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Safety Analysis applied to electric vehicles

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Summary

Technological developments including those issued from electric propulsion require the application of appropriate risk assessments to ensure the safety of the driver, passengers and external people. The current safeties standards (e.g. ISO 26262) are not always appropriate and do not systematically cover all causes of risk or any type of technology. SECTOR specializes in risk analyses adapted to the vehicle as a whole and the context in which it is marketed, whatever the technological innovations it presents.

Keywords: Safety - Reliability - RCS (Regulations Codes and Standards) - EV (Electric Vehicle)

Introduction

Designing, manufacturing and offering to your customers a product which guarantee an adequate level of security (compliant with the highest level of the state of the art) is an unavoidable issue. Beyond regulatory constraints, to ensure the highest level of security is also a major consumerist challenge.

In a broader sense, unlike existing systems whose technology is known and recognized by its users, the appearance of a new technology such as electric propulsion naturally generates a certain apprehension with it.

However if we have a look on the status of xEV (plug-in vehicles) accidents [1], we note that there is a close correlation between the percentage of xEV and the percentage of accidents on this category of vehicles. It means clearly that Electric plug-in vehicles do not seem to be more involved in accidents than conventional vehicles.

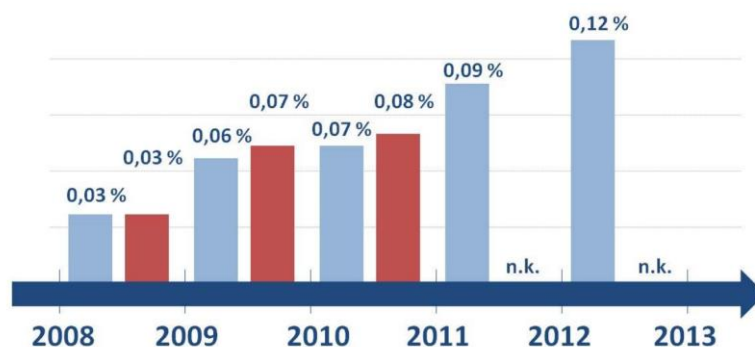


Figure 1 – Percentage market share xEV's vs. Accidents xEV's/accidents overall (w. injuries) – Germany (2013) [2]

Nevertheless, new risks appeared with the emergence of electric propulsion technology:

- Specific risks issued from electric traction: thermal runaway, fire, overvoltage, lack of engine noise for pedestrians...;
- Risks relating to the interactions between the electrification of the traction and other systems powered by the vehicle like air conditioning, heating...;
- The risk of electrocution related to the presence of high voltage;
- Risks issued from external components of the vehicle like public charging station, individuals charging stations, specific tools for vehicle maintenance...;
- Etc.

In this context, security becomes an even greater challenge, convincing the user that the innovative system presents no more risk than those using established technologies, this including the system devices incorporating existing technologies. For example, a fire caused by an intrinsic failure of an electronic component (overheating, short circuit) which is independent of the propulsion technology of the vehicle will generate a negative impact among consumers even higher if the accident occurs on an electric vehicle than if it occurs on a conventional combustion engine vehicle, increasing thereby a feeling of mistrust of vehicles equipped with new technologies.

1 ISO 26262 approach and scope limits

In terms of functional safety of Electrical / Electronic / Programmable Electronic systems (E / E / PE), manufacturers have gradually equipped with effective and recognized normative tools whose primary is the ISO 26262 standard for automotive systems [5].

ISO 26262 is considered as the technical state of the art for functional safety in automotive and most of automotive industrials apply the standard in its actual form. Here is for illustration an extract of the German law about it:

“According to German law, car producers are generally liable for damage to a person caused by the malfunction of a product. If the malfunction could not have been detected by the technical state of the art, the liability is excluded”

[German law on product liability (§ 823 Abs. 1 BGB, § 1 ProdHaftG)].

Implementing ISO 26262 allows leveraging a common standard to measure how safe a system will be in service. It also provides the ability to reference specific parts of the system thanks to a common vocabulary provided by the standard. This falls in line with other safety-critical application domains where a common standard provides a way to measure how safe your system is.

However, this reference standard was not designed specifically as part of major developments in propulsion technology. ISO 26262 focuses on the functional safety of electrical and electronic (E/E) systems in vehicles, considering other technologies components as “out of scope” of the standard. This gap is critical because most of the security functional chains contains (at minimum in the actuator part), some mechanical, hydraulic or pneumatic components (e.g. airbags systems, brake systems, etc.).

