Faculdade de Engenharia da Universidade do Porto

Arquitecturas de Hardware para um Veículo Eléctrico

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Resumo

A indústria automóvel tem vindo ao longo dos anos a sofrer uma evolução exponencial. Os veículos modernos estão cada vez mais a ser dotados de funcionalidades que providenciam uma maior segurança, conforto, eficiência e performance. Estas funcionalidades são baseadas não só em sistemas computacionais isolados, mas resultam também da interacção entre vários sistemas, que são suportados por várias redes de comunicação de dados com requisitos e aplicações distintas.

À medida que os componentes mecânicos têm vindo a ser substituidos por equivalentes electrónicos, são exigidos a estes níveis de confiança elevados no seu funcionamento, que podem apenas ser atingidos com o recurso a técnicas de concepção de arquitecturas tolerantes a falhas.

Este trabalho apresenta uma visão geral de várias funcionalidades que podem ser encontradas nos veículos modernos, das arquitecturas e redes de comunicação que suportam o seu funcionamento, e de algumas das técnicas de concepção que permitem aumentar a confiança que pode ser depositada no funcionamento destes sistemas. Por fim, é apresentada uma proposta para uma arquitectura de um sistema de travagem com requisitos de segurança crítica.

Abstract

The automotive industry has been evolving over the years in an exponential fashion. Modern vehicles are increasingly being provided with features which provide greater security, comfort, safety and performance. These features are not only based in isolated computational systems, but also result from the interaction between various systems, which are supported by several data communication networks with distinct requirements and applications.

As mechanical components are being replaced by their equivalent electronic, higher levels of dependability are being demanded from these, which can only be attained by means of fault tolerant design techniques.

This work presents an overview of the various features that can be found on modern vehicles, the architectures and communication networks that support their operation, and some of the design techniques which allow an increase of their dependability. Finally, a proposal for the architecture of a braking system with safety critical requirements is presented.

Agradecimentos

Aos meus pais por me terem feito acreditar que o caminho mais difícil é o que mais compensa, e por me terem dado todas as condições e mais algumas para que tivesse sucesso.

Ao Prof. Doutor Paulo Portugal, não só pelo seu profissionalismo, mas também pela sua capacidade de motivação, indispensável nos momentos mais complicados deste trabalho.

À Joana, por todo o apoio que me deu e por continuar comigo após esta longa ausência.

A todos os meus amigos que de algum modo procuraram ajudar.

"***All the so called secrets of success will not work unless you do***"

Unknown Author

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Symbols and Acronyms

4WS - Four Wheel Steering
ABS – Antilock Braking System
ACC - Adaptive Cruise Control
ASIC - Application Specific Integrated Circuit
CAN - Controller Area Network
CRC - Cyclic Redundancy Check
CSMA/CD - Carrier Sense Multiple Access with Collision Detection
DEEC - Departamento de Engenharia Electrotécnica e Computadores
EBA - Electronic Brake Assist
EBD - Electronic Brake Force Distribution
ECU - Electronic Control Unit
EHB - Electro Hydraulic Brake
EMB - Electro Mechanical Brake
ESC - Electronic Stability Control
ETA - Event Tree Analysis
ETC - Electronic Throttle Control
EV - Electric Vehicle
FEUP - Faculdade de Engenharia da Universidade do Porto
FMEA - Failure Modes and Effects Analysis
FSU - Fail Silent Unit
FTA - Fault Tree Analysis
FTU - Fault Tolerant Unit
HCU - Hydraulic Control Unit
LED - Light Emitting Diode
LIN - Local Interconnect Network
LSB - Least Significant Bit
MCU - Microcontroller Unit
MOST - Media Oriented Systems Transport
MSB - Most Significant Bit
RPM - Revolutions Per Minute
TDMA - Time Division Multiple Access
TTEthernet - Time Triggered Ethernet

Chapter 1

Introduction

1.1 Motivation

Recent environmental concerns allied to a decrease in the available sources of fossil fuel are leading vehicle manufacturers to invest on the development of alternative transportation methods. The use of electrical energy on vehicles is promising, since it can be obtained in a more efficient way with a lower impact on the environment [1].

Even when the energy which supplies electric vehicles (EVs) is obtained by means of polluting fuel sources such as coal, crude or oil, the efficiency provided by electric vehicle powertrains results in cleaner ecological footprints when comparing to internal combustion engine (ICE) vehicles [2, 3]. The future is even brighter, as efforts are widely being put together to convert carbon emitting power stations into clean renewable sources of energy, motivated by European Union targets of having at least 20% of the energy consumed coming from renewable resources until the year of 2020 [4].

It has been demonstrated that the acceleration, speed and handling of electric vehicles can equal or exceed that of ICE vehicles [5]. Moreover, electric vehicles produce less noise and emit zero tailpipe gases, making them the appropriate choice for use in urban transportation.

Figure 1.1 - Tesla roadster, a fully electric sports vehicle

The department of electrical and computer engineering (DEEC) at the Faculty of Engineering of the University of Porto (FEUP) has just finished building a new laboratory which will host the development of many projects related with EVs. This new infrastructure will allow students to develop solutions related to EVs along their academic career.

