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## **Battery Safety Evaluation of Electric Driven Motorcycles from the Perspective of Accident Research**

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### **Abstract**

Li-ion batteries, that actually represent the most promising technology also for the traction of electric driven motorcycles, can be subjected to high mechanical loads, inter alia in case of road accidents, with relevant hazards ( e.g. toxic gases, high temperatures and explosions) for the rider and the surroundings. Nevertheless in the actual State of Art no standard regulations specifically addressed to electric driven motorcycles are defined for the assessment of the crash safety of the traction battery.

This study develops a methodology to evaluate the safety of the battery of an electric motorcycle in case of road crash, based on relevant accident configurations and provides a load comparison with the existing transport tests.

An intense review of the Austrian statistical database was analysed with the assistance of the investigation of in-depth analyses of real accidents and computer aided reconstruction of relevant scenarios, for the definition of five relevant accident configurations.

The defined crash scenarios were then reproduced in entire vehicle crash tests with an electric motorcycle with the purpose to analyse the consequences at battery pack and cell level of the loads that acts in a real accident. The results ensured the crash safety of the traction battery of the test electric motorcycle and provided important information for the improvement of the actual standards in order to enhance the safety of electric driven motorcycles.

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## **1 Introduction**

Electric driven motorcycles are the vehicle type with the highest potential for the mobility in urban areas, both in terms of diffusion and impact for the environment. [1] In order to achieve the desired performance and electric range, high energy traction batteries, usually based on the lithium-ion technology [2], are necessary, with notable potential chemical (e.g. release of toxic gases and liquids), electrical ( e.g. electric shock) and thermal ( e.g. high temperatures ) risks for the rider in case of damage. [3,4]

In fact in case of mechanical load or deformation of the battery pack, inter alia in case of road crash, an irreversible exothermal reaction at single cell and battery pack level (thermal runaway) can be triggered with high hazards for the rider and the surroundings. [3,4]

In order to protect the electric energy storage system (EESS), the State of the Art solution is the placement of the battery pack in an area of the vehicle that experiences reduced to no deformations and mechanical loads in an eventual crash phase. Moreover, usually a protective structure is integrated in the vehicle in order to provide extra protection to the traction battery. These strategies can be successfully applied in case passenger cars [5] but only partially in case of electric motorcycles, especially the former. In fact, Electric Powered Two Wheelers (E-PTWs), due to the reduced dimensions, do not present zones not subjected to deformations or loads in case of crash and the traction battery is therefore subjected to higher risks in comparison to electric passenger cars.

In order to ensure a safety integration and use of traction batteries in all electric vehicles, mechanical abuse tests are provided by standards and current regulations [6,7] and extensively analysed by [4]. The crashworthiness of the traction battery of electric vehicles is assessed with various configurations, that focus on the deformation of the battery either with a force [6] or a deformation [7] amplitude limit in quasi-static-tests. Dynamic loads can also be applied for the same purpose as described in [8] and [6]. These tests aim to ensure the overall safety of the traction battery not just after the integration into the vehicle but also in the manufacturing, storage and transportation phases. Nevertheless, no specific references about tests for electric driven motorcycles are present. Moreover in the actual State of the Art the focus in the motorcycle crash research lies on possible injuries of the rider [9] not on loads at the traction battery or the hazard associated with its damage, leading to relevant risks for the consumers.

This study focuses therefore on defining a methodology to assess the crashworthiness of the traction battery of an E-PTW in order to ensure a safe behaviour also in case of the involvement of the E-PTW in a road crash, based on real-world scenarios and a comparison to existing transport tests.

## 2 Method

For the assessment of the crash safety of an E-PTW traction battery a three steps method was developed, including different techniques from the road vehicles passenger safety State of the Art.

The first step of the analysis is the definition of relevant crash configurations with the potential to lead to dangerous load conditions of the EESS. In order to define hazardous accident scenarios for electric motorcycles, the Austrian basic accident statistic database was investigated. Due to the recent introduction of electric driven motorcycles in the actual market, no statistically relevant accident data regarding this vehicle type are available. For this reason, the statistical analyses were developed with the data of internal combustion engine (ICE) motorcycles. The investigation of basic road accident databases permits not only the definition of frequent crash configurations but also the calculation of their distribution between urban and rural zones, providing important information for the characterisation of relevant crash configurations depending also on the PTW type.

