EVERSAFE

Everyday Safety for Electric Vehicles

Recommendations for New Safety Requirements and Research

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EXECUTIVE SUMMARY

The main objective of EVERSAFE is to facilitate integration of electrical vehicles (EVs) into European vehicle traffic. The performance and control characteristics of electric machines also offer more opportunities for vehicle designs and systems that benefit segments of the population, an example being semi-automated vehicles that provide mobility to an aging population. There are many opportunities for a strong market value of European vehicle manufacturers that can be exported worldwide.

Customer acceptance increases when EV safety is guaranteed for normal operation or an accident. The consequences of a negative image for EVs are considerable and will limit the development and penetration of a new vehicle type that can have financial, environmental, and social benefits for Europe. The EVERSAFE project had three main areas of research to ensure a robust market for EVs:

1. The perceptions of electric vehicles from a user point of view
2. Investigations of vehicle safety encompassing both active and passive vehicle safety implications that are part of the vehicle's design
3. Developing guidelines and recommendations for post-crash handling of electric vehicles that are not addressed in the practice for conventional (internal combustion) drivelines

The research plan was developed to identify the most high risk scenarios, investigate their potential consequences, and identify any corrective actions in terms of further research, industry standards, or government regulations.

The project used focus groups of consumers to identify perceived issues as well as expert judgement to identify specific research cases. Building on accident analysis, critical load cases for investigation for both active and passive safety were identified. Lateral and longitudinal load conditions for the vehicle were identified. For active safety the longitudinal case of interest was regenerative braking and yaw stability due to wheel hub motor failure on one wheel was the lateral case. Passive safety research was focused on pole side impacts for the lateral load case and rear end crashes for the longitudinal case. Post-crash handling of vehicles with electric drive trains was also identified as an area for investigation.

The main findings of the active safety investigations suggested that the potential failures for regenerative braking and wheel hub motors could be compensated by the drivers. Volunteer drivers participated in controlled studies in a driving simulator and a modified vehicle. For the investigated controlled cases there were no major safety issues identified, however the cases were not in real traffic and did not present complex traffic threats.

Passive safety investigations used component tests of battery cells, full scale crash tests, and numerical simulations to study the risks during a crash. The tested cells and vehicle crash tests demonstrated good safety levels. The simulations and component tests were useful to identify that the main risk for vehicles is crushing the battery pack and battery modules.

The safe handling of electric vehicles after a crash requires updates to the conventional rescue operations. The main issue is to identify when an electric vehicle is involved in a crash and to ensure the high voltage system is disconnected and preferably neutralized.

Suggestions for new research, standards, and regulations were developed in the following tables.

Table 1: Recommended Actions for Longitudinal Braking Issues

EVERSAFE results – RB failure field study	Regulation	Standard	Further research
Effects of different driver workload levels (e.g., traffic, mobile phone use) on the subjective ratings of the driver and driver reactions			X
Effects in case of a stronger RB deceleration			X
Effect of RB failure in other maneuvers			X
Inform driver about RB failure	May produce amendments to R13-H	X	X

Table 2: Recommended Actions for Battery Crash Protection

EVERSAFE results	Regulation	Standard	Further research
Improved cell level models to understand cell deformations during crash events, expand to all cell geometries			X
Investigate direct loading of battery pack during crash events		Check test procedures for their representativeness with respect to traffic crashes, e.g. wider penetration impactor	X
Study influence of stiff battery structures on vehicle acceleration pulses			X
Identify acceleration limits (pulse and duration) for battery packs	Potential regulation if third party battery packs should be tested independent of vehicle	Potential Standard	X

Table 3: Recommended Actions for Post-Crash Handling

EVERSAFE results	Regulation	Standard	Further research
Develop better e-Call protocol to include vehicle fuel type identification and battery health status (temperature, fault diagnostics)		X	
Include measurement of toxic / flammable gases in addition to liquid electrolyte in crash tests (R94, R95)	X		
Develop standardized identification and location of service/rescue disconnects for traction (high voltage) power system		X	
Develop effective methods to neutralize battery after a crash			X
Decrease the required disconnection of the traction battery circuit in R94, R95 from 60 s to less than 3s.	X		
Check viability of handling procedures for rescue teams approaching severely damaged electric vehicles			X
Compare and harmonise legal requirements for functional, crash safety, and transport of batteries	X		

The results of the EVERSAFE project indicate that the general level of EV safety is quite high and that no critical safety issues have been identified. There are areas where the industry should develop universal standards to improve the driver interaction with the new EV systems and minimise the risk of crashes due to inappropriate driver expectations. When a crash with an EV occurs there appears to be little chance for fire or the emission of toxic substances, but there needs to be more work to assist the firefighters in identifying EVs, disconnecting electrical systems, and possibly neutralizing batteries after a crash.

