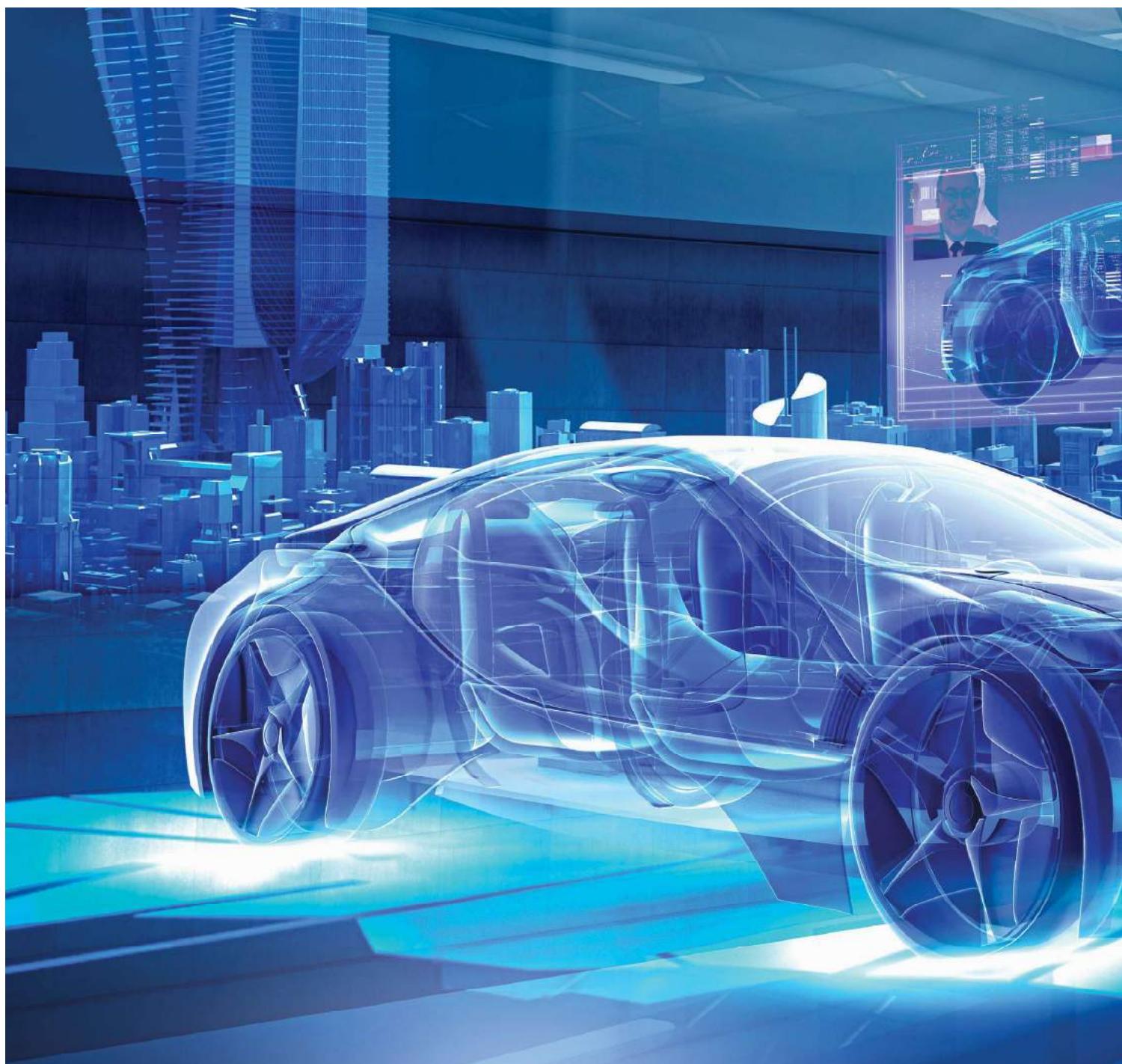


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### TOWARDS FUNCTIONAL SAFETY IN DRIVE BY WIRE VEHICLES

Modern vehicles are continuously becoming more complex with vehicle development becoming increasingly challenging since additional and more complex functionalities from different domains are being demanded not only by customers but also by regulators.



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In the past, the design approach in Embedded Systems in the automotive industry has been to use mechanical sub-systems with electronic control due to multiple advantages including

- a) increased reliability of using electronically supervised systems,
- b) faster introduction and implementation of features in vehicles, and



- c) greater authority of vehicle level functions through more effective digital interfaces between vehicle sub-systems.

Electronic control has been mainly used to control and supervise the functionality and to adapt the behaviour of mechanical systems. In case of an error in electronic control systems, the performance of the mechanical system is reduced while still providing minimum functionality (fail-safe operation). Drive-by Wire systems (XBW) do not have mechanical systems as backup and in the presence of an error, electronic systems will have to provide minimum functionality and ensure that errors are confined.

The number of interconnections and interdependencies in the Electrical and Electronic (EE) systems is rapidly increasing on the functional and hardware level, which in turn leads to increased vehicle complexity. Engineers continue to face the dual challenges of the need to address increased complexity while simultaneously addressing Functional Safety (FuSa) of the systems in the vehicles. With the advent of Drive by Wire (XBW) systems in modern vehicles, especially in Electric Vehicles (EVs) with electrified powertrains and accessories, steering, and braking systems, failure of EE components or a faulty decision by an on-board controller can lead to disastrous results and even vehicle crashes and fatalities. The increased complexity and demand for Functional Safety in EVs demand fundamental reconsideration of established EE architecture, especially for XBW systems.

Most drive by wire (XBW) systems can be split into two physically separated sections as shown in Fig 1 (Ref. [1]). One section consists of the User Interface (UI) while the other

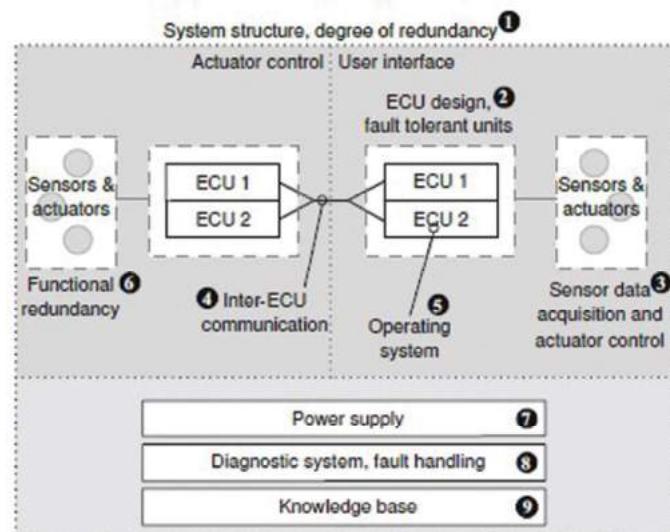


Fig 1. Drive by Wire (XBW) Systems – Generic Architecture (Ref. [1])

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section controls the actuators on the vehicle that are used for steering, braking, suspension and ride control, etc. For UI, customers are given the choice through Gesture Control or Voice or Haptic feedback, or plain touch screen. The actuators and sensors are controlled and monitored by closely mounted decentralized Electronic Control Units (ECUs). Depending on the level of safety being offered by a specific system in the vehicle, the redundancy of ECUs is determined, especially for safety-critical systems as no single unit can achieve the required failure rates. However, it is important to keep the degree of hardware redundancy minimal to optimize the costs.

