interestingly, the higher intrusion was achieved with the bigger impactor diameter. The slope of the dynamic load is significantly steeper as the quasi-static characteristic. In the 3rd test, the battery was attached to the barrier, in order to apply higher energies to the battery. As a consequence, the back side of the battery, being weaker than the center, was deformed significantly, while the intrusion at the impact side were similar as in the prior tests. Again, no electric or thermal reactions occurred, the shock-proof protection was ensured, and the battery SOC was 75 %.

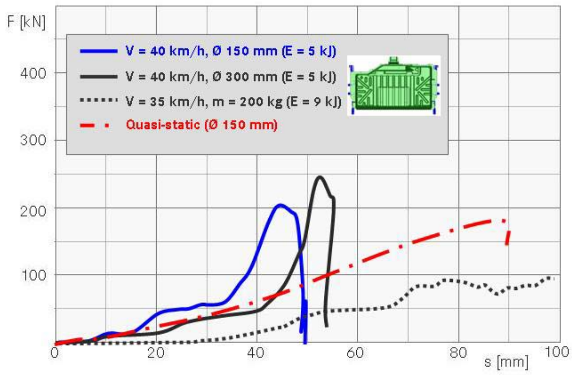


Figure 10. Load characteristics of the full-hybrid NiMH battery.

BEV-Battery (Li-ion)

Due to the size of the battery, no quasi-static tests were performed. Alternatively, the parameters of the dynamic impact test were evaluated from the battery loads experienced in the relevant crash tests. Utilizing crash simulation, a maximum energy of 6 kJ was estimated. Accordingly, the battery was impacted with 32 kph against a pole (300 mm diameter) in the 1st test, resulting in 35 mm deformation of the battery housing (Figure 11). Although the energy was 50 % higher in the 2nd test (9 kJ, 40 kph), resulting in 55 mm at 230 kN maximum load, no electric or thermal reactions occurred in either test. The shock-proof protection was ensured, and the battery SOC was 95 %.

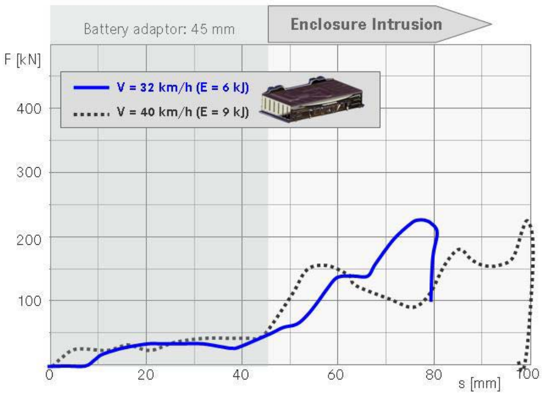


Figure 11. Load characteristics of the BEV Li-ion battery.

DISCUSSION OF THE TEST RESULTS

Despite the high loads applied and the resulting major battery intrusions, no critical thermal or electric reactions occurred in the described test series (Figure 12), and the shock-proof protection was ensured. No short circuits, no electrolyte leakages, no fire or even explosion occurred. Given the very realistic test method along with the loads applied being much higher than in severe accidents, a very high crash safety performance could be demonstrated for the batteries currently used in the actual Mercedes-Benz hybrid and electric vehicles.

While some of the dynamic impact tests correlated relatively well with the equivalent static tests with regard to maximum loads and intrusions, major differences were observed with the bigger batteries, the load characteristic in particular. This is also true for the performance data of the different battery types in the dynamic impacts. Evidently, the mechanical stability of the battery housing, and the interior compliance of the battery play a key role in the crash performance. Both concepts, a very stiff housing allowing only minor intrusions (i.e. the mild hybrid battery), and a compliant battery interior tolerating major intrusions (i.e. the F-CELL battery), have been proven as crash-safe even if directly impacted in a crash. Nevertheless, the traction battery should always be located in a very stiff area which is protected against major deformations.

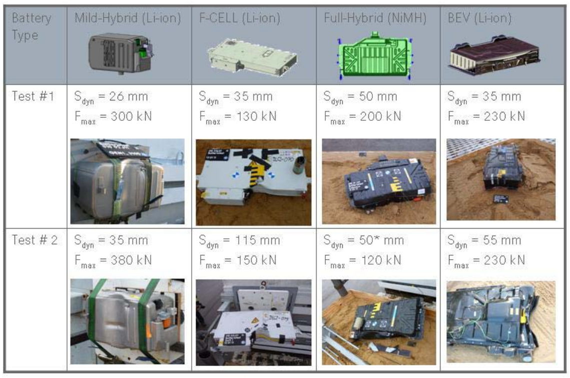


Figure 12. Test results of dynamic impacts with HV-batteries.

CONCLUSIONS

It is obvious from the test results, that the current test standards for high voltage batteries, based on quasi-static tests, do neither reflect the mechanical loads experienced in the vehicle crash tests, nor in the dynamic impact tests. This is true for the specification of a minimum crush of the battery package, and it is even more for the correlation of the maximum load to the battery weight. As a result, these battery standards must be modified appropriately. I.e. a minimum load could be specified where no battery cells must be damaged resulting in electric short circuits or electrolyte leakages. The current standards only address the chemical safety performance of individual battery cells.

As a next step, the partially major differences in load characteristic between the dynamic impact and quasi-static tests must be further analyzed, with the ultimate goal, to specify relative simple and reproducible and most realistic component tests for traction batteries. Finally, these tests must be verified in tests with different crash loads and different battery types.

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TECHNOLOGY NEEDS FOR SAFE ELECTRIC VEHICLE SOLUTIONS IN 2030

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ABSTRACT

Today's society depends heavily on the mobility of people and goods and the need for transport is predicted to grow strongly in the coming decades. Environmental and energy concerns create a strong demand for alternative automotive technologies and in particular for electric vehicles. A serious limitation of large scale introduction of electric vehicles is the limited storage capability for electrical energy of the current generation of batteries and capacitors. Furthermore, there is a strong trend to design significantly lighter vehicles needed to consume much less energy, and to introduce new vehicle architectures due to specific demands of electric vehicles like hub motors, relatively large space needed for batteries etc.

Without new safety technologies there is a large risk that the new vehicle designs will become less safe in case of accidents. In a project recently conducted in Sweden, called SEVS (Safe Efficient Vehicle Solutions), the necessary technologies for the 2030 generation of environmentally friendly safe vehicles have been identified. The SEVS project has resulted in a number of possible societal scenarios for 2030 and a number of future vehicle architectures. Furthermore SEVS has identified the required technological breakthroughs for passenger transport as well as the transport of goods, to realize mass introduction of high efficient and safe electric vehicles on the road in 2030.

This paper will after an overview of the SEVS project focus on a number of safety related technology topics, identified in SEVS, where significant further research is needed, i.e. balance of active/passive safety, light weight design methodology, crashworthiness of future vehicles and " information needs and availability".

An overview of research needs for these topics will be presented.

INTRODUCTION

Today's society depends heavily on the mobility of people and goods and the need for transport is expected to grow even further over the coming decades [1]. Environmental and energy concerns create a strong demand for alternative automotive technologies. An attractive alternative for future motorized transport of persons and goods will be electric vehicles (EV's) and market introduction of a number EV models has started. Most of the EV designs appearing on the market rely largely on existing technologies. For significant breakthrough's in EV's in the longer term however new enabling technologies will be needed.

A serious limitation of large scale introduction of EV's is the limited storage capability for electrical energy of current generation of batteries and capacitors. Furthermore, there is a strong trend to design significantly lighter vehicles needed to consume significantly less energy, and to introduce new vehicle architectures due to demands of EV"s (hub motors, relatively large space needed for batteries etc.).

Without new safety technologies there is a large risk that the new vehicle designs will become less safe both in terms of electric and fire safety (high voltage and potentially explosive energy storage systems) and accident safety. On the other hand, new components in EV's might open up for better/other safety solutions than today, if safety is taken on board in the requirements already in the initial (concept) phase of the vehicle design process.

In a project recently conducted in Sweden, called SEVS (Safe Efficient Vehicle Solutions), the Swedish industrial and research expertise and experience in efficient power trains and vehicle safety has joint efforts to identify the enabling technologies for the generation of safe and green vehicles on the road in 2030. A large number of partners have participated in the project: the vehicle manufacturers SAAB, Volvo Car Corporation and Volvo AB (Volvo Technology) and their supplier Autoliv,; the consultant companies Etteplantech, Semcon and Epsilon; the research institutes SP, Swerea SICOMP AB, Viktoria Institute and the authority VTI. The project has been conducted by the Centers of Excellence SAFER (Vehicle and Traffic Safety Centre) and SHC (Swedish Hybrid Vehicle Centre), which are both related to Chalmers University of Technology in Sweden.

The objective of SEVS was to develop new knowledge to understand the technology, strategies and the principle solutions needed for a new generation of vehicles 2030, which fulfil high standards on both safety and environmental aspects. The level of safety offered to road users should be significantly higher than the level of safety offered by the current generation of ICE-powered vehicles. The new generation of vehicles should address the need for short range (city) as well as long-distance travel either by modular solutions or by having different solutions.

Specific objectives of SEVS were:

1. To identify and analyse the driving forces that shape the future society, and describe four extreme societal scenario's for 2030
2. To identify of a number of promising virtual new vehicle design concepts for 2030
3. To identify the required technological breakthroughs and research needs both for passenger transport as well as the transport of goods to realize mass introduction of high efficient and safe electric (and hybrid) vehicles on the road in 2030.

For passenger cars the target in SEVS was set to reach a reduction of energy consumption by 80% as well as a reduction in fatalities of also 80% by 2030+.

Concerning objective 1, SEVS has resulted in 4 societal scenarios that are illustrated in Figure 1. The scenario process is the result of a detailed analysis of groups of driving forces including demographic trends, life style changes, politics, environmental impact etc… Two of the driving force groups namely "politics" and "personal values" were identified as drivers with the largest uncertainty and with the largest impact on a future sustainable and safe transport system.
The 4 scenarios shown in Figure 1 have been based on these two groups of drivers. The x-axis corresponds to personal values (in particular concerning travelling) and the outcome of this driving force varies from *no change* (left) to *radical change in transportation patters* (right). The y-axis corresponds to politics (in particular concerning transportation legislation and incentives) and varies from *political passive* (bottom) and *proactive political control* (top). The resulting scenarios in the 4 quadrants are denoted: *Incremental development, eco political, eco individual and radicalism in harmony,* respectively. For more details on the work done in SEVS related to drivers and scenarios please refer to [2].

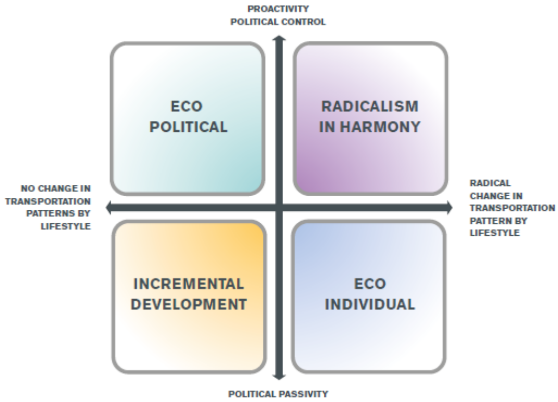

Figure 1. The 4 different societal scenarios resulting from the SEVS project

Concerning objective 2, SEVS produced seven different vehicle concepts (virtual demonstrators) with different placements of electric drive-train components. The concepts included 3 different city movers each linked to a different societal scenario, 2 long distance vehicle linked to 2 societal scenarios and a medium-heavy truck and bus also linked to 2 of the scenarios. Figure 2 illustrates the various concepts as well as their link to the various societal scenarios. The main drivers for the developments of these vehicle design concepts where vehicle safety, lower environmental impact and lower energy consumption, taking the specific characteristics of the 4 scenarios into account. The development of the vehicle concepts influenced also the selection and prioritization of the required technology developments for 2030 (objective 3 of SEVS). More details on the concept development can be found in [2].

This paper will further focus on objective 3 of the SEVS project: the identification of the required technological breakthroughs and research needs for EV's in 2030. In the next section first the process and methodology in SEVS to identify the most important technology topics for EV's in 2030

will be described. Seven of these topics appeared to have a high impact on safety.
Out of these seven topics, 4 topics where significant further research is needed, will be presented in more detail namely balance of active/passive safety, light weight vehicle design, crashworthiness of future vehicles and "information needs and availability".

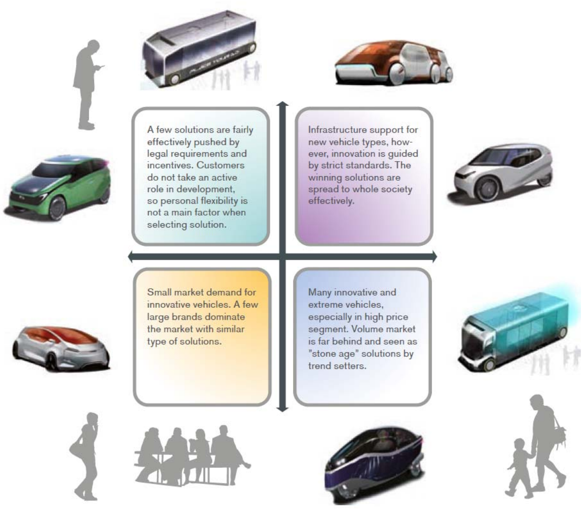

Figure 2. The SEVS project resulted in 7 different virtual vehicle concepts each linked to one of the 4 societal scenarios.

METHOD

The first step in the process of identifying the most important technology research questions was a review of the various technologies needed for electric (and hybrid) and a future outlook of technologies to be developed. The technology area's considered as critical at the start of SEVS for future electric vehicles were:

- Light weight construction
- Batteries
- Sensors, control and communication
- Driveline
- Safety
- Infrastructure

In the next section a short description of these 6 technology areas is presented.

For each of these 6 technology areas a group of experts has reviewed the state of the art for that technology, including its dependency with other technologies, starting with existing technology roadmaps for these areas, interviews with other experts etc... A roadmap of R&D needs for that specific technology was developed and subsequently discussed and finalized in a joint workshop. As a result of this process 6 technology reports have been produced (internal SEVS reports).

The technology teams were also asked to define for their technology field the most important research topics. This resulted in more than 60 technology research topics considered to be of high importance. In a joint workshop involving all experts from the various technology teams the various topics were prioritized concerning their impact on future safe and green transport solutions, keeping the targets set in SEVS for 2030 in mind: a reduction of energy consumption (from well to wheel) by 80% and at the same time an 80% reduction in fatalities. Also an integration and refinement of some of the research topics took place during this workshop.

A further reduction and prioritisation of the research topics took place by:

(1) Taking into account the priorities resulting from the vehicle concept development task,
(2) A review of the various research topics by the key organisations involved in the SEVS project. These organisations were invited to identify the areas which were considered most relevant for their organisation in view of the possible transportation needs in 2030 as identified by the 4 scenarios developed within SEVS
(3) An external workshop with a large number of stakeholders.

This process finally resulted in a list of the 10 most important technology research topics presented in Figure 3 (Top 10 list). The research topics are presented in this Figure according to their estimated impact on energy efficiency (vertical) and safety (horizontal). Seven of the research topics have a large impact on safety and out of these 4 topics (orange in Figure 3) will be discussed in more detail in this paper.

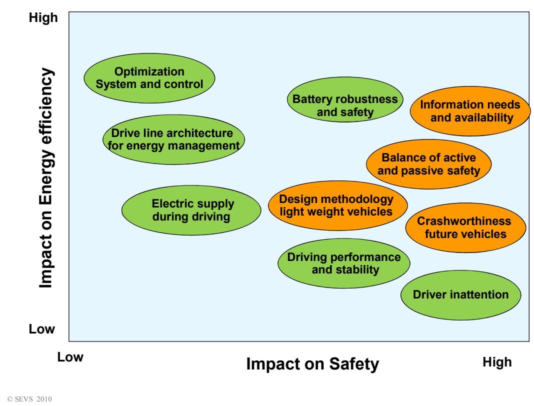

Figure 3. Top 10 technology research topics prioritized according their impact on energy efficiency (vertical) and safety (horizontal).

TECHNOLOGY AREAS IN SEVS

Lightweight Construction

To meet the demands for lightweight in future electric and hybrid vehicles the use of lightweight metals including aluminium and high-strength steels and non-metals like polymer composites in automotive structures is crucial. Examples of material technologies that need further development before economical application in automotive is possible includes carbon fibre reinforced polymers that present outstanding potential for weight reduction, innovative multifunctional polymer composite materials, providing combined load-carrying and electrical energy storage capabilities and intelligent materials that can optimize their properties in various accident conditions.

Batteries

Future electric and hybrid vehicles will rely on batteries for power support and energy storage. Lithium-ion batteries (like those used in laptops) are today the most volume and weight efficient battery technology for electric energy storage onboard vehicles. However, the adoption of the technology has for several reasons been slow in the automotive industry. The battery chemistry is inherently unstable causing severe concern about the safety onboard a vehicle, especially when subject to external damage. The cost has been (and is still) high, making storage of large amounts of energy onboard a vehicle economically unfeasible. Battery lifetimes substantially shorter than the rest of the vehicle have also been limiting. The technical development is however rapid, and batteries better adapted to the demanding constrains in vehicles are now entering the market, and a further fast development can be expected. Thus, inherently safe batteries, with better lifetimes and at lower costs are to be expected. However, when it comes to energy density only moderate improvements can be expected, at least in a short and medium time frame.

The capacity of the battery will continue to severely limit the electric driving range of plug-in and all electric vehicles. Improvements must therefore rather rely on better integration of the batteries in the vehicles and the development of vehicles with lower total energy demands. Abuse tolerant batteries able to withstand collisions without being damaged are required and this aspect must also be included in the integration of batteries in vehicles.

Sensors, control and communication

A large market growth can be seen for sensors and electronic components leading to increased telematics and vehicle system control possibilities. This includes navigation systems in combination with digital maps and traffic information and information about adjacent vehicles achieved by radar or lidar (laser based “radar”) and vehicle to vehicle communication. This development is also creating new serious problems in particular concerning reliability and robustness (fault tolerance) of electronic and intelligent (embedded software) systems. Integrating these, up to now, often separate information sources can yield a more reliable, more accurate and cheaper measurement solution for all kind of applications in and around the vehicle and a multivariable reliable system control approach becomes feasible (adaptive systems).

Driveline

The electric or hybrid-electric driveline needs to include safety requirements already in its design and optimization. The type of driveline selected will have fundamental influence on the vehicle architecture and thus on the safety level. Electric motors can be moved to completely different parts of the vehicle and so can the battery and power electronics. Thus the weight distribution and the room for crash structure can be very different from today’s vehicles. Considering safety implications when optimizing the driveline is a necessity in order to find an architecture which has a balance between safety and cost effectiveness and fuel economy.

The driveline can optimize the fuel economy significantly better if it has access to information about surrounding traffic and the road conditions ahead. Knowledge about future accelerations or braking profiles as well as road conditions will allow an optimized use of the energy storage and the different parts of the driveline. The same type of information is also an enabler for many advanced active safety systems, and thus coordinated development of the traffic and road information system may benefit both areas.

Safety

Active safety (accident prevention) will play a much larger role in the future, but further progress in passive safety (injury prevention) will also be necessary, if the target of considerably safer traffic shall be met. Many future vehicles for transportation of people will be smaller and lighter to save energy. To make these vehicles safer to people inside the vehicle (car occupants) as well as to those outside (vulnerable road users) is a challenge, difficult but not impossible. Conventional boundaries between passive and active safety are disappearing rapidly leading to a new, more overall approach to safety.

In future hybrid and electric vehicles, the added flexibility of electric drive actuators can provide more vehicle dynamics functionality. It will be possible to estimate road surface conditions with less effort. EV's with lightweight design and new vehicle concepts (e.g. low speed city vehicles and modular vehicle combinations) give opportunities to decrease energy consumption and increase active safety. New motion stability problems might arise caused by regenerative braking together with the fast dynamics for low weight vehicles or the complicated dynamics of vehicle combinations. It is also important to consider how existing vehicle dynamics functionality (e.g. ABS, TCS, ESC) can be migrated in a safe way and improved for electric vehicles.