Improving safety for the road user is an ongoing process and EVERSAFE has recommendations to further improve the good level of safety of the existing vehicle fleet. The results of EVERSAFE indicate that current and potential owners of vehicles with electric drivetrains should not consider these vehicles as less safe than vehicles with conventional (internal combustion) drivetrains.

LIST OF ABBREVIATIONS

BEV	Battery-Electric Vehicle
ESS	Energy Storage System
EV	Electric Vehicle
FEV	Fuel-Cell Vehicle
HEV	Hybrid Electric Vehicle
ISO	International Organization for Standardization
NHTSA	National Highway Transportation Safety Administration
ODB	Offset Deformable Barrier
RB	Regenerative Braking
UN-ECE	United Nations – Economic Commission for Europe
WHM	Wheel Hub Motor

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1. INTRODUCTION

The main objective of the EVERSAFE project was to facilitate integration of electrical vehicles (EVs) into European vehicle traffic. The basic prerequisite for successful product integration is gaining customer acceptance which involves a brand identity with appropriate features for the targeted markets. Partially (hybrid) and fully electric vehicles already produce fewer tailpipe emissions and can directly improve air quality in urban centres. The performance and control characteristics of electric machines also offer more opportunities for vehicle designs and systems that benefit segments of the population, an example being semi-automated vehicles that provide mobility to an aging population. The previous examples are only a few opportunities for the strong market value of European vehicle manufacturers that can be exported worldwide.

Customer acceptance increases when EV safety is guaranteed for normal operation or an accident. The consequences of a negative image for EVs are considerable and will limit the development and penetration of a new vehicle type that can have financial, environmental, and social benefits for Europe. To reduce the risk of negative customer perceptions, the project had three main areas of research:

1. Identify the perceptions of electric vehicles from a user point of view
2. Investigate vehicle safety encompassing both active and passive vehicle safety implications that are part of the vehicle's design
3. Develop guidelines and recommendations for post-crash handling of electric vehicles that are not addressed in current practice for conventional (internal combustion) drivelines

The research plan was developed to identify the most high risk scenarios, investigate their potential consequences, and identify any corrective actions in terms of further research, industry standards, or government regulations. It has to be noted that type approval of electric vehicles in series production must fulfil equivalent legal requirements regarding their operations, system functions, and crash safety as demanded for conventional powered vehicles, plus specific requirements towards the on-board high-voltage system. Therefore EVERSAFE was tasked to identify if existing regulations suitably address the new components introduced by electric drivetrains.

2. IDENTIFICATION OF CONSUMER ISSUES AND REAL WORLD SAFETY RISKS

2.1 Introduction

The research plan for EVERSAFE was developed with two entry points. The first was the existing expertise in vehicle and traffic safety within the consortium. This allowed the group to use its collective knowledge to identify key areas that needed to be investigated. The second point was the feedback from the road user that is not an expert in the area. Both of these approaches were needed to establish areas of research that were relevant for short term investigation yet capturing the points raised by end users that may be overlooked by the expert.

The group initiated the project with a scanning of the literature and review (focus groups) of consumer issues. These were refined and lead to specific research activities in the active and passive safety parts of the project. Post-crash handling of batteries is an area attracting media attention and was known to be an area of concern for rescue services. These research questions were combined with the passive safety research activities as these were the closely related in terms of the research approaches and issues involved.

2.2 Focus Group Contributions to Research Activities

The results of conducted focus groups provided a taxonomy of user concerns that defined scenarios depending on the role of the individual (Figure 1) [1]. The users who participated in the focus groups were either drivers with no experience or drivers with daily experience driving EVs. The taxonomy developed in these investigations helped clarifying the research direction under EVERSAFE. The active safety team in the project (WP 2) used the “While driving” scenario and the passive safety group (WP 3) used the “In case of accident” scenario to direct their research tasks.

The active safety group had to consider several issues listed in Figure 1 but the main points that directly affected vehicle stability and jeopardized traffic safety (during normal driving conditions) were related to regenerative braking and wheel hub motor failures. Other road users (pedestrians, cyclists, etc.) essentially identified low noise as a safety issue. The latter issue was not addressed in EVERSAFE but is part of parallel activities internationally.

In the passive safety group the battery was the main unique safety issue identified in Figure 1. It is interesting that both the vehicle occupants and other road users groups expressed concerns for the release of battery chemicals. It was not expected that non-experts would be aware of the chemicals and potential for hazardous substance release. The consequences of large batteries for the rescue teams were also stated as a concern. The lack of handling procedures for firemen was a surprising comment from the focus group. Again, non-experts were not expected to be aware of firefighting techniques. This may have been related to the timing of different battery related incidents reported in the media (Chevrolet Volt, Boeing Dreamliner, laptop fires).