Nevertheless the analysis of basic road accident databases does not permit the definition of all necessary parameters in order to completely describe a crash configuration (e.g. collision speed, Principal Direction of Force, collision object,...). Therefore an analysis of in-depth databases is necessary for a complete definition of a crash scenario. Relevant accidents are reconstructed using the software PC-Crash. Infrastructures, such as roadside objects and parking vehicles, are included too. Complete accident situations, from the pre-crash phase to the final after-crash position, were analysed with particular attention to the evaluation of the impact speeds and Principal Directions of Force (PDOFs) of the different crash configurations. [10] The comparison of the defined scenarios with the configurations prescribed by current regulations ( ISO 13232 [9]) permits a consolidation of the validity of the analysis.

The relevant crash configurations derived from the previous step are then reproduced in entire vehicle crash tests with the goal to analyse the real loads acting on the EESS and therefore define possible hazards for the motorcyclists or the people nearby. As Vehicle Under Testing (VUT) an actual electric motorcycle (see Figure 1) was used.



*Figure 1 : Photo of the KTM Freeride E, used as test vehicle in the study [11]*

The results of the data of the entire vehicle crash tests are investigated in the last step of the study. The EESS of the test motorcycle is analysed focusing on possible mechanical as well as electrical damage and the possible hazards are categorized with the use of State of the Art approaches [7].

The analysis of the data from the crash tests campaign permits the assessment of the crash safety of the traction battery and the comparison between the load conditions in the current State of the Art transport regulations (e.g. IEC 62281 [12] and UN 38.3 [13] ) and those in a road crash (e.g. ISO 13232 [9] ) in order to identify possible lacks in the actual standards.

## **3 Results**

### **3.1 Accident statistical analysis**

#### **3.1.1 Basic road accident database analysis**

The analysis of basic road accident databases can provide the base for the definition of relevant crash configurations. For the actual study more than 450.000 road accidents, present in Statistik Austria between the years 2002 and 2011 were considered. [14] In particular 36048 accidents with injured people involving at least a motorcycle were found in the data set. These accidents cover all the vehicles included in the European class L3e, spanning from light motorcycles to PTWs with an engine displacement of more than 1000 cm<sup>3</sup> [15], and were used for the definition of relevant accident scenarios.

The two most frequent accidents type found in the analysis, responsible for 68 % of all road accidents for motorcyclists, are collisions at a junction and single vehicle accidents, nevertheless their distribution between urban and rural roads shows relevant differences (see Figure 2). In urban areas the most frequent accident scenario is a collision at an intersection. This crash situation represents often a “looked-but-failed-to-see” scenario [16,17]: accidents where the driver looked in the direction of the motorcyclist but could not see him or estimate rightly the relative distance and position, causing then an accident. This leads to configurations with Principal Directions of Force (PDoFs) oriented principally to the front of the vehicle. In rural areas single vehicle accidents are the most frequent type of motorcycle accident. In these cases it is difficult, without an in-depth analysis, to individuate the impact object as it can vary, among others, between road infrastructures, trees or the road itself. The last two groups of relevant crash scenarios, that together covers 27 % of all motorcycle accidents are collisions between two vehicle driving in the same direction (17 % of all considered accidents) and collisions between two vehicle proceeding in the opposite direction (10 % of all considered accidents).