Several features which provide greater safety, comfort, efficiency and performance, are being increasingly integrated in modern vehicles. The information about such features, their hardware architectures, the communication networks that support their operation, and the techniques used by manufacturers to provide them with the required dependability levels, is significantly widespread.

The agglomeration of such information on a single document will allow students to easily move for the actual implementation of these features.

1.2 Objectives

Two main objectives have been defined for this thesis. The first objective is the elaboration of a survey covering:

- The various features that are commonly found on modern vehicles, their general concepts of operation, and the hardware architectures which support their behavior
- The networking solutions used in the automotive industry which support the behavior of the identified features

The second objective of this work is the proposal of a conceptual architecture for the braking system whose implementation can be achieved taking in consideration:

- The background obtained by students along their academic career
- The feasibility of the braking system by the students
- The availability and cost of the components that will support the proposed architecture
- The aspects of dependability in which a braking system much rely on

1.3 Document Structure

This document is divided into 6 chapters.

Chapter 1 presents the motivation behind this work and the objectives that have been defined.

Chapter 2 provides an overview on the systems that are commonly found in modern vehicles, their major requirements, and a closer look on the systems which are considered to be a priority for the development of projects within the context of the new automotive laboratory.

Chapter 3 addresses the networking solutions which are used to interconnect the systems referred in Chapter 2. Controller area network (CAN), local interconnect network (LIN) and Flexray are presented due to their actual importance in the automotive industry. TTEthernet is presented as a promising solution for future vehicles.

Chapter 4 presents the emerging concept of *by-wire* systems applied to the automotive industry. Several techniques and ideas that can be used by students to increase the dependability of their systems are introduced in this chapter.

Chapter 5 presents the proposed hardware architecture for the braking system architecture and the algorithms which support its dependability.

Chapter 6 overviews all of the work that has been done and future work.

Chapter 2

In-Vehicle systems

2.1 Introduction

The first part of this chapter starts with an overview of the different systems that can be usually found on vehicles. Afterwards, several of these systems which are considered to be a priority for the development of the EV project are explored with further detail.

2.2 Automotive Systems

The various subsystems that compose a vehicle can be classified into several domains according to their functionalities. The number and name of these domains varies along the literature [6, 7]. In this section, seven domains are considered and an overview of typical systems and requirements is presented.

2.2.1 Powertrain

The powertrain enclosures the systems that are responsible for converting power into the motion of the vehicle. Examples of systems in the powertrain domain are

- the propulsion system controller which has the task of controlling the propulsion device (which can be an electric motor or an internal combustion engine) according to the driver's inputs and requests from other systems, such as the electronic stability control, traction control system or adaptive cruise control.
- automatic transmission controllers
- battery management systems

Systems belonging to this domain are characterized by:

- High computational power to deal with the complex algorithms that support the control of the propulsion and transmission devices
- Low sampling/actuation times to allow for smooth control

- Hard real-time requirements

2.2.2 Chassis

The chassis domain integrates the systems responsible for the interaction between the vehicle and the road [6]. This domain includes braking, steering and suspension systems. Examples of systems in the chassis domain are

- Power steering which monitors the driver's steering intentions and provides an assisting force in steering the vehicle
- Antilock braking system (ABS) for wheel lock-up prevention upon braking
- Electronic Stability Control (ESC) to prevent the vehicle from skidding
- Traction Control System (TSC) in order to control vehicle traction when accelerating
- Adaptive Cruise Control (ACC) to enhance comfort by the autonomous control of the distance or headway time to front vehicles
- Electronic Damper Control (EDC) to control the vertical movement of the wheels

Systems which belong to this domain are characterized by having:

- High computational power
- High sampling/actuation rates
- Hard real-time requirements
- Fail safe constraints which allow these systems to fail in a safe way
- Fault tolerance in the case of x-by-wire and steer-by-wire systems

2.2.3 Body

The body domain comprises systems that do not interfere with the vehicle dynamics. Examples of systems belonging to the body domain are

- interior and exterior lighting systems
- air conditioning systems which control the temperature of the cockpit
- vehicle access systems which ease the access to the vehicle and provide security
- seat control systems which provide more comfort
- park distance control which monitors the distance to obstacles to aid the driver when parking the vehicle

Systems belonging to this domain are typically characterized by having:

- Low computational power
- Low sampling/actuation rates as events are mostly triggered by human interaction
- Soft real-time requirements

It must be noted, however, that lighting systems are evolving in a way in which they do not share the computational requirements with other systems from the body domain. Several lighting systems whose requirements are most approximated with the powertrain and chassis requirements are presented in Section 2.6.