The results of the focus groups were one input to the scenario definition workshop held at the beginning of the project.

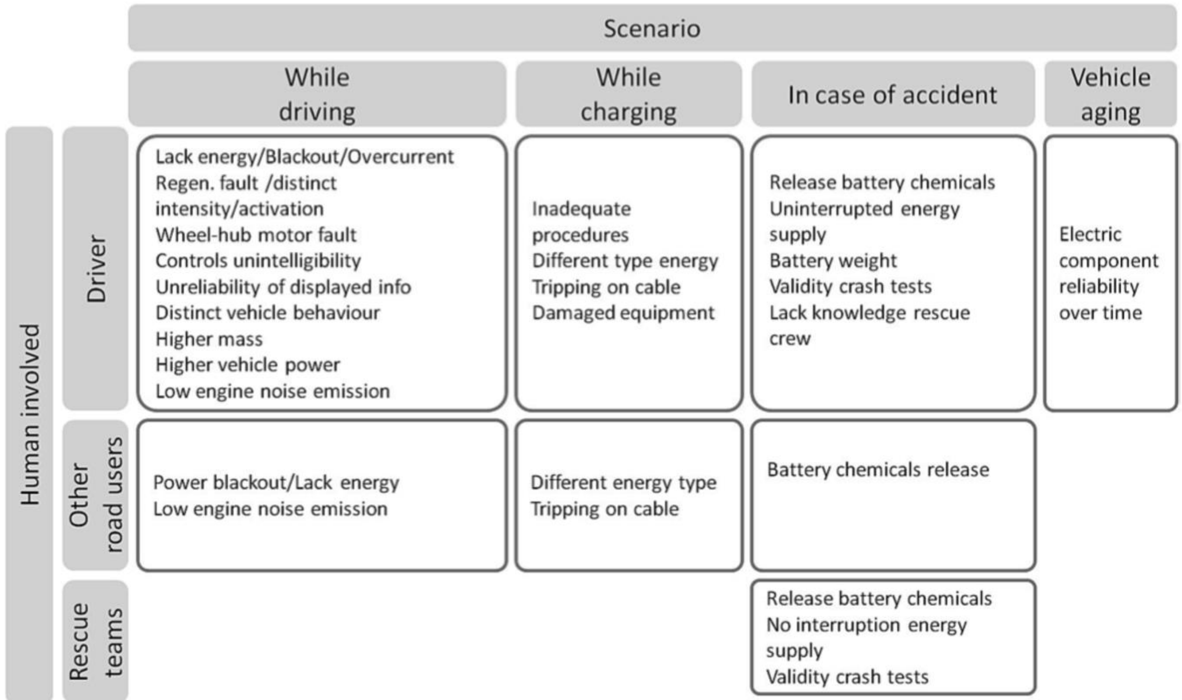

Figure 1: Taxonomy of User Concerns [1]

2.3 Accident Research

The penetration of electric vehicles in the vehicle fleet is still low and this is reflected in the analysis of vehicle crashes based on national data sources such as police reports. The most relevant report describing electric vehicles was that provided by Daimler [2]. Although electric vehicles could not be directly analysed, they used conventional vehicles as a surrogate and identified deformation maps (for vehicle structures) that could identify the most safe areas for battery placement based on deformation from real crashes as well as deformations from standard crash tests (Figure 2). This assumes that electric vehicles will tend to operate in a similar manner as existing vehicles in the road system thus the accident configurations most commonly observed should also be relevant for the near future. A study by NHTSA [3] and Japanese statistics [4] show that the most common accident types (not necessarily the most severe) are rear end and intersection collisions.

The frequency and severity of accidents are not easy to precisely define for EVs with the data described or with other data sources. However, the areas of concern for existing safety systems, available regulations, and predicted safety trends were used to refine the research activities for EVERSAFE and are divided into the active and passive safety activities described below.

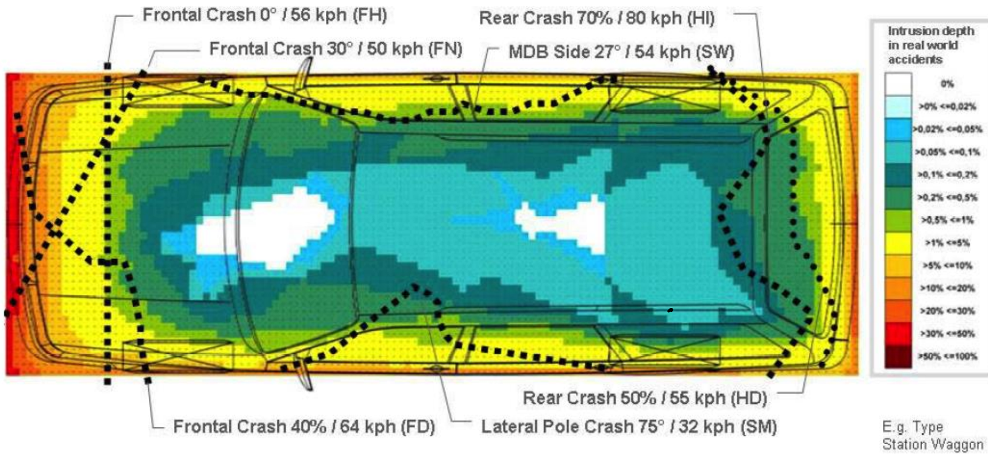

Figure 2: Deformation patterns for conventional vehicle [2]