Concerning passive safety many new and improved protection possibilities will become available due to improved pre-crash sensing (of relative speed and direction to impact/impacting objects and identification/classification of impact/impacting object).

The effect of the added battery mass (more severe crash pulses) on the loading of car occupants in frontal and side impacts needs to be taken onto account.

Vehicle-to vehicle compatibility for various impact conditions (frontal, side, rear) and for impacts between vehicles of different sizes (truck, SUV, small car) is very important and must be improved.

Infrastructure

A good infrastructure domain is crucial for electric vehicles in particular for fast, safe and efficient reloading of batteries. The infrastructure provides the road authority the possibility to allow for a better and safer traffic situation for low weight, energy efficient vehicles by providing incitements for their use. Possible options are special lanes but also other possibilities will be reviewed. An advanced communication infrastructure (V2I communication) is important both from the safety point of view as for lowering energy consumption, for instance by providing safe and shortest road to the destination information using novel sensors and traffic systems etc...

EXAMPLES OF SAFETY RELATED FUTURE RESEARCH TOPICS RESULTING FROM SEVS

Design methodology for lightweight vehicles

Objective The objective is to develop knowledge and methods to win acceptance and confidence for high performance composites and mix material lightweight design (LWC) solutions in crashworthy automotive applications. Of specific importance are:

- Development of material and structural models of composites for crashworthy LWC solutions related to the adopted manufacturing process, typically comprising forming of the material undergoing mechanisms such as: solid-fluid wet-out, solid consolidation and solidification. The modelling will be developed in a CAE perspective, focusing material and structural properties at failure and energy dissipation, linked to the manufacturing process.
- Testing, validation and further development of CAE methods for high performance composites in the field of crash. This includes evaluating material models and elements for crash CAE. Simplicity in terms of needed material data and methods to obtain material data and mapping of process history is important.
- Development of joining strategies and technologies for mixed materials interfaces like: composite-composite, composite-metal and metal-metal solutions in the context of a LWC electric vehicle 2030.
- Design guidelines for automotive composites comprising thermal insulation, design limitations and affordability issues.

Motivation In many applications, such as the car body structure, it appears that high performance composites is the alternative with the highest potential for lowering weight, while still maintaining the proper crashworthiness. In order to meet the requirements on robust and crashworthy light future electric vehicles based on high performance composite materials or other lightweight materials, the development of material- and structural models for composites is crucial [3]. This concerns both the development of new material- and structural models and the development of design methodologies based on well established models. Focus will be on the material- and structural properties as a result of the manufacturing process. In addition an increased application of a mix of lightweight materials such as carbon fibre reinforced polymers (CFRP) and the light metals aluminium, magnesium and possibly titanium can be expected. These materials have applications in different structures, but there will also be a mix of these materials in the same structure ,such as mix material unibodies. This means that robust joining technologies for the new mix of lightweight materials, like adhesive joining, rivets, co-curing and/or bolting, need to be developed. To win acceptance and confidence in the automotive design and engineering process new LWC solutions must be implemented with concurrent design guidelines for integration of LWC materials in the vehicle.

Balance of active and passive safety

Objectives It is generally believed that large improvements of vehicle and traffic safety in the future can be achieved by various new active safety measures. In order to save energy for transportation of people on the roads in 2030+ the vehicles have to be smaller and lighter. This is a challenge for the passive safety. The need of passive safety may increase instead of decrease. New active safety measures will avoid many accidents from happening, but they will not eliminate the risks. Accidents will still take place. Pre-crash sensing systems and other systems (like V2V and V2I communication) for intervention of active safety systems will not be 100 percent reliable. If the speed of a vehicle is high enough a crash cannot be avoided.

The main objective, therefore, is to find the balance between active and passive safety measures for accident and injury prevention for the most common and typical accident situations. These situations have to be defined based upon data from available in-depth accident data bases and, if possible, supplemented with sequences recorded in Field Operational Testing and Naturalistic Driving studies. The objective for each type of accident is to develop a method and to use it to estimate how much various active and passive safety measures (to be defined for each case) for the various types of vehicles in the different traffic environments, as outlined in the four different scenarios in the SEVS project, will reduce the risk for people involved (vehicle occupants and/or vulnerable road users) of sustaining injuries of different severities. What measures will have the greatest potential for improvement of the safety in the four different scenarios? This will be a guide for those working with development of future safe and energy efficient vehicles as well as for those working with road infrastructure and communication (V2V and V2I).

Motivation There is a consensus that future vehicles for transportation of people have to be smaller and lighter to save energy regardless of propulsion system. Smaller vehicles will also have a smaller “foot print”, which will improve the traffic flow. To make these vehicles safer to people inside the vehicle (car occupants) as well as to those outside (vulnerable road users as pedestrians and bicyclists) is a challenge, difficult but not impossible. Active safety (accident prevention) will play a much larger role in the future, but further progress in passive safety (injury prevention) will also be necessary, in order to meet the target of considerably safer traffic. Since vehicles must be affordable there is a great need to also have the economy in mind when developing new safety measures. It is therefore important to study which safety measures (active and/or passive) have the greatest potential to improve the safety in various common and typical traffic accident situations. Only solutions that are both very safety effective and cost effective will have a chance to penetrate the market.

Crashworthiness of future vehicles

Objectives The objective is to develop knowledge and methods to design the vehicle architecture of future electric small vehicles (City Movers) for an increased protection of its occupants in a crash (in comparison with the protection offered by current vehicle designs) and to protect batteries during a crash in an optimal way. Two areas’ are of specific importance:

- Protection in frontal impacts. The front end structure should be adaptive to type, severity, and location of impact. It must be compatible in collisions with vehicles of various heights and it should allow the front end structure to easier slip off the other vehicle in a frontal collision.
- The vehicle should offer geometrical compatibility in side and rear-end impacts involving larger and higher vehicles.

Motivation In spite of the large progress in technologies that have become available to help avoiding that an accident would happen, also in the future not all accidents can be prevented and consequently vehicles should de designed in such a way that they offer optimal protection to their occupants in case a crash would happen. This challenge is particular of importance in case of future lightweight and small, green electric vehicles. Smart solutions are necessary to enable lightweight vehicles with reduced carbon footprint and improved safety [4].

The most critical issue for the passive safety of future small cars is the design of the vehicle structure (vehicle architecture). The passenger compartment must retain survivable space for the occupants in any type of accident (front, side, rear, rollover etc.). Geometrical compatibility with other vehicles is important and this compatibility must be much better than today. The challenge for small vehicles is particular also is in frontal collisions. The front end structure of future smaller vehicles needs to be more energy absorbing than structures of cars today in order to allow the car to become shorter.

From accident investigations it is known that most vehicles rotate and translate after impact. This lowers the crash pulse in the longitudinal direction of a car compared to an impact without such motions. The structure of future smaller vehicles should be designed in order to optimize these rotational and translational motions.

Information needs and availability

Objectives Research will be based on accident data with the aim to develop understanding of what type of information available to an advanced active safety system could have prevented the accidents. The main objectives are:

- To find what information is necessary for the function of driver independent active safety systems. This information includes knowledge about the state of the own vehicle, other vehicles and pedestrians, the road and its condition etc.
- To find what information is necessary for energy efficient driving. This information includes knowledge about the map, the traffic situation locally and along the route, availability of parking places etc.
- To understand and report the general availability of this information based on fundamental limitations of sensors and radio communication.
- To quantify the limitations of radio communication and satellite bases positioning.

Motivation From a theoretic point of view an automatic driving system can avoid accidents if it has complete knowledge about the local situation. Some of this information is available and used already today. This includes cameras detecting lane marks, radars detecting vehicles etc. The energy consumption can be minimized if sufficient knowledge about the route is available. The local situation influences directly the drive line control. The data collected by the vehicle will be used for information, warnings and active intervention. Inaccurate information and false warnings are confusing and disturbing but an active intervention based on insufficient or erroneous information may in itself cause an accident. The decision making must take this into account. The validity, accuracy and completeness of the information must be a part of the decision process. The possibilities of satellite positioning and vehicle communication in critical safety systems are not well understood yet. The limitations in accuracy and reliability decide for what active systems application is feasible. Some of these limitations concern fundamental problems in wave propagation.

DISCUSSION AND CONCLUSIONS

In this paper the technology research questions defined within the SEVS project as well as the selection and prioritization process leading to these questions is described. Also a brief overview of the work done in SEVS related to drivers and societal scenarios for 2030 as well as the work leading to a number of vehicle concepts for 2030 has been presented.

Focus in this paper is given to the following research questions relevant for green and safe future transportation solutions:

- Balance of active and passive safety
- Design methodology lightweight vehicles
- Crashworthiness future vehicles
- Information needs and availability

In the discussions on research questions also a number of possible research areas of a non-technological nature (societal, political) were identified but not extensively elaborated in SEVS into specific research questions. Examples of such research areas are: expected traffic flows in megacities, special infrastructure for different road users, new business models for mobility, user expectations etc.. Such questions are, even more than most of the technology research questions, heavily depended on future societal and political scenarios. A continuation of the SEVS project is in preparation were both technical and non technical research questions will be addressed in a holistic approach.

ACKNOWLEDGEMENTS

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MASS REDUCTION AND PERFORMNANCE OF PEV AND PHEV VEHICLES

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ABSTRACT

Within the context of the U.S. government's recent announcement on fuel economy standards for 2017 to 2025 model year vehicles, automakers are looking to next generation hybrids, plug-in electrics and even fuel cells. When looking at these next generation vehicles, weight reduction technology cannot be overlooked. Complementing vehicle advances, lightweighting produces vehicles that are more efficient, achieve better fuel economy and produce fewer emissions. Proven in strength and safety, aluminum offers automakers the key to vehicle weight reduction. Research findings pertaining to the impact of weight reduction through lightweight materials on plug-in electric and hybrid vehicle performance, show that opting for aluminum bodies over steel can save on battery needs and the associated higher costs, since lighter vehicles require less battery power (batteries being a significant cost barrier). Greater use of aluminum can help speed the transition to greener and cleaner vehicles.

Areas of focus

- Electric vehicles (EV) or plug-in hybrid electric vehicles (PHEV) as a unique class of vehicle(s) in that they contain a relatively small amount of stored energy, and as such are great candidates for lightweighting;
- The role of vehicle, battery and powertrain mass, as well as drive cycle on range and performance;
- Potential cost-savings by upgrading from traditional steel to an advanced aluminum body structure due to lower energy requirements to move lighter vehicles.
- The function of vehicle mass and its influence on energy recovered during regenerative braking.

Key Findings

- A savings of up to $3,000 can be reached by reducing electric vehicle structure weight by 10 percent with aluminum.
- Using aluminum in select automotive components could reduce vehicle weight safely by as much as an additional 40 percent over today's vehicles.
- An additional 525 pounds (including primary and secondary weight) safely could be taken out of a vehicle by 2020, which would result in saving 2.7 MPG, a nearly 10% fuel economy improvement.
- Reducing vehicle weight will be vital to improving fuel economy and cutting carbon emissions.

Not all cars will or should be made of aluminum (though some are, and more will be); however, it is clear that aluminum components will continue to provide vehicles that are safe for consumers and the environment.

INTRODUCTION

In previous studies with Ricardo and IBIS, fuel economy versus weight versus engine (type or displacement) versus vehicle type (car or SUV) versus manufacturing cost versus LCA has been examined. In all cases, a very positive synergy was found between primary and secondary weight reduction, engine displacement and cost. Less weight = smaller engine = better fuel consumption = better economic LCA. Usually, 2-4 years of driving were required to recover the upfront investment. Aluminum lightweight structures have real long term value. The barriers are the up front costs (investment, knowledge) by the OEM, and having the customer value the operational costs versus initial purchase price.

With the growing popularity, or interest, in PEVs (plug-in battery powered electric vehicles) or PHEVs (plug-in hybrid electric vehicles) it was desired that a more complete examination of weight versus electric motor size versus battery versus cost be completed. It was anticipated that these vehicles would be good candidates for lightweight structures since the battery pack contains a relatively small amount of energy that must be well managed.

In this study, all vehicles will perform using only the battery pack and electric motor. However, the PHEV is still considered, since the range extending ICE in these vehicles must be considered as additional mass when the vehicle is operating only as an EV (the first 40 miles or so) and is an additional cost to consider in the overall economics, which will be a topic of a future study.

All vehicles used lithium ion batteries. These batteries are attractive because they have relatively high specific energy and power densities, and adequate volumetric energy densities, and charge/discharge rates; but, they are relatively expensive and in some applications have a history of thermal run away. Significant research and development is being applied to battery development, so rather rapid advances in battery capacity, manufacturing and cost reduction are anticipated or claimed.

No specific mention of battery chemistry will be noted in this report, other than to comment that there are a broad range of anode and cathode chemistries with a corresponding broad range of claims for capacity or cost. For this study, we believe we have picked generally accepted, nominal values for battery packs associated with vehicles. Certainly better, albeit generally smaller or single purpose battery claims can be found. Battery packs for vehicles are essentially an assembly of smaller individual batteries or cells and for reasons of balancing out the various cells and managing the thermal discharge of the pack; the pack is designed to operate in a more conservative mode than that of the individual cells. Further, battery packs are somewhat customized for EV or PHEV applications; but, we assumed a common battery pack in the current study.

Background and Assumptions

In this study, based on publicly available info, some private discussions with battery makers, and some information Ricardo had from their previous government studies, we assume a useable specific energy of 115 W-h/kg with a specific volume of 155 W-h/l. We assume a state of charge (SOC) of 0.9 - 0.25 of the rated energy (starting and ending voltage that could be routinely used without damaging the battery). The price for the battery pack is estimated at $750/kWh. This number is based on some public disclosures and private discussions. Costs in the range of $500/kWh to $1,000/kWh can be found. This rather broad range of costs reflects the rate of anticipated development and promotional pricing, as well as the completeness of the battery pack. Is all the associated structure included, including the thermal management requirements? This makes estimating the total battery weight quite difficult. From published values, the Tesla battery pack (52 kWh/450kg) has a density of 0.115 kWh/kg, while the Volt battery pack (16kWh/170kg) has a density of 0.094kWh/kg.

Existing PEV vehicles

The most acclaimed of the current PHEV vehicles is the Chevy Volt. The Volt has a 16 kWh Li-Ion (220 cell) battery pack, with a 111 kW electric drive. It has a 53kW ICE-generator to extend the range. While the vehicle mass has not been reported, a conventional steel vehicle with the same footprint would weigh about 1,384 kg (3050 lbs) and the BIW would weigh approximately 249 kg (549 lbs). The Volt achieves a 40 mile range based on the EPA city drive cycle (FTP75) and has a top speed of 100 mph. The reported SOC is 0.85-0.3 which gives a usable energy of 8.8 kWh. The reported mass of the battery pack is 170 kg (375 lbs).

Another point of reference is the Tesla Roadster. This production vehicle is an aluminum structured vehicle with a curb weight of 1,221 kg. It has a motor of 165 kW, powered from a Lithium-Ion battery pack of 53 kWh with an excellent sporty performance and a range (EPA combined city/highway) of 244 miles. The battery contains about 6,800 cells grouped into 11 modules and is fluid cooled with a weight of 450 kg. The battery is about 37 percent of the total vehicle curb weight. It has been suggested that Tesla's next generation midsized vehicle would have a 70 kWh battery pack, but this number has not been confirmed.

Regenerative braking is generally applied to PEVs, although specific details are not known. For our study the regenerative-braking threshold was set at 1,000N braking, when throttle = 0. (Vehicle will generate energy back into the batteries, first, and up to threshold. Beyond the threshold conventional friction braking is used.) The value of regenerative braking is particularly important to understand fully because it has been suggested that a high degree of regen-braking would make these vehicles less weight sensitive; heavier vehicles would recover their energy better or at least would not be penalized as much.

The current study is in part based off the previous Ricardo study (FB769) in that two of the previous vehicles, approximating the BMW Mini (small car) or the Saturn Vue (small SUV) where converted to an EV or PHEV. These baseline vehicles serve to provide the size, tire and aero losses. In the previous study, the powertrain was sized to perform with a "fully loaded" vehicle. In this study only the driver is considered. It is should be noted that the current study did not consider the energy drain associated with power accessories, including brakes, steering or HVAC. The latter in particular can be quite significant since the AC can be 2-3 kW or larger.

It might be interesting to briefly contrast the power embodied in gasoline. One gallon of gasoline contains approximately 35 kWh of energy, before conversion with an ICE. So 16 kWh represents about 0.5-1.5 gallons of fuel depending on the assumptions for conversion to useable energy. We certainly need to be thinking about the equivalent of a 55+ mpg vehicle. (How these vehicles will be rated by the EPA is ongoing. Based on a proposed draft, the Volt has been rated at 230 mpg and 25 kWh per 100 miles.)

Mass of Vehicles and their associated Powertrains

In this study we consider a total of 16 vehicles or vehicle variants:

- Small car constructed in steel, or aluminum
- Small SUV constructed in steel or aluminum
- EV or PHEV
- 40 or 80 mile range

Since only the starting conventional (steel structure and ICE) curb masses are published, it is necessary to estimate the individual masses. (How much does the ICE weigh? What would the equivalent aluminum structure weigh?) Further, while the battery size and motor are directly calculated, this must be done in an iterative fashion because of a weight spiral up or down and its associated impact. (See slopes of response surface maps in Ricardo's Appendix.)

The mass breakdown for all vehicles is shown in the Appendix.

Vehicles are titled by their case number as follows:

Case 1 = Steel PHEV
Case 2 = Aluminum PHEV
Case 3= Steel EV
Case 4= Aluminum EV
And these are under the header of 40 or 80 mile range.

In this study since all vehicles are running only on batteries, the ICE in the PHEV is in effect a weight penalty that must be carried. There is an ongoing debate about the relative value/cost/performance of PEV vs. PHEV. PHEV certainly provide increased range and avoid the concern about running out of energy, but the cost and weight must be carried while performing as a PEV.

The Volt (PHEV) has a 53kW ICE-generator (1.4-liter, I4) to recharge the battery. It doesn't directly drive the wheels, but it still requires a fuel system, exhaust, cooling etc. Since this ICE generator combo is quite unique with no published values, it was estimated at a 40 percent weight saving would occur, resulting in a 223 kg weight savings compared to a conventional small vehicle ICE powered vehicle. The SUV had a weight saving of 361 kg.

Results for Small Car

After several iterations for the various powertrain components, the results for the small car are summarized in Table1. (Slide 21 in Ricardo report.)

Please note in Table 1 the battery cost gain (cost saving) relative to the Case 1 vehicle are given. (Case 1 is always the heaviest vehicle and hence has the largest battery pack. Case 4 is always the lightest.) While it is valid to compare all cases together, because in this study the vehicles perform the same task, it is probably more informative to compare Case1 vs. Case 2 and Case 3 vs. Case 4.) See later comments on cost.