2.2.4 Passive Safety

Passive safety systems operate in order to reduce the effects of a crash. Examples of systems belonging to this domain are:

- Airbag systems which deploy inflatable envelops upon impact according to the type (front impact, lateral impact) and severity of impact, with the intention of reducing shocks applied to the driver
- Seat belt pretensioners which maintain the driver in a steady position during crashes and sudden vehicle movements

Systems belonging to this domain are typically characterized by having:

- High computational power
- High sampling/actuation rates
- Hard real-time requirements
- Fail safe constraints

2.2.5 Human-Machine-Interfaces (HMI)

HMI systems provide the interaction between the driver and the vehicle. Examples of systems belonging to this domain are:

- Instrument panels which provide information on the status of many of the vehicle variables of interest such as speed, rpm, fuel level among others
- Tire pressure management systems which monitor tire pressure and informs the driver of possible dangerous situations

Systems belonging to this domain are typically characterized by having:

- Low to high computational power depending on the complexity of the display systems
- Medium sampling/actuation times, congruent with human perception
- Soft real time requirements

2.2.6 Infotainment and Telematics

Infotainment and telematics systems provide information, entertainment and the interaction between the vehicle and the exterior world. Examples of systems belonging to this domain are:

- Global positioning systems that provide the driver with information on its location, direction and speed
- Audio Systems
- DVD Players
- Fleet management systems which allows the tracking of vehicles
- Vehicle internet connection

Systems belonging to this domain are typically characterized by having:

- Very high computational power
- Soft real-time requirements

2.3 Braking Systems

This section presents an overview of the features and architectures of braking systems.

Braking systems are safety critical on their nature. This means that the failure of these systems to perform their expected operations can result in a catastrophic event, such as the damage of the vehicle and ultimately the injury or dead of people and environmental harm. The architectures of braking systems are therefore conceived taking in consideration the required dependability for their operation. Throughout this section, these systems are presented without the consideration of these issues as general references for the development of safety critical systems are given Chapter 4.

The architectures presented in this chapter may reflect slight adaptations from the studied systems. Therefore, several details that do not contribute for the understanding or the concepts involved were omitted.

2.3.1 Antilock Braking System (ABS)

According to [8], the ABS system reduces fatal collisions with pedestrians in thirteen percent and achieves a twelve percent reduction in collisions between vehicles on wet roads. The ABS was proven to grant more efficiency in nonfatal crashes, reducing the overall crash rate by six percent for passenger cars and eight percent for light trucks and vans.

The ABS is a safety-related feature that assists the driver in deceleration of the vehicle in poor or marginal braking conditions, such as wet, icy or sandy pavements [9].

When the driver presses the brake pedal, a force is generated on the wheels which counteracts its motion. Depending on the surface in which the wheels are spinning, this braking force can achieve a value that can cause the wheels to slip.

The relationship between the vehicle speed and the slip of the wheel is denominated brake slip and is defined as the ratio between the speed of the wheel and the speed of the vehicle itself

$$\lambda = \frac{S_{vehicle} - S_{wheel}}{S_{vehicle}} \times 100\% \qquad (2.1)$$

$$where:$$

$$\lambda: brake\ slip$$
$$S_{vehicle}: speed\ of\ the\ vehicle\ (meters/second)$$
$$S_{wheel}: speed\ of\ the\ wheel\ (meters/second)$$

Figure 2.1 illustrates the relationship between the wheel slip and the adhesion coefficient of the wheels for several surfaces. The higher the adhesion coefficient is, the more braking force is effectively used to reduce vehicle speed and consequently its stopping distance.

Disregarding snowy surfaces, it can be denoted that the adhesion coefficient reaches its maximum value, and after decreases with the increase of wheel slip. It can be concluded that the higher the wheel slip is, the higher the stopping distance of a vehicle will be.

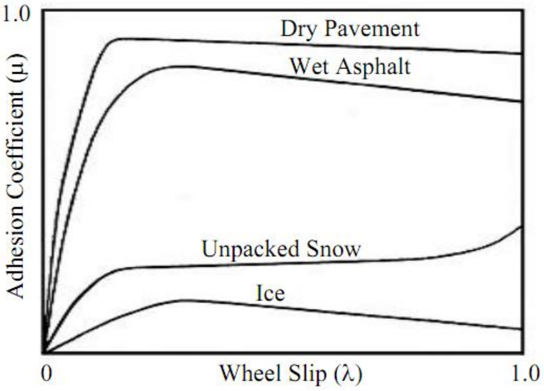


Figure 2.1 - Relationship between the adhesion coefficient and wheel slip in different road conditions [10].

The lateral friction is what enables the vehicle to steer [10]. Its value is also dependent on wheel slip, as illustrated by Figure 2.2. It can be seen that as the wheel slip ratio increases, the lateral friction coefficient decreases and so the vehicle maneuverability.

The chart on Figure 2.2 depicts two distinct zones in respect to wheel slip: the stable and the unstable zone. The stable zone ends where the maximum value of the friction coefficient is reached. The unstable zone is characterized by a rapid deceleration of wheel speed, that leads to wheel lock-up, corresponding to the minimum lateral friction coefficient. At this point, wheels are completely blocked and the vehicle maneuverability is drastically reduced.