In general, two components for one task, in combination with a sufficiently powerful diagnostic and decision unit and a fail-safe behaviour of each component are assumed to be able to achieve the required failure rates. A combination of two or more units is regarded as a Fault Tolerance Unit (FTU). In certain instances, an FTU can also be constructed based on only one ECU if the ECU features a multi-core architecture and an appropriate board design in combination with special mechanisms to allow the execution of multiple safety critical functions independently on this platform.

An alternate approach to reducing the number of redundant ECUs is to have a network-centric

architecture, wherein the distributed network nodes monitor each other. If a single ECU fails, other ECUs react by adapting their mode of operation. Though the number of ECUs is reduced, the complexity of individual ECUs will increase. For example, Brake-by-Wire (BBW) systems typically benefit from a network-centric approach if each brake is set up as an independent unit, which is capable of coordinating with other brakes.

Similar redundancy strategies have to be applied for sensors, on the lines of ECUs, to ensure safe operation. Measurements are required with 3 sensors simultaneously to allow majority voting among the measurements and thus to detect faults. To reduce HW costs, one or two sensors could be replaced by SW algorithms.

A vehicle must have proper networking to connect all the electronic components with at least one redundancy including physical separation in the wiring. The overall network has to support a precise timing of messages to ensure that the lost or delayed messages are detected and a maximal roundtrip time is guaranteed. Examples of such networks include TTCAN, TTP/C, FlexRay, and Ethernet in combination with time-triggered extension. The safety-critical applications within the network are synchronized using precise data timings to ensure defined latencies which are enabled by operating



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systems such as modified OSEK, OSEK Time, FTCom, and AUTOSAR.

As a basis for safe operation of XBW systems, availability of fault tolerant power supply system is mandatory. Typically, systems with redundancy and mutual isolation are implemented. Certain vehicle architectures are known to implement double redundancy and an additional control unit to configure the power supply in case of failure.

To monitor the overall system, a suitable diagnostic unit or function has to be implemented. These

units have to ensure that faults that are occurring are detected such that the remaining system can be reconfigured to maintain sufficiently safe operation. As per regulatory requirements, the system has to tolerate at least one independent fault and still maintain (degraded) performance. Most components of the XBW system already provide local diagnostic functions and provide the output of these functions. Additionally, information can be extracted by network overarching monitoring mechanisms for timings and interfaces. To derive suitable actions from this information, different approaches, mostly relying on heuristics and probabilistic mechanisms, are applied. The challenges for these algorithms are to guarantee short execution times and to provide traceable decisions, which renders most machine learning (ML) based approaches unsuitable. Typically, the vehicle is regarded as not “self-healing”, wherein restart of components is considered to heal the system and improve functional safety.

Recent trends in Functional Safety (FuSa) indicate the need to consider the overall system including the power supply, Battery Management System, Steering System, and propulsion system capable of accommodating torque vectoring.

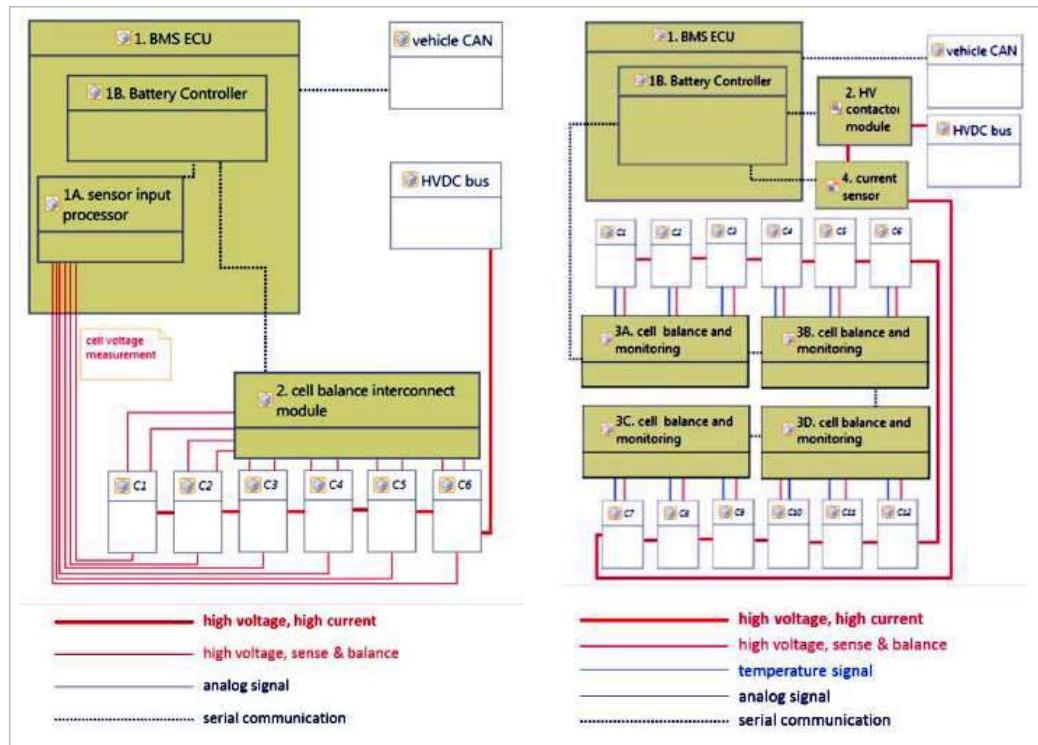


Fig 2. a) BMS Architecture w/o Safety (Ref. [3])

Fig 2. b) Updated Architecture w/ Safety (Ref. [3])

## I. Functional Safety in Battery Management Systems

The ISO 26262 standard establishes a standardized process for Hazard and Analysis and Risk Assessment (HARA), which can be applied to a gamut of automotive systems (Ref. [2]). Recent studies have attempted to illustrate several key steps of an ISO 26262 compliant development process for automotive battery systems and develop a system architecture and functional safety requirements for Battery Management System (BMS), elucidate the use of decomposition method to achieve higher ASILs, and to compare alternate BMS architectures against the ISO 26262 standard so the system designers can provide multiple options based on FuSa compliance, cost, quality, and timeline.

In Figure 2(a), a typical BMS architecture comprising of multiple cells arranged in a series/parallel configuration to achieve the required voltage and traction power to propel an EV is shown. Though such BMS architectures incorporate active or passive cell balancing and advanced State of Charge (SOC) estimation algorithms to improve charge/discharge efficiency, durability, and extended battery life, they do not incorporate the required Functional Safety requirements. The updated BMS architecture to reflect the safety goals

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outlined in Figure 3 is shown in Figure 2(b) wherein the architecture incorporates cell temperature sensors, cell voltage sensors, battery pack current sensor, serial communication, HV contactor and associated logic to isolate the battery-pack from HV DC bus in case of exigencies, to monitor cell internal shorts, and to achieve upgraded SOC estimation.