**Distribution of motorcycle accidents with respect to the accident type in urban and rural areas**

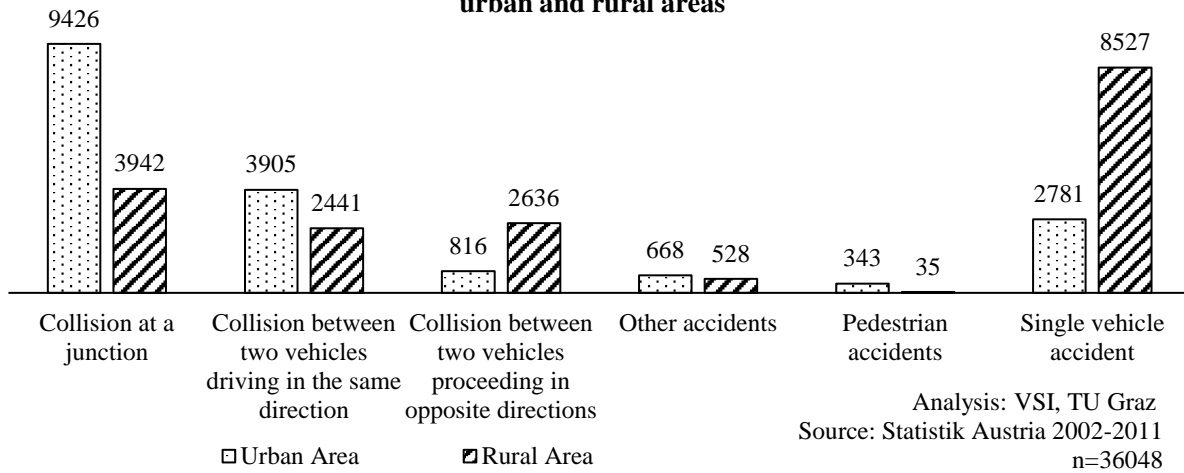


Figure 2 : Frequency of different accident scenarios as found in Statistik Austria

### 3.1.2 In-depth database analysis

The further investigation was conducted with the data from the CEDATU Database (Central Database for In-Depth Accident Study) [10]. The CEDATU was built based on the STAIRS protocol (Standardization of Accident and Injury Registration System) [18], which was developed in the homonym EU project. Data sets from the EU projects PENDANT (Pan-European Coordinated Accident and Injury Databases) [19], RISER (Roadside Infrastructure for Safer European Roads) [20] and ROLLOVER (Improvement of rollover safety for passenger vehicles) [21] were also included in the database. Moreover data from the Statistik Austria were implemented in order to provide a direct correlation with the national statistic. [22] In particular 104 accidents were sampled for the in-depth analyses.

Particular attention had to be posed in collisions with passenger cars, that represent the collision partner of PTW in 44,2 % of the analysed cases (see Figure 3). As noted in the Austrian statistical database, a high percentage of single vehicle accidents were also found and therefore considered in the further steps. It has to be noted that in these cases the impact object can vary between a wide range of possible structures, spanning from road infrastructures to safety barriers, poles or the road itself. Nevertheless due to the high frequency such a case should be included in the test matrix for the full vehicle crash tests.

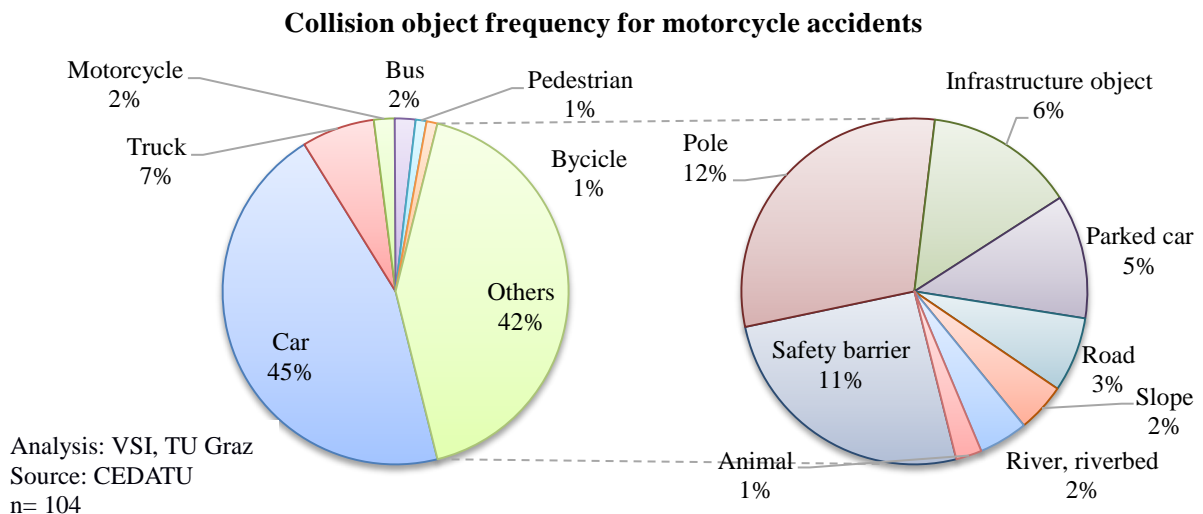


Figure 3 : Resuming chart of the collision partners for PTW

Moreover, the reconstruction of real accidents permitted the evaluation of the PDoFs of the accidents. In particular a PDoF at 12 o'clock could be found in 51,7 % of the analysed cases (see Figure 4). Force directions oriented at 01, 02 and 11 o'clock are also relevant and need to be considered. Rear end collisions (PDoFs 06 o'clock), as well as side collisions (PDoFs 03 or 09 o'clock) cover together 6,7 % of the analysed accidents and represent therefore rare collision scenarios.