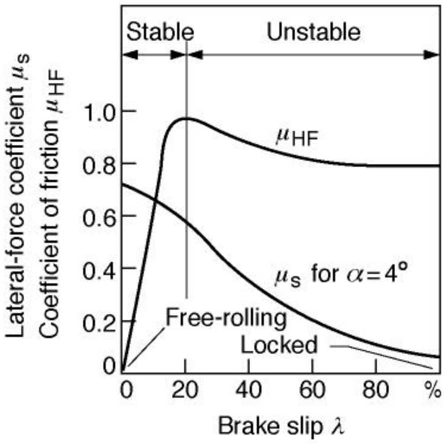


Figure 2.2 - Relationship between brake slip, lateral force coefficient, and coefficient of friction [11]

2.3.1.1 ABS Operation

The objective of the ABS system is to ensure that the brakes operate near their most efficient point, therefore granting steering control at all times and shorter stopping distances [12]. This is achieved by controlling wheel slip so that its value is kept below the unstable zone. Wheel slip is controlled by controlling the force applied to the brakes.

The ABS constantly monitors wheel speed for situations that might indicate wheel slip approaching the unstable zone. If such situation is detected, the brake force applied is prevented to be raised any further. In case that the wheel slip steps into the unstable zone, the ABS reduces brake force so wheel slip is taken back into the stable zone. To avoid under braking and maximize braking efficiency, the brake force is then increased and the process repeats itself.

An example of the braking force modeled by the ABS against the braking force that would be applied without ABS is illustrated on Figure 2.3. In red it can be seen the driver's braking intension while at blue the actual brake intensity performed by the ABS system on one of the wheels in order to prevent lock-up.

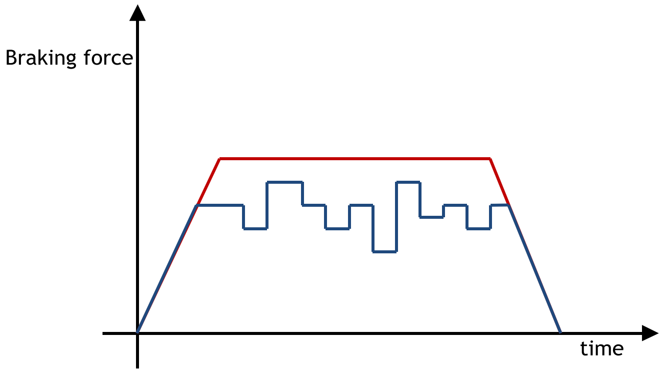


Figure 2.3 - ABS preventing wheel lock-up

2.3.1.2 Types of ABS

According to the number of wheels whose braking is individually controlled, the ABS can be implemented in four main distinct ways. The number of control channels on the ABS refers to the number of wheels that are individually controlled.

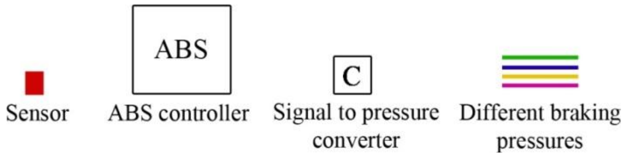


Figure 2.4 - Symbolic Nomenclature

Single Channel ABS

The single channel ABS is the most simple and inexpensive type of ABS. It consists on a ABS controller, a sensor that is placed on the differential or axle of rear wheels and an actuator controlling brake force in both rear wheels at the same time. No front wheel slip is detected and rear wheel slip is only detected when both wheels are slipping.

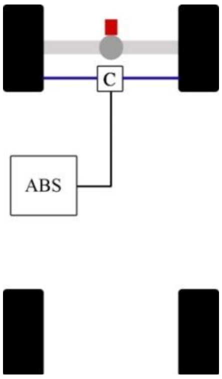


Figure 2.5 - One channel ABS

Two Channel ABS

The different configurations of two channel ABS are organized below in Figure 2.6.

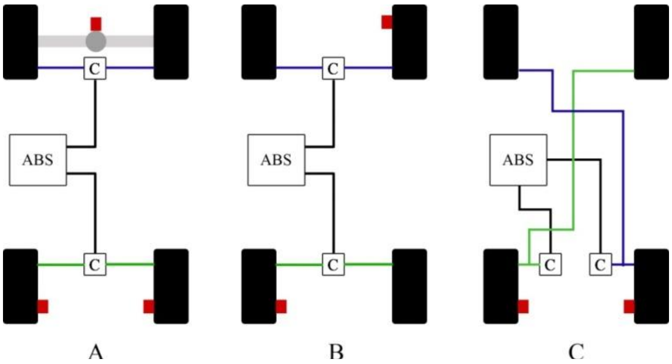


Figure 2.6 - Different arrangements for two channel ABS systems. Front wheels facing down

- **A:** The brake force applied to both front wheels corresponds to the brake force required for achieving the highest possible friction coefficient on any of the wheels. Therefore, one of the front wheels may block and rear wheels are only controlled when both lock-up
- **B:** One rear and one front wheel is monitored. The applied braking force ensures that the sensed wheels do not block
- **C:** Both of the front wheels are sensed separately and the braking force is applied diagonally

Three Channel ABS

On three channel ABS both front wheels are sensed individually while rear wheels are sensed in the differential/rear wheel axle.