### I. a) Proposed Safety Goals for BMS

For an automotive BMS, safety goals are proposed as per Figure 3 with the assumptions that HV contactor, temperature and voltage data of individual cells are available along with battery pack voltage and current data. The HV contactor helps connect or disconnect the battery pack while the current sensor helps determine battery pack SOC, individual cell voltage sensors help determine overcharging or internal shorts and cell balance or imbalance, and temperature sensors help monitor overheating of cells that may lead to thermal runaway of the battery pack.

number	safety goal	ASIL
SG-BMS-001	battery overcharge condition shall be prevented	ASIL D
SG-BMS-002	battery overcurrent condition shall be prevented	ASIL D
SG-BMS-003	unintended power delivery to HVDC bus shall be prevented	ASIL B
SG-BMS-004	power to HVDC bus shall be provided when requested	ASIL A
SG-BMS-005	thermal event from cell internal short shall be prevented	ASIL D
SG-BMS-006	thermal event from thermal management failure shall be prevented	ASIL D

Fig 3. Proposed Safety Goals and ASILs for BMS (Ref. [3])

### I. b) FuSa Architecture with Decomposition and ASILs

To meet the safety goal “battery overcharging shall be prevented”, two different concepts can be developed independently. As per the guidelines provided in ISO 26262 (Ref. [2]), this goal can be “decomposed” into separate requirements, with major reductions in the process rigor of each requirement. The specific safety goal of “battery overcharge prevention” can be achieved through controls enabled in the powertrain controller (**overcharge prevention through control**) and also

through the self-monitoring mechanism built into the BMS (**overcharge prevention through self-isolation**). These two mechanisms work independently to meet the same safety goal allowing decomposition into separate requirements as per the ISO 26262 framework, part 9, clause 5. The ASIL D requirement in this case can be decomposed into two ASIL B(D) Functional Safety Requirements (FSR), as shown in Fig. 4 (Ref. [3]). The critical benefit of decomposition of ASIL D requirement into ASIL B(D) FSR is the reduced process rigor, which allows nearly all the ISO 26262 requirements to be achieved at ASIL (B) level itself. The corresponding BMS architecture is shown in Fig. 5 (Ref. [3]).

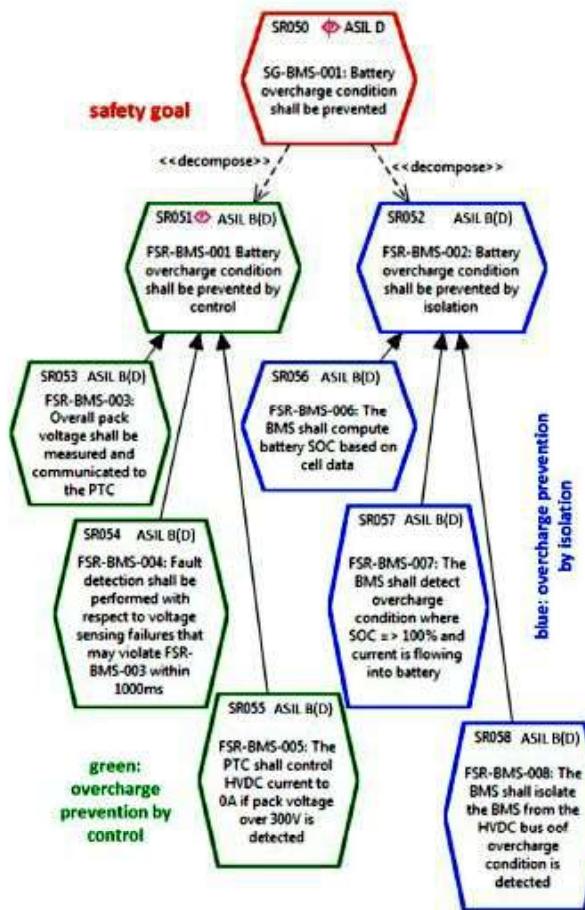


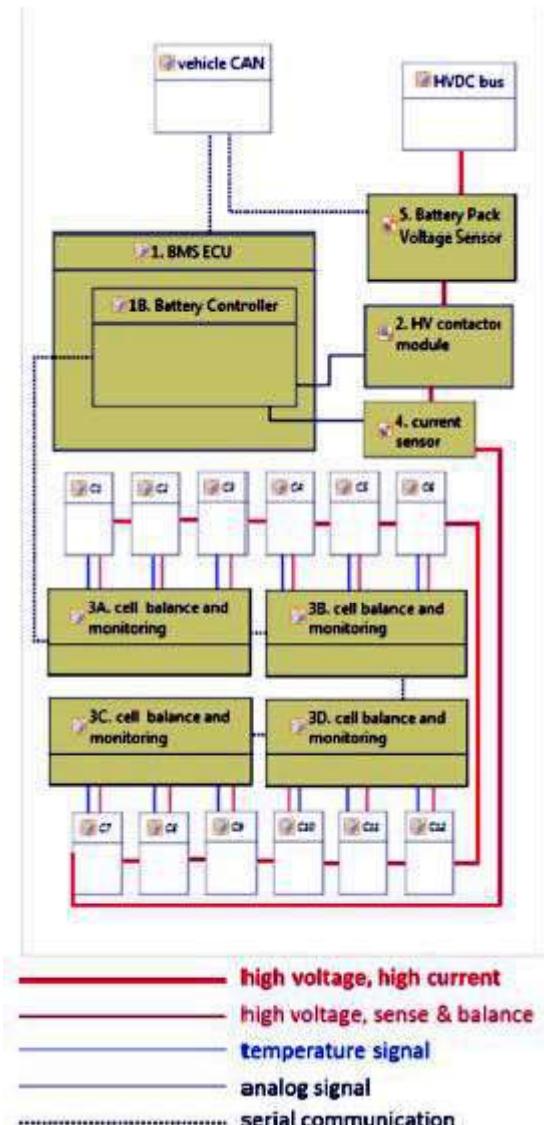
Fig 4. Safety Goal SG-BMS-001 and extension to FSR with decomposition (Ref [3])

In “Overcharge prevention through Control” mechanism, the BMS would provide battery pack voltage information to the Powertrain Controller (PTC). If the battery pack is fully charged, the PTC would take the battery pack voltage and take decisions not to carry out additional charging of the battery pack which otherwise may lead to the risk of fire or explosion. If the sensed pack voltage

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itself is not accurate, BMS sends a “signal-not-available” message via CAN to PTC which would, in turn, respond by stopping any battery charging functions in the charger.

In “Overcharge prevention through self-isolation” mechanism, the BMS carries out regular self-monitoring through measurement of cell voltages, cell temperatures, State of Charge (SOC), and pack-level current. If SOC has already reached 100% and if the PTC still tries to overcharge the HV battery pack, the BMS isolates the contactor and protects the battery pack. In advanced contactor management strategy implementations, the contactor may remain closed but the current allowed might be (close to) zero, effectively not charging the battery pack any further.