2.4 Strategy for EVERSAFE Research

The experts reviewed the state-of-the-art at the beginning of the project, including previous accident research. It was known that the most violent collisions, in terms of acceleration, tend to be longitudinal (front or rear) impacts while the most deformation to structures likely to house a battery are lateral (side) impacts. The causes of these accidents are not easily characterised but longitudinal and lateral control of the vehicle is an important part of active safety design.

For the active safety research team the scenarios were refined and can be described as:

Longitudinal Scenarios: A key issue for longitudinal accidents are the regenerative braking issues and these must be reproduced in a physical vehicle to get the best environment for valid driver behaviour and response, particularly for the longer braking events at low “g” levels that cannot be recreated authentically in a driving simulator. For safety and ethical reasons, the tests must be done outside of real traffic.

YAW (or lateral) Scenarios: The scenarios for vehicle stability focused on the wheel hub motor failures even if there are no production vehicles with this technology. Simulations were used to recreate the scenarios and conduct human volunteer tests. Physical tests with a modified vehicle on a closed test track were conducted. The methodology was primarily driver in-the-loop simulations driving simulator and a test vehicle.

The passive safety group within EVERSAFE had front and rear impacts for the longitudinal case and side or intersection accidents for the lateral scenario. The approach was to begin with simulations of different accident scenarios and load case studies should be conducted to investigate intrusion and acceleration levels expected for the vehicle.

Longitudinal Scenarios: Frontal impacts are an active area of investigation in other projects and unnecessary for EVERSAFE to focus in depth studies. Rear impacts are essentially the most critical condition for analysis since the legal requirements are quite limited for this crash type if the legislation in

Europe is considered [5]. There is the potential that vehicles without a “fuel tank” will not be required to demonstrate crashworthiness protection of a battery structure with physical tests currently required by convention fuel vehicles as specified in UNECE Regulation 34 for fire protection.

Lateral Scenarios: Impacts to the vehicle side, particularly involving poles, are important for understand in terms of potential deformation or intrusions into the battery structures. There is some test data available and ongoing data available from EuroNCAP. There are standards for legal and consumer tests for side impact but with limited variation of parameters. It would be important to conduct further simulation activities investigating the sensitive parameters for electric vehicles in pole impacts. The types and severity of angled car-car side impacts are also relevant for analysis and part of the car-car crash simulation activities.

Summaries of the research findings are divided into the vehicle safety themes (active and passive safety) as well as post-crash handling and presented in the following chapters.

3. OVERVIEW OF ACTIVITIES AND RESULTS OF ACTIVE SAFETY

The full documentation of the research activities related to active safety is provided in the EVERSAFE Deliverable 2.1 [6]. This report describes full scale tests with a modified test vehicle and a driving simulator study of the defined driving and safety critical scenarios for EVERSAFE.

3.1 Longitudinal scenario: Regenerative Braking Failure

Longitudinal driving was the focus of tests with regenerative brake (RB) failures. The drivers drove the vehicle in normal traffic before the experiment to be trained in the use of regenerative braking in the context of "eco-driving". They were instructed to drive in a manner that would create the expectation of moderate vehicle deceleration developed from the electric motor working as a generator. The experiment was then conducted with simulated regenerative braking failures. The participants were driving in an oval course, (closed from traffic) that required the RB to control the vehicle speed before entering and while driving in the curve. To investigate the effect of driver knowledge, half of the participants were warned that they will experience an RB failure during the test.

The regenerative braking failure field tests revealed that only half of the subjects noticed the failure, but compensation efforts for all drivers were sufficient to avoid a potential accident. Although the situation was rated as more risky than solely driving on a road, the RB failure did not induce more stress or workload in the drivers. Informing people about an upcoming failure produced a higher frequency of mild braking manoeuvres. Road and traffic conditions can influence the perception of this failure and highly influence the behavior of the driver. This will most likely influence the driver's perception of the situation and have consequences on their maneuvering actions. The regenerative braking tests need to be further investigated as the test condition on the closed-off test area was artificial and did not reflect traffic conditions where other road users or extreme driving conditions (weather, traffic congestion) may present additional conflicts if RB does not operate as expected.