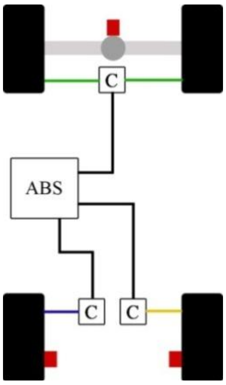


Figure 2.7 - Three channel ABS configuration

Four channel ABS

Four channel ABS systems are found in most modern vehicles nowadays. In this system, all of the wheels are sensed and controlled by a dedicated control channel thus granting the maximum possible controllability and enabling the implementation of other features.

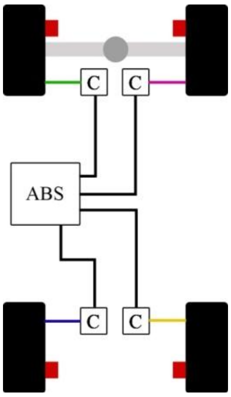


Figure 2.8 - Four channel ABS system

2.3.1.3 ABS Architecture

Figure 2.9 illustrates the main blocks that compose an antilock braking system.

The ABS actuates when the driver presses the brake pedal. Hence it requires the knowledge of the state of the brake pedal. A brake switch connected to the microcontroller unit (MCU) serves this purpose.

Signal conditioning circuits are required whenever the range or type of sensors are not suited to the inputs of the microcontroller unit (MCU). This is usually required when the outputs of wheel speed sensors are not in the form of PWM signals, which can be interpreted directly by the MCU.

Whenever the antilock braking system intervenes, the driver must be notified that a potentially dangerous situation has occurred. Furthermore, the ABS must perform self diagnostics in order to detect faulty units. The network interface serves these purposes, interconnecting the ABS with the systems that perform driver notification.

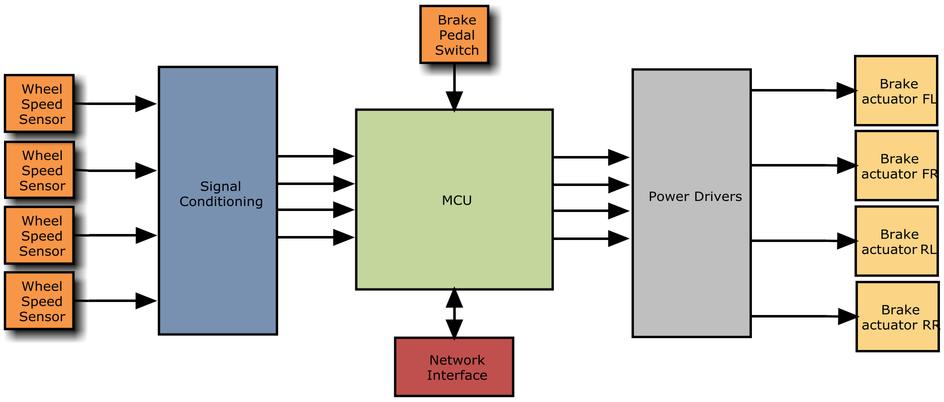


Figure 2.9 - Architecture of the Antilock Braking System

Figure 2.10 depicts an alternative architecture for the ABS. All sensor acquisition circuitry are placed in a application specific integrated circuit (ASIC). A dedicated microcontroller computes sensor values and, through a network interface such as CAN or Flexray (discussed in Chapter 3) delivers the state of all variables of interest. This enables relieving the main ABS MCU processing requirements. The ASIC can be provided with safety related mechanisms such as temperature sensors, watchdog timers and other safety related devices, so more dependability and computational relief of the ABS is achieved.