**Fig 5. Revised BMS Architecture to meet Safety Goal SG-BMS-001 with Decomposition (Ref [3])**



It is important to understand that the decomposition of ISO 26262 requirements necessarily requires independence between the decomposed requirements, which in turn demands that there are no common failure modes between the decomposed requirements, which get extended to hardware and software that they do not have common failure modes. The specific design features that may be used to achieve independence of decomposed requirements include the following:

- Use of separate and distinct sensor designs for the two methods of preventing overcharge, which can be achieved using a battery pack voltage sensor that can communicate to the PTC through CAN protocol. The cell temperatures and voltages could be processed by BMS alone with independence from PTC.
- Independence of data processing with no commonality in Hardware or Software.
- Rating for PTC of at least ASIL B in order to perform the function that meets ASIL B(D) FSR.
- Physical separation of the independent circuits in general such that common cause failures such as EMI/EMC, short circuit paths etc. are avoided.
- Independent design and manufacturing test procedures for soldered connections, harness connections etc. to protect against systematic errors in the design of components.

## I. c) Functional Safety Hardware Architectural Metrics

In order to meet ASIL D requirement, ISO 26262 defines several Hardware Architectural Metrics (HAM), given as follows:

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- The Single Point Fault Metric (SPFM), which quantifies the HW architecture's exposure to single-point failures as a share of total failure rate. The SPFM requirements are 90%, 97%, and 99% for ASIL B, ASIL C, and ASIL D systems, respectively.
- The Latent Fault Metric (LFM), which quantifies the HW architecture's robustness against latent failures as a share of total failure rate. The LFM requirements are 60%, 80%, and 90% for ASIL B, ASIL C, and ASIL D systems, respectively.
- The Probabilistic Metric for Hardware Failure (PMHF), which quantifies the risk of safety-related random HW failure. The PMHF requirements are  $< 10^{(-8)}$ /hour,  $< 10^{(-7)}$ /hour, and  $< 10^{(-7)}$ /hour for ASIL B, ASIL C, and ASIL D systems, respectively.

The BMS architecture in Figure 6 with decomposition meets lower requirements of ASIL B(D). However, the HAM should be performed at the Safety Goal level before decomposition to comply with ASIL D, ensuring that nearly all HW failures are not Single Point Failures (SPFs) as redundancy is paramount. In the architecture shown in Figure 5, HW or SW errors arising out of the BMS board do not lead to SPF as redundancy is established through the safety requirement in PTC by "prevent overcharge by control" requirement, leading to high levels of SPFM. On similar lines, errors through the HV contactor weld do not lead to SPF and may not need a redundant contactor in HV battery pack. High levels of LFM need to be achieved

through detection and prevention of Latent Failures in the entire system by a) self-diagnosis status of BMS to be communicated to PTC through CAN and b) self-diagnosis status of PTC to be conveyed to BMS through CAN.

### II. Functional Safety in Steering Systems

As modern vehicles are moving away from Electro-Hydraulic Power Steering (EHPS) towards Electric Power Steering (EPS) systems, there is an increasing need to design for Functional Safety requirements of the EPS units consisting of three key elements viz a) power supply unit, b) microcontroller, and c) gate driver unit (GDU). The functional safety of these units is driven by the safety goals and the ASIL determination of the EPS systems. Though the ASIL levels and failure rate metrics as per ISO 26262 Part 5 Section 8.4.5 as shown in Table 1 (Ref [4]) are applicable for Functional Safety in Steering systems also, the use of more Advanced Driver Assistance System (ADAS) application in the EPS and the continuous need for increased torque and better manoeuvrability of vehicles has been posing new challenges for EPS systems

ASIL	Failure Rate	SPFM	LFM
A	$< 1000 \text{ FIT} (< 10^{-6}) h^{-1}$	Not Applicable	Not Applicable
B	$< 100 \text{ FIT} (< 10^{-7}) h^{-1}$	$\geq 90\%$	$\geq 60\%$
C	$< 10 \text{ FIT} (< 10^{-7}) h^{-1}$	$\geq 97\%$	$\geq 80\%$
D	$< 10 \text{ FIT} (< 10^{-8}) h^{-1}$	$\geq 99\%$	$\geq 80\%$

Table 1. ASILs and Failure Rates as per ISO 26262 Standard (Ref [2])

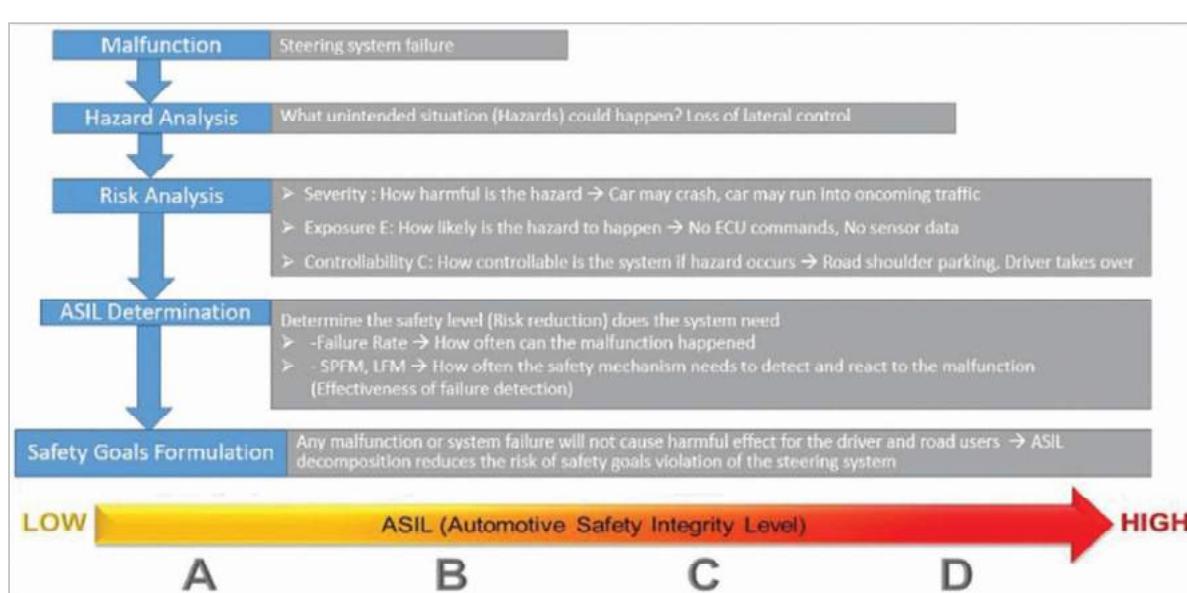


Figure 6. HARA Analysis for Electric Power Steering Ref. [4]

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in the form of higher forces at the steering rack and increased ADAS functionalities. This resulted in changes in ASIL computation for the EPS system because any sudden loss of assistance (LOA) may lead to catastrophic accidents.

In Figure 6, the steps taken to determine the ASIL of the steering system in the vehicle based on Hazards and Risks (HARA analysis) are shown. The objectives of HARA include a) identification of the hazard events of sudden LOA caused by a malfunction in the steering system and b) formulation of the safety goals with their corresponding ASILs in order to mitigate any hazard event and avoid any unreasonable risk.