Brake performance of European vehicles is addressed in UNECE R13-H (Uniform provisions concerning the approval of passenger cars with regard to braking). This specifies the braking requirements, user inputs, and light activation for vehicles for a given set of initial driving speeds. It is important to note that the regulation requires the driver to be warned (through an indicator) when the brake system is experiencing a component failure. The test program for type approval also includes the simulation of different sub-system failures. This regulation should be reviewed for criteria for RB actuations, braking level, and warnings to the driver when RB malfunction occurs.

Research prior to EVERSAFE identified that regenerative braking strategies are important to consider [7]. The manner in which regenerative braking occurs (i.e. when the throttle is released or if the brake pedal is pressed) should be standardised or regulated for all vehicles so that driver expectations are fulfilled independently of vehicle make and model and create no false expectations when switching between cars with different drive trains. In terms of braking performance, many vehicles have user selected settings for regenerative braking and there must be consideration for the range of decelerations possible with the system to avoid misapplication when changing vehicles. Similarly the connection of brake lights to regenerative braking can be considered when regenerative braking levels are defined. Current vehicles are only required to activate rear brake lights when the vehicle is braking at greater than 1.3 m/s^2 and not activate the brake lights under 0.7 m/s^2. The interval of optional activation should be benchmarked with different regenerative braking systems to ensure there are no conflicts for following traffic that is unprepared for a slowing vehicle without tail lights.

3.2 Lateral (Yaw) Scenario

Yaw instability was introduced by partially braking one rear wheel in cornering and straight driving situations (simulation of wheel hub motor failures). The yaw scenarios were investigated in low speed (30 km/h on the test track) and high speed (110 km/h in the driving simulator) conditions.

Three different failure conditions were tested in the field as well as in the simulator test resulting in driving situations where the induced yaw to the vehicle caused a rotation inwards (towards the road centreline) or outwards (towards the roadside). Failures were simulated in straight and cornering conditions. In combination of the driving manoeuvre and the failure location, the following three failure types were tested:

1. WHM failure on the left rear side during straight line driving (straight inward),
2. WHM failure on the left rear wheel during a left curve (curve inward) and
3. WHM failure on the right rear wheel during a left curve (curve outward).

It can be concluded from the outcomes of the simulator study, that wheel hub motor at speeds of 110 km/h are rated more stressful, risky, disturbing and demanding than simply driving without a failure and the curve inward failures are rated the most severe, possibly due to the risk of collision with an oncoming cars. The simulator study showed that steering is the principal reaction to all types of failures. The usage of the brake pedal was neglected, which might be due to the deceleration caused by the failure itself.

In contrast to the simulator study, which was implemented at higher vehicle speeds, no significant differences between baseline and failure condition were found for curve failures regarding subjective evaluation for the field study. Only for the straight inward failure, subjects perceived the driving situation significantly more demanding, stressful, risky and less controllable than in the baseline condition. Comparing the subjective evaluations from the simulator and the field study, it can be assumed that failures are perceived as more severe at higher speeds compared to lower ones. Furthermore, the subjective evaluation of the different failure types was more differentiated at higher speeds.

Regarding the results of analysis performed on the objective data collected during the field study, it appeared that in contrast to the simulator study, participants did not steer due to straight inward and curve outward failure. Participants in both studies used the accelerator pedal during failure activation, regardless of failure type, and it could be concluded that drivers try to overrule the failure triggered deceleration at low and high speeds. Whether this was an effect of the instruction to maintain a steady speed during the experiment should be clarified by further research. The accelerator pedal reaction time had a shorter reaction time in the field study. This could be caused by the higher workload during fast driving manoeuvres on motorways, but also by the differences of the simulator and test track experiment settings. For instance, longitudinal accelerations and other driving manoeuvres in the driving simulator may not be perceived to the same extent as in a real vehicle.

Yaw instability caused by a system failure should be compensated by the use of an electronic stability control system (ESC). These systems are now required in vehicles type approved for Europe after 2011 as specified in Regulation 13-H. As the failures introduced in the studies above did not include the effect of

ESC, the actual response of a modern vehicle under the tested conditions could be less severe than that found in the tests and the driver should have less trouble compensating to sudden braking action applied to one wheel. At the same time, there is no evidence that an ESC system will function when system faults occur. A further understanding of the interaction between ESC and electric drivetrains is warranted.

3.3 Summary

The global observation in the active safety research conducted within EVERSAFE was that the drivers were able to maintain control of the vehicle in all tested conditions. The drivers responded that the vehicle was controllable in all cases and an evaluation of perceived stress [8] did not report any event as uncontrollable or stressful enough to rate beyond “Disturbing” and reach “Dangerous”. This result can be partly due to the limitations of test and driving simulator conditions but all the objective and subjective data suggests that drivers can be expected to compensate for the foreseeable failure, particularly for wheel hub motor failures that will introduce yaw moments to the vehicle. Future research should address situations with higher workload (e.g., including other road users, varying road conditions).