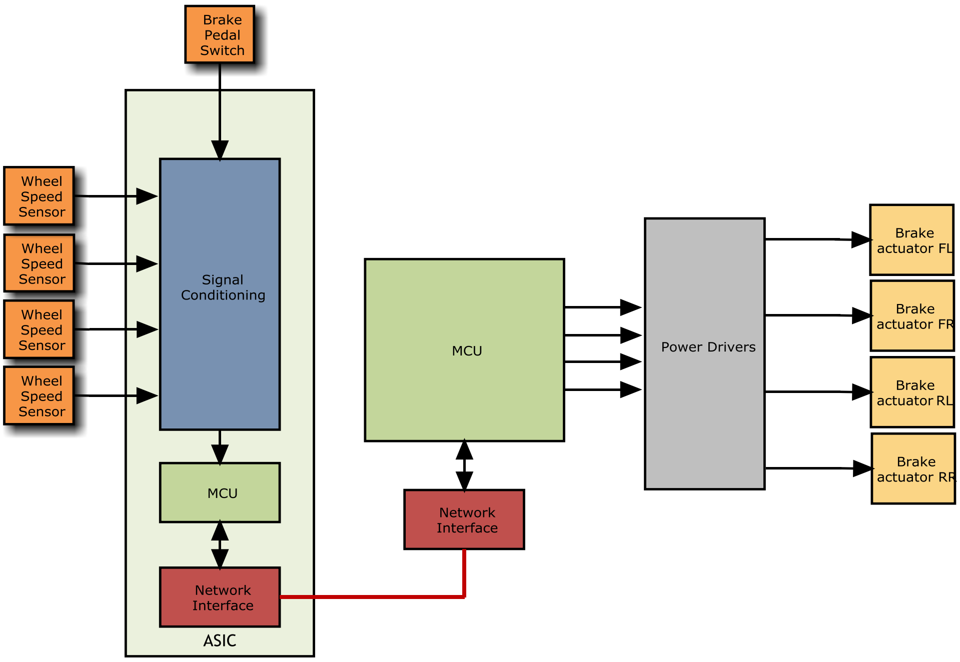


Figure 2.10 - Architecture of the Antilock Braking System with an ASIC for sensor processing and distribution

2.3.2 Traction Control System (TCS)

When starting off on low frictional coefficient surfaces, excessive throttle can cause the driving wheels to slip, making it harder or even impossible for the driver to move the vehicle. This situation frequently happens when vehicles start off on icy or wet pavements, as the required throttle to move the vehicle is lesser than the driver with its inputs can perform.

A single drive wheel standing in a low frictional surface is enough to immobilize a vehicle. This is due to the physical properties of the differential gear, the mechanical component that enables torque to be delivered to driving wheels spinning at different speeds. When the wheel which is standing on the low friction surface starts slipping, its torque is zero, which will induce a zero torque on the other wheel coupled to the differential. This causes the vehicle to be immobilized.

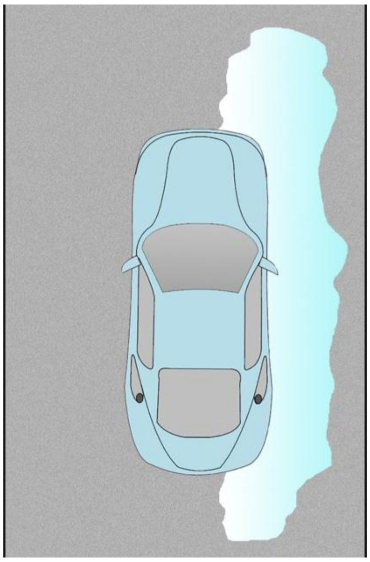


Figure 2.11 - Vehicle in a split friction coefficient surface

The TCS prevents wheels from spinning due to excess throttle. It improves forward traction and vehicle stability [13] and is specially required for preventing the situations mentioned above.

TCS can be thought as being the dual of the ABS. The TCS stands for acceleration as ABS stands for braking and therefore, while the ABS limits braking force, the TCS limits acceleration. The chart on Figure 2.12 illustrates the duality between the TCS and the ABS. Analogously to what was described when discussing the ABS, stable and unstable values of wheel slip during acceleration exist. When wheel slip during acceleration reaches the unstable zone, the affected wheel experiences a rapid acceleration, and a consequently lower friction coefficient.

The computational unit controlling the TCS monitors wheel speeds during acceleration. Upon detection of a wheel that is spinning or accelerating faster than the others, the TCS enables corrective actions by braking the wheel and requesting for a torque reduction to the motor control unit, so that wheel slip is maintained at all times in the stable zone of the friction/wheel slip chart.

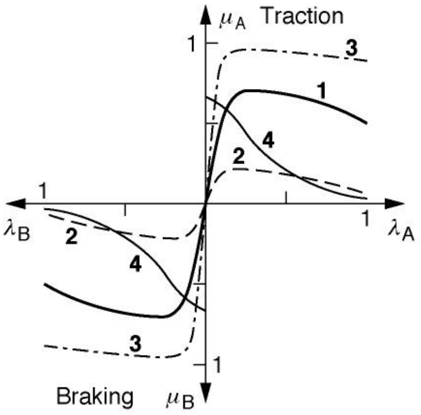


Figure 2.12 - Duality between ABS and TCS [11].

In vehicles equipped with electronic throttle control (ETC), torque reduction is achieved by controlling the throttle electronically. In internal combustion engine vehicles which are not equipped with ETC, torque reduction is achieved by means of reducing/suppressing the spark of one or more cylinders.

As the TCS main composing blocks and principles are shared with the ABS, generally both units operate in the same electronic control unit (ECU).

2.3.3 Electronic Stability Control (ESC)

The electronic stability control (ESC) is an active safety system developed by Bosch in the 90’s and, according to [14], it is extremely successful in reducing not only fatal crashes but also other crash involvements. The United States National Highway Traffic Safety Administration issued a report pointing a reduction in 35% in passenger car accidents and 67% reduction in SUV accidents, both for single car accidents [14]. This crash reduction rate in vehicles equipped with the ESC, made it that every new automobile sold in the United States from 2012 on will have ESC mandatorily.

In optimal conditions where no wheel slip is observed, when a driver steers a vehicle a yaw momentum is generated. This yaw momentum is responsible for the change in the vehicle direction. However, when the vehicle is skidding, i.e. its direction is not congruent with the wheels direction, the generated yaw is diminished and consequently the steering effect. This may result in loss of the vehicle control by the driver.