As the definition of controllability in ISO 26262 is not fully mature, a recent study proposed a new metric to relate a range of torque magnitudes to the controllability class C0 – C3 in Table B.6 part 3 of ISO 26262 standard, as shown in Table 2 (Ref [4]), wherein the controllability class has changed from C2 to C3 with ASIL changing from B to C.

Proposed severity class	Exposure	Controllability		
		C1	C2	C3
S3	E1	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

**Table 2. New ASIL assignment for ADAS and higher steering rack forces (Ref [4])**

As ASIL C accepts up to 3% of single-point failure and 20% of latent failure as shown in Table 3 (Ref [2]), for steering systems with ASIL C levels, a single logic or control system is not adequate to mitigate or reduce any potential risk of sudden LOA. This inherently calls for redundancy for the control and logic gates of the EPS system to ensure high reliability and avoid sudden LOA. Two kinds of redundant systems are applicable for EPS viz, Homogeneous and Heterogeneous. In the case of Homogeneous redundancy, multiple elements of a single type or component are used to achieve redundancy,



such as the use of dual ECUs, microcontrollers, sensors, and power supplies for steering motor. It is easier to implement but susceptible to systematic faults. In the case of Heterogeneous redundancy, multiple components of different types are used to achieve redundancy such as steering control using differential brakes. This design is inherently more resistant to systematic faults.

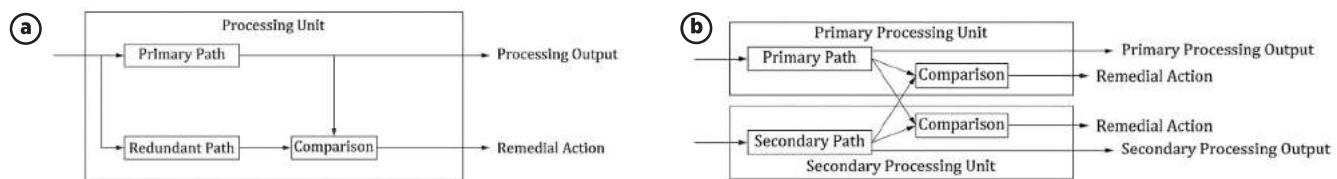
The Functional Safety requirements as per ISO 26262 Part 5 Annex E are applicable to both non-programmable and programmable elements such as Application Specific Integrated Circuits (ASICs), Field Programmable Gate Arrays (FPGAs), and Programmable Logic Devices (PLD). The main Failure in Time (FIT) contributor is the microcontroller with a range of Probabilistic Metric for Hardware Failure (PMHF) 41% to 45% considering Single Point Fault Metric (SPFM), which is more than the safe allowance of 3% SPFM for ASIL C as per Table 3. In order to mitigate the potential risk of sudden LOA due to FIT from the microcontroller, it is imperative to incorporate redundant logic in EPS system architecture. The Software (SW) redundancy can be achieved using

Safety Handling	QM	ASIL A	ASIL B	ASIL C	ASIL D
	Rigorous design and test to avoid potential failures			Control potential failure	
SPFM	No	No	$\geq 90\%$	$\geq 97\%$	$\geq 99\%$
LFM	No	No	$\geq 60\%$	$\geq 80\%$	$\geq 90\%$
PMHF	No	No	<100 FIT	< 100 FIT	< 10 FIT
FTA	No	No	No	Yes	Yes
DFA	No	No	No	Yes	Yes
FMEA	No	No	Yes	Yes	Yes

**Table 3. Handling of Safety Matrices of ASILs (Ref [2])**

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**Fig 7. Redundant SW Comparison using a) same processing unit; b) different processing units (Ref. [4])**

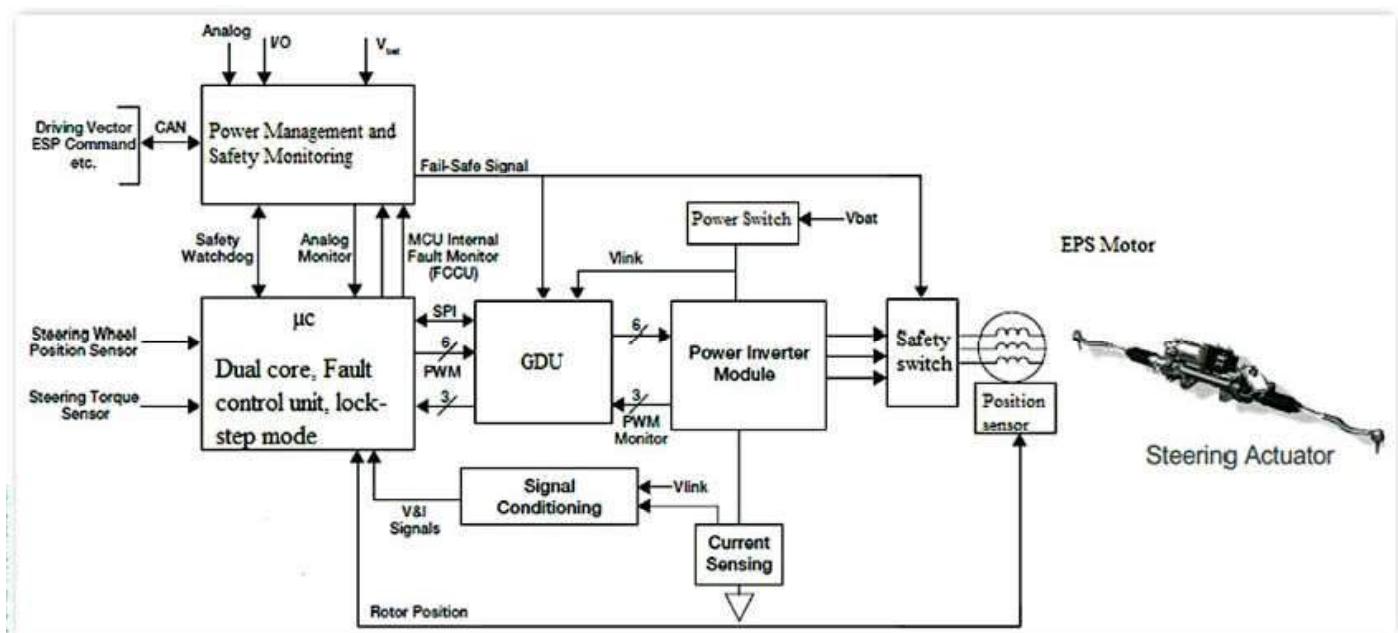
same processing unit or different processing units, as shown using different architectures in Figure 7 (a) and 7 (b). The aim of the SW redundancy is to detect a failure in the processing unit as early as possible by dynamic SW comparison whether using the same or different processing units. In the case of failure of the primary path, the redundant path is responsible for verifying the primary path's calculation and taking appropriate actions if a failure is detected. This can be done using separate algorithm designs and code to provide SW diversity. As per the SW redundancy using a reciprocal comparison of SW in different processing units shown in Fig. 7 (b), failures are detected as early as possible through exchange and comparison of data in each unit on real-time basis to detect differences that might cause failure. The SW architecture in Fig 7 (b) allows for HW and SW diversity in addition to processor types (dual or tri-core), separate algorithm designs, code, and compilers.