Moreover, ISO 26262 is not a real “testing standard”. It defines pass/failed criteria for testing verification activities. But the many testing items it contains are not prescriptive. It is necessary to rely on other regulations and references industry standards. If we take for example the specific case of an electric powertrain (e.g. a BEV vehicle operating with a lithium ion battery), these references are ECE UN 100 ([13]), ISO 12405 ([6],[7] and [8]) and ISO 6469 ([9],[10],[11] and [12]).

Finally, this standard deals with random or systematic functional failures, but does not really deal with the cases of an aggression generated by the vehicles or environmental threats that may affect the safety of the vehicle, including human factor. Hazards related to electric shock, fire, smoke, heat, radiation, toxicity, flammability, reactivity, corrosion, release of energy and others, are not considered unless directly caused by malfunctioning behavior of E/E safety-related systems.

These problematics means that automotive industrials have to consider further analysis to ensure an adequate level of global safety of their vehicles.

2 Complements to be considered for electric vehicle safety

2.1 Electric propulsion functional specific risks

Experience feedback taken from thermic vehicles isn't sufficient enough to perform a safety analysis for electric vehicles. There are specific risks that may occur with the use of a new drive technology. ISO 26262 doesn't really help to identify these new functional risks, which are for example:

- Risks related to electrocution of firemen, ambulance men or other stakeholders in case of vehicle crash or maintenance phases (necessity of specific skills, information, procedures...);
- Dangers due to battery chemical reactions (run away, fire, explosion, aging...);
- Chemical risk due to toxic liquids (electrolyte) and gases emissions;
- Thermal danger due to high temperatures;
- Mechanical risk because of the higher weight of the battery components;
- Vandalism and theft (expensive materials, e.g. copper cables...);
- Overvoltage & battery reloading related risks;
- Others specific situations risks, for example related to the absence of characteristic noise of a moving vehicle to alert people which are outside the vehicle (pedestrians, cyclists);
- Etc.

With its 25 years of experience in risk management, SECTOR capitalized many skills in identifying these risks and can help customers identify and control them for their automotive related products.

2.2 Other technology than E/E/PE

As shown in chapter I, ISO 26262 focuses on the functional safety of electrical and electronic (E/E) systems in vehicles, considering other technologies components as “out of scope” of the standard.

This limitation makes it difficult to perform a complete evaluation of a safety level of a function, due to the presence of some mechanical, hydraulic or pneumatic components in most of safety functions architectures:

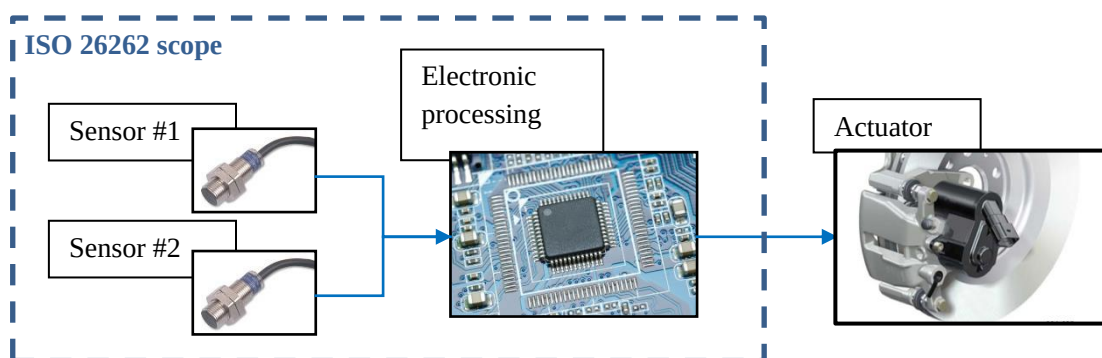


Figure 2: simplified architecture of an electrical braking-related safety function (example)

The second problematic is that one of the metrics for the safety assessment of E/E/PE parts is based on random hardware failures. This is quite relevant for E/E/PE technologies, but not for other technologies, especially for mechanics which are concerned by “failures of aging” cases.

To solve this problematic, SECTOR uses to perform durability analyses for the other technologies than E/E/PE in order to calculate reliability metrics which permits to perform a safety assessment of the whole safety function.

This approach provides more realistic and relevant safety assessment. In other words, only estimate random failure rates of E/E/PE components for a safety assessment is an approximation that can be quite distant from reality, in particular by not taking into account components of other technologies and their “failures of aging” cases (see figures 3 and 4 below).