Table 1.
Summary of Small Car results

Small Car Results

RICARDO

			40 MILE RANGE				80 MILE RANGE			
	Small EV	Units	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
	Base Weight	kg	1304	1142	684.6	539.2	1304	1142	684.6	539.2
	Subtract Conv. Powertrain	kg	223	223	Fully Substracted	Fully Substracted	223	223	Fully Substracted	Fully Substracted
	Base EV/Ext. EV Weight	kg	1082	920	685	539	1082	920	685	539
ITERATION 1	Battery Size [Total]	kWh	12.9	11.8	10.5	9.4	25.8	23.7	20.6	18.8
	Motor Size	kW	110	110	110	110	110	110	110	110
	Battery Weight	kg	73	67	59	53	146	134	117	106
	Motor + Controller Weight	kg	50	50	50	50	50	50	50	50
	E-Powertrain Weight	kg	123	117	109	103	196	184	167	156
	Weight Iteration 1	kg	1205	1037	794	642	1278	1103	851	695
ITERATION 2	Battery Size [Total]	kWh	13.8	12.6	11.1	10.2	28.3	26.0	22.8	20.8
	Motor Size	kW	110	110	110	110	110	110	110	110
	Battery Weight	kg	78	71	63	57	160	147	129	117
	Motor + Controller Weight	kg	50	50	50	50	50	50	50	50
	E-Powertrain Weight	kg	128	121	113	107	210	197	179	167
	Weight Iteration 2	kg	1210	1041	797	647	1292	1117	863	707
Un-optimized	Battery Cost Gain	$	$0	$923	$2,077	$2,769	$0	$1,731	$4,154	$5,654
OPTIMIZA TION	Motor Size	kW	101.0	88.0	73.0	70.0	107.0	93.0	80.0	70.0
	FDR		5.37	5.34	5.37	5.20	5.32	5.37	5.34	5.31
	Rated Speed		0.58	0.58	0.61	0.70	0.58	0.58	0.62	0.58
	Battery Size [Total]	kWh	13.5	12.2	10.3	9.1	28.2	25.4	21.5	19.1
	Battery Weight	kg	77	69	58	51	159	17	121	108
	Motor + Controller Weight	kg	47	43	38	37	49	44	40	37
	Optimized Weight	kg	1,205	1,031	781	627	1,290	980	846	684
	Battery Cost Gain	$	$0	$1,038	$2,423	$3,346	$0	$2,077	$5,008	$6,808
	HWFET Range	mi	37	36	35	33	76	74	69	67
	45 mph range	mi	41	41	39	37	82	81	77	74
	70 mph range	mi	28	26	24	21	57	54	49	46
	0-30 mph Accel Time	s	4.8	4.9	4.8	5.0	4.9	4.9	4.8	4.9
	0.60 mph Accel Time	s	9.9	10.0	10.0	9.9	10.0	10.0	10.0	10.0
	Top Speed	mph	100	100	100	100	101	100	100	100

See Appendix A for plots

Case 1: Weight Represent a Series Hybrid / Extended EV Configuration with Steel Structure
Case 2: Weight Represent a Series Hybrid / Extended EV Configuration with Aluminum Structure
Case 3: Weight Represent a Full EV Configuration with Steel Structure
Case 4: Weight Represent a Full EV Configuration with Aluminum Structure

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Energy Balance: Small Car

To understand better the summary in Table 1, it is informative to understand how the energy in the battery is expended. See slide 22 in Ricardo report. These percentage values are converted into an energy balance and are shown in Table 2.

Table 2.
Small Car Energy Balance as percent and absolute (kWh)

	Case 1 FTP %	Case 2	Case 3	Case 4	Case 1 FTP kWh	Case 2	Case 3	Case 4
Aero	22.3	24.8	29.4	32.7	1.97	1.97	1.97	1.93
rolling	30.2	28.9	26.2	23.6	2.67	2.29	1.75	1.40
battery	4.1	4.1	4	3.8	0.36	0.33	0.27	0.22
converter	7.6	7.5	7.2	6.8	0.67	0.59	0.48	0.40
motor/ generator	33.2	32.2	30.8	30.8	2.93	2.55	2.06	1.82
differential	2.5	2.4	2.3	2.2	0.22	0.19	0.15	0.13
brake	0.1	0.1	0.1	0.1	0.01	0.01	0.01	0.01
regen	20.9	20	18.1	15.6	1.85	1.59	1.21	0.92

For the small car about 1.97 kWh (40 miles using FTP75) is required to overcome the aerodynamic loses, and this doesn't change as the vehicle weight changes. (Some small rounding errors occur across the different vehicles in the calculations.) As the vehicle gets lighter, the energy to overcome the rolling resistance decreases from about 2.67 to 1.4 kWh. For Case 1, more energy is required to overcome the rolling resistance, than the aero, but for the lightest vehicle, overcoming the aero loses is the largest energy drain.

During the drive cycle the regenerative braking returns about 1.85 kWh for the Case 1 vehicle, and about 0.92 kWh for the Case 4 vehicle. As a percentage of the rolling resistance they both recover about 65 percent. (1.85/2.67=0.92/1.4) The lighter vehicle is not disadvantaged.

Figure 1 depicts the Table 2 data graphically to better display the overall energy balance. (Negative values are for energy expended, positive from the regenerative gain.)

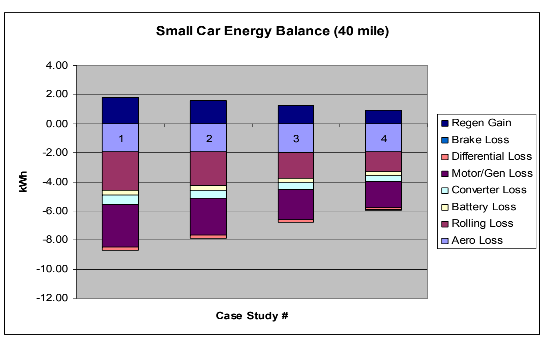


Figure 1. Illustrative Energy Balance for Small Car (40 mile range)

For FTP75 there are numerous stop/starts. The actual step by step regeneration is graphically presented in Figure 2. The difference between the yellow and white line represents the amount of energy recovered in the FTP75 drive cycle.

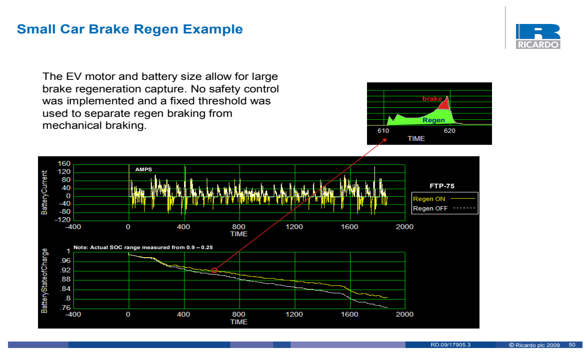
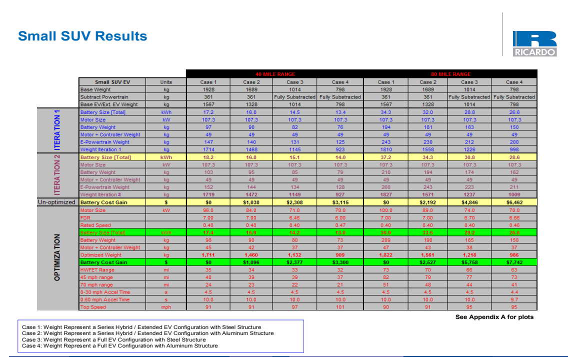


Figure 2. Regeneration Illustration

Please note the values in Figure 1 are for illustration purposes. The total individual values are correct, but positive contribution from the regenerative braking has already been factored into the overall sizing of the battery.

Small SUV

Table 3. Summary of Compact SUV results



Small SUV Results

	Small SUV EV	Units	40 MILE RANGE Case 1	Case 2	Case 3	Case 4	80 MILE RANGE Case 1	Case 2	Case 3	Case 4
	Base Weight	kg	1928	1689	1014	798	1928	1689	1014	798
	Subtract Powertrain	kg	361	361	Fully Substracted	Fully Substracted	361	361	Fully Substracted	Fully Substracted
	Base EV/Ext. EV Weight	kg	1567	1328	1014	798	1567	1328	1014	798
ITERATION 1	Battery Size [Total]	kWh	17.2	16.0	14.5	13.4	34.3	32.0	28.8	26.6
	Motor Size	kW	107.3	107.3	107.3	107.3	107.3	107.3	107.3	107.3
	Battery Weight	kg	97	90	82	76	194	181	163	150
	Motor + Controller Weight	kg	49	49	49	49	49	49	49	49
	E-Powertrain Weight	kg	147	140	131	125	243	230	212	200
	Weight Iteration 1	kg	1714	1468	1145	923	1810	1558	1226	998
ITERATION 2	Battery Size [Total]	kWh	18.2	16.8	15.1	14.0	37.2	34.3	30.8	28.6
	Motor Size	kW	107.3	107.3	107.3	107.3	107.3	107.3	107.3	107.3
	Battery Weight	kg	103	95	85	79	210	194	174	162
	Motor + Controller Weight	kg	49	49	49	49	49	49	49	49
	E-Powertrain Weight	kg	152	144	134	128	260	243	223	211
	Weight Iteration 2	kg	1719	1472	1149	927	1827	1571	1237	1009
Un-optimized	Battery Cost Gain	$	$0	$1,038	$2,308	$3,115	$0	$2,192	$4,846	$6,462
OPTIMIZATION	Motor Size	kW	96.0	84.0	71.0	70.0	100.0	89.0	74.0	70.0
	FDR		7.00	7.00	6.46	6.00	7.00	7.00	6.70	6.66
	Rated Speed		0.40	0.40	0.40	0.47	0.40	0.40	0.40	0.46
	Battery Size [Total]	kWh	17.4	15.9	14.2	13.0	36.9	33.5	29.2	26.6
	Battery Weight	kg	98	90	80	73	209	190	165	150
	Motor + Controller Weight	kg	45	42	37	37	47	43	38	37
	Optimized Weight	kg	1,711	1,460	1,132	909	1,822	1,561	1,218	986
	Battery Cost Gain	$	$0	$1,096	$2,377	$3,300	$0	$2,527	$5,758	$7,742
	HWFET Range	mi	35	34	33	32	73	70	66	63
	45 mph range	mi	40	39	39	37	82	79	77	73
	70 mph range	mi	24	23	22	21	51	48	44	41
	0-30 mph Accel Time	s	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.4
	0.60 mph Accel Time	s	10.0	10.0	10.0	10.0	10.0	10.0	10.0	9.7
	Top Speed	mph	91	91	97	101	90	91	95	95

See Appendix A for plots

Case 1: Weight Represent a Series Hybrid / Extended EV Configuration with Steel Structure
Case 2: Weight Represent a Series Hybrid / Extended EV Configuration with Aluminum Structure
Case 3: Weight Represent a Full EV Configuration with Steel Structure
Case 4: Weight Represent a Full EV Configuration with Aluminum Structure

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Results for the compact SUV are presented in Table 3.

In qualitative terms, the results of the compact SUV are very similar to the small car. More energy is required to move the heavier vehicle and the battery requirements have correspondingly increased.

Energy Balance Compact SUV

Table 4. Small SUV Energy Balance as percent and absolute kWh

	FTP %				Case 1 FTP kWh	Case 2	Case 3	Case 4
Aero	24.1	26.5	30.1	32.9	2.71	2.77	2.80	2.78
rolling	32.8	32.1	30.6	29	3.69	3.35	2.85	2.45
battery	4.1	3.9	3.6	3.3	0.46	0.41	0.33	0.28
converter	7.9	7.6	7.2	6.8	0.89	0.79	0.67	0.57
motor/generator	28.4	27.2	26	25.6	3.19	2.84	2.42	2.16
differential	2.7	2.6	2.4	2.2	0.30	0.27	0.22	0.19
brake	0.1	0.1	0.1	0.1	0.01	0.01	0.01	0.01
regen	22.7	21.4	18.3	15.6	2.55	2.23	1.70	1.32

The energy balance for this vehicle is shown in Table 4.

More energy is expended to overcome the aero losses, but as a percentage they are quite close to the small car. The percentage of the energy and absolute amount to overcome the rolling resistance is higher than for the small car.

Influence of Range Requirements (40 vs. 80 mile range)

The calculations were repeated for an 80 mile range. (See Ricardo slides 21 and 24) Since the aero losses are somewhat similar, it is possible to look at the influence of range for both vehicles. Figure 3 plots the energy required (usable battery requirements) for both vehicles for both the 40 and 80 mile range.

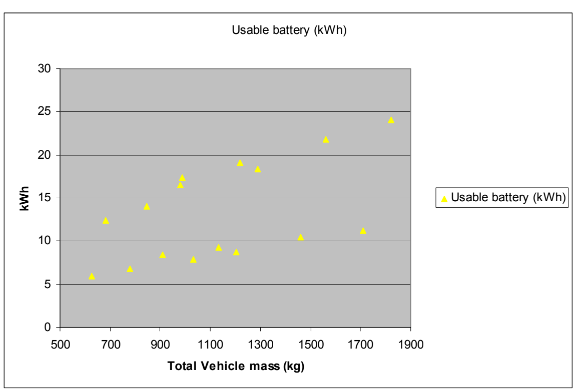

Figure 3. Energy Requirements, both vehicles. (80 mile range on top)

Comparison of the energy requirements indicates a small upwards weight spiral. For the heaviest vehicle, the battery increases 2.14 times to double the range. (The offset between the "paired" points for 40 or 80 miles is the additional incremental battery weight due to the weight spiral.)

Alternatively, the energy consumed per mile driven can be calculated and is shown in Figure 4. (Both vehicles)

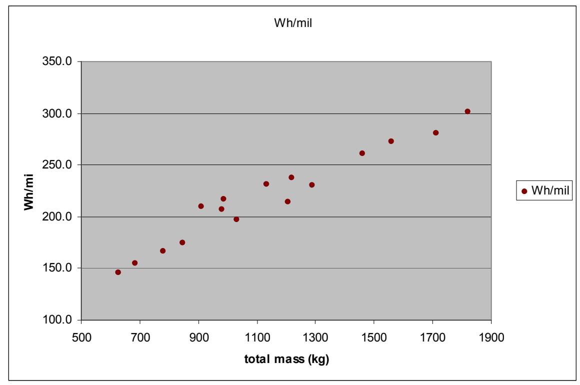

Figure 4. Energy Consumed per mile driven vs. total vehicle mass.

The energy requirements scale approximately linearly against vehicle mass. Consumption ranged from 0.146 kWh/mi for the lightest vehicle (627 kg) to 0.302 kWh/mi for the heaviest (1,822 kg). Contrasted to the specific battery output of 0.115kWh/kg results that the vehicle would require 1.5-3kg of battery for every mile traveled.

Cost

A detailed cost analysis has not been done. Many of the component costs are evolving or only approximate cost data is publicly available. But a few comments can be made. The total battery requirements ranged 9.1 to 36.9 kWh. At $750/kWh this represents a cost of approximately $7,000 to $28,000.

More interesting is to compare the incremental battery size between Case 1 and 2, and Case 3 and 4. In this case the incremental battery size grows from approximately 1.2 to 3.4 kWh. And the motor requirements grow up to 15 percent with the associated increase in controller costs to handle the high loads. Certainly the aluminum structure has an incremental cost increase, but all in, the lightweight structures should be less expensive in the range of $1,000 to $3,000.

Alternatively the lighter structures could be used to extend the range of the vehicles. The slope of the response map in the Ricardo Appendix indicates that for large mass saving, where the weight spiral becomes significant, the range can be extended approximately equal to the mass saved. For the vehicles studied, a 20 percent weight reduction (PEV) produced a range increase of 14 percent.

SUMMARY

Sixteen vehicles (small car, small SUV, EV, PHEV (running as EV), aluminum structure, steel structure, 40 or 80 mile range) were modeled using FTP75 drive cycle with an energy consumption ranging from 0.146 kWh/mi to 0.302 kWh/mi. Contrasted to the specific battery output of 0.115 kWh/kg results that the vehicle would require 1.5-3 kg of battery for every mile traveled.

The associated battery energy (rated/useable) ranged from 9.1/5.92 kWh to 36.9/24 kWh.
The associated vehicle mass ranged from 627 kg to 1822 kg. No additional mass was added to "support" the battery. Battery mass ranged from 51 to 209 kg. (For the lighter vehicles, the battery weight is approximately equal to the weight of a tank of gas.) Contrasted against the 16 kWh, 170 kg Volt battery suggests this study has calculated the battery energy requirements quite well, but might have underestimated the overall battery mass. However the effect of vehicle mass vs. battery requirements does appear to have been well captured

The battery size (kWh) requirements scaled approximately linearly with range, though as the vehicles got heavier, a small weight spiral became more noticeable. Similarly, as the range is increased beyond 80 miles, this weight spiral would be expected to be more pronounced.

Regenerative braking was applied to all vehicles. For the FTP75 drive cycle, about 65-69 percent of the rolling resistance energy could be recovered, irrespective of the vehicle mass. This equates to 15.6-23 percent of the total energy. (As the vehicle gets lighter the percentage of energy allocated to "aero" grows relative to the rolling resistance. For the HWFET the regenerative recovery drops to 2.8-5.3 percent of the total energy.)

The range of the vehicle is dominated by the sizing of the battery. The next largest factor is the vehicle mass, since about 30 percent of the energy is used to overcome the rolling resistance in the FTP75 cycle. Vehicle mass reduction can reduce the battery size requirements by about 10 percent, or about 1.2 to 3.4 kWh, for the vehicles studied.

With such a relatively small amount of energy contained in the batteries, all aspects of the vehicle most be carefully optimized to produce a vehicle of acceptable range, performance, and cost. Battery cost dominates. Reducing the vehicle mass to reduce the battery capacity requirements appears to be cost effective and should be further quantified with an LCA type analysis. Tesla Motors, Fisker Automotive and Bright Automotive are all using lightweight aluminum to reduce the mass of their vehicles.

Other OEM's have opted for a more or less tradition body structure, with some light weight components for their first generation vehicles while their efforts are directed to developing a robust propulsion system. The current study suggests that mass reduction and improved aerodynamics will be a high priority for a sustainable, affordable vehicle.

Appendicies

The starting point for the vehicle mass breakdown comes from the first and second IBIS studies based on the mid-sized Ford P2000 architecture. The actual weights for the vehicle structure and closure panels in steel or aluminum are known. The powertrain and other masses for glass, interior, etc. could be estimated from IBIS regression analysis. The "steel" vehicle mass breakdown for the mid-sized, 1,533kg, vehicle is shown in Figure A1. The corresponding "aluminum" vehicle at 1,270 kg is shown in Figure A2.

The powertrain accounts for about 45 percent of the overall mass. The steel BIW is about 18 percent, the closures about 5 percent of the overall vehicle mass. While more mass is certainly saved with the aluminum structure, slightly different percentages arise, since not all components can be resized. (The glass and interiors remain unchanged and grow in percentage terms.)

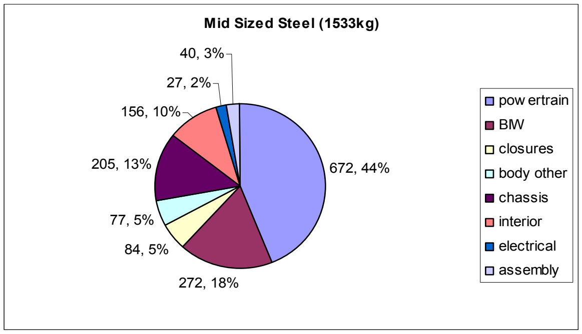

Figure A1. Mid-Sized "Steel" Vehicle with Conventional ICE by kg and percent.

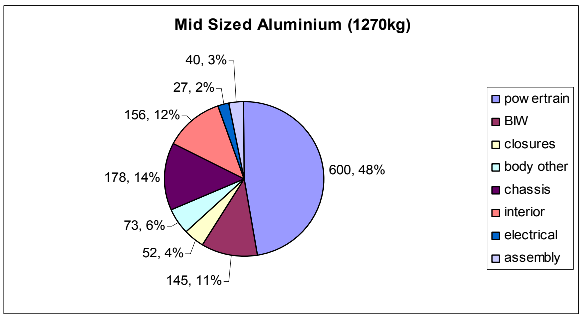

Figure A2. Mid-Sized "Aluminum" Vehicle with Conventional ICE by kg and percent.

It should be noted the mass of the powertrain includes all fluid masses, as well as exhaust, cooling, starter battery and engine cradle etc.

For this PEV study, the curb masses of the conventional small car and small SUV are reported as 1,304 kg (2,874 lbs) and 1,928 kg (4,249 lbs) respectively. To estimate the BIW mass in either steel or aluminum, a regression technique based on the vehicle size is used. (Warren 1997) The weight savings of the closure panels can be directly calculated, and the other masses estimated from regression analysis.