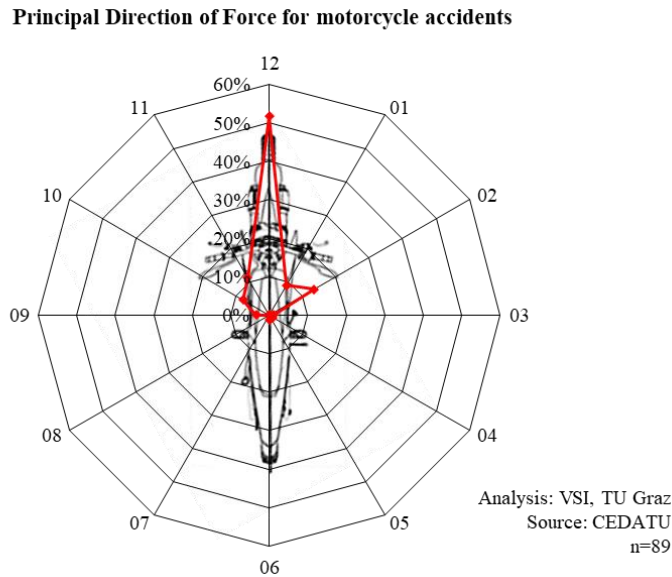


Figure 4 – Principal direction of force found at the analysis of the CEDATU Database

The complete reconstruction of real accidents permitted moreover the investigation of the impact speed. In the accidents from the CEDATU database the 50 % percentile of the impact speeds is in the range 60-69 km/h: The MAIDS Database offers a different range, with the 50 % percentile laying at 40 km/h. [23] It can therefore be stated that the impact collision lays between 40 and 70 km/h. The ISO 13232 provides seven different impact configurations for motorcycles, where the impact speed varies between 24,12 km/h und 45,24 km/h. [9] It appears clearly that the impact speed in real accidents is underestimated in the actual norms. The analysis of the impact speed in accident in urban area in the CEDATU database (n=12) provides an impact speed of 36,7 km/h, while rural accidents shows an average impact speed of 69,5 km/h.

## 3.2 Entire vehicle crash tests

### 3.2.1 Definition of the crash scenarios

The results of the analysis of the Austrian basic road accident statistical database combined with the information provided by the reconstruction of real accidents from the CEDATU database define the basis for the definition of the relevant crash scenarios.

In order to reflect the high percentage of collisions with passenger cars, four crash configuration with a passenger car involved are defined. In particular two configurations with PDoF respective 12 and 01 o'clock are defined in order to consider a collision at an intersection. This crash configurations represent the most frequent accident scenarios. The possibility of other PDoFs led to the definition of other two configurations: one with PDoF 3/9 o'clock representative of a side collision and a rear end collision with PDoF 6 o'clock. As single vehicle accidents are the first accident scenario per frequency in the rural areas their inclusion in the real crash test configuration is necessary. In these cases a wide range of possible impact object is possible (see Figure 3), nevertheless a pole or pole similar objects are the most frequent impact object, found in 12,5 % of the analysed accidents. In such a case a sliding motorcycle is a realistic configuration and therefore proposed as fifth configuration.

The definition of the impact speed is also necessary for the complete definition of the crash configurations. For four configurations an impact speed equal to 36 km/h was selected. This velocity is representative of a typical collision speed in an urban scenario as highlighted in chapter 3.1.2 and similar to the impact speed of 35,28 km/h defined in the ISO 13232 for similar scenarios [9]. Moreover for a frontal collision the possibility of a rural accident is also considered. The average initial speed for these accidents from the CEDATU database is 69,5 km/h. This speed is almost coincident to the maximal speed of the test vehicle (70 km/h) [11] and represents therefore a rare possibility. The impact speed was for this reason reduced to 50 km/h considering also the typical braking deceleration found in the reconstructed accidents and applying it to the maximal speed of the test vehicle. The define crash configurations are resumed in Table 1.

