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"Functional Safety Layered Architecture based on AUTOSAR OS for Automotive Systems."

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Introduction

Automotive Industry is general going through drastic changes where customers have become very demanding in terms of features. Increasing in demand of new features in the Automotive has led to increase in electrification of the Car.

Automotive Evolution and growth have been traditional been different from the other embedded/electronics/product industry. Normally there are many driving factors in the automotive electronics Electronic Control Unit (ECU) development and some of the main important factors have been quality and safety of the products.

For Automotive ECU development Multiple Companies Collaborate together to come up with integrate product which formulates a vehicle Component. Figure 2 shows the collaboration Model between Original Equipment Manufacturer (OEM)- Generally Car Manufacturers, Tier 1 – Generally System Manufacturers, Tier2 – Component Manufacturers and Supplier – Generally Service Providers and Vendors

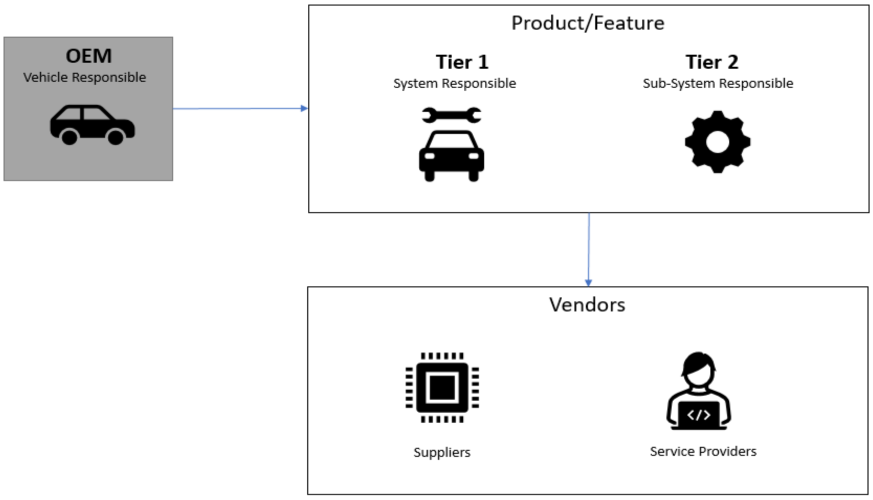

Figure 1: Automotive Collaboration Model

Automotive Features are classified into multiple domains. Features like interior light and exterior light comes under Body Domain. Similarly, there are multiple domains like Chassis, Advance Driver assistance system (ADAS), Transmission etc. Automotive gives the rough idea of the set of features that falls under the purview of Automotive ECU development.

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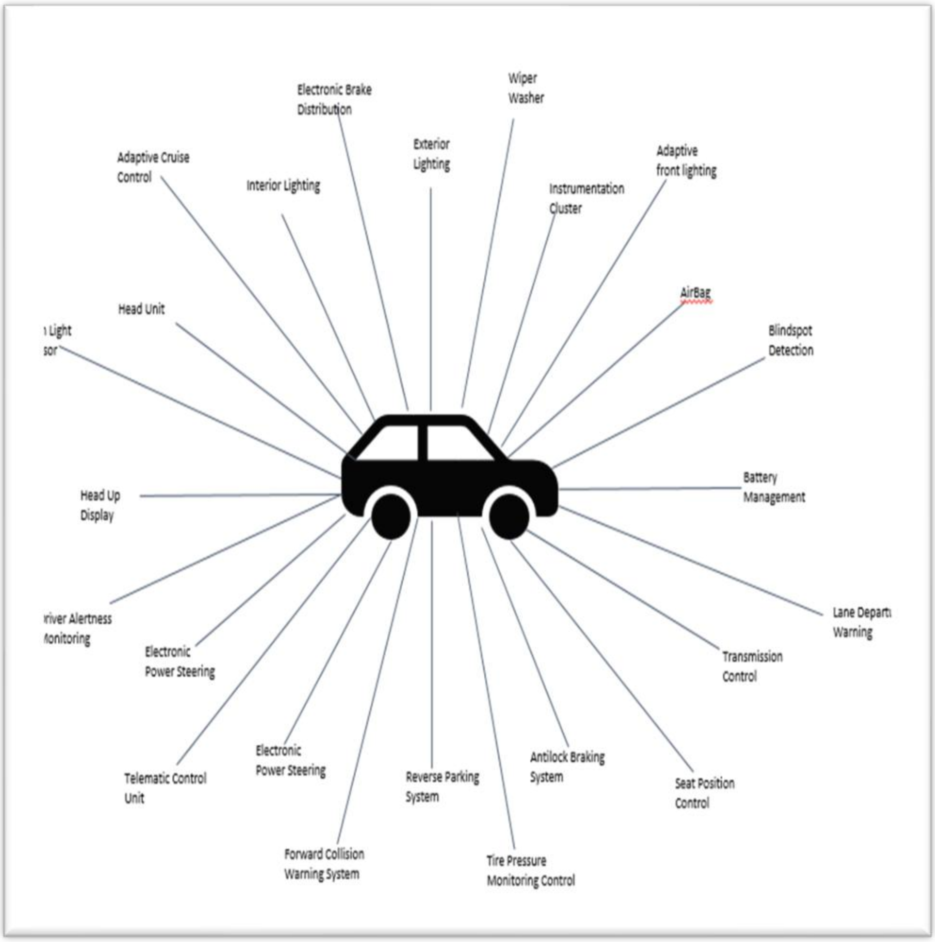

Figure 2: Advancing Features in Automotive

Literature survey

Government across the globe are bringing in norms to bring such features under the umbrella for common standard. With this combined Effort ISO26262 standards was developed to cater to the needs of Automotive Domain.

National Road Safety Report

Government of India under created "National Road Safety Policy" under the ministry of Road Transport and Highways [5]. Government of India in its preamble has recognized road accidents as a major public health issue. The National Road Safety policy not only focusses on creating better road infrastructure and creating awareness among the general audience but also have established a road safety information database but also is concentrating on ensuring that safety features are built in at the stage of design in line with internationals standards and practice. With increasing use Automobile and infrastructure development has enabled rapid development of the society, But the downside is also increase in the number of accidents on the road and in turn has increased the fatalities to the human life. According to the data cited on National Road Safety website the trend in the Database shows that the road accidents have started decreasing over the period from 2011 to 2018 after the policy came into effect. [5]