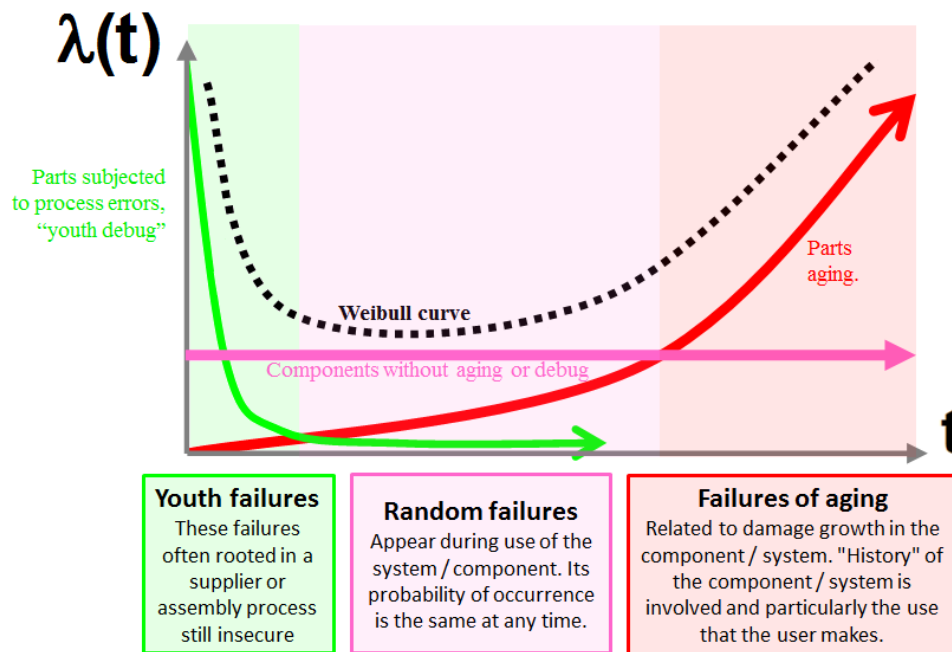


Figure 3 - Typo of failures conducting ton Weibull curve

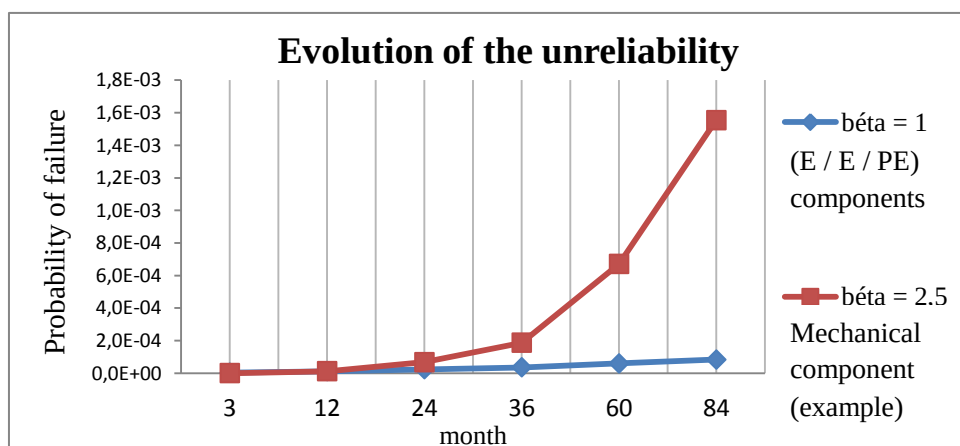


Figure 4 - Evolution of unreliability in function of beta factor

These data confirms that durability has to be considered in the reliability assessment of safety functions.

Regarding the mechanics like gear boxes, shafts or any other component subject to mechanical stress during the life of the vehicle, SECTOR offers components durability analyses, estimating the probability of default based on their conditions (constraints, kilometers...). The main approach is based on the “strain / strength” method (reliability-sizing) [14]. The basics of the method are shown in Figure 5 below.