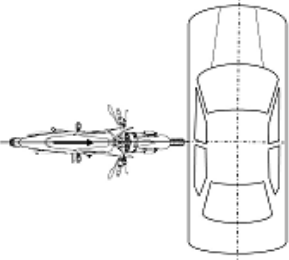
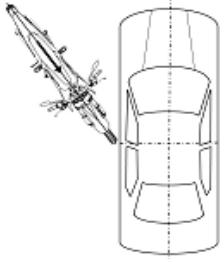
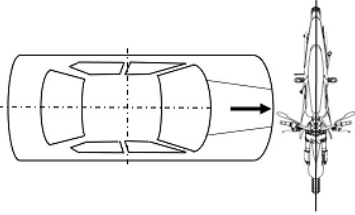
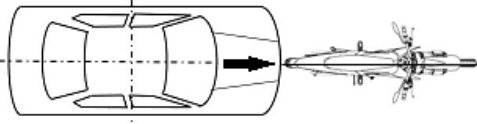
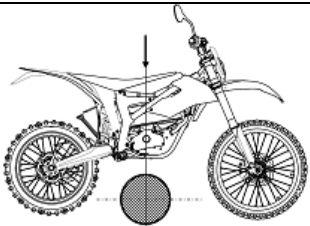
Definition	Drawing	Motorcycle speed [km/h]	Passenger car speed [km/h]
Frontal collision (PDoF 12 o'clock)		51	0
Frontal collision (PDoF 01 o'clock)		36	0
Side collision (PDoFs 03 or 09 o'clock)		0	36
Rear end collision (PDoF 06 o'clock)		0	36
Pole collision		36	/

Table 1 : Resuming table of the crash configurations for the entire vehicle crash tests

### 3.2.2 Preparation of the test vehicle

A test vehicle was used in order to analyse the safety of the EESS of a current electric motorcycle in road accidents. The vehicle represented in Figure 1 was modified removing all the plastic components in order to provide a direct view of the battery during the entire crash phase. Moreover, the front and rear brakes were removed, as well as the traction chain, in order to avoid the possibility of an undesired braking of the vehicle. This caused a change of the total weight of the motorcycle of 5,03 kg that can be considered negligible compared to the total kerb mass of the vehicle ( 108 kg) [11]. The State of Charge of the EESS was set to 0 % in order to reduce the risk of a damage of the measurement instruments due to possible hazardous reactions of the battery pack.

The hazard detection results from the data of different sensors. As high mechanical shocks are also cited as possible cause of internal damage to cells [24] the resulting acceleration pulses at the motorcycle and at the traction battery were also considered in the investigation and measured with two tri-axial accelerometers (Accelerometer model 1203, Measurement Specialties)(see also Figure 5). Temperature and voltage of the battery were measured using the internal CAN bus. Moreover two post-crash measurements were developed. The isolation resistance between housing and negative pole as well as between housing and positive pole were controlled after the crash in order to check the possibility of a possible contact between the inner cells of the EESS and the housing of the battery pack. Moreover the kinematic of the motorcycle was registered with a camera system (SpeedCam MacroVis, Weinberger) capable of 1000 fps and the battery pack after the test scanned with the use of a 3D laser scanner (FaroArm Platinum P08, FARO technologies).