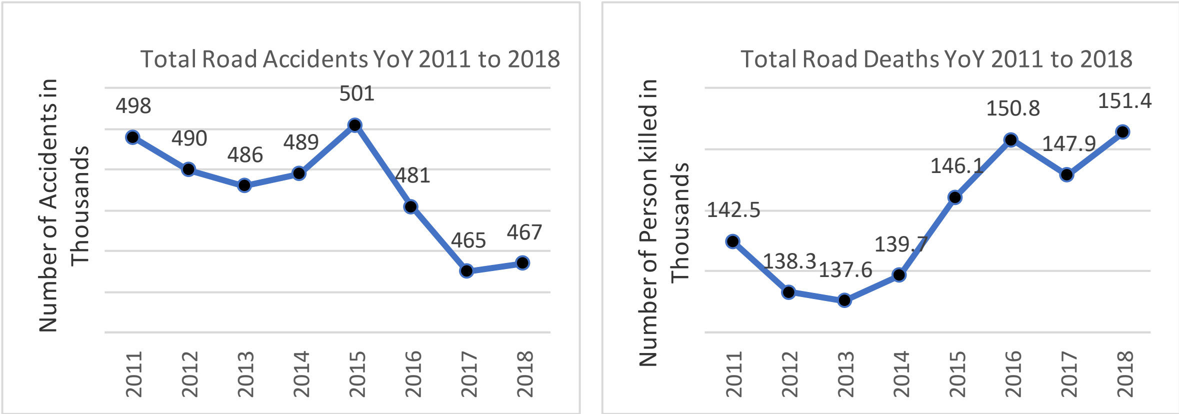

Figure 3:Summary of Accidents & Road Deaths from National Road Safety Database

The trend seems to point out good progress done in the direction of creating awareness and implementing strategy. Also, road infrastructure has not improved over the years. But unfortunately, is it also visible from the information database that the number of fatalities due to accidents is constantly increasing. The trend shows similar behavior for not only for national highways but also for the state highways. Fatalities has increase by 6% from 2011 to 2018. Figure 3:Summary of Accidents & Road Deaths from National Road Safety Database show the trend line of fatalities. When the data is investigated in isolation it points to the direction where the road accidents seem to decrease but Fatalities on the roads point in the directions of increasing trends. But there 3 more data points which helps are understand the current trend.

1) Accidents trends on different Roads

National road safety data shows an important characteristic where the percentage accident trend which respect to state highways Vs National highways vs Other Roads shows the same trend.

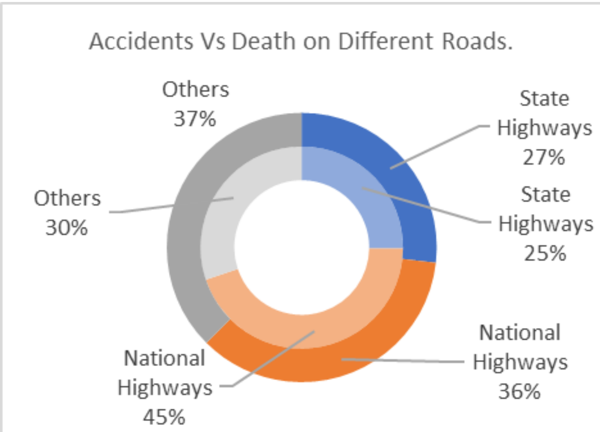

Figure 4: Accidents vs Deaths on Different Roads.

2) Accident Trends on type of road

It is also evident from the database that the greatest number of accidents are happening on straight road followed by curved road. Nearly 66% of the accidents are happening on the straight Road.

3) Impacting Vehicles

Based on the observation of the trend data is clear fatalities risk are high in Passenger and commercial vehicles compared to other type of vehicles. Figure 5: Accident vs Death Impacting vehicles shows the National figures for the year 2018 from the national safety database. [5]

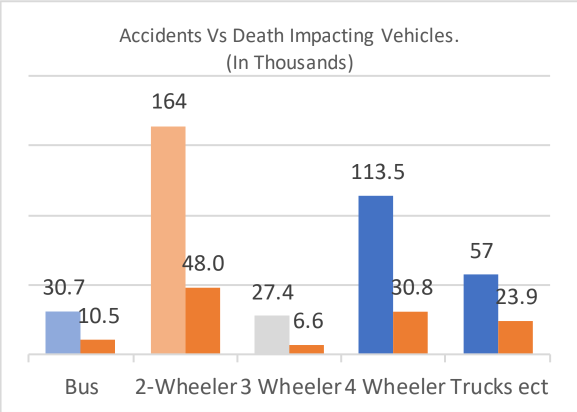

Figure 5: Accident vs Death Impacting vehicles

4) Cause of Accident

National Figures have a very clear graph showing that the greatest number of accidents are happening due to over speeding. Figure 8: Cause of Accidents shows the detailed analyses for the year 2018.

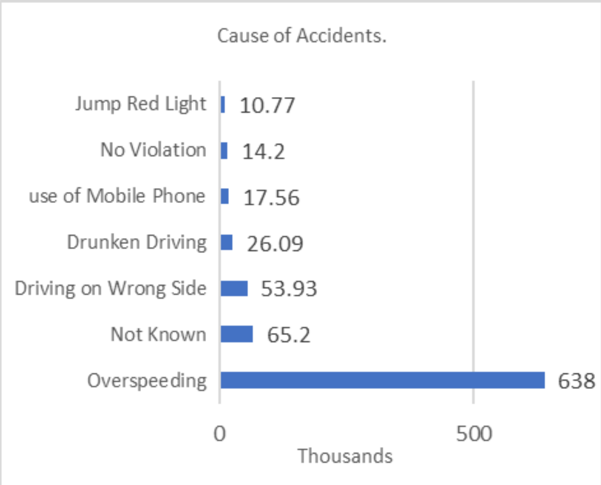

Figure 6: Cause of Accidents

Based on the following 4 factors viz Accidents trends on different Roads, Accidents Trends on type of Roads, Accidents vs death ratio based on impacting vehicle and Cause of Accidents an inference can be drawn those Accidents and deaths are higher in Passenger and Commercial car on a straight or curved road irrespective of the road condition and the top 2 causes are either Over speeding or not Known. Hence it is imperative to work on the design of such types of vehicles to make them more and more Safe to drive. It calls for implementation of safety standards implementation across the design and development phase of Vehicle and ECU.

AUTOSAR

AUTOSAR (AUTomotive Open System ARchitecture) is an open and standardized software architecture for automotive electronic control units (ECUs). It is a collaboration between automotive manufacturers, suppliers, and tool developers, with the aim of improving the development, integration, and maintenance of software in vehicles. AUTOSAR provides a common software architecture that can be used across different automotive platforms and manufacturers, which helps to reduce the complexity of developing automotive software. The architecture is based on a layered approach, with different software modules providing different functions and services. The modules communicate with each other through standardized interfaces, which helps to ensure interoperability and compatibility.

Some of the key features of AUTOSAR include:

Standardized interfaces: AUTOSAR provides a set of standardized interfaces that enable communication between different software modules and hardware components.