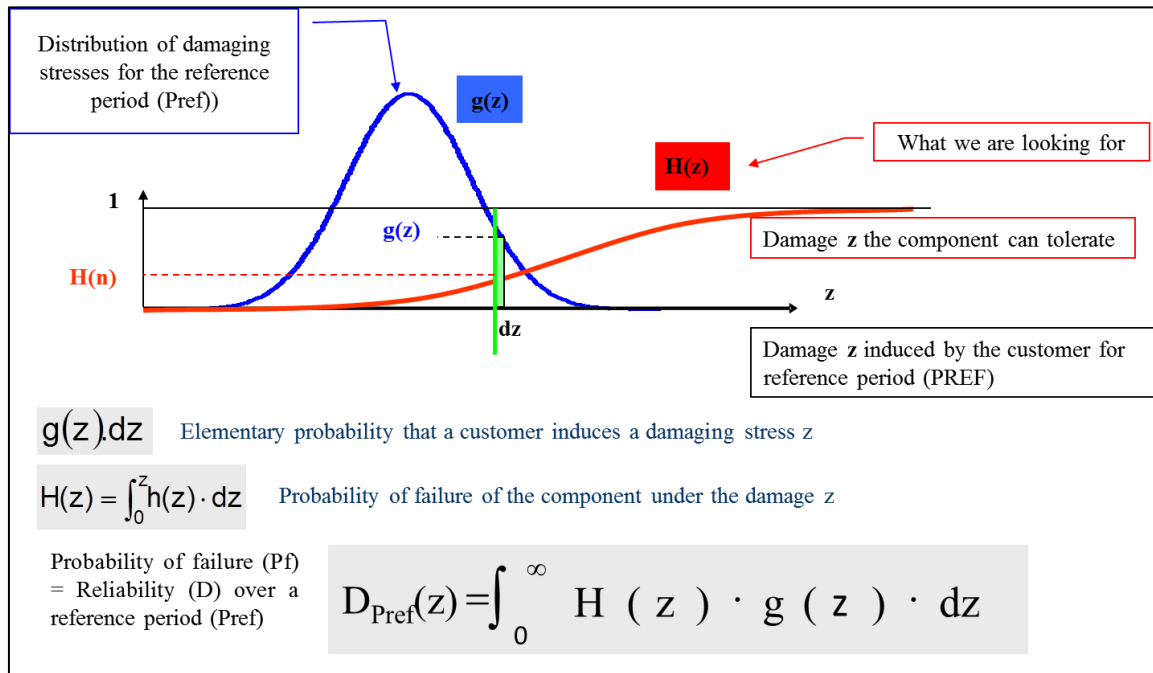


Figure 5 - Basics of durability analyses

2.3 Threats, aggressions and human factor

According to several studies [3], the technical causes of accidents are less than 10% (most of which are related to the tires). By comparison, accidents due to human failures account for more than 85% of the total. Thus for xEV, it is crucial to make a special effort to protect the battery and HV electrical components in case of crash, especially because crash behavior changes with the emergence of the electric propulsion systems (e.g. effect of the addition of a large mass such as the battery).

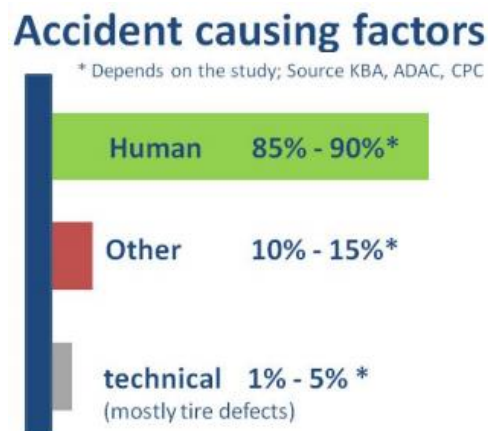


Figure 6 – Accident causing factors

However if we only look at accidents involving batteries, the battery is at the origin of the event in 66% of the cases (public aeronautic data available) [4]. Because of the inherent instability of lithium ion elements (especially during charging) battery design, manufacturing and use must be at the center of comprehensive risk management methodology.

It is essential to keep in mind that functional safety is not the only way to secure a system. It has to be completed by further safety analyses, like threat & aggressions analyses, especially during phases where interaction with humans is omnipresent (e.g. maintenance, crashes...).

Here are some examples of what we call “threats and aggressions” risks. These examples are issued from experiences of SECTOR’s collaborators:

- Automotive: A user keyring was too heavy, then the contactor was subjected to a high mechanical stress leading to a false internal contact, resulted to untimely stops the engine during driving;
- Automotive: An automatic sliding side door of a vehicle opened accidentally during travel. This was due to a short-circuit caused by some wool fibers of a sweater that had remained stuck in the "surface-contact" (metal pins coming out of the inside of the door to make contact with the rest of the vehicle when the door is closed);
- Aeronautic: LEDs maintenance indicators implemented on electronic cards of a navigation system, dazzled the pilot during a night flight with night vision goggles during an automatic auto-test of these LEDs;
- Etc.