The EPS control path using a multi-core microcontroller (dual or tri-core) with integrated power supply

management, as shown in Fig 8 (Ref [4]), enables an internal self-test and lockstep mode, monitors the microcontroller, and controls the safety switch of the EPS motor thus providing a higher level of safety. The Failure in Time (FIT) for this architecture significantly reduces to be in line with ASIL C requirements ( $PMHF < 100$  FIT). This architecture provides high availability and controllability

Safety Handling	QM	ASIL A	ASIL B	ASIL C	ASIL D
	Rigorous design and test to avoid potential failures			Control potential failure	
SPFM	No	No	$\geq 90\%$	$\geq 97\%$	$\geq 99\%$
LFM	No	No	$\geq 60\%$	$\geq 80\%$	$\geq 90\%$
PMHF	No	No	<100 FIT	< 100 FIT	< 10 FIT
FTA	No	No	No	Yes	Yes
DFA	No	No	No	Yes	Yes
FMEA	No	No	Yes	Yes	Yes
Path Architecture	Single logic path is sufficient			Dual-core logic path satisfies or fulfils all above metrics	

**Table 4. Safety and ASIL Target Metrics and Logic Requirements (Ref [4])**



**Fig 8. EPS Control path using a dual core microcontroller integrated with power management and safety monitoring (Ref. [4])**

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for the EPS systems to decompose ASIL-C determination of EPS in case of LOA. The ASIL target metrics and the logic path architecture of the EPS system are shown in Table 4.

### III. Functional Safety in Motor Control Systems

The traction control systems in Electric Vehicles (EVs) have been increasingly using Permanent Magnet Synchronous Motors (PMSM) with the high power density and high energy efficiency. Owing to the criticality of motor control systems, high ASILs (Level C and above) are typically assigned to these systems during design and development.

Function	Provide drive torque		
Malfunction	Provide torque when not requested	Provide more drive torque than requested	Provide braking torque
Driving Situation	Driving in city or on country roads behind another car	Pedestrian area (e.g., cross-roads, parking lots). Low speed	Highway (Wet road)
Impact	Front/rear collision with the vehicle in front.	Frontal collision with pedestrian	Unintended rotational motion
Exposure of operational situation	E4	E3	E3
Severity of potential harm	S3	S3	S3
Controllability of hazardous event	C2	C3	C3
ASIL	C	C	C
Safety Goal	MCU shall not provide drive torque when drive torque is not requested	MCU shall not provide more drive torque than requested	MCU shall not provide braking torque when drive torque is requested

Fig 9. Electric Drivetrain HARA Analysis (Ref [5])

For the basic EV drivetrain architecture shown in Figure 11 (a), a portion of the HARA analysis is captured in Figure 9 wherein the malfunctions, driving situations, and impact on the vehicle and users are elucidated with severity of potential harm as S3 and Controllability of hazardous event ranging from C2 to C3, resulting in ASIL C level in each case (Ref [5]).

In Figure 10, the corresponding safety goals are depicted ranging from the Motor Control Unit (MCU) not to provide drive torque when it is not requested (SG 1) to MCU not providing more brake torque than what was requested (SG 4) with all of them having ASIL C requirements.

A three-layer system architecture to capture the Functional Safety requirements for the EV drivetrain is captured in Figure 12 (Ref [5]) wherein Layer 1 (functional level) accounts for Vehicle level management functions, Layer 2 (function monitoring level) recognizes the faults in functional SW of Layer 1, and Layer 3 (controller monitoring level) interacts with the function controller and enables HW and SW diagnostics.

NO	Safety Goal	Safe State	ASIL
1	MCU shall not provide drive torque when drive torque is not requested	Motor generates no active torque	C
2	MCU shall not provide more drive torque than requested	Motor generates no active torque	C
3	MCU shall not provide braking torque when drive torque is requested	Motor generates no active torque	C
4	MCU shall not provide more brake torque than requested	Motor generates no active torque	C

Fig 10. Electric Drivetrain Safety Goals (Ref [5])

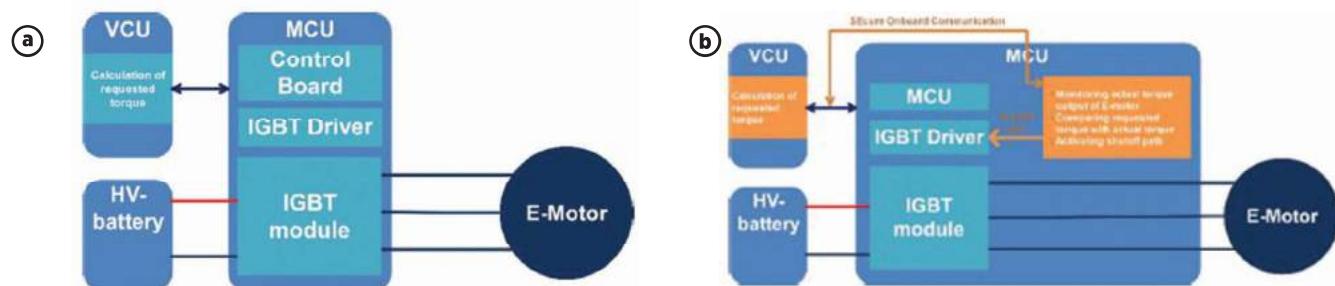


Fig 11. Electric Drivetrain System Architecture a) without and b) with Functional Safety (Ref [5])

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The EV drivetrain system architecture with Functional Safety implementation is shown in Figure 11 (b) wherein the system is implemented with a multicore microcontroller which is developed as a safety element out of context (SEOOC), supports up to ASIL D application, and provides 2-lock stepped CPUs (core 0 and core 1) and 1 non-lock-stepped core (core 2). While Layer 1 is assigned to core 0, Layer 2 is assigned to core 1, and Layer 3 periodically checks the microcontroller and monitors the supply voltages to the system for other layers to function properly. Both Layer 2 and Layer 3 offer shutoff with Layer 2 acting as Torque Monitor and Layer 3 providing a redundant shut-off path in case Layer 2 fails (Figure 12).

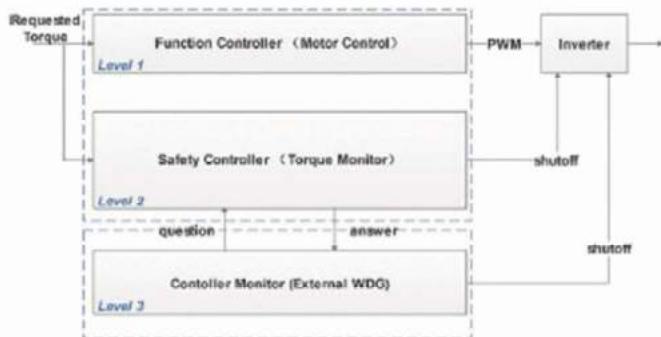


Fig 12. Electric Drivetrain Functional Safety 3-Layer Architecture (Ref [5])



### Functional Safety in Brake by Wire Systems – Centralized vs Distributed Redundancy

The traditional centralized redundancy and advanced distributed redundancy Brake by Wire (BBW) architectures are given in Figures 13 (a) and 13 (b), respectively while the corresponding dependencies are given in Figures 14 (a) and 14 (b).