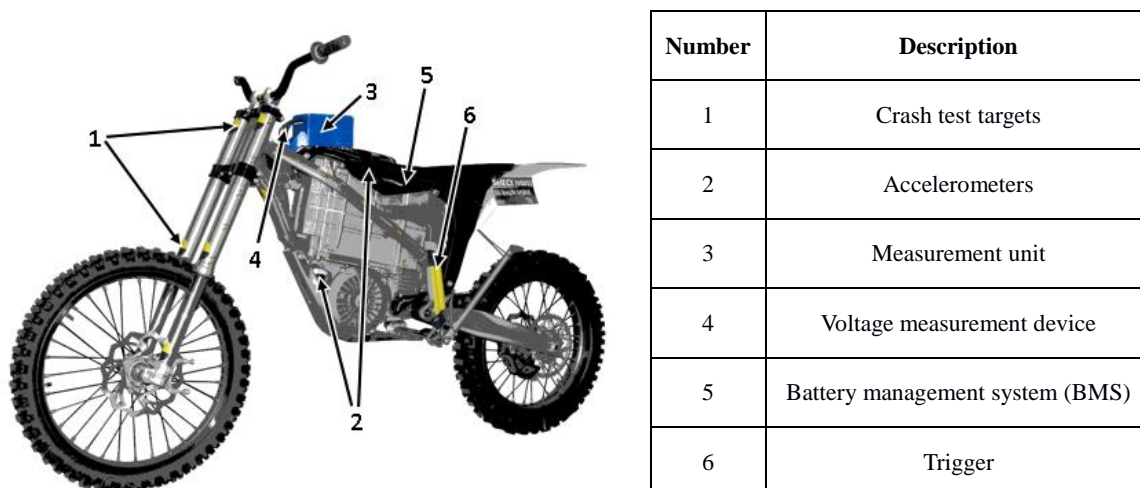


Figure 5 : Photo of the instrumented test vehicle

In comparison with the ISO 13232 [9], no dummy was used in the tests in order to reduce the risk of irreversible damage of the measurement device due to a possible exothermal reaction of the traction battery. A Ford Focus Model Year 2000 was used as representative of a typical passenger car in the configurations with also another vehicle involved.

### 3.3 Safety assessment of the EESS

Different possible damages of the EESS were controlled during the crash and in the post-crash phase in order to assess the crash safety of the traction battery.

As the mechanical deformation, especially at cell level, is often cited as onset cause of a short circuit [3,4], the traction battery of the motorcycle was inspected with the use of modern 3D scanning techniques in order to measure possible intrusions. Nevertheless no relevant mechanical damage of the traction battery was found in any of the developed tests.

Moreover the analysis of the voltage of the battery pack showed no loss of electric potential and no presence of short circuits. The isolation of the battery pack after the tests was checked, as the contact between electrically charged components of the battery pack and the battery pack housing itself can lead to high

hazards in case of contact. The results showed no variation of the electric isolation after the impacts. It can therefore be stated that the EESS showed in every test a Hazard Level 0, according to the EUCAR Hazard Table [7].

The acceleration at the traction battery provided important information for the assessment of the traction battery not only of the test vehicle but also for electric vehicles in general. Due to the relevance of the accident configuration, the acceleration at the traction battery in the direction of the main load of a frontal collision configuration after being filtered with a SAE J211 [25] CFC 180 filter is proposed ,as example, in Figure 6.

During the first 14 ms the movement and damping of the front fork is responsible for the slow increase of the measured acceleration. After this time the front fork achieves its maximal compression and it is loaded by a rotational moment. 18 ms after the impact the first deformation of the steering head can be found. Shortly after, 20 ms after the first contact, the contact between the tire and the motor is responsible for the first peak of the acceleration, which achieves -50 g. The acceleration achieve its maximal peak 62 ms after the first contact, when the measured acceleration is -62 g due to the contact between the steering head and the handlebar and the side of the passenger car. After this time the kinematic analysis from the high speed shows an elastic return of the front fork of the motorcycle that combined with a rotational movement lead to a decrease, at first, and then stabilisation, of the acceleration.