Small Car

The resulting mass breakdown for the small car PEV in steel, after the battery mass and motor have been calculated, is shown in Figure A3. See Ricardo report for full details on calculations for batteries, motor etc.

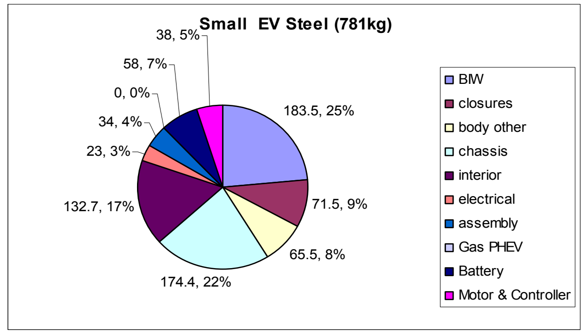

Figure A3. Small car "Steel" EV for 40 mile range.

The corresponding vehicle in aluminum is presented in Figure A4.

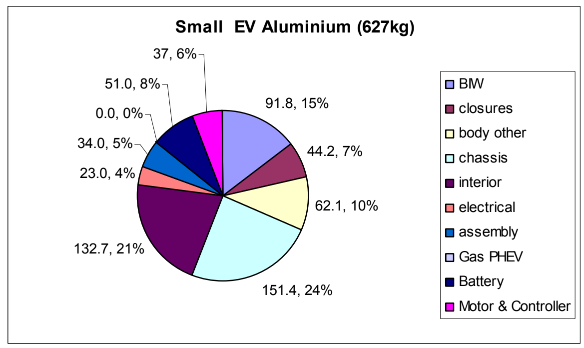

Figure A4. Small car "Aluminum" EV for 40 mile range.

The mass of the aluminum BIW is reduced to only 92 kg. As a reference point the BIW for the Audi A2 aluminum structure was 110 kg, and this was a larger vehicle.

PHEVs (Small Car)

Figure A5 is for the "steel" PHEV. Figure A6 is for the "aluminum" PHEV.

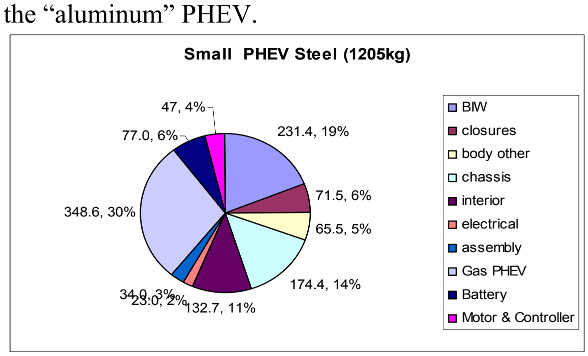

Figure A5. Small car "Steel" PHEV for 40 mile range. Case 1.

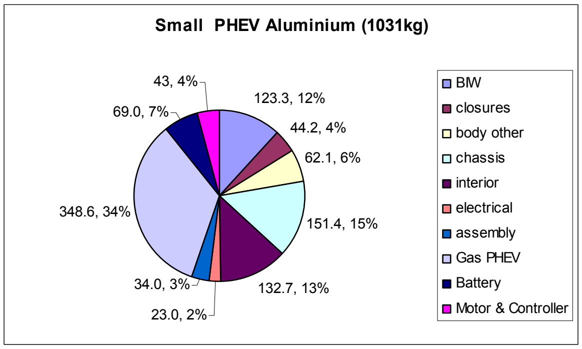

Figure A6. Small car "Aluminum" PHEV for 40 mile range.

LITHIUM ION BATTERIES FOR HYBRID AND ELECTRIC VEHICLES – RISKS, REQUIREMENTS AND SOLUTIONS OUT OF THE CRASH SAFETY POINT OF VIEW

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Paper Number 11-0269

ABSTRACT

The main focus of the current development projects in the automobile industry is on the vehicles with an alternative power train such as hybrid vehicles and electric vehicles. The first hybrid and battery electric vehicles are already available. Companies are working on a final "roll out" for all vehicle classes with high pressure. With the use of these new technologies, some safety issues and risks could take place.

For these kinds of vehicles, the use of lithium ion batteries seems to be the most common approach out of the range and performance point of view. Because of the existing risks, special safety systems have to be developed and included.

How do these existing risks influence the passive safety level of a vehicle and what has to be done to reduce the post crash severity? Within this paper, an overview of the risks of the lithium-ion-technology like chemical and electrical risks that are dependent on the several used chemistries will be given, as well as an overview of the worldwide requirements and existing test configurations. I will discuss the solutions as to why these risks are relevant for the vehicle crash safety, what kind of reactions could take place in a crash event and how the existing battery component tests compare with the common vehicle crash test characteristics. The results of a statistical research according the relevant crash configurations based on the GIDAS- and NASS-databases will be shown, as well as an investigation according to the packaging positions of the lithium ion batteries in the vehicles. Finally an overview of some approaches used by manufacturers concerning crash safety will be given.

A concept of an approach to assess the safety level of a lithium hybrid battery of an electric and hybrid vehicle will be shown. This method includes the used cell form and cell chemistry as well as other influencing factors. It should be noted that the used crush pulses of battery component tests are different when compared with the vehicle crash tests and the characteristic of real world accidents.

A possible finding is that it is necessary to develop and integrate systems that guide the released energy (in a worst case assumption for a crash) of the batteries in a direction away from the vehicle and the occupants. This means to stiffen and weaken the housing of a battery according to the packaging and to include passive cooling systems, which could be helpful after a crash event. This approach is different compared to existing approaches, which are based on using a very stiff housing to protect the battery cells. This may work for smaller batteries, but could be very dangerous for bigger ones.

This study is limited to electric and hybrid vehicles, in which lithium ion batteries are used. To gain the first results, only a small set of available lithium ion battery cells could be used.

INTRODUCTION

It is expected that in 2020 1.000.000 battery electric vehicles will be on the roads in Germany – the German government and the automobile industry defined this goal. Other countries defined goals as well, so the raising of the technology of electric and hybrid vehicles can't be stopped.

All of the manufacturers are still working on vehicles with electric powertrains. They are used in mild hybrids, plug-in hybrids as well as in battery electric vehicles. All of these concepts include a high-voltage system and a high-voltage battery, which can base on several available technologies.

A detailed description of these technologies will not be given because they should be known very well.

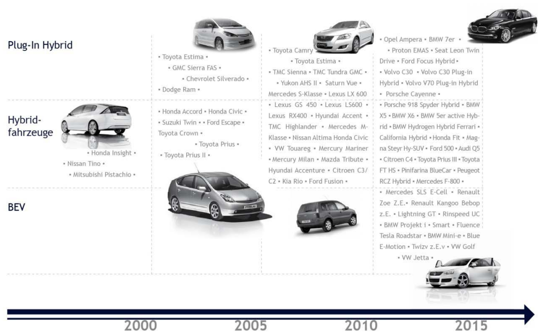

Figure 1: Overview of existing and planned vehicles with electric power train

Different forecast give the information, that in 2015 more than 2.5 up to 10 million vehicles with electric power train will be existing and in use.

LITHIUM ION BATTERY TECHNOLOGY – A SHORT OVERVIEW

Because of their characteristics and behavior lithium ion batteries seem to have the biggest potential for the use in electric and hybrid vehicles. A high energy density combined with a high power output is typical for them compared with other battery technologies like lead acid or nickel metal hydrid. This leads to more compact and low weight battery systems.

As energy storage device in laptops lithium ion batteries are well known and in use since a couple of years.

Because of the higher power density compared with other battery technologies a higher efficiency of the power train can be reached. This results in a lower fuel consumption of hybrid vehicles or in a wider range of electric vehicles.

The so called "memory effect" does not exist for lithium ion batteries.

At the moment the produced numbers of lithium ion batteries for electric vehicles are relatively low; but for the future much bigger sales numbers are expected, which can result in much lower costs and prices.

One milestone for the success of the lithium ion technology was the first series produced system for a hybrid vehicle, which is part of the power train of the Mercedes "S400 Hybrid".

Lithium ion batteries for electric vehicles consist of the cells, the housing with the vehicle interfaces, the cooling system as well as the battery management system.

Figure 2: Parts of a battery system [1, 2]

There are existing different concepts for the single cells, but even if they are cylindrical, prismatic or according to the pouch-concept they consist of an anode, cathode, separator and electrolyte.

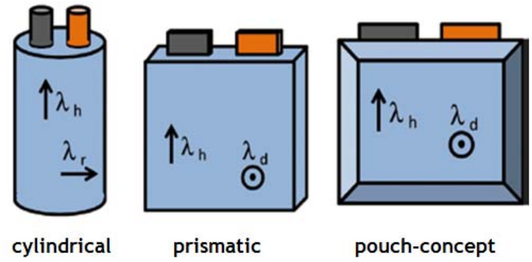

Figure 3: Concepts for single cells [1, 2]

RISKS AND DANGERS OF THE LITHIUM-ION-TECHNOLOGY

The following potential risks and dangers that exist through the use of lithium ion batteries:

- electric danger (short-cut)
- fire and explosion
- danger out of chemical reactions and dangerous goods
- thermal danger out of high temperatures
- mechanical danger because of the higher weight of the battery components

Starting with the assumption that an electric vehicle is „self-safe“ after leaving the factory, electrical risks like short cuts or electric shocks can be caused and initiated by failures of the high voltage system or by physical impacts from the outside, like it happens in a vehicle crash.
In addition these dangers can be caused by misuse or human error of a mechanic, technician or hobby assembler.

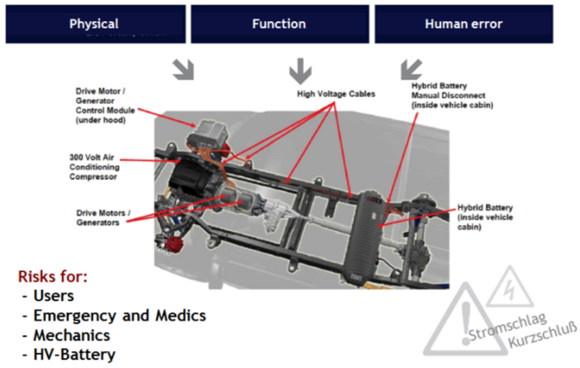

Figure 4: Risks and potential dangers of high voltage systems [3]

Out of the point of view of the high voltage battery potential defects can be caused out of internal and external short cuts, cell aging processes, overcharging and over-discharging, external high temperature or crash events as well.
All of it can cause reactions inside of the battery which can lead to overheating and fire, to the destruction of the separator or to a thermal runaway.
In addition deflagration and explosion are possible, if there is a local gas concentration and an ignition by spark will take place.
Dangerous chemical substances can escape from the component housing as well.

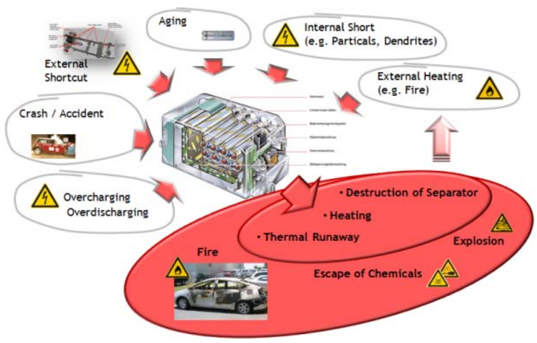

Figure 5: Risks by the high voltage battery [4, 5]

Vehicles which are delivered to the costumer have to be so called „self safe“. That means that by

technical solutions a complete contact and electric arc protection is realized and can be assumed.
Out of this no special risks by the used technology have to be expected as long as the vehicle will be used inside of the defined and allowed limits.
If manipulation of the technical systems takes place, the safety cannot be guaranteed for this case.
That these risks exist and occurring accidents can be seen in the following figure showing electric shock that took place during a Formula 1 race.

Figure 6: Accident during a formula 1 race caused by electric shock of the KERS system [6]

LEGAL REQUIRMENTS AND REGULATIONS OUT OF THE SAFETY POINT OF VIEW

Requirements and regulations are existing on different levels; out of the point of view of the vehicles, the battery systems and the single cells as well. There are requirements from out of the vehicle crash safety, there are regulations concerning the transport, storage and the recycling of lithium ion batteries. In addition there are requirements according to the high voltage safety and the safety at work.

The well known legal requirements out of the vehicle safety point of view are the ECE-R100 and the FMSS 305 respective SAEJ 1766.

The ECE-R 100 describes the requirements according to the approval of electric vehicles in Europe, but it doesn't include any crash requirements. For the crash the vehicles have to meet the crash requirements of the conventional vehicles. Most of the OEM's have special internal requirements, for example the there has to be a protection according to short cuts or fire after a crash test.
The FMVSS 305 and the SAE J 1766 are requirements according to the post crash characteristics of hybrid and electric vehicles. After a crash test according to the impact configurations of the FMVSS 208 the occupants have to be protected against electrical shock and fire. In addition the leakage of electrolyte is limited.
To meet these requirements the electrical components and wires have to be packaged in crash protected areas. In addition the high voltage system usually will be disconnected after a crash event.

There are other legal requirements existing for lithium ion batteries like the UN manual of test and criteria for the transport of dangerous goods. To transport lithium ion batteries in general without exceptions it is needed to pass a test series of in sum 8 tests for the cells and the modules. This test series includes vibration test, temperature and pressure test as well as overcharging, shock and external short test. To pass the test it is not allowed that a fire, explosion, abnormal heating, leakage of electrolyte or a mass reduction takes place.

Other requirements according to storage, recycling and safe handling exist as well, but this depends on the local conditions. For Germany a special safety concept for a development or production site has to be defined and implemented.

Overview Battery Tests

Component test configurations for an evaluation of the crash safety of battery systems are already under development.

There are several test procedures existing, mainly developed and provided by several institutes like VDA, Sandia, UL, ISO, Batso and so on, but most of them were developed years ago for the safety of transport and handling of cells and batteries focused on the use by the costumer in applications like notebooks.

These test procedures consist out of shock, drop, crush, squeeze and penetration test and are very similar from institute to institute.

Most of the test results don't give enough information according to the crash safety of a battery, even if the battery passed all the tests erase. The load characteristic of the test compared with a real crash pulse is completely different and not comparable.

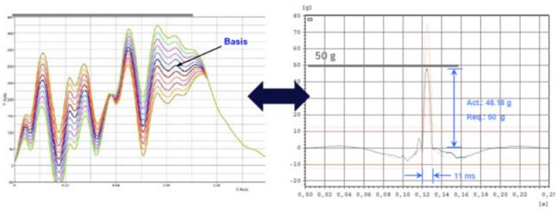

Figure 7: Comparison of crash pulse and safety test pulse (drop test, example) [7]

A different test configuration was developed and introduced by the TÜV Süd in Germany. In these tests different impactor types with a maximum weight of 550 kg will hit and probably penetrate a battery with a velocity of max. 55 kph and an energy input of max. 60 kJ.

The Chinese regulation QC/T 743-2006 is a requirement according to component tests for lithium ion batteries for electric vehicles with a "nominal voltage 3.6V for secondary cell and *n*x3.6V for module (*n* is number of batteries)" [8].

It contains of a couple of tests on cell and battery system level which addresses issues like aging, cycle life, storage, vibration or safety.

Out of the safety point of view several tests have to be done. On the cell level as well as on battery system level over-discharging, over-charging, short circuit, falling heating, squeezing and the needle punch test are part of the requirement. To pass the test a fire or explosion doesn't take place during or after the test.

Especially the squeeze test is quite difficult to pass. On cell level the cell has to be squeezed until the battery case cracks or an internal short takes place. On battery system level the battery module has to be squeezed in a first step to 85% of the original size. In a second step the battery module should be squeezed to 50% of its original size. For the squeezing a special squeezing device should be used.

In addition there are several internal OEM impact test configurations and requirements existing, which have to be met.

The statistical relevance of all of these test configurations according to the real world accident scenario is not verified.

Finally it has to be accepted that it is a myth to believe that the batteries are safe because the passed the tests. In the past all of the battery types passed the required tests (UL and so on) but the history shows that even if they past the tests accidents took place [9]. Some other myths like "ceramic separator solves the problem" or "non flammable electrolytes are the solution for a better safety" are shown in the following figure. These statements about the myth were given at a battery conference in 2010.

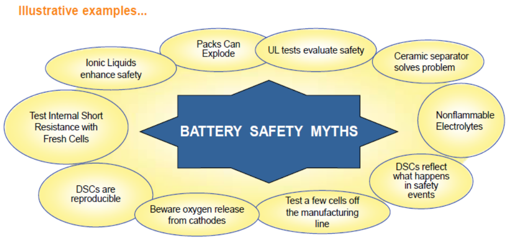

Figure 8: Myth of battery safety [9]

STATISTIC OVERVIEW

In 2009 were 51.8 million vehicles recorded. (according to the data of the German departure for statistic [10]) By the police were 2.3 million accidents registered. Out of this approximately 89,500 accidents were with bigger material damage only and 311,000 accidents with bodily injury.

69 percent of the accidents with bodily damage took place inside of urban areas.

Based on the fact that currently approximately 30,000 HEV's and 1,600 EV's are in use in Germany and a predicted number of 1 million EV's in 2020 it seems to be impossible to predict a realistic accident statistic of HEV's and EV's.

It is for sure that percentage of involved HEV's and EV's will be low. In addition it is for sure that these vehicles – especially the EV's – will be used in urban areas. Because of the speed limits there the crash severities and velocities can be predicted at a lower level.

But it is for sure as well that vehicles with an alternative power train will be involved in accidents in the future.

Out of a statistical analysis basing on the German GIDAS-database crash velocity below 50 kph have to be expected.

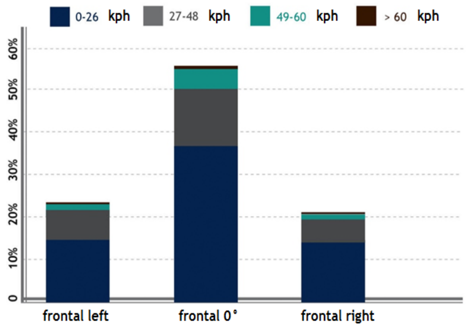

Figure 9: impact velocity for frontal accidents

In result it seems to be that intrusions and penetrations of the batteries will not take place that much. Most of the vehicles are designed to avoid these reactions.

It will be much more important to understand the reaction of the batteries according to acceleration impacts at different levels and directions.

In addition it is needed to answer the question from which acceleration impact level the battery has to be assessed as "defective", for example in result of an low speed crash and without any damage or penetration of the battery housing.

SAFETY CONCEPTS FOR LITHIUM ION BATTERIES

Because of the special characteristics and risks of the battery technology additional safety concepts for the lithium ion batteries only were developed. These safety concepts are working on the three levels cell chemistry, cell and battery system. In addition the protection of the battery system in the vehicle influences the whole safety level.

On the level of the cell chemistry it is important which kind of material for the cathode, the anode, the separator and the electrolyte is chosen. The used combination defines the thermal stability, the lifetime, the charging- and discharging characteristic as well as the reaction during a

physical impact from the outside. It is well known that in china for example lithium iron phosphate is used as material for the cathode. It is the try to get a safer battery by the price of less energy performance.
The choice of the chemistry is important for a possible fire fighting as well. Not every extinguishing media will work well for the used chemistry; sometimes the effect can be worse.
On the level of the cells the design of the housing and the implementation of several safety technologies like a safety vent are defining the safety characteristic. The cell housing protects against impacts and intrusions.

For the battery system the design of the housing is important as well. In addition the battery management system controls and checks the performance (temperature, current, voltage, isolation etc.) of the battery during the use.
The position and the package of the battery as well as integrated additional protection and deformation elements are responsible for the vehicle safety level. A deformation of the battery housing has to be avoided. For the case of a deformation an explosion or a fire can take place.
It has to be taken into account that the position of the battery can influence the dynamic behavior of the vehicle because of the additional weight and the different center of gravity.
Out of this the crash behavior can be different compared with conventional vehicles.
The positioning of the battery is important for the fire fighters and emergency aid too. Is the battery packaged under the hood it is not complicated to extinguish the fire. It is much more difficult if the battery is positioned in the rear part of the vehicle or directly in the middle under the vehicle.