Scalability: The architecture is designed to be scalable, so it can be used in a wide range of vehicles, from small cars to heavy-duty trucks.

Flexibility: AUTOSAR allows for the development of customized software components that can be integrated into the architecture, which provides flexibility for different vehicle platforms and manufacturers.

Safety: AUTOSAR includes a concept for functional safety, which ensures that the system is designed and implemented in a way that provides a high level of safety, even in the presence of faults or errors.

Tool support: AUTOSAR includes a set of tools for software development, including code generators, configuration editors, and test tools, which helps to improve the efficiency of the development process.

AUTOSAR is widely adopted in the automotive industry and is used by many major automotive manufacturers and suppliers. Its open and standardized approach has helped to improve the interoperability and compatibility of automotive software, which has led to increased efficiency and reduced development costs.

PMSM (Permanent **magnet synchronous motor)**

PMSM motors are widely used in battery electrical vehicles and hybrid electrical in automotive industry. PMSM is a AC synchronous machine.

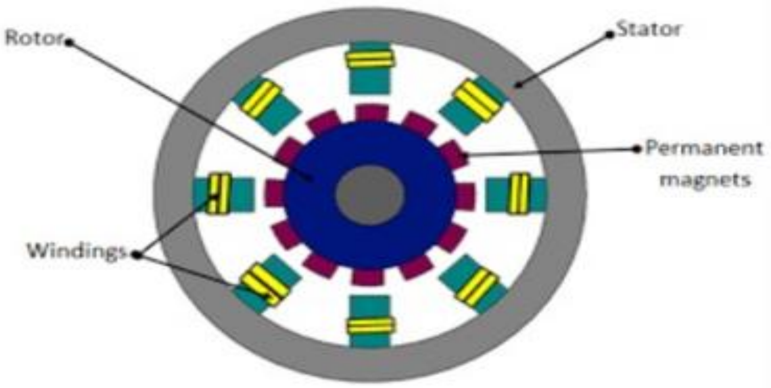

Figure 7: PMSM motor Construction

Rotor and Permanent Magnets:

Permanent magnets are embedded in the rotor to create a constant magnetic field which does not changes polarity. Normally high magnetic strengths permanent magnets are used in PMSM construction.

Stator and Windings:

Stator windings consist of copper wires that are excited by the electrical power. The stator windings generate a sinusoidal flux density in the air gap of the machine, like that of the asynchronous motor. The power density is higher than that of asynchronous motors at the same nominal values, because the stator magnetic field is generated without a power supply.

Working Principle:

When stator windings are energized, rotating magnetic field is produced & emf created rotor is affected by this force and starts rotating at synchronous speed. PMSM runs on AC as the coil winding over the stator is in a sinusoidal manner. The PMSM generates sinusoidal back emf and produces low torque repulsion. Due to low torque repulsion, PMSM has higher, and smooth torque, higher efficiency and low noise compared other synchronous motors (e.g., BLDC)

Field Oriented Control (FOC) Principle:

In context of Automotive applications, battery packs are normally DC Sources. The DC voltage cannot be directly fed into the windings of the 3-Phase motor (in this case, the PMSM motor). The DC voltage must be converted into AC phase voltages. This is what an inverter does.

Torque is directly proportional to the current flowing in the motor. The higher the current flowing in the motor, higher will be the torque. This implies, that controlling the current flowing in the motor can result in controlling the torque. This is where Field Oriented Control (FOC) comes into picture. There are other motor control techniques also, but one of the key differentiating factors of the Field Oriented control (FOC) technique is its ability to provide good control capability over the full torque and speed range of the motor and hence, it is used in a widespread manner for control of the Permanent Magnet Synchronous Motors.

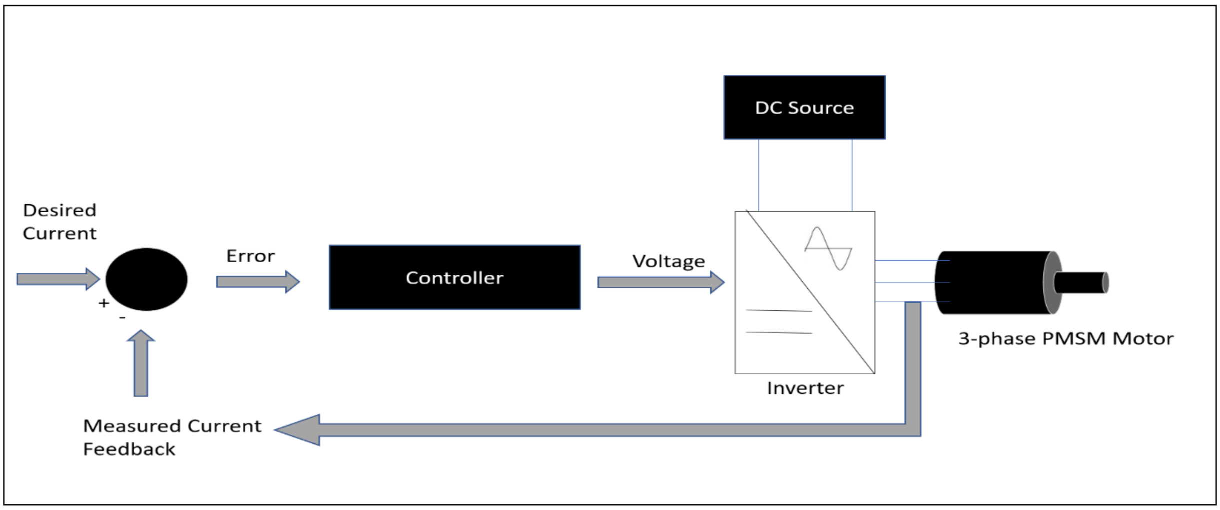

Figure 8: Motor Control Basic Principle

The basic principle of the Field Oriented Control technique is the following:

- Read the feedback current (e.g., via a current sensor).
- Read the reference current i.e., the desired current.
- Calculate the error between these two values.
- Give this Error value as the input signal to a PI Block to calculate the output voltage.
- This Output Voltage is given to the inverter.
- All the above steps to be repeated at a high sampling frequency.

To control the torque in a PMSM motor, the 3-phase sinusoidal currents must be controlled i.e., we need three control systems. For doing so, the FOC algorithm first converts 3-phase sinusoidal currents into a 2-axis system. This 2-axis system is referred to as the Stationery Reference frame. This conversion is achieved by the Clarke Transformation. In FOC, the sinusoidal currents, voltage and magnetic flux are represented as space vectors.