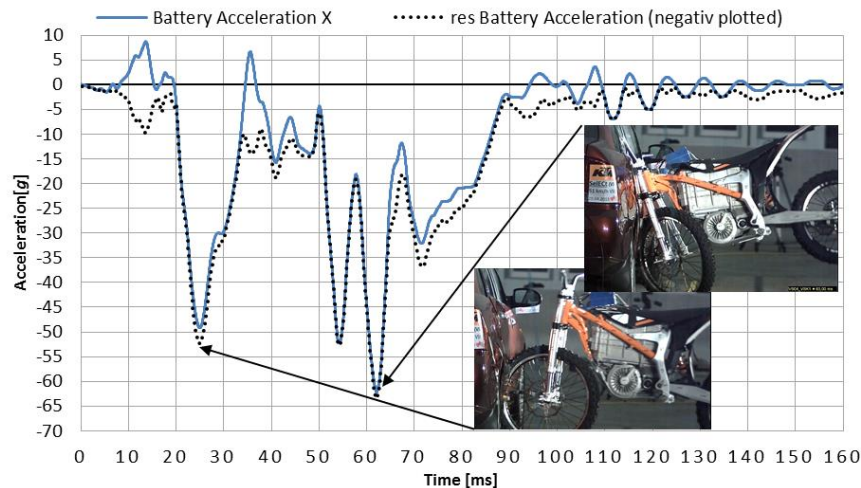
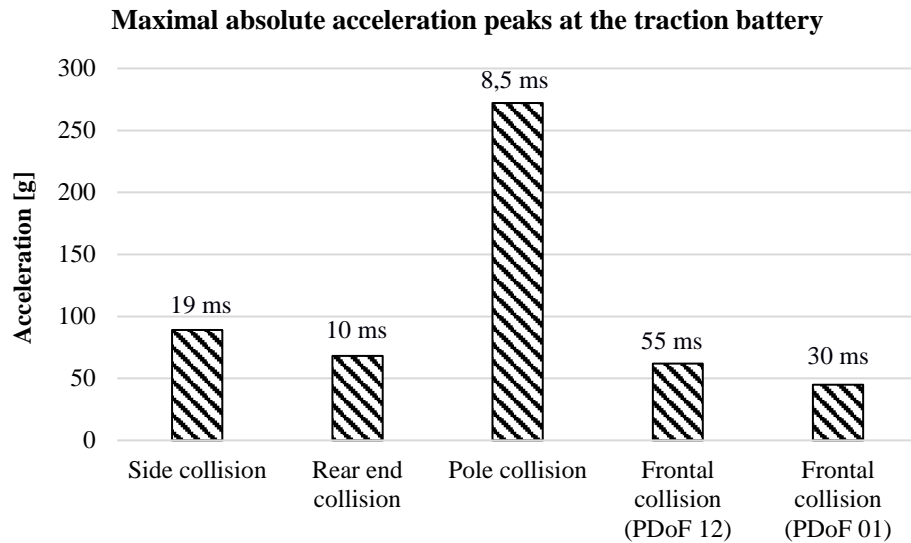


Figure 6 : Measured acceleration at the EESS in a frontal collision for an E-PTW with a passenger car

The analysis of the maximum acceleration peaks in the different tests needs to be developed more in details. The maximal absolute acceleration peaks registered during the tests are presented in Figure 7. The highest measured peak is 272 g in the pole collision crash test. This high acceleration peak is caused by the direct contact between two stiff components, the pole and the engine. Due to the absence of components able to absorb the load, short (8,5 ms ) but relevant accelerations peaks could be measured at the traction battery.



*Figure 7 : Resuming chart of the maximal acceleration peaks and their duration achieved during the entire vehicle crash tests*

The resultant acceleration peaks were then compared to the definition of relevant norms for the assessment of the crashworthiness of EESS. In particular the highest acceleration pulse found in current norms is provided by the IEC 62281 [12] and by the UN 38.3 [13]. The acceleration pulses defined in the two norms are equal to 150 g, and lay therefore 44 % under the maximum achieved peak at the traction battery. This underestimation of the maximal acceleration pulses whom the battery pack can be subjected in a crash phase can lead to relevant hazards in case of the onset of a short circuit due to a not safe enough design of the battery pack.

## 4 Conclusion

The presented study covered the crash safety assessment of the traction battery of a current electric motorcycle. The analysis of 36048 accidents present in the basic Austrian road accident statistical database permitted the definition of relevant accident types for motorcycles. The investigation and reconstruction of real accidents from the CEDATU database provided the definition of typical impact speeds and angles, leading to the complete definition of five relevant accident configurations.

The reproduction of the defined relevant crash configurations in entire vehicle crash tests provided the data for the assessment of the safety of the traction battery. With the investigation of numerous possible failure and hazard causes (mechanical damage of the traction battery, variation of isolation of the battery housing, voltage drops or short circuits and accelerations pulses) it was possible to assess the safety of the vehicle in the defined crash configurations. In particular the EESS of the test vehicle did not exhibit any hazardous reaction (no short-circuit, no exothermal reaction, no smoke, no relevant deformation of the battery housing) after the crash and could therefore be classified as Hazard Level 0 according to the EUCAR Hazard Table [7], assessing the crashworthiness of the traction battery in possible crash phase, also under heavier loads as the ones described in the current regulations.

Moreover the comparison of the measured loads with the definition of the actual mechanical test conditions highlighted relevant lacks in the actual regulations. In particular an underestimation of the load conditions acting on the traction battery in a possible crash phase was found in the actual test regulations. Due to this underestimation an insufficient safe design of the battery pack is possible with consequent relevant hazards in case of accident.

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