4. OVERVIEW OF ACTIVITIES AND RESULTS OF PASSIVE SAFETY

The research approach in the passive safety group (WP3) of EVERSAFE was similar in WP2 in that there were investigations of both longitudinal and lateral load cases for the whole vehicle response. There was additional general mechanical and chemical investigations of battery performance that are independent of the load cases but necessary to understand battery performance in any crash. A comprehensive simulation series was developed to investigate both cell level and vehicle level response and determine scenarios not predicted by the expert judgment used in the initial scenario development. Finally, there was a study of the post-crash handling of EVs to determine if current rescue services are suitably equipped for crashes with EVs in terms of training and equipment. Full documentation of the passive safety and post-crash handling work program are available in D3.1 [9]

4.1 Battery Cell Tests

The cells tested in EVERSAFE were pouch cells and a series of nail penetration, shear, overcharging, and external short circuit tests were conducted. The tests covered existing standard cell tests procedures (nail penetration) as well as non-standard test conditions. The goal was to understand cell deformations induced by possible crash induced vehicle deformations. The short circuit case can be considered as a case when pack or module deformations compromise the electric wiring. The overcharge case is not reflective of crash conditions but provided information on thermal response and chemical releases.

In general the tested pouch cells were quite resistant to the abuse. Only 1 of the mechanically tested cells resulted in a thermal event. The only other case where thermal runaway was observed was in the overcharge case. A special area of concern is the reproducibility and the robustness of these tests, as the results might differ depending on the testing conditions. The most sensitive test conditions were those where the cell experienced crush. Swelling of the cell and thermal activity were observed and temperatures up to 300° C were recorded. Otherwise no serious chemical or thermal response (<60° C) was observed for the other mechanical tests. Simulations and full car crash results showed that some current cell abuse tests, e.g. SAE J2464, might not be representative of what may happen in a vehicle crash as the intruding object would probably be wider as a thin nail, the load case prescribed in the existing standards.

None of the cell level tests involved accelerations. Current battery acceleration requirements are governed by the UN regulations for transport and do not cover the acceleration magnitudes and frequencies arising in a crash. For homologation in Europe, electric vehicles need to fulfil crash requirements on vehicle level according to UNECE-R94 and UNECE-R95. Although not conducted in EVERSAFE, there is a need to identify acceleration damage thresholds for batteries to ensure future component testing of batteries is consistent with real world conditions or those encountered in regulated crash tests.

4.2 Vehicle and Battery Simulations

Two levels of vehicle simulations were undertaken in the project where both a detailed battery cell model was developed and a first generation EV was created from an existing vehicle model. The battery cell model was used to understand how the different cell structures deform when loaded. Using this model it was possible to understand how the ductility of the plastic separators and pouch enclosure was able to electrically isolate the battery poles. The plastic ductility was able to explain how the tests with shearing or point penetration of the pouch cell did not lead to short circuit conditions and resulting thermal issues.

Whole vehicle simulation of the tunnel based vehicle model provided insight to the distribution of loads within the battery structures distributed in the car. The model did not represent an existing vehicle but was useful for investigating the relative loading arising from different impact scenarios. The most severe loading conditions for this specific concept were a frontal pole impact and an undercarriage impact. Any serious outcome of the frontal pole impact event could be attributed to the non-optimized front design of the modified vehicle. The original conventional drivetrain was removed and the new design provided an opening for direct loading of the battery pack. A main finding of the simulations was that vehicle crash structures should be designed to always avoid punching (direct loading) or penetrating the high-voltage battery modules.

4.3 Lateral (Side Impact) Scenario

The accident and compatibility analysis indicated that side impacts with a pole would be the one of the worst case test conditions. A Mitsubishi iMiEV (first generation EV) was subjected to a non-standardised pole side impact but equivalent to the energy release in a Euro NCAP pole impact test. A trolley with a rigid pole was used to strike the co-driver side of the iMiEV. The test speed was 35 km/h and the trolley mass was 2,051 kg compared to the 1,123 kg iMiEV. The impact location was chosen as the most vulnerable for the vehicle due to battery placement and surrounding protection.

The impact caused minor damage to the battery casing but no damage was visually obvious in the battery tray after the crash. The high volt electric system outside of the propulsion battery was shut-down automatically starting around 0,2 seconds after crash and crossed the 60V DC threshold after 1,3 seconds which is much faster than the 60 s required in crash regulations such as UN-R95 for the side impact. The vehicle was monitored for several weeks after the test for unusual temperature changes. As a result of the undamaged battery housing, no emission of battery chemicals outside the car and inside the battery pack could be detected by the highly sensitive and selective mobile Fourier Transformation-Infrared Spectrometer (FT-IR) nor by the on-site handheld analytical devices provided by the fire brigades.