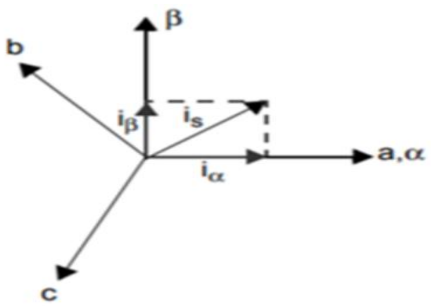

Figure 9: Clark Transformation

Hence, in the above example, the 3-Phase feedback currents Ia, Ib, Ic are converted into equivalent Iα and Iβ in the 2-axis Stationery reference frame vectors. This implies, that we need two control systems to control the three currents.

The currents Iα and Iβ are sinusoidal i.e., AC quantities. These AC quantities are difficult to control than the corresponding DC quantities. This is solved by the Park Transformation which essentially converts the stationery reference frame vectors (α, β axis frame) into rotating reference frame vectors (d, q axis frame) i.e., Iα and Iβ are converted to Id and Iq. Id and Iq are constant DC values.

To convert the stationery reference frame vectors (α, β) to rotating reference vectors (d, q), it is also essential for the FOC algorithm to calculate the rotor position i.e., the rotor angle (θ). This can be usually done with the help of a position sensor. The d-q frame is rotating with the rotor flux the d-axis is parallel to the rotor flux and the q-axis is perpendicular to rotor flux. Maximum torque is produced when the stator flux vector and rotor flux vector is 90 degrees. In other words, maximum torque is produced when the current vector is perpendicular to rotor flux. The q-axis component controls the torque of the motor, and the d-axis component controls the flux.

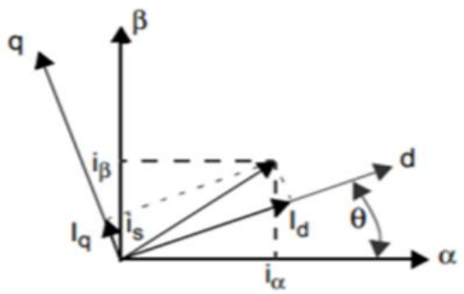

Figure 10: Park Transformation

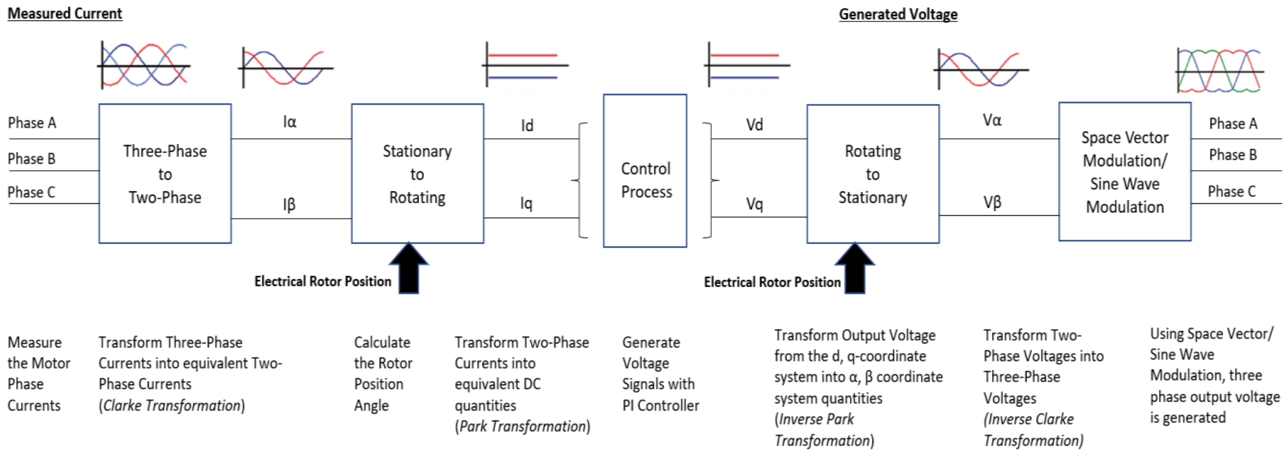

Figure 11: Steps in FOC Technique

To summarize, the FOC technique for controlling a PMSM motor can be represented in the following steps:

- Measure the 3-Phase Feedback currents (Ia, Ib, Ic). This can be done via ADC unit of the microcontroller.
- Convert the 3 -Phase currents into 2-axis Stationery reference frame vectors (Iα, Iβ) using Clark Transform.
- Calculate the rotor angle (θ) i.e., the angle between the flux vector and the α axis.
- Using the rotor angle (θ), convert the (Iα, Iβ) vectors into (Id, Iq) axis i.e., the rotating reference frame vectors.
- Provide the rotating reference frame vectors (Id, Iq) to as an input to the respective PI controllers to calculate the output voltage signals (Vd, Vq).
- Covert (Vd, Vq) to (Vα, Vβ) using inverse Park transform.
- Convert (Vα, Vβ) to (Va, Vb, Vc) using inverse Clarke Transform.
- Convert the output voltage into PWM signals.

- Repeat all the above steps at a high sampling frequency.

Proposed Methodology

ASIL stands for Automotive Safety Integrity Level, which is a risk classification scheme for automotive systems defined by the ISO 26262 standard. The ASIL classification is used to determine the appropriate level of safety measures and requirements for the development of electronic and electrical automotive systems. There are four levels of ASIL, ranging from A to D, with ASIL A representing the lowest level of risk and ASIL D representing the highest level of risk.

Here's a brief overview of each ASIL level[2]:

ASIL A: This level is used for systems that have a low risk of causing harm to humans, such as systems that control the air conditioning or audio system.

ASIL B: This level is used for systems that have a moderate risk of causing harm to humans, such as systems that control the engine or brakes.

ASIL C: This level is used for systems that have a high risk of causing harm to humans, such as systems that control the steering or transmission.

ASIL D: This level is used for systems that have the highest risk of causing harm to humans, such as systems that control the autonomous driving functions.

Severity class	Exposure class	Controllability class		
		C1	C2	C3
S1	E1	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	E1	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	E1	QM	QM	A[a]
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

Figure 12: Asil Classification

Error! Reference source not found. Shows the table of reference defined by ISO26262 [1] for Risk Classification of ASIL based Systems. Where Classes of severity probability and controllability is defined as,

Classes of severity

S0: No injuries

S1: Light and moderate injuries

S2: Severe and life-threatening injuries (Survival Possible)

S3: Severe and life-threatening injuries (Survival uncertain), Fatal injuries

Classes of Probability of exposure regarding operational situations

E0: Incredibly Low Probability

E1: Very Low Probability

E2: Low Probability

E3: Medium Probability

E4: High Probability

Classes of Controllability

C0: Controllable in general

C1: Simply controllable

C2: Normally controllable

C3: Difficult to control or uncontrollable.