The slip angle is a measure of the amount of skidding a vehicle is experiencing. Figure 2.13 depicts a skidding vehicle in which the slip angle ß can be observed.

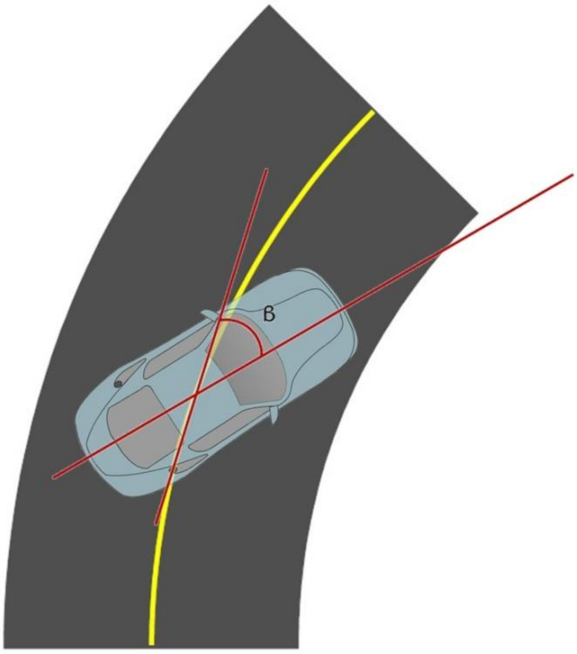


Figure 2.13 - Vehicle side slip angle

The relationship between the yaw moment and the slip angle for a set of steering angles varying from -4 to +4 is given on the chart on Figure 2.14.

It can be noticed that the greater the slip angle is, the less effect a steering action by the driver will be actually turned into the pretended steering effect. Also, two different situations can happen: when the required yaw moment is bigger than the actual yaw moment (understeering) and when the required yaw moment is smaller than the actual needed (oversteering). These situations are depicted in Figure 2.15.

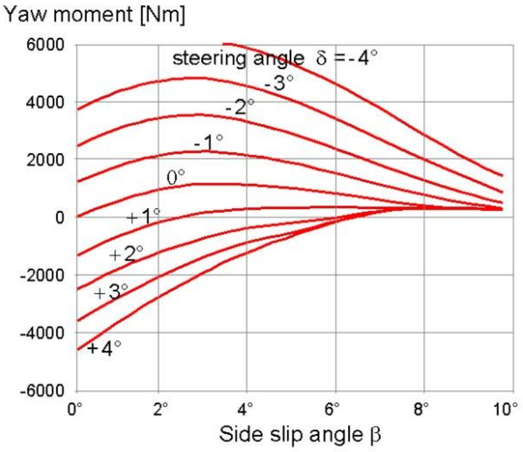


Figure 2.14 - Relationship between the yaw moment and the side slip angle [11]

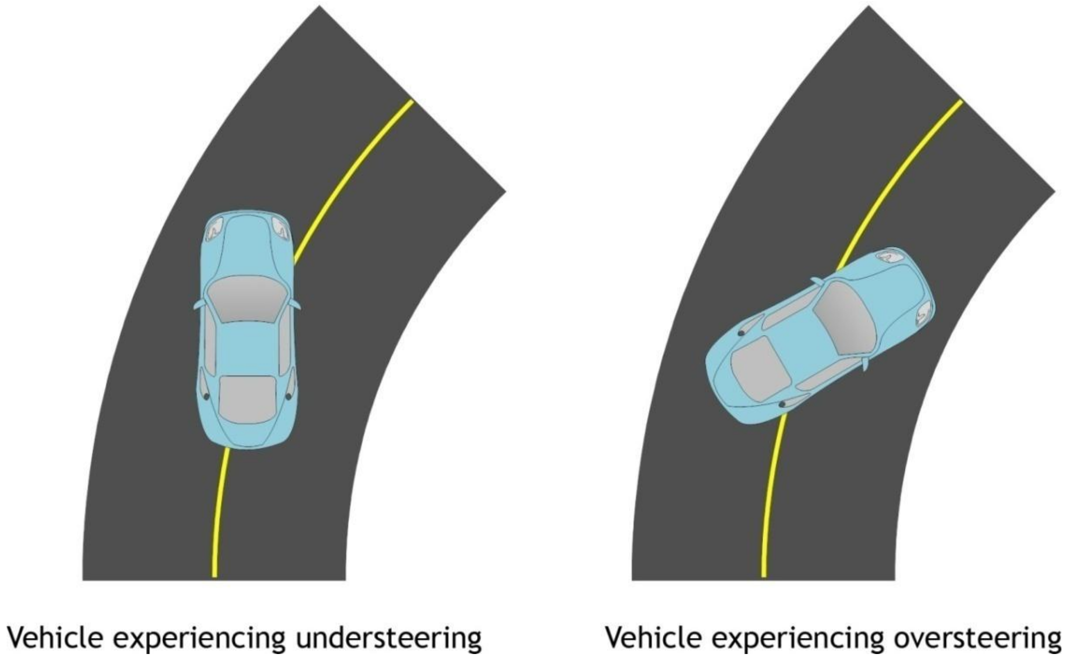

Vehicle experiencing understeering
Vehicle experiencing oversteering

Figure 2.15 - Vehicle experiencing under and over steering

The objective of the ESC system is to guarantee that the driver steering intentions are actually performed by the vehicle.