4.4 Longitudinal (Rear Impact) Scenario

A BMW i3 (second generation) EV was used to investigate the rear impact performance of EVs. The i3 is also a unique vehicle design with a composite body and metallic energy absorbing structures in the front and rear. The non-standardised test represented a potential high speed rear impact on the highway in a traffic jam situation. The i3 (1,303 kg) was struck from behind at 80 km/h with a 2 tonne trolley equipped with a deformable barrier face. The i3 was placed in neutral 2 m behind a parked truck and the impact resulted in a second impact between the front of the i3 and the rear of the truck. This extreme test condition (far beyond standard) allowed both front and rear impact performance of a modern EV to be investigated.

Similar to the i-MiEV, the i3 high volt electric system shut down much faster than required in UNECE crash regulations. The time required was under 1 second (however this was further accelerated by cut high-voltage wires). Also, the vehicle battery system was not at all compromised by mechanical intrusion and no thermal change was observed. Further, no release of gaseous toxic substances were detected by the hand held or FT-IR system suggesting that no occupant safety issues occurred from the battery systems. The composite body structures and stiff battery enclosure produces an extremely stiff vehicle structure and no intrusions were observed in the passenger compartment although vehicle accelerations were quite high (up to 50g).

5. POST-CRASH HANDLING

The EVERSAFE project reviewed the post-crash handling requirements for rescue services in Germany and Sweden with an additional investigation of US procedures. There was also a parallel project in Sweden in the “Räddningskedjan”[10] project that worked closely with Swedish rescue services to develop training information for electric vehicle handling after a crash.

Rescue services need to consider how electric vehicles influence the following steps (not necessarily chronological) when approaching any vehicle after a collision:

1) Information on the way to the scene
2) Appraisal of the vehicle on the scene, identification of vehicle
3) Securing/stabilizing the vehicle if required on scene
4) Fire and/or hazardous fluids control (fuel, battery electrolyte)
5) Shut down electrical systems (reduce fire risk, unintentional airbag deployment)
6) Occupant extraction
7) Hand-off to towing company

In steps 1) and 2) it is important to determine early on if the vehicle has electric propulsion and significant electrical storage capacity. It is important that electrical vehicles can be easily identified from conventional vehicles. When appraising the vehicle at the scene it is important to be aware of the critical impact conditions and which deformation/damage patterns need to be flagged as most hazardous. Systems and standards that assist in the identification of EVs, such as e-Call or dedicated markings, would assist rescue services to identify EVs.

Although not covered by testing or analysis in EVERSAFE, it is not expected that securing/stabilizing the vehicle is significantly different for electric and conventional vehicles. The main issue is that the main electrical shutoff should be accessed to confirm the high voltage system has been disconnected even if this should occur automatically for crashes producing damage to the vehicle. Electric shock protection is already required by existing safety requirements (UNECE Regulation R100, R94, R95).

Fire control with water is not dangerous [10]. The main issue that may arise is the increased potential for toxic substances even when thermal activity is not observed. Thus there may be a need to have portable gas detectors of common battery substances available to monitor a vehicle as well as monitors of battery temperature to identify the risk of imminent gas generation. It is important to have information of impending thermal activity or gas development. Vehicle diagnostic systems could assist in notifying rescue services. Neutralisation of a battery after the crash would eliminate these issues from developing.

Once the vehicle has been stabilised, then occupant extraction can proceed as normal, however the cutting and deformation of the vehicle should be closely monitored to avoid mechanically abusing the battery components, particularly if the battery has been damaged. Once the occupants are extracted, the disposal of the vehicle needs to follow the manufacturer’s handling guidelines and the vehicle structure should be stabilized to not induce further mechanical damage to the batteries.

6. RECOMMENDATIONS FOR NEW RESEARCH, STANDARDS, AND REGULATIONS

The results of EVERSAFE's research program were used to generate a list of recommendations for future research, industry standards, or government regulations. These three categories are in order of increasing impact where future research may not lead to direct changes to the vehicle fleet while government regulations have direct impact on vehicles sold. Industry standards are best practice guidelines and manufacturers are not obligated to apply all elements of all standards.

6.1 Active Safety Issues

6.1.1 Longitudinal Scenarios – Regenerative Braking Failures

The operating performance of EVs needs to be consistent with driver expectations and must be similar to other similar vehicles. Internal combustion vehicles have engine braking that is an expected performance characteristic for drivers and no confusion should be introduced with the introduction of EVs, particularly when electric drivetrain control is more controllable with electronic systems.