Some of the challenges of implementing ISO 26262 include[4]:

- **Complexity:** The standard is very detailed and covers a wide range of topics, making it difficult to fully understand and implement.
- **Time and Cost.** Meeting the requirements of the standard can be time-consuming and costly and may require significant changes to existing development processes.
- **Testing and Validation.** Ensuring that a system meets the requirements of the standard can be challenging, as it may require extensive testing and validation.
- **Risk Assessment.** Identifying and assessing potential hazards and risks can be difficult, especially in complex systems.
- **Traceability.** Maintaining traceability of requirements and design decisions throughout the development process can be difficult, especially in large and complex projects.

Each ASIL level has its own set of requirements and safety measures that must be met to ensure the system is safe for use. The higher the ASIL level, the more stringent the requirements and safety measures become. FMEA (Failure Mode and Effects Analysis)[3], FTA (Fault Tree Analysis), and HAZOP (Hazard and Operability Study) are all techniques used in risk management and quality control, but they have different applications and methodologies.

FMEA is a proactive approach for identifying potential failures and their effects on a system, product, or process. It involves identifying all potential failure modes and their effects, ranking them according to severity, and developing mitigation strategies to prevent or reduce their occurrence. FMEA is often used in the design and development of new products, processes, and systems.

FTA, on the other hand, is a deductive approach for identifying the root cause of a specific undesired event or failure in a system. It involves constructing a graphical representation of all the possible events or conditions that could lead to the failure, and then analyzing the logical relationships between them to determine the root cause of the failure. FTA is often used to investigate incidents or accidents and to identify the underlying causes.

HAZOP is a technique for identifying hazards and operability issues in a process. It involves systematically examining the process design and identifying potential deviations from normal operating conditions that could lead to hazards or operability issues. HAZOP is often used in the design and operation of chemical processes, oil and gas facilities, and other complex systems.

In summary, FMEA is used to identify potential failures and their effects, FTA is used to investigate the root cause of a specific failure, and HAZOP is used to identify hazards and operability issues in a process. All three techniques are valuable tools for risk management and quality control, and they can be used in combination to achieve a comprehensive approach to risk management.

Safety Critical Time Intervals

One of the important aspects to consider for determining the feasibility of the various safety designs is the Fault Tolerance Time Interval (FTTI). Fault Tolerance Time Interval is the time-period from the occurrence of a fault to the violation of a safety goal.

Figure 13: Safety Critical Time Intervals

Fault Detection Time (FDT): Time to Detect/ Mature a fault.

Fault Reaction Time (FRT): Time to take corrective action to reach safe state.

Fault Tolerance Time Interval (FTTI): maximum time to react to a fault beyond which potential hazard can occur.

Hazards Analysis

ID	Hazards	ASIL
H1	Potential unintended vehicle lateral motion	D
H2	Potential insufficient vehicle lateral motion	C
H3	Potential loss of steering-assist	B
H4	Potential reduced responsiveness to the driver's commands due to increased rear-wheel drag	A

Table 1: Hazard analysis of EPS System

Safety Goals

ID	Safety Goals	ASIL
SG1	The EPS system is to prevent unintended self-steering in any direction under all vehicle operating conditions.	D
SG2	The EPS system is to provide the correct level of steering-assist under all vehicle operating conditions.	C
SG3	The EPS system is to prevent the unintended loss of steering-assist under all vehicle operating conditions.	B
SG4	The EPS system is to prevent rear-wheel drag under all vehicle operating conditions.	A

Table 2: Safety Goals of EPS system

Block diagram of the proposed system:

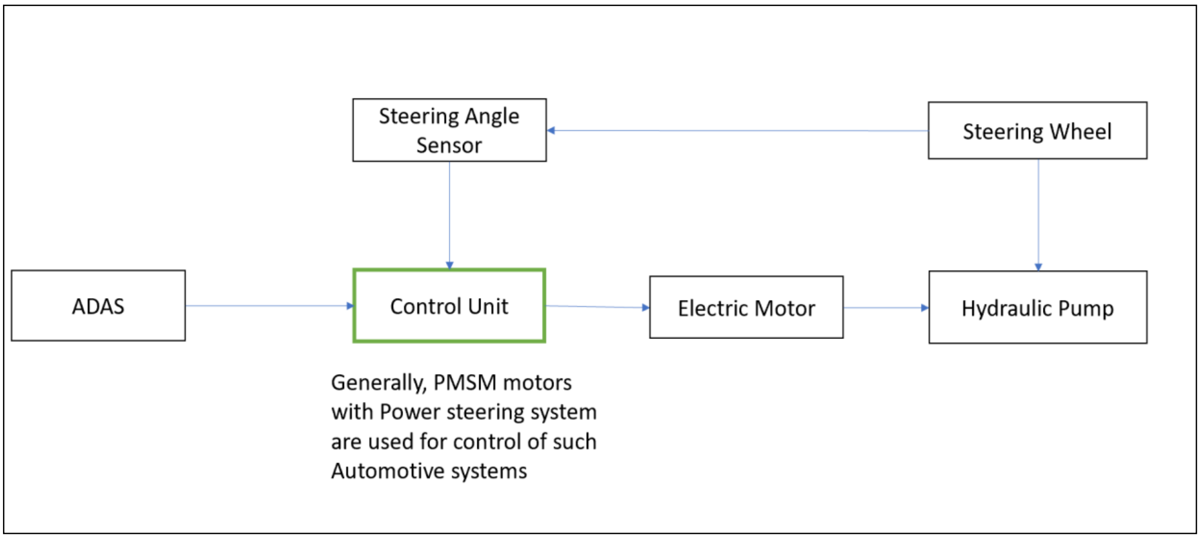

Figure 14: EHPS Block Diagram

Here is a simplified block diagram of an electrohydraulic power steering system [6]:

Steering Wheel: The driver inputs the steering command by turning the steering wheel.

Steering Angle Sensor: Measures the angle of the steering wheel to provide feedback to the control unit.

Control Unit: The electronic control unit (ECU) receives inputs from the steering angle sensor and other sensors, such as vehicle speed and engine speed. The ECU then calculates the required power assist and sends a signal to the hydraulic control valve.

Electric Motor: The electric motor provides the power to drive the hydraulic pump.

Hydraulic Pump: The hydraulic pump generates hydraulic pressure to assist the driver's steering effort.