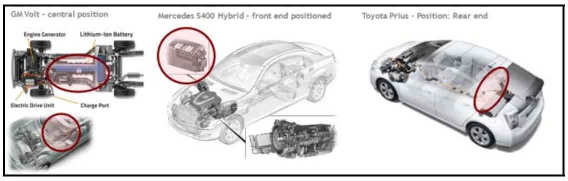

Figure 10: Current packaging and positions of high voltage batteries in vehicles [11, 12, 13]

Finally the chosen cooling system is important for the safety as well. It takes care for the optimal temperature. The temperature is one of the most important factors for the aging behavior of a lithium ion battery. The age of a cell is another important factor according to the failure sensitivity and with it on the risk level of the battery.

At last it should be noted that it is quite common to provide the fire departments with information about the vehicle, the position of the emergency disconnect device, the position and type of the used battery as well as information about the position of the high voltage harness.

DEFINITION AND ASSESSMENT OF A BATTERY SAFETY SYSTEM

The decision for a battery system depends on several factors. First it is needed to define the characteristics like range, power, capacity, volume, weight and the expected cost. Out of this the decision for the used technology, cell chemistry, cooling system, stability of the housing and so on has to be made.
After the first draft of a concept is finished an assessment according to the safety level should be done. This starts with the assessment of the used cell, the behavior during acceleration, penetration, charging and discharging, pressure and temperature.

Unfortunately it is not well known how the reaction of the cells under acceleration effects is. It is recommended to start further investigation according to this issue. A kind of a "landscape", which describes the cell chemistry, the acceleration level and the duration would be helpful to get an overview about the risks and reaction and which levels of acceleration have to be avoided. Out of this the risk for the cells can be assessed. Afterwards a decision for the used cell technology can be made.

In a third step and by knowing the risk level of the cells the safety devices for the cells can be chosen as well as the safety devices for the module. This includes the cell control parameters, the complexity of the battery management system as well as safety vents, the stability of the housings and the packaging.

In last and fifth step the safety devices for the vehicle have to be defined. This includes the kind of the cooling system (liquid or air), the positioning in the vehicle and the implementation of additional crash elements or deformation zones to reduce the acceleration effects. Special constructions like stiffer bars or a cooling system, which works in a passive way during and after the crash, could be very helpful to reduce the overall damages.

Afterwards the battery system should be tested according to the relevant test specifications.

If the target couldn't be reached and the system safety is less than required even if the best available technology was chosen for the modules and vehicles, changes on the cell chemistry have to be done.

With this method it should be possible to develop a safe battery system. The required "acceleration landscape" should be available for several cell chemistries and types within the next years and has to be improved permanently.

CONCLUSION

The use of lithium ion batteries in vehicles is not only important for the future of the e-mobility, it is the key. It doesn't matter for which kind of vehicles it will be used – electric vehicles or hybrid vehicles are possible as well.

There are several risks existing like chemical risk or electrical risk. It is important to understand the technology and the reactions of the material, the cell and the system during an accident. With this knowledge it is possible to design a safe system. An approach for a method is introduced within this paper.

Today's safety technology bases on four levels – the chemical material level, the cell level, the battery module level and the vehicle level. All of these levels are responsible for the final safety level, but they depend on each. An excellent safety rating on one level only doesn't guarantee an excellent safety rating for the whole system.

Out of statistical data's of real world accidents it seems to be more important to focus on the accelerations than on the intrusions. The battery modules are usually positioned in an area inside of the vehicle where an intrusion is less likely. That's why it is recommended to generate a landscape for the different cell technologies (the material and chemistry is included) and their behavior during different acceleration loads in duration and amount.

In addition there are a lot test requirements existing. Currently these requirements are not comparable with the expected load characteristic of vehicle accidents or crash events. Out of this it is needed to define more realistic component tests.

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[13] http://www.atzonline.de/cms/images/ toyota _090605a.gif; Einsatzhinweise für die Feuerwehren bei technischen Hilfeleistungen und Brandbekämpfungen nach Kollisionen von Fahrzeugen des Typs **Toyota Prius** mit Hybridantrieb, Toyota Deutschland GmbH - After Sales Operations - AT - 50420 Köln

NHTSA TIRE ROLLING RESISTANCE TEST DEVELOPMENT PROJECT – PHASE 2

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ABSTRACT

In December 2007, the United States Congress enacted the Energy Independence and Security Act (EISA) that mandated the USDOT-NHTSA to establish a national tire fuel efficiency rating system for motor vehicle replacement tires. The rolling resistance of each tire results in an energy loss for the vehicle and thus affects the vehicle's overall fuel economy. However, improvements in one aspect of tire performance, such as rolling resistance, may lead to reductions in other performance aspects, such as traction and treadwear.

As part of the development of the tire fuel efficiency rating system, NHTSA initiated two phases of research. The Phase 1 research focused on identifying the best rolling resistance test method for use in a rating system, with results being published in a full agency report and summarized in a paper at ESV 2009 (09-0300). The Phase 2 research examined possible correlations between tire rolling resistance levels and vehicle fuel economy, wet and dry traction, outdoor and indoor treadwear, and tread rubber properties. The Phase 2 results were published in a full agency report and are summarized in this paper.

Overall, the Phase 2 results indicate statistically significant improvements in vehicle fuel economy when using low rolling resistance tires and proper inflation pressure, with no expected impact on tire dry traction or treadwear rate. However, the tire models tested exhibited a strong and significant relationship between better rolling resistance and poorer wet slide friction. The wet peak friction displayed the same tendency, but the relationship was much weaker. An analysis of tire tread rubber compounds indicated that the type of polymer, type of filler, and amount of filler can influence both rolling resistance and wet traction properties.

INTRODUCTION

Rolling resistance is defined as the "*loss of energy (or energy consumed) per unit of distance traveled.*" [1] Approximately 80 to 95 percent of this loss is attributed to viscoelastic behavior of tire rubber compounds as they cyclically deform during the rotation process. Rolling resistance is reported in units of force (RRF), or as a coefficient when normalized to the applied normal load (RRC). In vehicle and powertrain dynamics, it is included as a force at the tire/surface contact area opposing the direction of vehicle motion. This simplifies the analysis of energy loss and the derivations of the equations of motion, and should not be understood as a loss at the contact surface such as Coulomb friction. Since vehicle fuel consumption calculations require tire inputs in units of energy, rolling resistance is reported in Newton-meter/meter (reduced to Newtons) in this paper rather than as the dimensionless rolling resistance coefficient.

The National Academy of Sciences (NAS), Transportation Research Board report of April 2006 concluded that a 10% reduction of average rolling resistance of replacement passenger vehicle tires in the United States was technically and economically feasible within a decade, and that such a reduction would increase the fuel economy of passenger vehicles by 1 to 2%, saving about 1 to 2 billion gallons of fuel per year.[2] The NAS report suggests that safety consequences from this 10% improvement in tire rolling resistance "were probably undetectable." However, the committee's analysis of grades under the Uniform Tire Quality Grading Standards (UTQGS) (FMVSS No. 575.104) for tires in their study indicated that there was difficulty in achieving the highest wet traction and/or treadwear grades while achieving the lowest rolling resistance coefficients. This was more noticeable when the sample of tires was constrained to similar designs (*i.e.*, similar speed ratings and diameters).

The NAS committee also concluded that the effects of improvements in rolling resistance on tire wear life and the waste tire stream were difficult to estimate because of the various means by which rolling resistance can be reduced (*e.g.*, initial tread depth, tire dimensions, tread compounding, tread pattern, etc.). However, due to the importance U.S. motorists place on long wear life, as reflected by the emphasis on mileage warranties in tire marketing, the committee deemed it improbable that tire manufacturers would sacrifice wear life to any major degree.

One of the primary recommendations of the NAS committee in their report was that:

> *"Congress (US) should authorize and make sufficient resources available to NHTSA to allow it to gather and report information on the influence of individual passenger tires on vehicle fuel consumption."*

In anticipation of possible congressional legislation, NHTSA began a large-scale research project to select a rolling resistance test procedure that would be best for a regulation, and to examine correlations between tire rolling resistance levels and tire safety performance. The first phase of the project evaluated five test procedures from SAE or ISO, two of which were single-point tests (a single set of test conditions) and three of which were multi-point tests (measured over a range of conditions). The variability of the rolling resistance results from lab to lab, machine to machine, and for multiple tests on the same tire was compared.

The five tests studied were all capable of providing data to accurately assess the rolling resistance of the tires surveyed. The variability of all tests was low, with coefficients of variation below 2 percent. The rank order grouping of tire types was statistically the same for each of the rolling resistance test methods evaluated. However, the analysis showed that there was a significant offset between the data generated by the two labs that is not consistent between tests, or even between tire types within the same test in some cases. Therefore, a rating system must institute a methodology to account for the lab-to-lab variation.

It was concluded that while multi-point rolling resistance test methods are necessary to characterize the response of a tire's rolling resistance over a range of loads, pressures, and/or speeds, either of the two shorter and less expensive single-point test methods were deemed sufficient for the purpose of simply assessing and rating individual tires in a common system. The draft single-point ISO 28580 method had the advantage of using defined lab alignment tires to allow comparison of data between labs on a standardized basis. The use of other test methods would require extensive evaluation and definition of a method to allow direct comparison of results generated in different laboratories, or even on different machines in the same laboratory. The Phase 1 research results were published in a full agency report (DOT HS 811 119) [3] and summarized in a paper at ESV 2009 (09-0300).[4]

In December 2007, the United States Congress enacted the Energy Independence and Security Act (EISA) that mandated the USDOT-NHTSA to establish a national tire fuel efficiency consumer information program to educate consumers about the effects of tires on automobile fuel efficiency, safety, and durability.[5] The program was to include:

> *"A national tire fuel efficiency rating system for motor vehicle replacement tires to assist consumers in making more educated tire purchasing decisions;*
>
> *Requirements for providing information to consumers, including information at the point of sale and other potential information dissemination methods, including the Internet;*
>
> *Specifications for test methods for manufacturers to use in assessing and rating tires to avoid variation among test equipment and manufacturers; and*
>
> *A national tire maintenance consumer education program including, information on tire inflation pressure, alignment, rotation, and tread wear to maximize fuel efficiency, safety, and durability of replacement tires."*

Tire fuel efficiency is assessed by measuring the rolling resistance of each tire. The level of rolling resistance measured represents an energy loss for the vehicle during operation, and thus affects the vehicle's overall fuel economy. Lower rolling resistance therefore contributes to improved vehicle fuel economy. However, improvements in one aspect of tire performance, such as rolling resistance, may lead to reductions in other performance aspects. This tendency is normally expressed in the tire industry as the "Magic Triangle" as shown in Figure 1. Any improvement in one of the vertices' properties of rolling resistance, wet traction, or treadwear may cause a decrease in performance for one or both of the remaining properties.

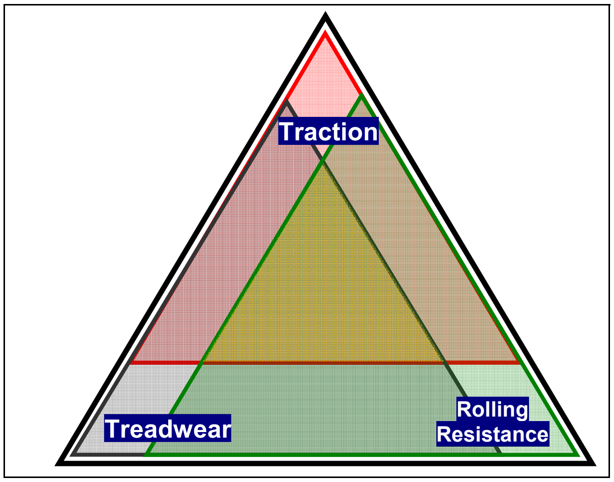

Figure 1. "Magic Triangle" Illustration of Tire Performance Tradeoffs.

In order to understand the possible effects of the EISA requirements on tire performance, the agency conducted a second phase of the project to examine possible correlations between tire rolling resistance levels and vehicle fuel economy, wet and dry traction, outdoor and indoor treadwear, and tread-rubber properties. The specific questions that Phase 2 research was structured to explore were:

1. How sensitive is the overall fuel economy of a typical passenger vehicle to changes in tire rolling resistance and inflation pressure?
2. Do current low-rolling-resistance production tires exhibit any tradeoffs in wet or dry traction?
3. Do the properties of the tread rubber compound affect tire rolling resistance, traction, or treadwear performance?
4. Do current low-rolling-resistance production tires exhibit any tradeoffs in initial tread depth or treadwear rate?

The results were published in a full agency report (DOT HS 811 154) [6] and are summarized in this paper.

EXPERIMENTAL METHODOLOGY

Fifteen passenger tire models that were previously measured for rolling resistance in Phase I of this work, along with the tires that were original equipment on the fuel economy test vehicle, were used in this work. As described in the ESV 2009 paper, [4] the tires were selected to represent a cross-section of manufacturers and performance levels of all-season tires, as well as summer, winter, and run-flat type tires. The tires are described in detail in Table 8 in the Appendix. Because of cost and time constraints for the project, not every test could be conducted on every tire. Table 8 also shows which tests were completed for each tire model.

Rolling Resistance

The rolling resistance for each tire was measured using the conditions of the then draft ISO 28580 test procedure, which was later finalized in equivalent form as ISO 28580:2009(E) *Passenger car, truck and bus tyres – Methods of measuring rolling resistance – Single point test and correlation of measurement results.* The conditions of 80% of maximum tire rated load, 80 km/h (49.7 mph), and 210 kPa (30.5 psi) inflation for standard load tires, or 250 kPa (36.3 psi) for extra load tires are a reasonable approximation of average on-vehicle tire service conditions.

On-Vehicle Dynamometer Fuel Economy

The effects of tire rolling resistance on automobile fuel efficiency were evaluated by installing fifteen different tire models on a new 2008 Chevrolet Impala LS using the 2008 five-cycle EPA fuel economy test.[7] This procedure measures fuel consumption under simulated conditions of city and highway driving, and adds a highway driving cycle which includes higher speeds and harder acceleration, a city cycle with air conditioning use, and a city cycle at cold (-7°C or 20°F) conditions. A summary of the five-cycle test conditions is given in Table 9.

Testing was completed under contract by the Transportation Research Center Inc.'s emissions laboratory. The test apparatus and vehicle are shown in Figure 2.

Figure 2. Vehicle on Fuel Economy Dynamometer.

Since tire inflation pressure affects the operational rolling resistance of a tire, the vehicle fuel economy measurements were conducted at two different tire inflation pressures. All 15 tire models were tested at the vehicle placard pressure of 210 kPa (30 psi). Six models were re-tested at 158 kPa (23 psi), which represents the Tire Pressure Monitoring System (TPMS) activation threshold of 25% inflation pressure reduction. It is important to note that these tests were research and not official EPA fuel economy ratings of the test vehicle. The many tire sets and repeats of test for statistical analysis/dual inflation pressure resulted in the new test vehicle acquiring nearly 6,000 miles by the end of testing. The EPA estimates that new vehicles will not obtain their optimal fuel economy until the engine has broken in at around 3-5 thousand miles.[7] Therefore the fuel economy of the test vehicle was expected to improve slightly during the course of testing, a factor that was tracked and accounted for by the repeated testing of the control and original equipment (OE) tires at regular intervals throughout the testing.

In order to minimize the mileage accumulated on the vehicle, as well as the limitations of time and budget for the project, it was not possible to run a separate coast-down measurement for each set of tires prior to the dynamometer testing. This measurement is used to correct the dynamometer force for the effects of the rolling resistance of the non-driven wheels as well as to correct for inertia and aerodynamic effects. Thereby all vehicle tests were conducted using the dynamometer input for the original equipment tires on the Impala. Coast-down measurements were run for a second set of tires with a significantly higher rolling resistance and equations were developed to correct the fuel economy for these effects.

Skid Trailer Traction Testing

UTQGS Wet Traction FMVSS No. 575.104, *Uniform tire quality grading standards* (UTQGS) requires manufacturers to provide a (wet slide) traction grade for all tires subject to the standard and manufactured after April 1, 1980. Per UTQGS literature:

> *"Traction grades are an indication of a tire's ability to stop on wet pavement. A higher graded tire should allow a car to stop on wet roads in a shorter distance than a tire with a lower grade. Traction is graded from highest to lowest as "AA", "A", "B", and "C"."*[8]

The UTQGS skid-trailer traction testing for the project was performed at the NHTSA test facility on Goodfellow Air Force Base in San Angelo, Texas. The traction grading tests are now performed on a purpose-built oval at the base rather than the original test surface diagram shown in 575.104. The test pavements are asphalt and concrete skid pads constructed in accordance with industry specifications for skid surfaces. ASTM E501 [9] reference (control) tires are used to monitor the traction coefficient of the two surfaces (which varies based on environmental conditions, surface wear, etc.). During a normal wet traction test, a vehicle tows a skid-trailer, shown in Figure 3, at 40 mph across the test surfaces. Water is dispersed ahead of the tire from a water nozzle just before the brake is applied. Instrumentation measures the horizontal force as the brake is applied to one wheel of the trailer until lock-up, and then held for a few seconds and released. The tests are repeated for a total of 10 measurements on each surface. The candidate test tires are conditioned by running for 200 miles on a pavement surface. The candidate tires are then fitted to the trailer, loaded to a specified load and pressure, then subjected to the same testing completed on the control tires. The average sliding coefficient of friction for the candidate tire on each surface is corrected using the coefficients of the control tire to yield an adjusted traction coefficient for the candidate tire on each test surface.

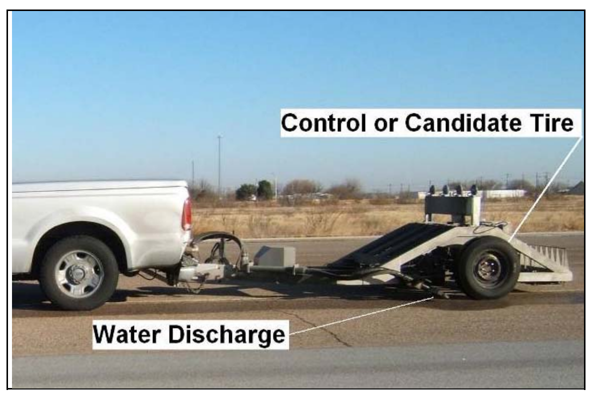

Figure 3. NHTSA San Angelo Skid Trailer.

Phase 2 traction tests were conducted with tires of 16 different models. Two tires had the highest traction grade "AA", and 14 tires were graded "A". Since these tires experienced some break-in during the 50 to 70 mile rolling resistance tests, these tires were only conditioned for 70 miles on a pavement surface rather than the normal 200 miles. Since the tires were previously tested for rolling resistance, and had a reduced break-in, the results generated are for research purposes and are unofficial.

Peak Friction Measurement of Traction The San Angelo trailer is instrumented to provide continuous monitoring of the traction and slip during the test procedure. Since modern anti-lock braking systems (ABS) and electronic stability control (ESC) systems operate in the lower slip and higher friction region, the peak coefficient recorded during the traction testing was also used for comparisons in Phase 2 in addition to the traditional slide values used for UTQGS wet traction.

Dry Traction Measurement The San Angelo skid trailer was also used to repeat the test matrix on dry asphalt and concrete test surfaces. Both the peak and sliding coefficient of friction was recorded. However, the number of measurements on the dry surfaces was reduced to five in order to preserve the limited test surface area from rubber buildup.