To respond to these kinds of specific risks, SECTOR applies a methodology called MOSAR approach [15]. The process begins with the use of an adapted table of a generic threats / aggressions risks resulting from the capitalization of SECTOR employees (25 years of experience in risk management). This list comes from not only the automotive industry but also rail, nuclear, aeronautics, medicine... and more generally throughout the tech industry. This capitalization permits to cover a wide range of situations and to consolidate customer’s risks analysis, in order to build robust systems for automotive purposes enjoying return of experience from larger industrial fields.

Example of thematic considered in MOSAR approach:

- Thermodynamics and Fluid (Pressures, Temperature, Thermal Radiations, Fluid Jet...);
- Electricity (Voltage, Static electricity, Intensity...);
- Electromagnetism (Radiation X-ray, nuclear, laser, light, magnetic field, ionization...);
- Chemical (Reactivity Acidity/Alkalinity/Corrosion/inflammability/Explosiveness, Toxicity, Carcinogenicity, asphyxiating...);
- Mechanical (Energy: Potential/Kinetic/Rotation, Projecting/Sharp/Cutting/ Roughness/Slippery, Compression Constraints/Strain/Friction, Forces: Linear/Torque/Vibration/Acceleration, Fragility Fracture/Tear; Noise...);
- Psychology (Lack of knowledge or skill, Susceptibility to error in the cognitive process, Limited human rationality, Emotionalism/Stress/Lack of adaptability/Claustrophobia, Lack of interest, Vandalism and theft...);
- Human Physiology (Physical weakness, Limited physical strength, Discomfort: Ergonomic, Noise, Darkness, Brightness...);
- Environment (Gravity, Geology, Pressure, Temperature, Radiation, Light, Contaminants, Climates...);
- Biology (Microorganisms Mushrooms/Bacteria/Virus/Yeasts, Toxicity...).

For each parameter, a specific analysis is performed, beginning by answering the following questions:

- Could the systems be potential victim of this kind of aggression?
- Could the systems cause this kind of aggression?
 - On users, public;
 - On the maintenance staff, professionals involved in an accident;
 - On the natural environment;
 - On the other vehicle systems (interactions);
 - Etc.
- Etc.

Another way to take into account risks related to other than functional failures is to perform a specific human factor risk analysis for special operations requiring human interaction with the vehicle:

- Assembly of the vehicle;
- Preventive and corrective maintenance on the vehicle;
- Firemen intervention after crash;
- Etc.

The methodology used by SECTOR for human factor analysis is the FMEA (Failure Mode and Effects Analysis) applied to the concerned operations. This FMEA approach is a systematic method to identify all potential human failures which can lead to a risk for the customer or all other people in interaction with the vehicle (firemen, mechanics...). Here are some examples of risks that can be detected with FMEA approach:

- Vehicle assembly phase (Electronic Stability Control system) : misalignment of a sensor that can lead to an erroneous value sent to the braking system, which can result to a wrong braking force applied to one or several wheels of the vehicle during ESC activation;
- Maintenance Phase : omission of a disconnection of a power cable of the battery which can lead to a mechanic injury by electrocution;
- Maintenance Phase : thermic injury when going downside vehicle for an inspection requiring manipulation(s) near of the battery place;
- Etc.

Once risks are identified, SECTOR helps the customer to sort these risks by high level of criticality (high severity, high probability of exposure...) and also helps to identify specific actions to reduce the criticality of each risk.

By performing these complementary analyses, SECTOR not only helps to consolidate the safety of automotive systems but can also help to avoid to the vehicle manufacturer expensive recall campaigns after defects found during the normal use life-phase (aftersales).

3 Complementary Standards & Regulations Approach

3.1 Non-exhaustive example of complementary Standards & Regulations to be considered

Although ISO 26262 is the general safety standard for automotive, it is not the only standard related to vehicle safety. To have an exhaustive approach, SECTOR performed comparative analysis of other standards and regulations applicable to automotive systems in order to identify potential gaps between them. Here are the main other standards analyzed in this publication:

- Regulation UN ECE R100 rev.2.[13];
- ISO 12405[6][7][8];
- ISO 6469[9][10][11][12].