Control Model of Targeted System:

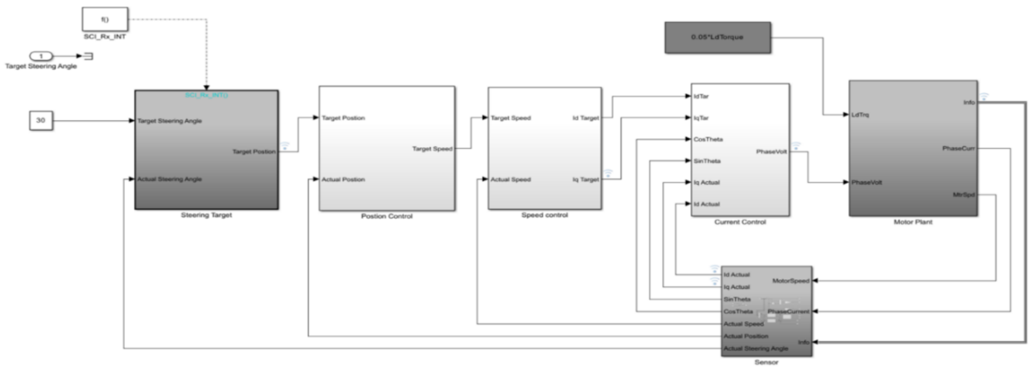

Figure 15: Control Model of Target System

Steering Target: It is a plant model of gear assembly. For the simplification of the model the gear ratio is assumed to be 1. Output of the steering.

Position control: The out of the positional control block is Target Speed. The block uses basic position time equation to calculate the speed.

Speed control: It uses the PI control block to assimilate and calculate the current needed for the torque generation.

Current control: It is based on standard inverse Clark and inverse Park transform for calculating the Iq value.

Motor Plant: It is a plant model of the PMSM motor. It simulates the basic motor characteristics.

Sensor: It is the plant model of the sensor. It Clarks and Parks transform for generation the current Id and Iq values.

Progress Update:

The entire system is dependent on the input receiver as a request for the steering Target.

Figure 16: Boundary Box of a Steering System shows if the input of the steering system is corrupted then the entire steering system would fail.

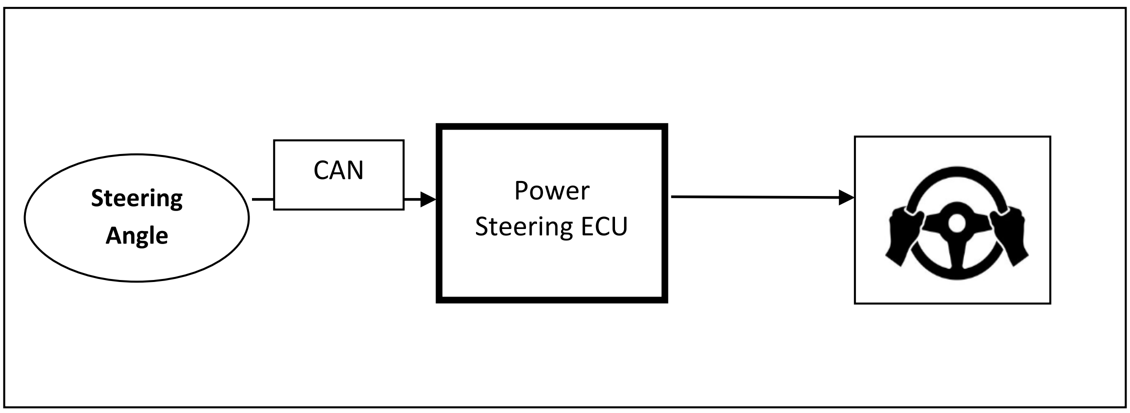

Figure 16: Boundary Box of a Steering System

The interface in a steering system from a steering angle sensor are realized by CAN (Controller Area network Protocol).The CAN protocols pack the information like "Request Steering Angle" on to CAN message. If the requested steering angle is corrupted, then the system should not fail only the manual steering should take over the operation for steering the vehicle. With this safety concept the system becomes fail passive system.

The failure in requested steering angle can happen because of the fault assumption mentioned in Table 3: Fault Assumptions for Communication failure.

Fault Assumption	**Type of communication Fault**	**Description**
FA1	Repetition of information.	A type of communication fault, where information is received more than once.
FA2	Loss of information.	A type of communication fault, where information or parts of in-formation are removed from a stream of transmitted information.
FA3	Delay of information.	A type of communication fault, where information is received later than expected.
FA4	Masquerading.	A type of communication fault, where non-authentic information is accepted as authentic information by a receiver.
FA5	Incorrect addressing.	A type of communication fault, where information is accepted from an incorrect sender or by an incorrect receiver.
FA6	Incorrect sequence of information.	A type of communication fault, which modifies the sequence of the information in a stream of transmitted information.
FA7	Information from a sender received by only a subset of the Receivers.	A type of communication fault, where some receivers do not receive the information.
FA8	Blocking access to a communication channel.	A type of communication fault, where the access to a communication channel is blocked.
FA9	Insertion of information.	A type of communication fault, where additional information is inserted into a stream of transmitted information.
FA10	Corruption of information.	A type of communication fault, which changes information.
FA11	Asymmetric information sent from a sender to multiple Receivers	A type of communication fault, where receivers do receive different information from the same sender.

Table 3: Fault Assumptions for Communication failure

The safety mechanism for communication failure and respective fault assumptions mentioned in "Table 3: Fault Assumptions for Communication failure" shall be E2E (End To End) protection mechanism specified by AutoSAR. The E2E protection mechanism normally consist of 3 important variables as follows.

1. Raw Data: Normally these are signals or information that needs to be protected.

2. Rolling Counter: This is an incremental counter that is packed with the message consisting of 4 bits.

3. CRC (Cyclic Redundancy check): This is a CRC which is calculated based a polynomial, Raw data and Rolling counter.

   E2E protocol defined in AutoSAR specification also has a lot of limitation.

1. Fixed profiles of E2E, which means the position of data and CRC are fixed.

2. Size of rolling counter

3. CRC has fixed size, and algorithm cannot change the polynomial.

4. There is no private Key separately defined for authentication.

Considering above limitation, the system is designed in such a way that the data consist of following element

1. Signals to be protected (Steering angle)

2. Private Key

3. Rolling Counter

4. CRC

It is important to note the size of above data in only restricted to the overall size of the CAN message which in normal case is 8 bytes but in case of CANFD it is 64 bytes. Also, the position of the data is variable. Hence the entire communication results into more reliable, safe as well as secure communication.