On-Vehicle Treadwear Testing

FMVSS No. 575.104, *Uniform tire quality grading standards* (UTQGS) requires manufacturers to provide a treadwear grade for all tires subject to the standard and manufactured after April 1, 1980. Per UTQGS literature:

> *"Treadwear grades are an indication of a tire's relative wear rate. The higher the treadwear number is, the longer it should take for the tread to wear down. A control tire is assigned a grade of 100. Other tires are compared to the control tire. For example, a tire grade of 200 should wear twice as long as the control tire."*[8]

Additional tires from five models were tested in the UTQGS treadwear test. The five tire models, with treadwear grades ranging from 300 to 700, were mounted and balanced on 16 x 7.0" rims. The groove depths of the tires were then measured.. The tires were then installed on five Mercury Marquis vehicles for testing on the UTQG test route near San Angelo, Texas. The vehicles were loaded to 1182 pounds per wheel within +/-1 percent. The vehicles were aligned to center of manufacturer's specifications for caster, camber, and toe.

Indoor Treadwear Testing

Advances in radial tire tread compounding since 1980 have resulting in longer life treads that exhibit only a marginal amount of wear after running the 7,200-mile UTQGS treadwear course. To evaluate the effects of bulk treadwear on tire rolling resistance, additional tires of the five tire models subjected to on-vehicle treadwear, as well as the original equipment tires from the Impala fuel economy vehicle, were subjected to a more aggressive indoor treadwear test developed by Smithers Scientific in Ravenna, Ohio.

The testing was completed on an MTS 860 Durability Machine (Figure 4) 3.048-meter (120-inch) diameter drum covered with 3M 180µ film with servo hydraulic control of tire radial load, tire slip angle and/or slip load, tire camber angle, roadway speed, and braking torque. A powder spray system is used to prevent rubber buildup on the drum 3M surface. The machine was programmed with a drive file that allows for consistent application of energy. The machine was run in force control so that the amount of energy input to the tire/wheel assembly was consistent between test specimens.

Figure 4. MTS 860 Durability Machine.

Two test methods were conducted: one was a 25% Fz (radial load) test and the other was a 20% Fz test. Two tires of each of the six tire models were tested using the 25% test. One each tire model was tested using the less demanding 20% test. The tires were of two load indexes and therefore tested using two different load and force levels to match the rolling resistance load differences. Table 1 lists these test conditions for two of the tested models.

Table 1. Indoor Wear Test Parameters

Tire Model Code	**G12**	**G8**
Radial Load (80% max)	5,725 N	5,882 N
Camber Angle	0°	0°
Speed	80 km/h	80 km/h
Inflation Pressure	210 kPa	210 kPa
25% Fy (Lateral) Amplitude	1,431 N	1,471 N
20% Fy (Lateral) Amplitude	1,145 N	1,176 N

A frictional work or work rate approach was conducted in which the side force was the controlled parameter and was varied throughout the wear test. The 25% Fz test consisted of 1,641 lateral force cycles. The input cycle was a sine wave of the following form, where Fz is the radial load and t is the time in seconds:

$$Fy = (25\,\%\,Fz)\sin\left(\frac{1}{15}\pi\ t\right) \quad (1)$$

A similar cycle was used for the 20% Fz profile. Data that were collected as part of the wear testing were tire/wheel assembly weight, and laser profilometry using a precision scale and a Bytewise CTWIST machine. The CTWIST machine collects 4,096 data points per tire revolution every millimeter across the tire. The data were collected at the new or pre-test point, at the half way point, and at the end of the test. This allows for wear rate to be evaluated. After the final wear cycle the tires were again weighed and measured for rolling resistance in their final state.

Tread Rubber Property Analysis

The tread rubber of the 15 tire models was analyzed for the type of polymer, the fillers and extender, and for dynamic mechanical properties using a variety of analytical procedures. The analysis is outside the scope of this report and was reported in the full DOT report.[6]

RESULTS AND DISCUSSION

Dynamometer Fuel Consumption Testing

Table 2 shows the results of the analysis of variance for the various fuel economy tests studied. The fuel consumption measured during each EPA cycle was modeled as a linear function of tire rolling resistance. The tires ranged in rolling resistance from approximately 40 to 65 N. It should be noted that although rolling resistance is actually an energy loss measured in N-m/m, the meter terms are customarily cancelled.

Table 2. Analysis of Variance for Change in Vehicle Fuel Economy versus Change in Tire Rolling Resistance

Highway FET	64.4	0.0001	0.764	+0.0142	0.0001
City FTP	48.5	0.0001	0.651	+0.0310	0.0001
High Speed US06	48.6	0.0001	0.511	+0.0292	0.0001
Air Conditioning SC03	16.0	0.0005	0.597	+0.0228	0.0005
Cold City FTP	45.7	0.0001	0.420	+0.0273	0.0001

The highway (HWFET) drive cycle was sequentially repeated three times for each tire model inflation pressure combination to provide a measure of repeatability. In addition, the ASTM F2493 Standard Reference tire (SRTT) was run periodically throughout the procedure to verify consistency of the test procedure and apparatus over time. The following analysis was conducted on the verified values, which include some retests to account for anomalous data. The raw data is available in the complete DOT report. The F values are significant indicating that the overall trend toward lower fuel economy with increasing tire rolling resistance is statistically significant. Values in the column "Probability > |t|" that are less than 0.05 indicate that tire rolling resistance has a significant effect on estimated fuel economy of the vehicle. Increases in fuel consumption range from 0.014 to 0.031 L/100 km for each Newton of increased tire rolling resistance.

The average fuel economy for each of the drive cycle tests versus the tire rolling resistance is shown in Figure 5 to Figure 9. The trend toward increased fuel consumption as tire rolling resistance increases is clearly evident for each of the EPA drive cycles.

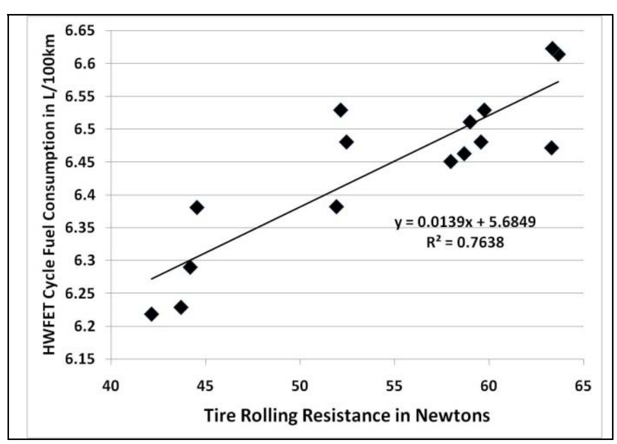

Figure 5. Highway Cycle (FET) Fuel Consumption versus Tire Rolling Resistance.

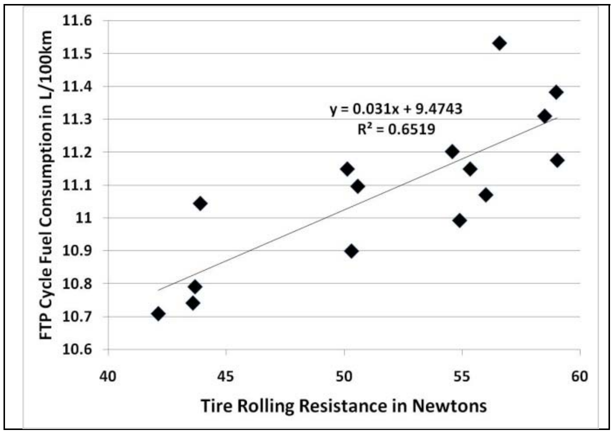

Figure 6. City Cycle (FTP) Fuel Consumption versus Tire Rolling Resistance.

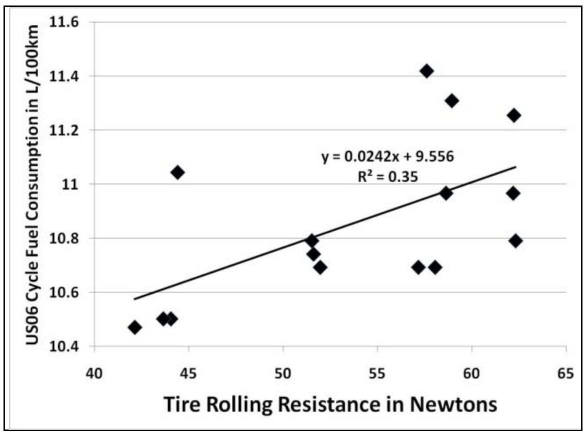

Figure 7. High Speed Cycle (US06) Fuel Consumption versus Tire Rolling Resistance.

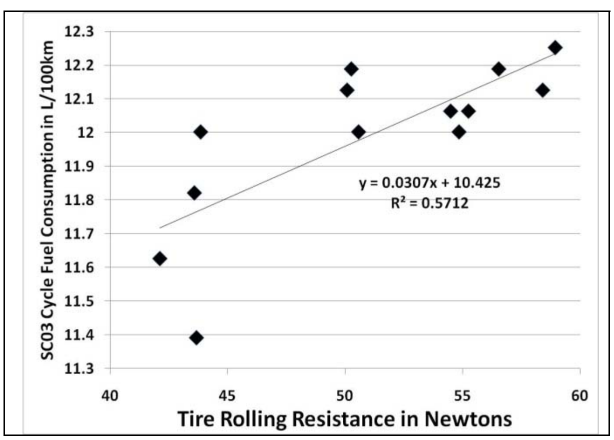

Figure 8. Air Conditioning Cycle (SC03) Fuel Consumption versus Tire Rolling Resistance.

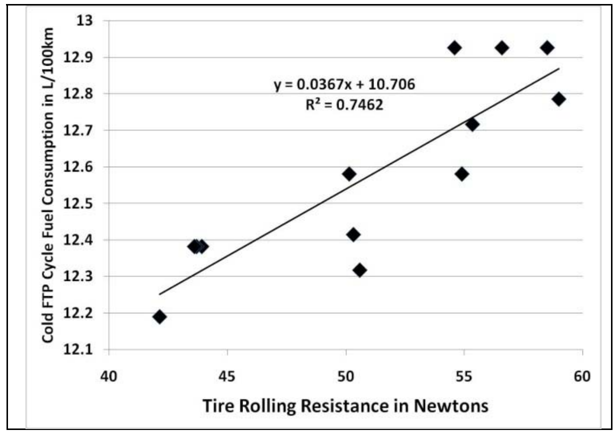

Figure 9. Cold City (FTP) Cycle Fuel Consumption versus Tire Rolling Resistance.

Figure 10 shows the fuel economy as a percentage of the mean for each EPA test cycle versus the rolling resistance as a percentage of the mean rolling resistance. The scatter in the data is evident, but the overall trends are clear and the percentage decreases in fuel economy as tire rolling resistance increases show very similar results.

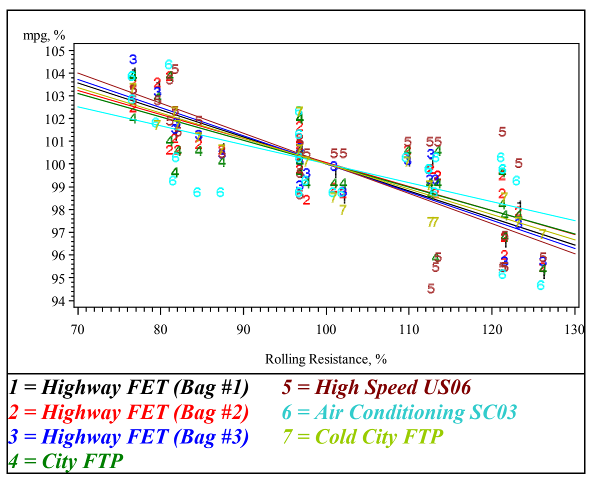

Figure 10. Normalized Fuel Economy versus Tire Rolling Resistance.

Table 3 shows the regression results for the percentage change in vehicle mileage which results from a 10 percent change in rolling resistance of the tires. The increase in mileage for a 10% decrease in rolling resistance is approximately 1.3%, ranging from a low of 1.2% for the Air Conditioning SC03 cycle, to a high of 1.6% for the High Speed US06 cycle. These results agree with the calculated values of a 0.7% to 2.0% change in fuel economy for a 10% change in rolling resistance that are shown in the Transportation Research Board, Special Report 286.

Table 3. Percentage Change in Vehicle Fuel Economy for a 10% Change in Tire Rolling Resistance

EPA Drive Cycle	% Change in Fuel Economy for a 10% Change in Rolling Resistance
Highway FET	1.29
City FTP	1.48
High Speed US06	1.62
Air Conditioning SC03	1.20
Cold City FTP	1.61

Under-inflated tires have been shown to be a prevalent issue for passenger vehicle safety. In 2001, NHTSA released the results of the *Tire Pressure Special Study*, showing that 28% of passenger cars had at least one tire under-inflated by 8 psi or more.[10] Recently NHTSA published the results of a sample of vehicles surveyed with and without tire pressure monitoring systems (TPMS).[11] Although the number of vehicles with underinflated tires was less with TPMS, there were still approximately 20% of vehicles equipped with TPMS systems that had at least one tire underinflated by 25% or more. While the primary safety issue for under-inflation of tires is reduced vehicle control and possible tire failure due to cumulative damage, studies have shown that underinflation increases the rolling resistance of a tire, thus increasing vehicle fuel consumption.

The effect of reduced inflation pressure was estimated from comparison of the dynamometer fuel economy of the vehicle with the tires inflated to the placard pressure of 210 kPa (30 psi), to tests with the same tires inflated to 158 kPa (23 psi). The lower pressure represents the 25% reduced pressure activation threshold of the tire pressure monitoring system (TPMS) specified in FMVSS No. 571.138. Six tire models that spanned the range of rolling resistances were chosen for the experiment. There was a trend for tires at the lower inflation pressure to generate lower fuel economy in all tests. Table 4 shows the results of the ANOVA analysis for the tests. All but one of the tests showed an increase of 0.3 to 0.6 percent in fuel consumption for all fuel economy cycles for a 10 kPa decrease in tire pressure. The High Speed US06 test showed no significant change in fuel economy, possibly due to the large effect of aerodynamic drag on the total fuel consumption.

Table 4. Decrease in Vehicle Fuel Economy for Decreases in Tire Inflation Pressure

EPA Drive Cycle	% Change in Fuel Economy / 10 kPa Reduction in Tire Inflation
Highway FET	-0.300
City FTP	-0.464
High Speed US06	-0.019
Air Conditioning SC03	-0.560
Cold City FTP	-0.364

Dry Traction Skid Trailer Testing

Sixteen tire models representing a range of rolling resistance and of other characteristics were tested for dry traction by NHTSA. The data is reported as Slide Number (coefficient of friction x 10^2). The ASTM E501 Standard Reference Test Tire is run along with the test tires. The coefficient of variation for the data ranged from 4% to 6%. There appears to be no significant correlation between dry peak or slide friction values on asphalt or concrete to rolling resistance for the tires studied. Table 5 shows the Pearson Product Moment Correlation of the values for dry traction to the tire rolling resistance. The Pearson value indicates the strength and direction of the correlation with values ranging from -1 for complete negative correlation, to +1 for complete positive correlation, with values near zero indicating no correlation between the measures. It is evident in Figure 11, that there is very little correlation between the dry traction and rolling resistance for these tires. For a value to be statistically significant the probability > |r| would have to be less than 0.050, and no value approaches that number.

Table 5. Correlation of Skid Trailer Dry Traction to Tire Rolling Resistance

	Asphalt		Concrete	
	Peak Value	Sliding Value	Peak Value	Sliding Value
Pearson Product Moment Correlation	0.209	-0.158	0.056	0.069
Probability > |r|	0.2518	0.3886	0.7602	0.7059

Figure 11 displays that the peak and sliding traction conducted on dry asphalt and concrete surfaces have no systematic change as tire rolling resistance changes.

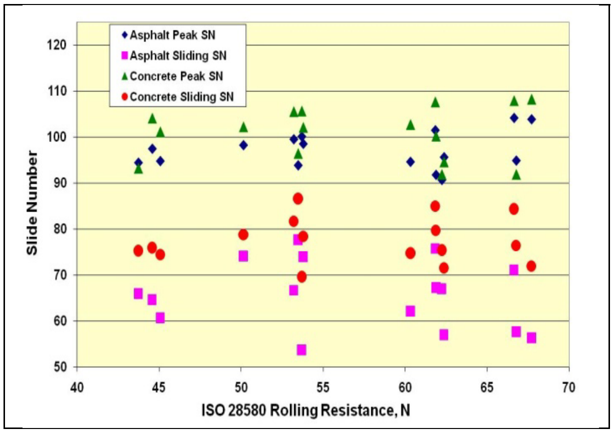

Figure 11. Dry Traction Slide Numbers versus ISO 28580 Rolling Resistance.

Skid Trailer Traction Testing on Wet Surfaces

Table 6 shows the Pearson Product Moment Correlation of the values for wet traction to the tire rolling resistance. The sliding values all have a strong and significant relationship between better rolling resistance and poorer wet traction. The peak values display the same tendency but the relationship is much weaker.

Table 6. Correlation of Skid Trailer Wet Traction to Tire Rolling Resistance

	Asphalt		Concrete	
	Peak Value	Sliding Value	Peak Value	Sliding Value
Pearson Product Moment Correlation	0.299	0.739	0.465	0.700
Probability > |r|	0.0965	<0.0001	0.0070	<0.0001

Even though these tires were not new, having been previously tested for rolling resistance in the laboratory, the UTQGS procedure was used for this testing and the results should display the same trends seen in new tires. The UTQGS traction rating is based on the wet sliding value on asphalt and concrete. Figure 12 displays the wet traction slide number on the asphalt surface with the critical values to achieve an A or AA traction rating. Figure 13 displays the data for the concrete surface. While most of these tires were labeled A traction and tested as such, it is clear that the values increase within the range as rolling resistance increases. From these data, it appears that the tires with lower rolling resistance values will have poorer wet traction performance in the sliding region. This will be particularly significant to consumers without ABS systems on their vehicles, since the sliding value will relate most closely to emergency stopping maneuvers.

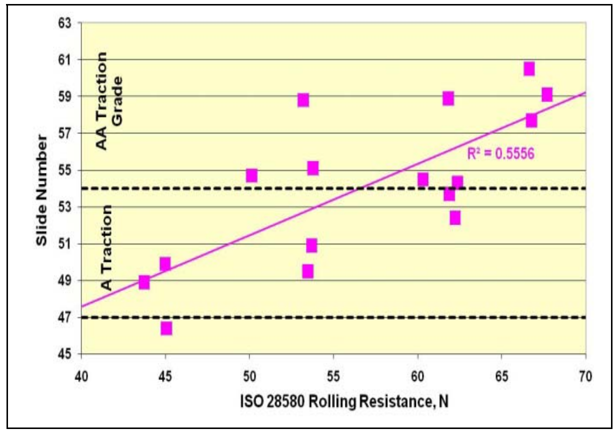

Figure 12. Slide Number on Wet Asphalt versus Tire Rolling Resistance.

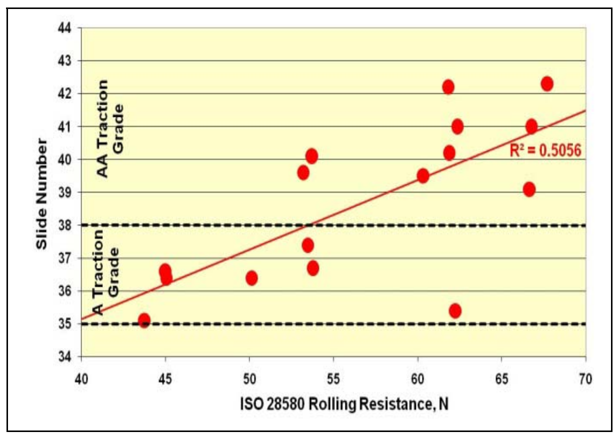

Figure 13. Slide Number on Wet Concrete versus Tire Rolling Resistance.

The wet traction versus rolling resistance for the peak measured traction on both asphalt and concrete surfaces are shown in Figure 14. The decrease in traction as rolling resistance improves is much less pronounced. Hence, for newer vehicles with ABS or ESC systems, the tradeoff is expected to be much less significant.