In the general safety regulation EC 661/2009 (EU directive) it's mentioned that "*manufacturers shall ensure that vehicles, systems, components and separate technical units comply with the relevant requirements set out in this regulation*". Requirements related to electrical safety included.

The approval process for electric and hybrid vehicles is identical to that of conventional vehicles, it is the Directive 2007/46/EC. Nevertheless, more precise recommendations have been set for the purpose of electric vehicles: UN ECE R100. Some European countries require the UN ECE R100 for the approval of electric vehicles. This is mandatory for importation, sale or use in all signatory countries. Considering its regulatory status, at minimum the safety requirements in this R100 document shall still be met. This is why we choose to include the R100 as one of the standards to be considered within the scope of this analysis.

3.2 Comparisons

SECTOR made comparisons between 4 references (ISO 26262, R100, ISO 12405, and ISO 6469) along two axes:

- A global vision according to the "life cycle" of products developments. The objective is to have a vision of their perimeter in all phases of the development cycle. (Starting point: ISO 26262 "life cycle" vision);
- A more precise vision in the form of a comparative table of contents, regarding different type of risks thematic. (Starting point: content of R100, ISO 12405 and ISO 6469).

3.2.1 Product life-cycle comparison

The ISO 26262 standard is much broader and covers all phases of the development cycle of a product. It addresses all topics (including process, change management...) and allows management of safety. However, it does address only the functional risks for E / E / PE.

Both references ISO 12405 and ISO 6469 are very focused on the testing and validation. They do not have a "life cycle" approach but are complementary to the ISO 26262 approach by offering highly targeted and tailored approaches to electric vehicles (functional but also type assault tests and validations).

This is also the scope of the R100, but it goes further, particularly from the perspective of the repartition of responsibilities between integrators and suppliers. It integrates quality monitoring, change management... (These points are also covered in the ISO 26262 standard).

Synthesis table of product life-cycle comparison is shown in figure 7:

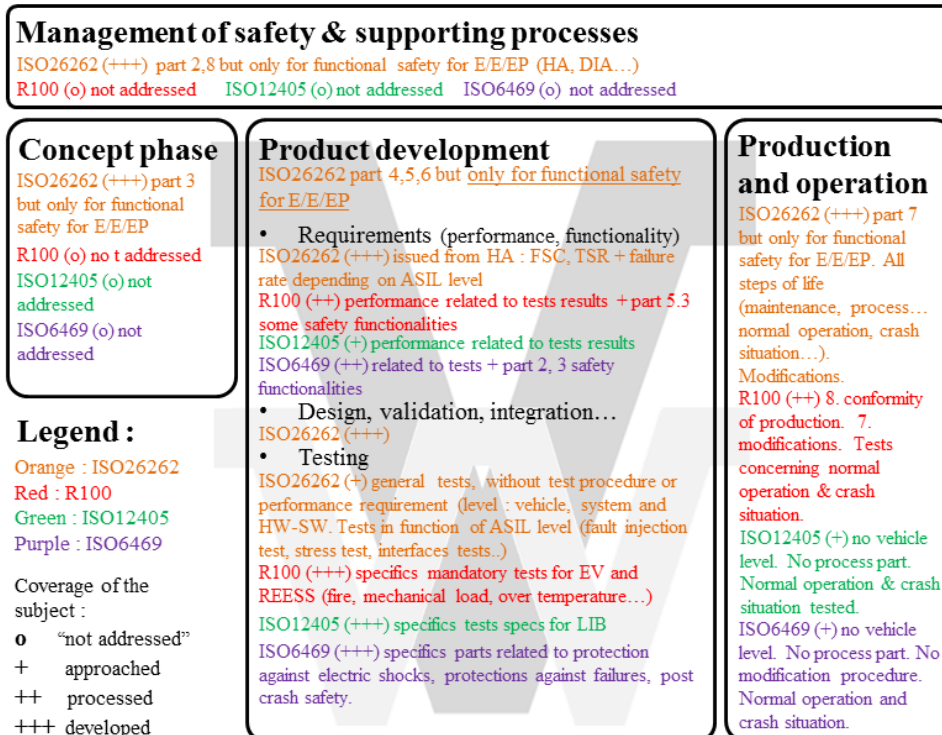


Figure 7 - Comparison between ISO 26262, R100, ISO 12405 and ISO 6469, regarding product development phases

3.2.2 Content-based comparison

In order to address more specifically the content of the standards, we organized the analysis into 3 parts:

- Comparison of descriptions and application areas (extract of results synthesis shown in table 1);
- Comparison of the content regarding type of risks, particularly in terms of testing / validation, functional requirements, various requirements (extract of results synthesis shown in table 2);
- Comparison from our thematic list type "threats / aggressions" (extract of synthesis in table 3).