The dependencies in Figure 14 clearly indicate the benefits of 4 vs 3 modules and 3 vs 2 links as we go from Centralized towards Distributed Redundancy.

The traditional centralized redundancy architecture and dependencies in Fig 13 (a) and 14 (a) consist of the following (Ref [6]):

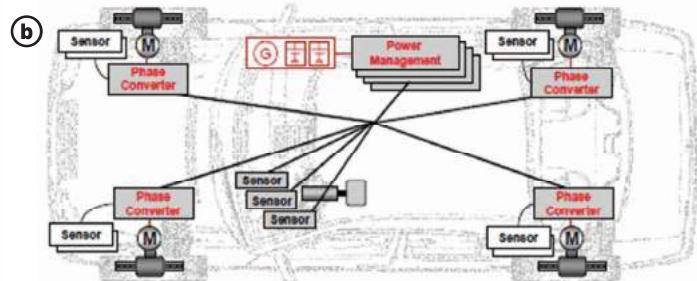
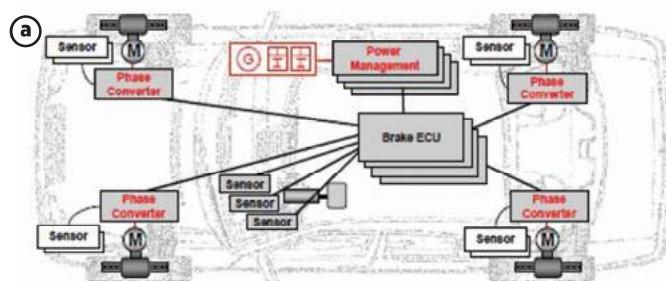


Fig 13. BBW Systems with a) Centralized Redundancy and b) Distributed Redundancy (Ref. [6])

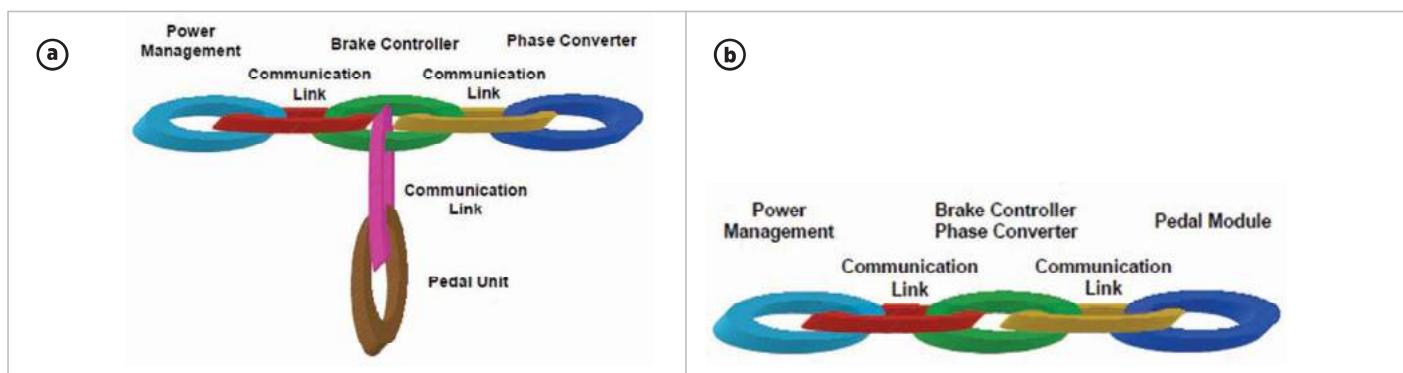


Fig 14. Dependencies of BBW Systems with a) Centralized Redundancy & b) Distributed Redundancy (Ref. [6])

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S. No.	Module	No. of Errors Tolerated	Sub-systems	Resource Requirements
1	Fault Tolerant Pedal Module	1-2 errors	3 (microcontroller, sensor, power supply, communication)	4 high end microcontrollers, 4 for brake modules, 3 low end microcontrollers for pedal module, 8-16 mid-range microcontrollers for power management module and phase converters.
2	Fault Tolerant Electronic Brake Module	1-2 errors	2 fail safe systems (4 microcontrollers, 4 control paths)	Total: 15-23 microcontrollers, 11 ECUs, 9 communication links
3	Fault Tolerant Power Management Module	1-2 errors	2 fail safe systems (4 microcontrollers, 4 control paths)	
4	Phase Converter	1 error	4 for each actuator for 4-wheel braking	

The advanced distributed redundancy architecture and dependencies in Fig 13 (b) and 14 (b) consist of the following (Ref [6]):

S. No.	Module	No. of Errors Tolerated	Sub-systems	Resource Requirements
1	Fault Tolerant Pedal Module	2 errors	3 (microcontroller, sensor, power supply, communication link)	3 low end microcontrollers for pedal module, 4 mid-range microcontrollers each for power management module and phase converters.
2	Fault Tolerant Power Management Module	1-2 errors	2 fail safe systems (4 microcontrollers, 4 control paths)	
3	Wheel Brake ECU a) Fault Tolerant Electronic Brake Module b) Phase Converter	2 errors	1 high end microcontroller, Power Electronics, Sensor I/O	Total: 11 microcontrollers, 9 ECUs, 8 communication links

An important requirement for effective BBW distributed architecture is the communication protocol that is deterministic, connects and correlates the distributed control units, is fault tolerant, encapsulates at the protocol and physical level, has compatibility with existing systems, is cost-effective, and acts as a truly open standard. Existing CAN communication protocols are not suitable for developing fault-tolerant safety-critical BBW applications because they are not deterministic, with the unpredictability of the timing of messages. Multiple organizations and consortiums have been working on Time-Triggered Protocol (TTP) CAN architectures with TTP/C and TTP/A being two real-time protocols of the Time-Triggered Architecture (TTA). The TTA offers high-bandwidth, scalable, and fault-tolerant communication with the safety-related features of pure time-triggered communication and the flexibility to support event-triggered communication for other

applications. TTP/C focuses on the interconnection of components in order to form a highly dependable real-time system suitable for safety-critical XBW systems. TTP/A supports the modular design, provides easy and economical integration and management of sensors and actuators into a network, and can be implemented on low-cost microcontrollers.