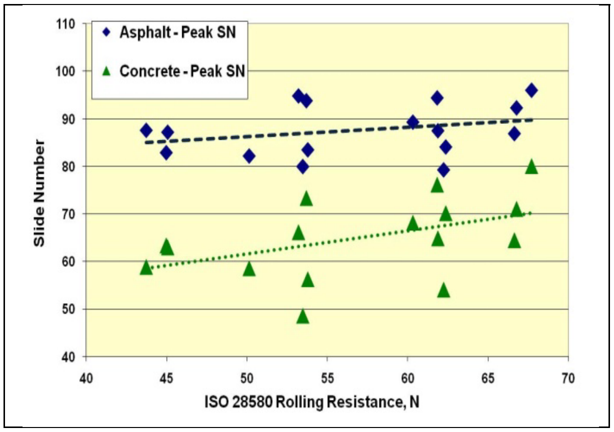

Figure 14. Peak Traction Results on Wet Surfaces versus Tire Rolling Resistance.

Technical literature indicates that the tradeoff between tire fuel economy and traction performance can be significantly reduced or eliminated with advanced compounding technologies, which are usually more expensive and proprietary. An analysis of tire tread rubber compounds, which was beyond the scope of this paper, confirmed that the type of polymer, type of filler, and amount of filler can influence both rolling resistance and wet traction properties.

On-Vehicle Treadwear Testing

Five tire models, including the ASTM F2493SRTT, that were selected to represent the range of rolling resistance of the models studied were tested according to the UTQGS testing protocol for treadwear. Measurements were taken across the tire at six locations in each groove (1 through 4). Data were analyzed by tire type, by groove, by shoulder (grooves 1 and 4) or tread center (grooves 2 and 3). The coefficients of variation for the wear rates are approximately 0.5% for all tire types indicating that comparisons between tire types at these conditions are reliable.

Table 7 shows the treadwear rates and projected mileage to1.59mm (2/32^{nds} in) tread depth for the tires. For each model the wear rates for the shoulder and tread center were compared along with the projected lifetime for each area. For tire type B11 the wear rate in the shoulder area was significantly faster than the wear rate in the tread center, with a corresponding decrease in projected mileage. For tire type M14 the wear rate in the tread center was significantly faster than in the shoulder area, with significantly shorter projected tread life in this area. Tire type M13 had faster wear rates in the tread center, but this was partially offset by a lesser groove depth in the shoulder area in projecting tire lifetime.

Table 7. Projected Mileage to Wearout for Tires with Varying Rolling Resistance

Tire Type	Rolling Resistance, Newtons	Reported Wear Rate, mil/1000mi	Average Projected Tread Life, km	Projected Life, km (Shoulder)	Projected Life, km (Tread Center)
B11	45.1	5.16	88,254	78,132	101,708
B13	66.8	6.46	83,716	83,346	87,771
G8	43.7	6.45	73,046	74,768	73,770
M13	53.7	5.45	66,480	72,660	65,177
M14	53.2	5.56	72,419	91,296	63,133

Figure 15 shows the projected average tire mileage to wear out and the minimum projected mileage, versus the rolling resistance for the tire. From the outdoor test data, there is no evidence that a tire with reduced rolling resistance will necessarily have reduced tread life.

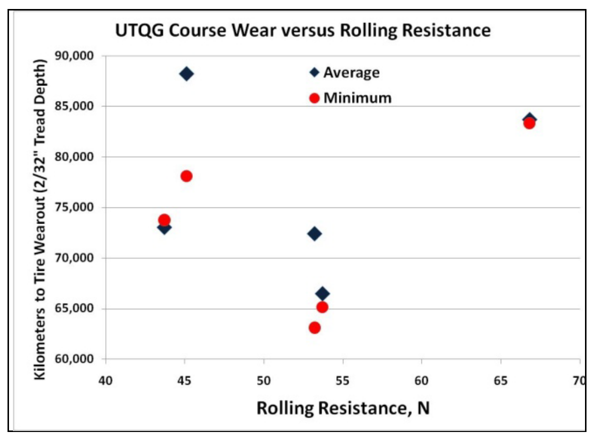

Figure 15. On-Vehicle Tire Test Miles to Wear-out versus Tire Rolling Resistance.

Indoor Treadwear Testing

The indoor treadwear test was designed to provide a faster rate of wear on the tire by minimizing the straight-ahead driving time where little tire wear takes place. The same tires that were tested on the on-vehicle wear test, along with the original equipment tires from the Impala fuel economy test vehicle were tested in the laboratory. At the severe conditions (25% Fz) the tire shoulders wore very quickly and were nearing complete wearout at the conclusion of the 1350 km test sequence. At the mild conditions (20% Fz) the shoulder area still wore significantly faster than the tread center. As seen in Figure 16, the indoor test data does indicate a trend towards shorter treadlife for the tires with lower rolling resistance.

The results for the indoor treadwear testing are contrary to results for the on-vehicle testing. However, given the large difference in the severity of the two tests (the on-vehicle test was minimal in severity and the indoor test was aggressive), it is likely that the tests were evaluating different wear regimes for the tire treads. In other words, the rank ordering of wear rates for individual tires at minimal wear conditions can change at more severe conditions.

Additional analysis of tire wear patterns was conducted using the data points provided by the Bytewise CTWIST machine and are provided in the full DOT report.[6]

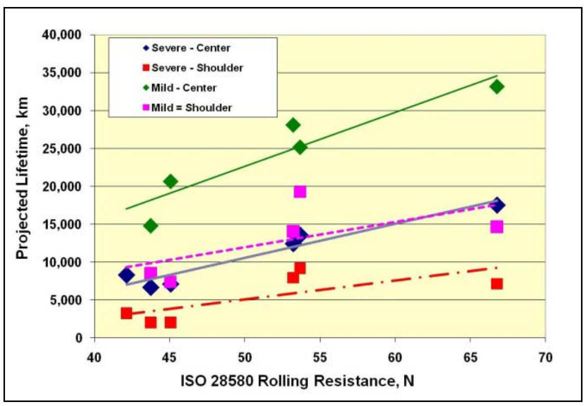

Figure 16. Indoor Treadwear - Projected Tire Tread Life versus Rolling Resistance.

CONCLUSIONS

Based on five different fuel economy cycles, a 10 percent decrease in tire rolling resistance resulted in an approximately 1.3 percent increase in fuel economy for the vehicle. This result was within the range predicted by technical literature. Reducing the inflation pressure by 25 percent resulted in a small but statistically significant increase of approximately 0.3 to 0.5 L/100km for four of the five fuel economy cycles, excluding the High Speed US06 cycle. This value was also within the range predicted by technical literature.

For the tires studied, there appeared to be no significant relationship between dry peak or slide numbers and rolling resistance. However, these tire models exhibited a strong and significant relationship between better rolling resistance and poorer wet slide numbers. The peak wet slide number displayed the same tendency, but the relationship was much weaker. This may be significant to consumers without anti-lock braking systems (ABS) on their vehicles since the wet slide value relates most closely to locked-wheel emergency stops. For newer vehicles with ABS or electronic stability control systems, which operate in the earlier and higher wet peak friction range, the tradeoff is expected to be less significant. The tire models were selected to represent a broad range of passenger tires in the marketplace and the authors feel that these results are generally applicable to the current tire market.

Technical literature indicates that the tradeoff between tire fuel economy and traction performance can be significantly reduced or eliminated with advanced compounding technologies, which are usually more expensive and proprietary. An analysis of tire tread rubber compounds, which was beyond the scope of this paper, confirmed that the type of polymer, type of filler, and amount of filler can influence both rolling resistance and wet traction properties.

For the subset of five tire models subjected to on-vehicle treadwear testing (UTQGS), no clear relationship was exhibited between tread wear rate and rolling resistance levels. For the subset of six tire models subjected to more aggressive inputs in the indoor treadwear tests, there was a trend toward faster wear for tires with lower rolling resistance.

ACKNOWLEDEGEMENTS

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APPENDIX

Table 8. Specifications for Passenger Tire Models and Tests Completed for Correlation with Rolling Resistance

Tire Model Code	MFG	Size	Load Index	Speed Rating	Model	UTQGS Treadwear	UTQGS Traction	UTQGS Temp.	Performance Level	Dynamometer Fuel Economy	Skid Trailer Dry Traction	Skid Trailer Wet Traction	On-Vehicle UTQGS Treadwear	Indoor Treadwear	Dynamometer Fuel Economy at 25% Reduced Tire Inflation
G12	Goodyear	P225/60R16	97	S	Integrity	460	A	B	Passenger All Season, TPC 1298MS	✓				✓	✓
G10	Goodyear	P205/75R15	97	S	Integrity	460	A	B	Passenger All Season		✓	✓			
G11	Goodyear	P225/60R17	98	S	Integrity	460	A	B	Passenger All Season	✓	✓	✓			
G8	Goodyear	225/60R16	98	S	Integrity	460	A	B	Passenger All Season	✓	✓	✓	✓	✓	✓
G9	Goodyear	P205/75R14	95	S	Integrity	460	A	B	Passenger All Season		✓	✓			
U3	Dunlop	P225/60R17	98	T	SP Sport 4000 DSST	360	A	B	Run Flat	✓	✓	✓			
B10	Bridgestone	225/60R16	98	Q	Blizzak REVO1		-		Performance Winter	✓	✓	✓			
B15	Dayton	225/60R16	98	S	Winterforce		-		Performance Winter	✓	✓	✓			
B13	Bridgestone	P225/60R16	97	T	Turanza LS-T	700	A	B	Standard Touring All Season	✓	✓	✓	✓	✓	✓
B14	Bridgestone	P225/60R16	97	V	Turanza LS-V	400	AA	A	Grand Touring All Season	✓	✓	✓			
B11	Bridgestone	P225/60R16	97	H	Potenza RE92 OWL	340	A	A	High Performance All Season	✓	✓	✓	✓	✓	✓
B12	Bridgestone	P225/60R16	98	W	Potenza RE750	340	AA	A	Ultra High Performance Summer	✓	✓	✓			
M13	Michelin	225/60R16	98	H	Pilot MXM4	300	A	A	Grand Touring All Season	✓	✓	✓	✓	✓	✓
D10	Cooper	225/60R16	98	H	Lifeliner Touring SLE	420	A	A	Standard Touring All Season	✓	✓	✓			
P5	Pep Boys	P225/60R16	97	H	Touring HR	420	A	A	Passenger All Season	✓	✓	✓			
R4	Pirelli	225/60R16	98	H	P6 Four Seasons	400	A	A	Passenger All Season	✓	✓	✓			
M14	Uniroyal	P225/60R16	97	S	ASTM F2493 SRTT	540	A	B	Passenger All Season	✓	✓	✓	✓	✓	✓

Table 9. 2008 EPA Fuel Economy 5-Driving Schedule Test (Source: US EPA, 2011)

Driving Schedule Attributes	**Test Schedule**(1)				
	City (FTP)	**Highway (HwFET)**	**High Speed (US06)**	**Air Conditioning (SC03)**	**Cold Temp (Cold CO)**
Trip Type	Low speeds in stop-and-go urban traffic	Free-flow traffic at highway speeds	Higher speeds; harder acceleration & braking	AC use under hot ambient conditions	City test w/ colder outside temperature
Top Speed	56 mph	60 mph	80 mph	54.8 mph	56 mph
Average Speed	21.2 mph	48.3 mph	48.4 mph	21.2 mph	21.2 mph
Max. Acceleration	3.3 mph/sec	3.2 mph/sec	8.46 mph/sec	5.1 mph/sec	3.3 mph/sec
Simulated Distance	11 mi.	10.3 mi.	8 mi.	3.6 mi.	11 mi.
Time	31.2 min.	12.75 min.	9.9 min.	9.9 min.	31.2 min.
Stops	23	None	4	5	23
Idling time	18% of time	None	7% of time	19% of time	18% of time
Engine Startup	Cold	Warm	Warm	Warm	Cold
Lab temperature	68-86ºF	68-86ºF	68-86ºF	95ºF	20ºF
Vehicle air conditioning	Off	Off	Off	On	Off

Research issues in Eco-driving

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ABSTRACT
Transport is a key economic sector, supporting economic development and growth, and facilitating exchange. At the same time, motor vehicles are major emitters of gaseous and particulate pollution in urban areas. The transport industry's quest to limit its impact on the environment and improve road safety continues to drive policy, research and development. Eco-driving is a well-established, affordable and simple behavioural change intervention, which could reduce fuel consumption up to 20%. Fully electric vehicles are predicted to be available for the mass market by 2020, however an energy efficient driving style will still be necessary for these vehicles due to a relatively poor battery performance. Furthermore Eco-driving could be applied to electric or thermal vehicles. Despite a widespread adoption of Eco-driving, its safety benefits have not been clearly established. This paper discusses research issues related to Eco-driving interventions. It covers policy, industry practice and research approaches ranging from education to in-vehicle technology. This paper demonstrates the lack of comprehensive systemic research analyzing the impacts of Eco-driving on road safety. Most of the methods used to assess the benefits of eco-driving lack scientific rigour and have methodological shortcomings. Ecological Driving Assistance Systems (EDAS) has emerged as a viable ITS intervention addressing Eco-driving but the associated Human Machine Interface is still neglected. Furthermore, there is not enough research assessing the long-term effects of Eco-driving driving.

INTRODUCTION
Transport is a key economic sector, supporting economic development and growth, and facilitating the exchange of goods. However, transport could damage the health of humans and the planet by creating road trauma, air pollution and greenhouse gases. Reductions in road trauma in Australia and across the Organisation for Economic Co-operation and Development (OECD) have stalled in the last five years and innovative interventions are needed to address this impasse. At the same time, passenger and freight travel are growing, with consequent increases in gaseous and particulate pollution in urban areas which have serious health effects, including respiratory and cardiovascular diseases

Eco-driving attempts to change drivers' behaviour through advice such as driving more smoothly by anticipating changes in the traffic, shifting gear sooner, operating the vehicle within an optimum range of engine revolutions, avoiding jerky braking/acceleration and avoiding traffic congestion. Many countries have promoted Eco-driving as a key element of national strategies to reduce CO_2 emissions but have not examined the safety effects (ECODRIVEN, 2009). European Union regulations already require Eco-driving to be taught to novice drivers. Japan achieved its 2010 goal of reducing CO_2 emissions by 31 million tons below 2001 levels by encouraging drivers to use their vehicles more efficiently through Eco-driving (Transport America, 2010). The claimed advantages of the Eco-driving approach are that it can apply to vehicles of any age or size, it can take effect across the entire fleet of vehicles immediately at low cost (as opposed to being phased in), and that it can result in immediate savings to individuals from greater fuel efficiency, better safety and perhaps lower insurance rates (Barkenbus, 2010).

TECHNOLOGICAL LIMITATIONS
Eco-driving goals are easily pushed to the background when they conflict with other goals, particularly goals related to safety and time saving (Dogan et al., 2011). Helping the driver to choose the best compromise between safety and CO_2 reduction driving techniques can be the goal of a new type of advanced systems called ecological driving assistance

systems (EDAS). This can be achieved through two different approaches:

- Adapt existing speed management systems developed within the area of Intelligent Transportation Systems such as Intelligent Speed Adaptation (ISA).
- Design a specific EDAS merging safety and environmentally driving tips.

The first possible solution relies on the assumption that controlling speed is sufficient to reach a reasonable level of fuel economy. Such an hypothesis has been tested through the impacts of ISA systems on fuel consumption. An ISA system monitors the location and speed of the vehicle, compares it to a defined set speed, and takes corrective action such as advising the driver and/or governing the top speed of the vehicle. There are several ISA implementation methods, based on how the set speed is determined (see Carsten & Fowkes (2000) for a review), but the most common implementation is the variable version. In this case, the set speed is determined by vehicle location, which leads the equipped vehicle never to exceed the speed limit for a given area. The French ISA system (LAVIA) has been extensively studied by the French public works laboratory (LCPC). A recent re-analysis of the collected data shows that there is no fuel consumption reduction (Saint Pierre & Ehrlich, (2008)) as was predicted by the models. This result is similar than recent findings for other ISA implementations (Regan et al., 2008; Carsten et al., 2008). ISA systems are therefore not so effective in preserving the environment, as speed advice alone is not precise enough to deal with the complexity of eco-driving behavior. Other tested devices such as a simple acceleration advisory tool have also lead to disappointing results (Larsson & Ericsson 2009).

Designing a new type of ecological device seems to be a more promising approach as many automakers are developing their own monitoring devices. Ranges of ITS-based interventions have been developed to facilitate the maintenance of the Eco-driving style once training is completed. In commercial fleets, IT applications are available that monitor fuel economy in real time and provide instantaneous readouts to drivers, or to fleet managers via mobile communications systems (Int Transport, 2008). Most of these devices are available as features of hybrid-electric vehicles with the purpose of providing instant feedback to the driver of the vehicle's fuel economy performance. Some of the newest hybrid-electric vehicles coming to market not only provide driver feedback, but also establish driving parameters for the vehicle that can assist in eco-driving. For example, Honda provides their insight hybrid model with a driver-activated ECON mode that adjusts vehicle performance for fuel efficiency purposes. The Toyota Prius allows the driver to receive fuel economy information through three different displays all delivering slightly different fuel economy information. Such monitoring devices are also present in other brands, but up to now they are equipping mainly hybrid-electric vehicles. For example, Honda has developed an Eco Assist dashboard display which uses a simple colour-coded display of ‘‘leaves’’ (the more leaves the better) to provide the driver with an assessment of how successful he/she is in achieving maximum fuel economy, while Ford uses the same principle with their SmartGauge system (White, 2009).

Since better fuel economy is the primary selling points for these vehicles, the importance of these devices is well understood. European project results (ECODRIVE) indicate that most drivers welcome feedback devices in their vehicles and are ready to modify their driving habits. Most of them will attempt to make a game out of it, searching for the best way to drive to maximize fuel efficiency.

But little scientific research has been published on the effects of such ITS devices on driver behaviour, fuel consumption and emissions and how to optimise the feedback to the driver.

EFFECTS OF ECO-DRIVING ON CONSUMPTIONS AND EMISSIONS

Despite its popularity, there is poor and inconsistent research evidence regarding the effects of Eco-driving on both fuel consumption and emissions. Most research projects on Eco-driving have demonstrated reductions in fuel consumption (Barth & Boriboonsomsin, 2009) and emissions (Barth & Boriboonsomsin, 2009; Carslaw et al., 2010). Other studies related to the use of different Advanced Driving Assistance Systems (ADAS) as opposed to eco-driving devices, have shown no impact (Larsson & Ericsson, 2009) or increased fuel consumption with the use of Intelligent Speed Adaptation (St Pierre & Ehrilich, 2008).

Research into the long-term (>3 years) effectiveness of Eco-driving training found that average fuel consumption fell by 5.8%

four months after initial training (Beusen et al., 2009). Most drivers had an immediate fuel consumption improvement that was stable over time but some tended to fall back into their original driving style. Eco-driving style is difficult to turn into driving habit as it is dependent to the driving situation such as traffic, environment and personal motivations (Dogan et al., 2011).

The impact on emissions (CO_2, CO, NO_x, PM and CH) has been estimated with simulation models. Simulation has been shown to produce valid estimations. Smit et al (2010) conducted a meta-analysis of 50 studies dealing with the validation of various types of traffic emission model by taking into account average speed, traffic situation, traffic variables, cycle variables and modal models. The results of the meta-analysis indicate that the mean prediction errors are generally within a factor of 1.3 of the observed values for CO_2, within a factor of 2 for HC and NO_x, and within a factor of 3 for CO and PM. A positive mean prediction error for NOx was established for all model types and practically all validation techniques. Their statistical analyses show that the mean prediction error is generally not significantly different ($p < 0.05$) when the data are categorised according to model type or validation technique. Such results are promising.