	R100 (2013)		ISO 12405 Test specs for LIB		ISO 6469 Electrically propelled road vehicles - Safety specifications				ISO 26262 Road vehicles - Functional safety (2011) (+part 10 2012)
	Rev2 all but Part II	Rev2 Part II	ISO 12405-2 (2012): High-energy applications	ISO 12405-3...	ISO 6469-1 (2009): On-board rechargeable energy storage system (RESS)	ISO 6469-2 (2009): ...	ISO 6469-3 ...	...	
We made this check considering a LIB, on a BEV.	Rev2 all but Part II	Rev2 Part II	ISO 12405-2 (2012): High-energy applications	ISO 12405-3...	ISO 6469-1 (2009): On-board rechargeable energy storage system (RESS)	ISO 6469-2 (2009): ...	ISO 6469-3 ...	...	ISO 26262 Road vehicles - Functional safety (2011) (+part 10 2012)
Applicable? Mandatory?	Mandatory (EU certification) since July 2016 in signatory countries...		Applicable	Applicable	Applicable	...	...	...	Applicable (often a contractual obligation)
Short description	Addresses the safety requirements specific for the electric powertrain of road vehicles, as well as those high voltage components and systems that are...		Provides specific test procedures for lithium-ion battery packs and systems specially developed for propulsion of road vehicles...		Specifies requirements for the on-board rechargeable energy storage systems (RESS) for the protection of persons...	...	...	...	Adapted from IEC 61508 as the automotive standard for functional safety of E/E systems...
On scope	Electric power train of road vehicles of cat. M and N, with max. design speed exceeding 25 km/h...	REESS, of road vehicles of cat. M and N...	Specifies test procedures for LIB packs and systems to be used in electrically propelled road vehicles. The specified test...	...	Electrically propelled road vehicles, including battery-electric vehicles (BEVs)...	...	...	...	Applicable to safety-related systems that include one or more electrical and/or electronic (E/E) systems and that are installed in series ...
Out of scope	Post-crash safety requirements...	...	...	...	...	...	...	...	...
Level : VEHICLE	YES	YES	NO	...	YES	...	...	...	YES
Level : REESS	NO	YES	YES	...	YES	...	...	...	YES
Normal Operation?	YES	YES	YES	...	YES	...	...	...	YES
Crash Situation?	NO	YES	NO	...	YES	...	...	...	

Table 1 - Description & scope-based comparison results (extract only)

	R100 (2013)		ISO 12405 Test specs for LIB		ISO 6469 Electrically propelled road vehicles - Safety specifications				ISO 262622 Road vehicles - Functional safety (2011) (+part 10 2012)
We made this check considering a LIB, on a BEV.	R100 Rev2 Part I Part II (and all parts other than Part II)	R100 Rev2	ISO 12405-2 (2012): High-energy applications	ISO 12405-3 (2014): Safety performance requirements	ISO 6469-1 (2009): On-board rechargeable energy storage system (RESS)	ISO 6469-2 (2009):	ISO 6469-3 (2011):	ISO 6469-4 (2015):	
Vibration	see part II	...	YES (8.3)	YES (6.1)	NO	...	...	...	YES & NO Test/validation methodology but not technical procedure for testing these targets in particular.
Mechanical shock	see part II	...	YES (8.4)	YES (8.1, 6.2)	NO	...	...	...	
Mechanical integrity	see part II	...	NO	YES (8.2)	YES (8.1)	...	...	...	
Nail penetration	NO	...	NO	NO	NO	...	...	...	
Falling	NO	...	NO	NO	NO	...	...	...	
Over-temperature protection (failure) (or "Loss of thermal control / cooling") (unsafe	NO	...	NO	YES (10.3)	NO	...	...	...	
Thermal shock and cycling	see part II	...	YES (8.2)	YES (7.2)	NO	...	...	...	
Fire resistance (aggression)	see part II	...	NO	YES (8.4)	NO	...	...	...	
Long-term fire resistance	NO	...	NO	NO	NO	...	...	...	
Propagation test	NO	...	NO	NO	NO	...	...	...	
Heat generation (risk of burns for people)	NO	...	NO	NO	YES (6.4)	...	...	...	
Water immersion	NO	...	NO	YES (8.3)	NO	...	...	...	
Dewing (temperature change)	...	...	...	...	...	...	...	...	
EMC	...	...	...	...	...	...	...	...	
...	...	...	...	...	...	...	...	...	
...	...	...	...	...	...	...	...	...	