It is important for a BBW architecture to have fault-tolerant safety strategies built on inherent system redundancy and with a deterministic communication system connecting and encapsulating the distributed subsystems from each other. Figures 15 a) and 15 b) depicting distributed star topology and unidirectional redundant ring structure, respectively, ensure that encapsulation is performed in the time domain and additionally to some extent in the value domain. The distributed star topology shown in Fig 15 a) suffers from the inherent weakness of single-point failure though it offers

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## Trends

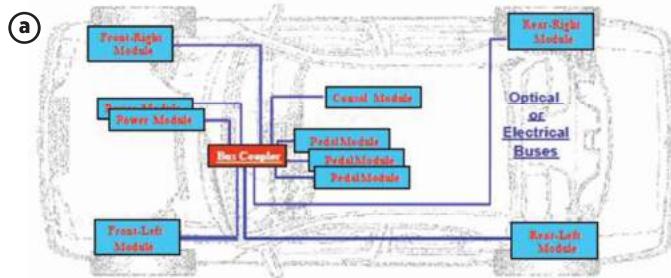


Fig 15. a) Distributed Star Topology (Ref. [6])

redundant bus-guardians and encapsulated sub-systems. The distributed ring architecture is shown in Fig 15 b) offers very high robustness against local, mechanical or electrical failures. Unidirectional wires can be routed separately, such that a loss of any single connection and many combinations of multiple cuts do not cause any loss of information.

The distributed BBW architecture as implemented in a vehicle is shown in Figure 16 wherein multiple displacement sensors and force sensor are connected to the wheel nodes to capture driver intent. Each wheel node calculates the actuation commands for all four wheels. These commands are communicated via the network so each of the four-wheel nodes can compare their own actuation commands with those calculated by the other wheel nodes. The voting mechanism in the network layer of each wheel node can then disable the power to individual actuators in case of a fault. If a node needs to be shut down the brake force is redistributed to prevent the vehicle from yawing. The advanced brake functions are executed in the two front-wheel nodes. If the front wheel nodes do not calculate the same output commands for these advanced brake functions, the function will be deactivated. This provides a fail-safe operation. The dependable power supply is provided by two 42V batteries. Each battery is connected to a distribution box that protects the 42V net from short circuits. Each wheel node is connected to each distribution box providing a redundant power supply. The communication system is itself failure tolerant. The computation and control are distributed to the available resources that verify against each other over the network with appropriate network support. Value domain encapsulation using a mutual distributed exclusion protocol feature is one further measure to allow detection of failures in the value domain across the network and without further software interaction. The communication protocol allows to have the incoming datasets to be

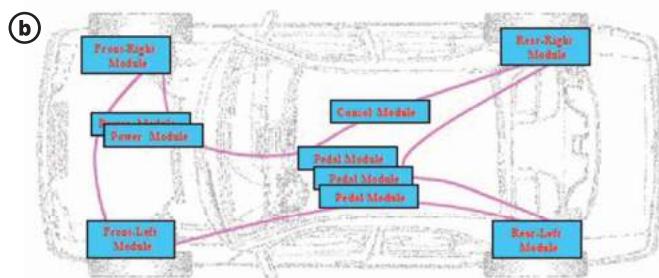


Fig 15. b) Unidirectional Redundant Ring Structure (Ref. [6])

compared against a reference dataset provided by the attached host and to determine the majority agreement within the network. In case of failure of one ECU that cannot detect its own faultiness, this network feature allows preventing the commanding of actuation with data from such faulty node.

### Summary

Functional Safety in Automotive Systems as per ISO 26262 standard is an increasingly necessary requirement due to higher levels of features and associated HW and SW architecture complexity in vehicles. Though ISO 26262 standard is a generalized document to ensure Functional Safety, it needs to be interpreted appropriately for specific systems such as BMS, steering systems, drivetrain, brakes etc. As Functional Safety standards evolved from IEC 61508 towards ISO 26262, avoiding SPF through structured analysis and safety mechanisms is still the underlying design philosophy. To achieve ASIL D level compliance, decomposition into independent and redundant ASIL B(D) systems is a crucial tool to avoid all types of errors. The SPF is almost 100% because no random failures lead directly to violation of a safety goal. For Functional Safety applications on BMS, high levels of LFM are achieved through fault detection and communication through CAN between systems such as BMS and PTC. The HAM should be performed at the Safety Goal level before decomposition to comply with ASIL D.

The use of more ADAS applications in the EPS and the continuous need for increased torque and better manoeuvrability of vehicles has been posing new challenges for Electric Power Steering (EPS) systems in the form of higher forces at the steering rack and increased ADAS functionalities. Recent trends indicate the design of highly available EPS system architecture with FIT is significantly reduced to be in line with ASIL C requirements (PMHF < 100 FIT) using control logic paths utilizing redundancy concepts. ASIL C mitigation

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was achieved by incorporating dual-core microcontroller integrated with power management and safety monitoring unit thus providing high availability and controllability for the EPS systems to decompose ASIL-C determination in case of LOA of steering systems.

As more and more OEMs demand their suppliers to provide drivetrain control systems adhering to ISO 26262 standard, innovative technical solutions employing multi-layer Functional Safety system architecture employing multicore microcontroller (developed as a safety element out of context (SEOOC)) are being pursued meeting ASIL C and higher requirements. The different layers of Functional Safety simultaneously address multiple ASIL C safety goals while also providing redundant shut-off paths in case a layer fails.

The distributed BBW architecture is the recent trend with multiple displacement sensors and force sensors connected to the wheel nodes, with each wheel node calculating the actuation commands for all four wheels. The fail-safe operation is provided by constantly checking if the specific wheel nodes do not calculate the same output commands for these advanced brake functions. Each wheel node is connected to each distribution box providing redundant power supply through the use of two 42V batteries that are protected from short circuits. The communication system itself is failure tolerant with the computation and control distributed to the available resources that verify against each other over the network.

In Automotive systems with growing complexity, all safety goals must be satisfied simultaneously with associated ASIL levels in a single implementation by

detecting and addressing systematic errors in advance through a higher degree of independence of systems to realize decomposition to lower levels, which will continue to be a challenge to design ISO 26262 compliant systems.



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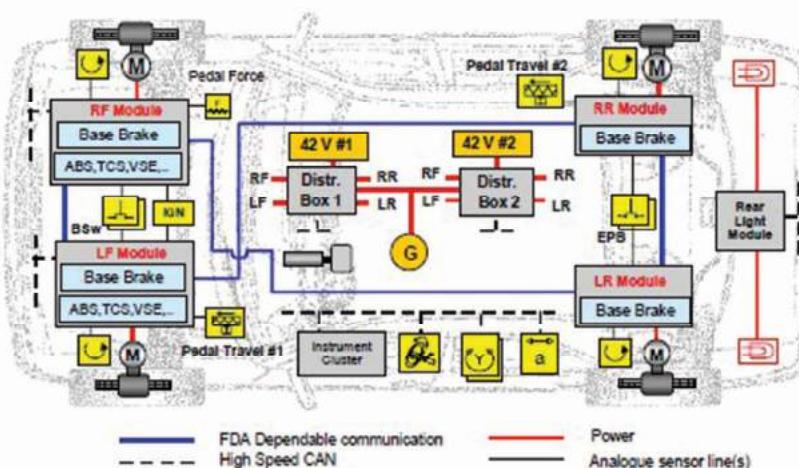


Fig 16. Distributed Brake by Wire Safety Architecture (Ref. [6])