Carslaw et al. (2010) have conducted a large field trial in which they developed individual vehicle model emissions models for CO_2 for 30 Euro III and Euro IV cars using Generalized Additive Models. Their models describe how emissions from individual vehicles vary depending on their driving conditions, taking account of variable interactions and time-lag effect.

EFFECTS OF ECO-DRING ON SAFETY

Little is known about the relationship between Eco-driving and safety. Driving safely requires drivers to make decisions about their own actions, as well as requiring interactions with other road users. Individual actions include decisions about speed choice (speed limits, or condition considerations), as well as skill errors (lapses or slips), or violations (Knapp et al, 2003; Vershuur & Hurts, 2008). Reducing speed decreases the likelihood and severity of crashes. Evidence has shown that greater speed variability in traffic streams increases the risk of crashes (Knapp et al. 2003). A low speed variability manifests in avoiding rapid starts and stops; maintaining a steady speed when travelling on highways; keeping rolling in traffic; and using the highest gear possible. These are several key safe driving behaviours, which also form the basis of Eco-driving (The Alliance of Automobile Manufacturers, 2010; Beusen et al, 2009). While many of these behaviours may improve safety (e.g. maintaining a steady speed may decrease speed variability on road segments), others may have a negative impact on safety (e.g. keeping rolling in traffic).

Some advice may therefore appear to be in conflict in specific situations. For example, when driving in a crowded urban area, it can be difficult to maintain a steady speed with a high gear, and safety should be prioritized by adopting a low speed although it is not fuel efficient. An experienced driver may understand easily that the best compromise depends on the situation, but problems may arise when trying to teach the Eco-driving style to young drivers. It should be noted that driving habits learned by experience could also be hard to change. CIECA (2007), has identified the following potential conflicts:

- Drifting around junctions and pedestrian crossings in an attempt not to stop.
- Driving too close to the vehicle in front in an effort to maximize your evenness of speed.
- Coasting too early and disrupting the pattern of traffic to the rear, thereby increasing the risk of a rear-end collisions.
- Rapid acceleration to cruising speed could cause shorter safety margins to vehicles in front.
- Trying to stay in a high (fuel-efficient) gear, but therefore manoeuvring at too high speed (e.g. cornering).
- Switching off the engine at short stops can lead to the steering wheel locking.

Eco driving tips need to be adapted depending on the driving context, and “drive safely and use eco-driving techniques where possible” is perhaps a more appropriate rule of conduct, although it may not emphasize Eco-driving as much as some experts would wish.

Driving behaviours can influence both fuel economy and safety. A positive correlation between crash rates and fuel consumption was found in a large corporate fleet (Haworth & Symmons, 2001). In contrast, another study demonstrated that the drivers who had the lowest fuel consumption were not necessarily the safest or those who complied with the Eco-driving instructions (Saint Pierre et al., 2010). Speed profile has a fundamental influence on both safety and environmental outcomes. For example, stop-start driving increases emissions, with the major reason for this being the acceleration component (Jayaratne et al., 2009). Motorists in a recent survey by RoadPilot reported that rising fuel costs affected their choice of speed more than speed cameras did. There remain cultural and educational barriers inhibiting the adoption of safe driving behaviours. An educational message related to reducing air pollution was more effective than safety messages in getting drivers to keep to the speed limit (Delhomme, Chappe, et al., 2010). This suggests that Eco-driving could be employed to achieve two goals simultaneously. A recent French study involving 1,200 passenger vehicles has shown that most of the drivers ignore the main Eco-driving instructions despite their strong motivation in reducing their fuel consumption (Delhomme, Paran & Nicolas, 2010).

There is very little scientific knowledge regarding the most effective driving behaviour for safety and fuel economy. Saboohi and Farzaneh(2009) defined an optimal eco-driving of passenger vehicle based on the minimum fuel consumption. They showed, with a traffic simulator, that an optimal driving strategy based on coordination of speed and gear ratio through engine load would lead to minimization of fuel consumption in an intense traffic flow.

Kamal et al. (2010) defined a predictive control model of a vehicle in a varying road-traffic environment for Eco-driving. The model is based on vehicle dynamics and includes factors such as resistances and traction forces, engine characteristic and road map. In addition the eco-driving performance index is based on driving efficiency instead of speed.

The emphasis on gear changing in Eco-driving reflects its European origins and it may not be as effective in the US or Australia where cars mostly have automatic transmissions. Symmons et al. (2009) note that "given that Eco-driving has been in official existence for some 20 or so years there actually seems to be remarkably few trials published in the peer-review literature" (p.49). Walhlberg (2007) concurs, stating that:
"*The claims regarding the Eco-drive benefits were mainly made by educators and bureaucrats, and lack scientific backing. More specifically, no literature on Eco-drive was found after a thorough literature search in major academic databases covering transport, energy, and psychology*".

HUMAN MACHINE INTERFACE OF ECO-DRIVING

There is a large body of research on how in-vehicle technologies such as navigation systems could distract the driver. However there is little understanding of the side effects of most new eco-driving technologies instructions on driver safety performance. The main research questions, which remain unanswered in eco-driving, are how in-vehicle eco-driving systems may influence driving behaviour; and whether they might distract drivers, particularly during potentially dangerous manoeuvres.

According to expert knowledge (interviews with eco-driving professionals), displaying the fuel use as an instantaneous variable can be difficult to interpret and can be misleading. Reaching a good level of fuel efficiency driving can be difficult as many parameters can impact. Displaying the fuel use, or the battery gauge, is not sufficient to help the drivers in understanding the dynamic relationship between driving actions and fuel efficiency: Sometimes, it is interesting to keep accelerating in order to reach a more efficient engine operating state. As most of the people want to keep ecological driving assistance systems (EDAS) simple (See for example Young Birrel Stanton "Design for Smart Driving: A Tale of Two Interfaces", (Young et al., 2009)), we believe that a global indicator, merging different driving parameters can be more efficient than fuel consumption.

Psychological theory strongly confirms that unless the individual can see or feel the results of their actions - preferably on an immediate and continuous basis - that individual is unlikely to maintain the behaviour over time (Huang et al., 2005). Feedback about the effectiveness of an individual's behaviour has long been recognized as essential for learning and motivation. There is a need for feedback related to driving performance such as eco-driving to be delivered to the driver in order to facilitate change or improvement. Both concurrent and retrospective feedback types have been found to help drivers to improve their performance (Donmez, Boyle, & Lee, 2008), and have been adopted by different car manufacturers. Feedback could give fuel saving a competitive game-like aspect, making the goal more challenging and more involving (Barkenbus, 2010). Research has indicated that drivers welcome feedback devices in their vehicles, and alter their driving habits as a consequence (Kurani, 2007). Particular care should be given to the design of the feedback mechanism to avoid driver distraction (Donmez et al., 2008).

Drivers do not simply react to their immediate environment, but are involved in complex forethought and decision-making. A substantial body of converging evidence shows that perceived self-efficacy significantly influences human self development, adaptation and change (Bandura, 1997). Self-efficacy is a social cognitive theory in which perceived self-efficacy is a major determinant of intention. A decision based on misjudgements of driving capabilities could produce detrimental consequences; and proper appraisal of one's own efficacy has considerable value. There is no all-purpose measure of perceived self-efficacy (Bandura, 1997) so there is a need to use self-efficacy theory to assess driver's judgement of capability to perform Eco-driving tasks by developing a new questionnaire tailored to the Eco-driving. In order to have a lasting behavioural changes, drivers need to *(i)* feel capable of adopting Eco-driving behaviour and *(ii)* be convinced that such behaviour will effectively reduce their consumption and emission.

RESEARCH NEEDS

As for road safety, there are still cultural, technical, and educational barriers inhibiting the adoption of eco-driving practices. A US survey showed that people mistakenly believe that fuel consumption decreases linearly rather than nonlinearly as a vehicle's gas mileage (Larrick & Soll, 2008). It has been shown that efficiency improving actions (e.g. installing more efficient appliances) generally save more energy than curtailing the use of inefficient equipment (e.g driving less, turning off lights) (Gardner & Stern, 2008). However, household perception of the most effective strategy that they could implement to conserve energy is the complete opposite (Attari et al., 2010). This suggests that caution is required in designing interventions related to energy savings such as eco-driving.

Given the worldwide popularity of Eco-driving instructions, it is of the utmost importance to not only assess the real changes in terms of fuel consumption and travel time, but also on emissions and safety. The joint consideration of optimal benefits for road safety and vehicle emissions is an area that merits further research because benefits to both issues are highly desirable (Carslaw et al., 2010). Specifically, there is a need to conduct research in which safety, fuel economy and emissions are jointly modelled and assessed and conveyed to the driver.

Ecological Driving Assistance Systems (EDAS) will become a standard part of future driving assistance systems. The heterogeneity of vehicles, the complexity of the driving task and variability of driving style will require simple advices through the use of aggregated indicators to safety and ecology. Furthermore, interventions focusing on continuous self-assessment and self-learning are more likely to be adopted by drivers. Such in depth study will help road transport stakeholders to identify and promote interventions to improve the likelihood of adopting Eco-driving behaviour

CONCLUSION

Pascala and Socolow (2004) demonstrated that increasing energy efficiency and curtailing activities that consume energy may be our cheapest options for stabilizing CO_2 concentrations below a doubling of preindustrial concentrations. Eco-driving provides one such strategy.

Most of the methods used to assess the benefits of eco-driving lack scientific rigour and have methodological shortcomings (e.g no control groups). They do not explicitly address the safety implications and have not provided sufficient attention to the human factors aspects such as acceptability of the intervention and willingness to adopt it.

There is an alarming lack of Eco-driving experiments, knowledge and data worldwide. Yet the potential economic and environmental benefits are large. The Swedish National Roads Administration estimate that 1 kg of CO_2 costs between 0.1 to 0.3 Euro to society and that Eco-driving can reduce fuel consumption by 5 to 15%. Applying these estimates to the 12 million vehicles in Australia that consume approximately 30,000 million litres of fuel per year, leads to potential CO_2 savings valued at between $250 and $750 million per year and fuel savings of between $1,800 million and $5,400 million per year. This would reduce the pressure on world oil supplies. While the health benefits of improving fuel consumption, and the resulting lower emissions, are harder to determine, there is a growing consensus that they do exist. Improving safety also has financial and health benefits. Road trauma results in high economic and social costs, both in lost productivity and demands on the health system.

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Lithium ion Based Rechargeable Energy Storage System (RESS) Safety Performance Measurement in Automotive Applications Test Plan

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ABSTRACT

In response to the planned increased availability of Li-ion based electrically propelled vehicles, NHTSA has initiated a safety research program. This programs' plan will assess the safety risks associable to Li-ion based rechargeable energy storage systems (RESS) during all operating conditions. NHTSA's plan is to analyze failure modes through a failure modes and effects analysis (FMEA), develop repeatable test procedures and safety metrics to measure effect of the failure modes, and analyze the performance characteristics of an effective RESS control system.

INTRODUCTION

The RESS is a completely functional energy storage system consisting of the battery pack(s), and necessary ancillary subsystems for physical support and enclosure, thermal management, and control, including electronic control. The automotive application and use of a RESS, such as a Lithium-ion battery based system, imposes certain theoretical safety risks to the operators and occupants of these vehicles because it is inherently different compared to that of vehicles using only an internal combustion engine. None of the safety risks associated with lithium-ion batteries have been demonstrated in the field since these batteries have had very limited field exposure to date. Hence all safety risks for these systems must be considered as theoretical or potential risks. Among the most severe potential safety risks are the failure modes which result in "thermal runaway" of an affected cell(s) or battery pack(s) which in some cases may result in potentially toxic effluent gas venting, fire, or explosion. These potential safety risks can be associated to the responses of undesired or unexpected abuse mechanisms during both normal and abnormal operating conditions. These abuse mechanisms originate in mechanical (i.e., shock, vibration, crush, penetration, or immersion), thermal (i.e., radiant heat, extreme ambient, or thermal shock), or electrical (i.e., short circuit, over-charge, or undercharge) conditions and/or environments.

These conditions may arise as a result of failure of specific RESS control and support hardware, operator negligence, vehicle traffic accidents, device or system defects, poorly informed or trained users or repair technicians, or transportation handling incidents. These potential safety risks may be observed in many operational modes and conditions including: storage, charging, normal vehicle operation, vehicle crash, and/or post crash conditions.

BACKGROUND

Due to significant advancements in Rechargeable Energy Storage Systems (RESS) the viability of electrically powered propulsion for use in passenger vehicles, light trucks, and multipurpose vehicles in the automotive industry have greatly improved. The automotive applications of Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), and Electric Vehicle (EV) propulsion systems represents a measureable and growing technology segment necessary for achieving increased demand for improved fuel economy, reduced green house gas emissions, and reduced dependence on foreign oil.

The U.S. Department of Energy (DOE) has been actively involved with battery, module, and cell characterization and performance testing through efforts with Sandia National Laboratories (SNL) and the Idaho National Engineering and Environmental Laboratory (INEEL) since 1973. In July 1999 SNL published the *Sandia National Laboratories Electrochemical Storage System Abuse Test Procedure Manual* [1]. The procedures in the manual were developed to characterize the performance of a RESS relative to the U.S. Advanced Battery Consortium (USABC) long-term battery requirements. The test procedure manual describes three levels of testing, low-level or common events where the RESS is expected to remain intact, mid-level tests were the RESS may become inoperative but not expose any known health risks, and high-level tests which result in destructive situations. The test procedures described in the report are intended to simulate actual use and abuse conditions (mechanical, electrical, and thermal) and internally initiated failures that may be experienced in a RESS. These tests were derived from Failure Modes and Effects Analysis (FMEA), user input, and historical abuse testing. Test procedure parameters were developed and are described in the general information of the SNL manual. Among these parameters, the SNL manual describes that the RESS test article shall be in fully charged state, at normal operating temperature, with cooling media in place, and with thermal control systems running, unless specified otherwise. These and other conditions and permutations including system age and level of assembly are based are based on the most susceptible condition of the technology.

In 1999 The Society of Automotive Engineers (SAE) published SAE J2464 *Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing* (revised 2009) [2] which adopted test procedures from the *Sandia National Laboratories Electrochemical Storage System Abuse Test Procedure Manual* as a basis for a body of tests which may be useful for abuse testing of electric or hybrid electric vehicle batteries to determine the response of such batteries to conditions or events which are beyond their normal operating range. However, neither SAE J 2464 nor the SNL Electrochemical Storage System Abuse Test Procedure Manual had intent of addressing performance acceptance criteria.

In February, 2011 SAE published SAE J2929 *Electric and Hybrid Electric Propulsion Battery System Safety Standard – Lithium Based Rechargeable Cells* [3] which describes performance criteria for some of the tests described in SAE J2464. These test procedure manuals and standards developed and published by SNL and SAE will serve as a foundation for consideration by NHTSA in developing performance based test procedures, safety metrics, and acceptance criteria.

SCOPE

The scope of the NHTSA RESS safety research program is to develop safety test methods and performance base safety-metrics to measure and compare Li-ion based RESS technologies. The program will include identifying and documenting appropriate test conditions, boundary limitations, and performance criteria that can be applied to vehicle level testing when possible, component level when necessary, or both. The RESS configurations in this program will be inclusive of and limited to presently identified Li-ion based RESS and foreseeable advanced electrical energy storage devices or battery technologies, to be utilized in a HEV, PHEV, or EV application on a passenger car, light truck, or multipurpose vehicle; while not unnecessarily limiting them to an individual or unique chemistry composition, cell format or construction, or cell arrangement. Utilizing test procedure and RESS development experience, the NHTSA safety research intends to develop and demonstrate meaningful, comparable, and quantitative evaluations that will link test procedures to failure modes associated with component failure, control system failure and/or induced faults from potential abuse mechanisms or conditions.

RESEARCH PLAN

For purposes of providing the most comprehensive research approach, NHTSA vehicle safety research will initiate three independent research projects.

1) An Analytical Approach (FMECA)
A Failure Modes and Effects Analysis (FMEA), is a bottom up analytical process, typically used in product development, of potential failure modes within a functional system for classification by the severity and likelihood of the failures. A successful FMEA activity helps to identify potential failure modes based on past experience with similar products or processes. A Failure Modes, Effects, and Criticality Analysis (FMECA) builds on the FMEA by including a criticality analysis, which is used to chart the probability of failure modes against the severity of their consequences. The result highlights failure modes with relatively high probability and severity of consequences, allowing remedial effort to be directed where it will produce the greatest value. This FMECA will be published as a standalone document and be used as a foundation for the analytical control system study.

2) Develop physical test procedures.
This NHTSA RESS safety research program is to develop and document repeatable vehicle level safety performance tests procedures with accurate boundary and/or test limit conditions for the battery pack (component level) and/or vehicle in which the testing should be conducted. In addition, detailed quantifiable measurement, performance criteria, and safety-metrics must be developed and documented. These test procedures may be used by NHTSA to objectively measure and compare safety performance of a RESS equipped vehicle or component system in their analysis.

The safety performance tests and methods shall address potential failure modes associated with RESS component failure, control system failure, and/or reaction to potential normal and abnormal thermal, mechanical, or electrical abuse conditions and their associated limitations. Failure modes such as thermal ramp up or thermal runaway of the battery cells, modules, pack(s), that could result in potentially toxic or harmful effluent venting into a vehicle passenger compartment, fire, or explosion will be examined. The research will consider all functional modes of operation including charging, storage, normal operation, and abnormal operation such as crash and post crash events. When possible, these methods will be considered at vehicle level but component level test methods will be considered when necessary.

The first phase of this research will focus on single point failure modes based on mechanical, electrical, and thermal abuse mechanisms potentially experienced by the RESS during normal and abnormal operating conditions described in but not limited to SAE J2464, and SAE J2929.

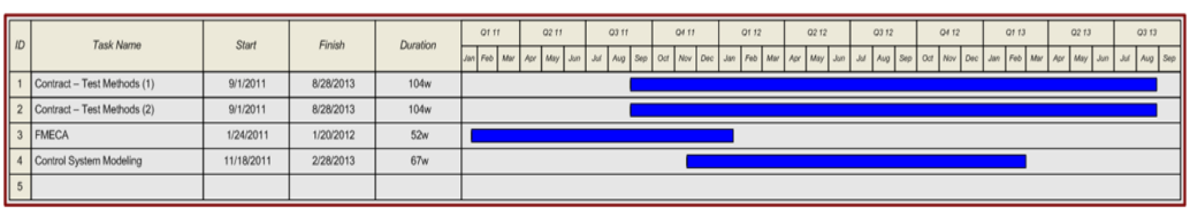
The second phase will focus on multiple point failure modes in which one of the failure modes is identified as loss of control or loss of function of the active portion of the control system, and the second mode as one described in but not limited to those described in SAE J2464, or SAE J2929. During both phases of this research, the resultant response of an individual cell to many of the imposed abuse mechanisms or failure modes is generally assumed to be that of thermal runaway. Since the cells or modules are a part of a greater RESS and/or entire vehicle subsystem, in both phases of test development, a comprehensive layered safety approach will be evaluated. The first priority is to quantify the effect of the failure as a function of safety to the vehicle occupants, second to measure the RESS system effectiveness at containing the failure to the enclosure and the quantified effect of the failure mode with respect to adjoining cells and physical surroundings in the form of thermal and/or mechanical propagation and the measured effect to the entire vehicle system.

3) Analytical Tools and Control System Modeling

Using the analytical results from the FMECA combined with those from a Fault Tree Analysis (FTA), a generic high level analytical tool utilizing control models will be developed for each of the configurations (HEV, PHEV, and EV). The use of this analytical model tool will be to define potential minimal control system performance requirements in terms of redundancy and passive protection for each of the major failure modes. Second, the model will be researched for use as a tool for functional comparison to an OEM control system in the event of field failures.

RESEARCH PLAN (TIMELINE)

NHTSA plans to award two contracts to begin the research this year and complete it during 2013. NHTSA has awarded the FMECA in January 2011 with a projected 12 month completion date. The control system model, which is heavily reliant on the FMECA, is projected to begin in the first quarter of the 2012 fiscal year.



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