Table 2 - Content-based comparison results (extract only)

Coverage of the subject: o “not addressed” + approached ++ processed +++ developed									ISO 262622 Road vehicles - Functional safety (2011) (+part 10 2012)
	R100 (2013)		ISO 12405 Test specs for LIB		ISO 6469 Electrically propelled road vehicles - Safety specifications				
We made this check considering a LIB, on a BEV.	Rev2 all but Part II	Rev2 Part II	ISO 12405-2	ISO 12405-3	ISO 6469-1	ISO 6469-2	ISO 6469-3	ISO 6469-4	
Thermodynamics and Fluid (Pressures, Temperature, Thermal Radiations, Fluid Jet.)	+		+		o				
Electricity (Voltage, Static electricity, Intensity)	++		+		+	+	++	++	
Electromagnetism (Radiation X-ray, nuclear, laser...; Light ; Magnetic field ; Ionization)	o		o		o	+	o		
Chemical (Reactivity Acidity/Alkalinity/ Corrosion/inflammability/...)	+		o		+	o			
Mechanical (Energy Potential/Kinetic/Rotation ; Properties Angular/ ...)	++		+		+	o	o	+	
Psychology (Lack of knowledge or skill ; Susceptibility to error in the cognitive process...)	o		o		o				
...	..		...		...				

Table 3 - Treats/Aggressions-based comparison results (extract only)

This kind of comparison permits to identify some differences and complementarities between the different standards. In conclusion, these comparisons also allow us to see that some topics, such as nail penetration, long-term fire resistance or human factor are never treated in the analyzed references.

With its safety complementary studies and its robust return of experience database (see chapters above), SECTOR can provide a solution to fill these gaps and help the customer to ensure a global safety of automotive system.

Nevertheless, people have to keep in mind that the use of all standard tests can't guarantee a "zero risk". According to the article referenced [16] : *"it has to be accepted that it is a myth to believe that the batteries are safe because it passed the tests"*. In the past, battery maybe passed the required tests but the history shows that even if they past the tests, accidents took place anyway. Some other myths like "ceramic separator solves the problem" or "nonflammable electrolytes are the solution for a better safety" are shown

in the Hollmotz figure given in Figure 8 below (These statements about the myth were given at a battery conference in 2010).



Figure 8 – Battery Safety Myths

Conclusion

With his experience in automobile safety and in a context where the growth of legal activism requires manufacturers to better ensure the security of their systems, SECTOR has developed a specific expertise in the application of the ISO 26262 standard for electric vehicles and more generally in the construction of an integral approach to safety, including:

- Preliminary risk analysis, FMECA, FTA and any other safety methods suited to automotive;
- A complementary approach dealing with « threats » and « aggressions » on the system;
- A complete analysis of safety functions including components of other technologies than E / E / PE (like mechanical or hydraulic components...);
- An exhaustive consideration of the human factor and user experience feedback data;
- Experience issued from comparisons of several automotive safety standards.

For this, SECTOR relies on methods and tools issued from the automotive industry but also nuclear and aerospace where safety is a paramount issue.

Finally, in addition of automobile safety skills, SECTOR's expertise relies on men and women with varied skills and experiences, to ensure a complete coverage of all risks inherent to the use of electric vehicles:

- Mechanical durability experts;
- Human factors experts;
- Quality experts;
- Etc.

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Authors



Working for respectively 10 and 20 years in the business of risk management applied in various fields like automotive, nuclear or aerospace, Mr. Jérôme BARBAT (left) and Mr. Julien RULLIER (right) have a real expertise in the application of various standards and methods for risk analyses related to automotive systems. Working on systems of multiple technologies where human factor is omnipresent has allowed them to capitalize over time all the necessary experience to offer a comprehensive approach of a risk analysis, taking into account all technologies and contexts in which the system is marketed. Mrs. Lise MORFIN assists both gentlemen in writing this article. She has been doing safety studies and eco-design analyses in the automotive and rail industry for 5 years.