Simulation Results:

1. **Working E2E protection Mechanism:** The following Figure 17: Simulation results for E2E Protection shows the how the data is packed in E2E

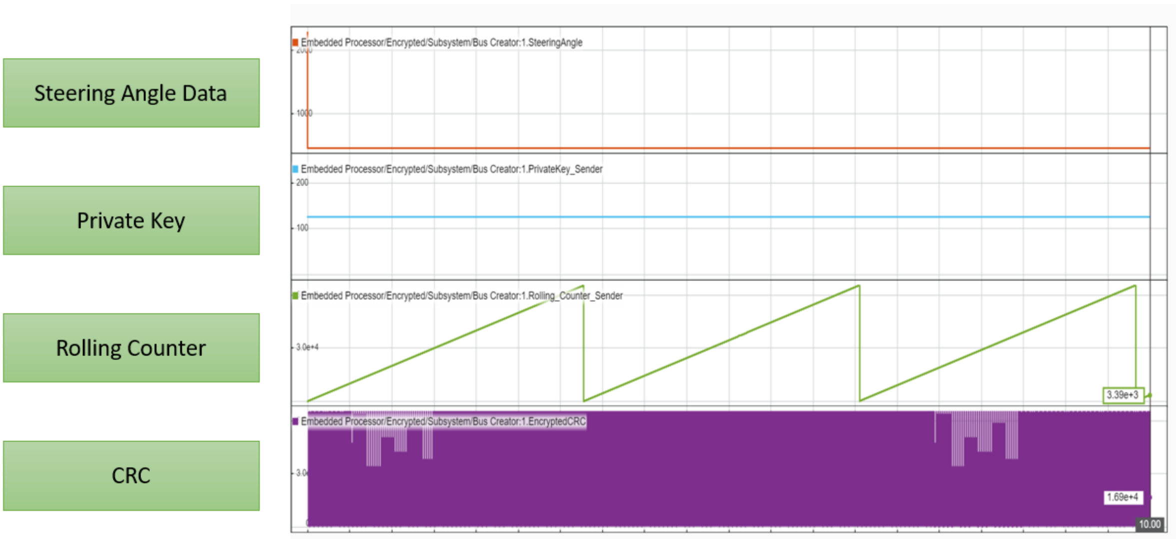

Figure 17: Simulation results for E2E Protection

2. **Fault injection Test – Corruption of information:** In the fault injection test for corruption of information, the CRC calculation algorithm on the receiver end should receive wrong CRC values. Figure 18: Fault injection Test – Corruption of information shows the behavior where if the received CRC does not match with the calculated CRC, then the steering assistance is zero.

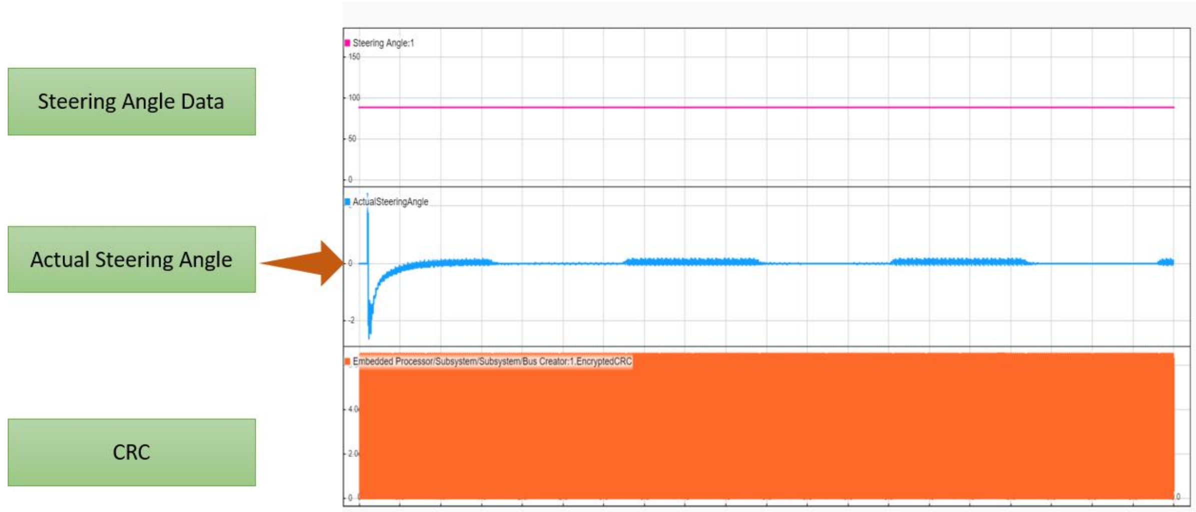

Figure 18: Fault injection Test – Corruption of information.

3. **Fault injection Test – Delay in Information:** In the fault injection test for delay of information, the transmitted rate of the sender message shall be greater than the expected received rate of receiver message. This can be achieved by comparing the rolling counter with the received rolling counter. Figure 19: Fault injection Test – Delay in Information shows that if the transmit message rate is more than receive message rate than the steering assist is zero.

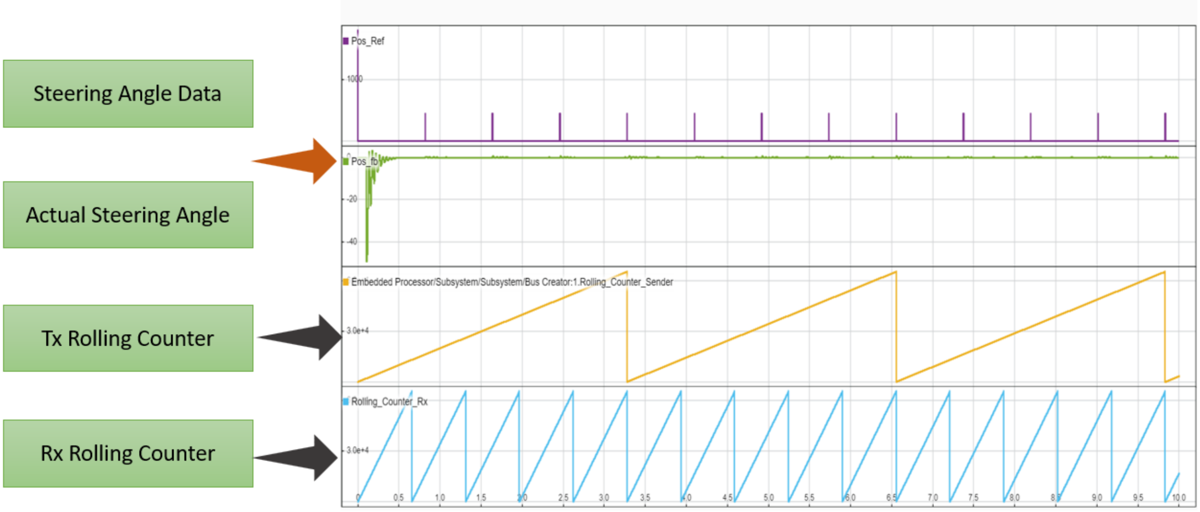

Figure 19: Fault injection Test – Delay in Information

4. **Fault injection Test – Insertion of Information & Masquerading:** In the fault injection test for insertion of information, the transmitted private key of the sender shall not match with private key information of the receiver message. This can be achieved by comparing the private keys of the transmit and received message. Figure 20: Fault injection Test – Insertion of Information & Masquerading. shows that if the private key does not match on the sender and receiver side than the steering assist should be zero.