Table 1: Recommended Actions for Longitudinal Braking Issues

EVERSAFE results – RB failure field study	Regulation	Standard	Further research
Effects of different driver workload levels (e.g., traffic, mobile phone use) on the subjective ratings of the driver and driver reactions			X
Effects in case of a stronger RB deceleration			X
Effect of RB failure in other maneuvers			X
Inform driver about RB failure	May produce amendments to R13-H	X	X

6.1.2 Lateral Scenarios – Wheel Hub Motor Failures

Most of the conclusions identified lead to recommendations for future research. There are recommendations to further study the effects of different workload levels (e.g., traffic, mobile phone use) on the subjective ratings of the driver and driver reactions during electrical system failures. Also how WHM failures affect the driver and vehicle response in other maneuvers should be studied as well as any effects on following traffic.

In terms of issues that may require development or modification of existing standards, there were recommendations to investigate how to inform the driver about WHM failures. This may have an interaction with existing ESC systems and can have implications for UNECE R13-H as well. The use of the brake lights was also an area of potential standardization during a wheel hub motor failure. If the vehicle begins decelerating at levels that will affect following traffic, the brake lights could be used to signal surround traffic. Again this is directly related to Regulation 13-H.

Every future vehicle complying with R13-H will have an ESC system to assist the driver in the case of yaw instability and now further regulations would be envisioned. Current regulations would need to be monitored to ensure that there are suitable warnings and test procedures to evaluate vehicles with electric drivetrains. A summary of the findings are presented in the table below.

Table 2: Recommendations for Lateral Stability

EVERSAFE results - WHM failure simulator/field study	**Regulation**	**Standard**	**Further research**
Interaction effects of ESC and WHM failures			X
Effects of different workload levels (e.g., traffic, mobile phone use) on the subjective ratings of the driver and driver reactions during failures			X
Effect of WHM failure in other manoeuvres (e.g., with oncoming traffic)			X
Effects on following traffic			X
Inform driver about WHM failures	May produce amendments to R13-H	X	X
Flash brake lights on in case the car decelerates under a certain level	May produce amendments to R13-H	X	X
Every EV with WHM should always have a system that compensates WHM failures	R13-H to be monitored		X

6.2 Passive Safety Issues

The research approach in the passive safety section of EVERSAFE used the longitudinal and lateral scenarios to direct the activities. The final recommendations were found to not be restricted to one scenario, but better grouped into a common crash protection matrix for electric drivetrain battery packs.

Table 3: Recommended Actions for Battery Crash Protection

EVERSAFE results	**Regulation**	**Standard**	**Further research**
Improved cell level models to understand cell deformations during crash events, expand to all cell geometries			X
Investigate direct loading of battery pack during crash events		Check test procedures for their represent-ativeness with respect to traffic crashes, e.g. wider penetration impactor	X
Study influence of stiff battery structures on vehicle acceleration pulses			X
Identify acceleration limits (pulse and duration) for battery packs	Potential regulation if third party battery packs should be tested independent of vehicle	Potential Standard	X

6.3 Post-Crash Recommendations

The details of Deliverable D3.1 [9] provides an updated guideline for performing rescue operations on vehicles with (and without) electric drivetrains. Recommendations for both equipment and training are provided. These new guidelines should be further developed with the regional rescue services. To facilitate this activity, further initiatives for research, standards, and regulations are presented in Table 4.

Table 4: Recommended Actions for Post-Crash Handling

EVERSAFE results	Regulation	Standard	Further research
Develop better e-Call protocol to include vehicle fuel type identification and battery health status (temperature, fault diagnostics)		X	
Include measurement of toxic / flammable gases in addition to liquid electrolyte in crash tests (R94, R95)	X		
Develop standardized identification and location of service/rescue disconnects for traction (high voltage) power system		X	
Develop effective methods to neutralize battery after a crash			X
Decrease the required disconnection of the traction battery circuit in R94, R95 from 60 s to less than 3s.	X		
Check viability of handling procedures for rescue teams approaching severely damaged electric vehicles			X
Compare and harmonize legal requirements for functional, crash safety, and transport of batteries	X		

7. CONCLUSIONS

The results of the EVERSAFE project indicate that the general level of EV safety is quite high and that no critical safety issues have been identified. There are areas where the industry should develop universal standards to improve the driver's interaction with the new EV systems and minimise the risk of crashes due to inappropriate driver expectations. When a crash with an EV occurs there appears to be little chance for fire or the emission of toxic substances, but there needs to be more work to assist the firefighters in identifying EVs, disconnecting electrical systems, and possibly neutralizing batteries after a crash.

Improving safety for the road user is an ongoing process and EVERSAFE has recommendations to further improve the good level of safety of the existing vehicle fleet. The results of EVERSAFE indicate that current and potential owners of vehicles with electric drivetrains should not consider these vehicles as less safe than vehicles with conventional (internal combustion) drivetrains.

8. REFERENCES

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