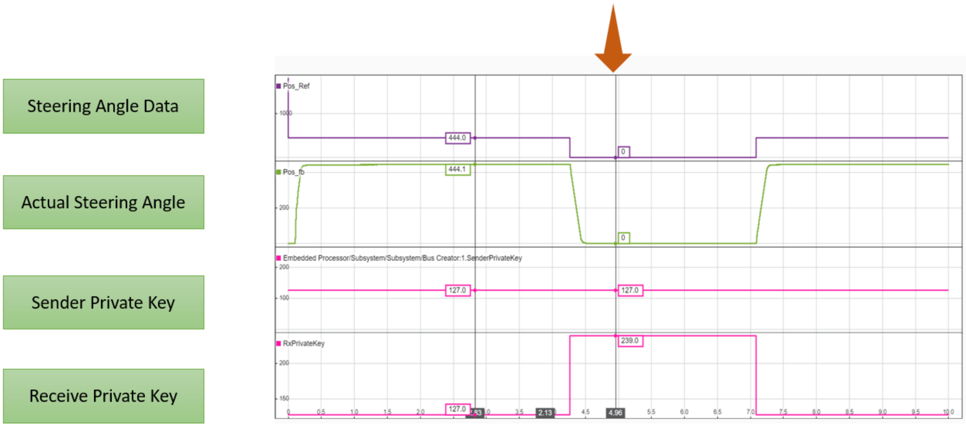

Figure 20: Fault injection Test – Insertion of Information & Masquerading.

5. **Fault injection Test – Loss of information:** In the fault injection test for loss of information, the transmitter will stop sending the message, but the receiver still expects the messages and reaction accordingly. Figure 21: Fault injection Test – Loss of information. Shows that the Tx rolling counter became zero means it was stopped but the receiver was continuously checking it to arrive and hence the steering assist should be zero.

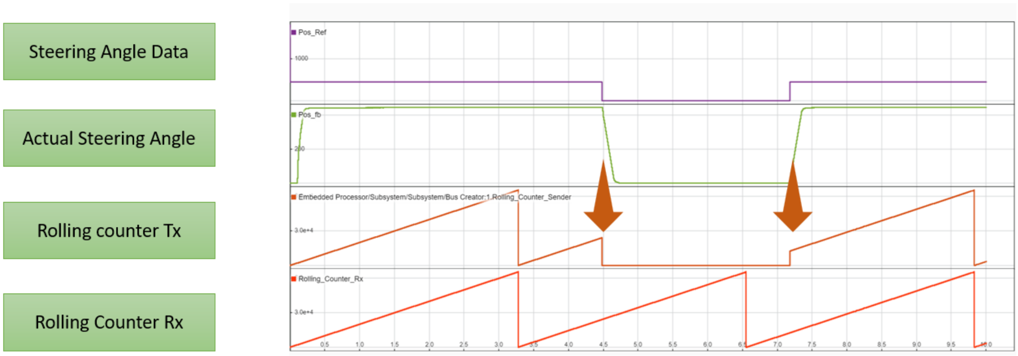

Figure 21: Fault injection Test – Loss of information.

6. **Fault injection Test – Repetition of information:** In the fault injection test for repetition of information, the transmitter will transmit will start repeating the rolling counter whereas the receiver shall expect the data with right increment value. Figure 22: Fault injection Test – Repetition of information shows that the transmitter is repeating the messages whereas the receiver expects the information to match hence the steering assist becomes zero.

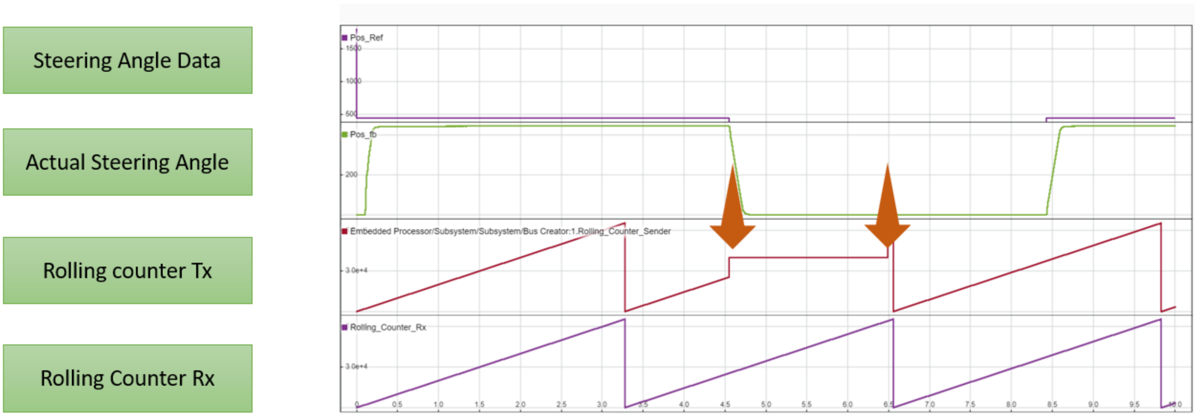

Figure 22: Fault injection Test – Repetition of information

Key findings from the simulation:

1. Fault injection test results shows that the system is more reliable compared to the non-protected communication channel.
2. Under no fault the communication is active, and the system has no effect.
3. System has become Fail Passive where the system does not assist when the wrong information is received, or no information is received.
4. Safe state for such system is to let mechanical assembly take over.

Work Planned

The research work requires understanding of basic concepts of functional safety.

1. Publishing the results of the injection test.
2. Mapping the Private Key specific to the car
3. Comparing the results to the standard E2E results.

Conclusions

“National Road Safety Database” provided by Ministry of Road Transport and Highway, Government of India gives concrete 5 trends viz. Accidents trends on different Roads, Accidents Trends on type of Roads, Accidents vs death ratio based on impacting vehicle and Cause of Accidents. An inference can be drawn those Accidents and deaths are higher in Passenger and Commercial vehicles on a straight or curved road irrespective of the road condition and the top causes are either Over speeding or not Known. Hence it is imperative to work on the design of such types of vehicles to make them safer to drive. It calls for implementation of safety standards implementation across the design and development phase of a Power Steering systems, because this system plays an important role in driving scenario concerning Over speeding, Curve Road etc.

Steering systems have been vastly studied across the globe and have detailed regional regulations defined for the same. Steering system norms and regulations are uniform across category of vehicles like internal combustion engines, hybrid electric vehicles and battery electric vehicles. Such systems are good case studies for generic functional safety impact analysis.

Based on the Simulation result it is very clear the that the most important factor for the safety system is the communication channel. The fault assumption is completely protected from external influence by the E2E mechanism. Further studies can lead to comparison in terms of efficiency for the proposed model based on the timing and FTT requirement.

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