2.3.3.1 ESC Operation

Firstly through vehicle dynamics calculations, the ESC must determine how the vehicle should be behaving with the driver's inputs. These are the steering wheel angle, the brake pedal pressure and the throttle position.

The vehicle's ideal behavior is then compared with its actual behavior. The actual behavior of the vehicle is obtained with aid of yaw moment sensors, lateral acceleration sensors and wheel speed sensors. If the actual behavior of the vehicle differs from the ideal behavior by a certain amount, called the threshold, the ESC kicks in by sending commands to the motor control ECU and to the brake actuators so a counteracting yaw that compensates the skidding effect is generated.

In case of oversteering and understeering situations, the brake forces applied to stabilize the vehicle are as high as the deviation between the ideal and the actual behavior of the vehicle.

Figure 2.16 illustrates an oversteering situation. As the vehicle direction starts pointing to the center of the curve, the ESC system detects the discrepancy between the driver inputs and the vehicle behavior and tries to minimize it by applying a counteracting yaw moment. This counteracting yaw moment is achieved by applying brake pressure on the right front wheel. As expected, if this discrepancy raises, so the counteracting yaw must raise and therefore the brake pressure is increased on sequence 3. As the vehicle goes back to the desired direction, the brake pressure on the right front wheel is progressively decreased until the vehicle behavior corresponds to the driver inputs.

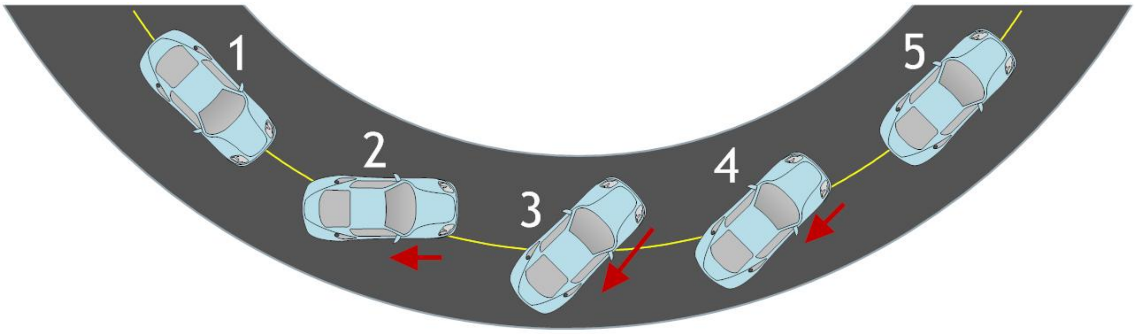


Figure 2.16 - ESC operation during over steering

Figure 2.17 depicts an understeering situation. Despite the driver's intention to steer the vehicle, the vehicle doesn’t respond in the way it should and it starts moving towards the outer part of the curve. Once the ESC detects this behavior it tries to compensate by creating a counteracting yaw by applying brake pressure on the rear left wheel. Just like in the previous example this force is as big as the difference between the actual behavior and the desired.

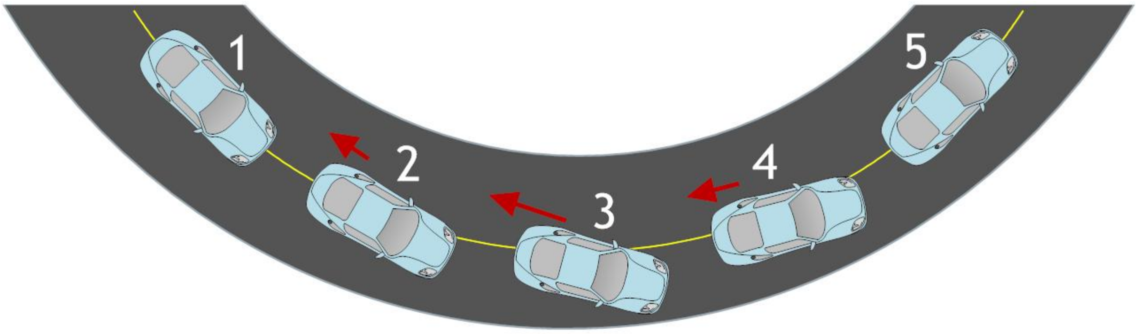


Figure 2.17 - ESC operation during understeering

2.3.3.2 ESC Architecture

Figure 2.18 illustrates a possible architecture for an ESC system. Due to the fact that the value of lateral acceleration and yaw sensors can be required by other systems, these might be placed on a dedicated ASIC embedding all the requiring components for their acquisition. Being dependent on other systems for its operation, the ESC is connected to the required systems by means of a network interface. The steering wheel position value is often transmitted by the power steering ECU.

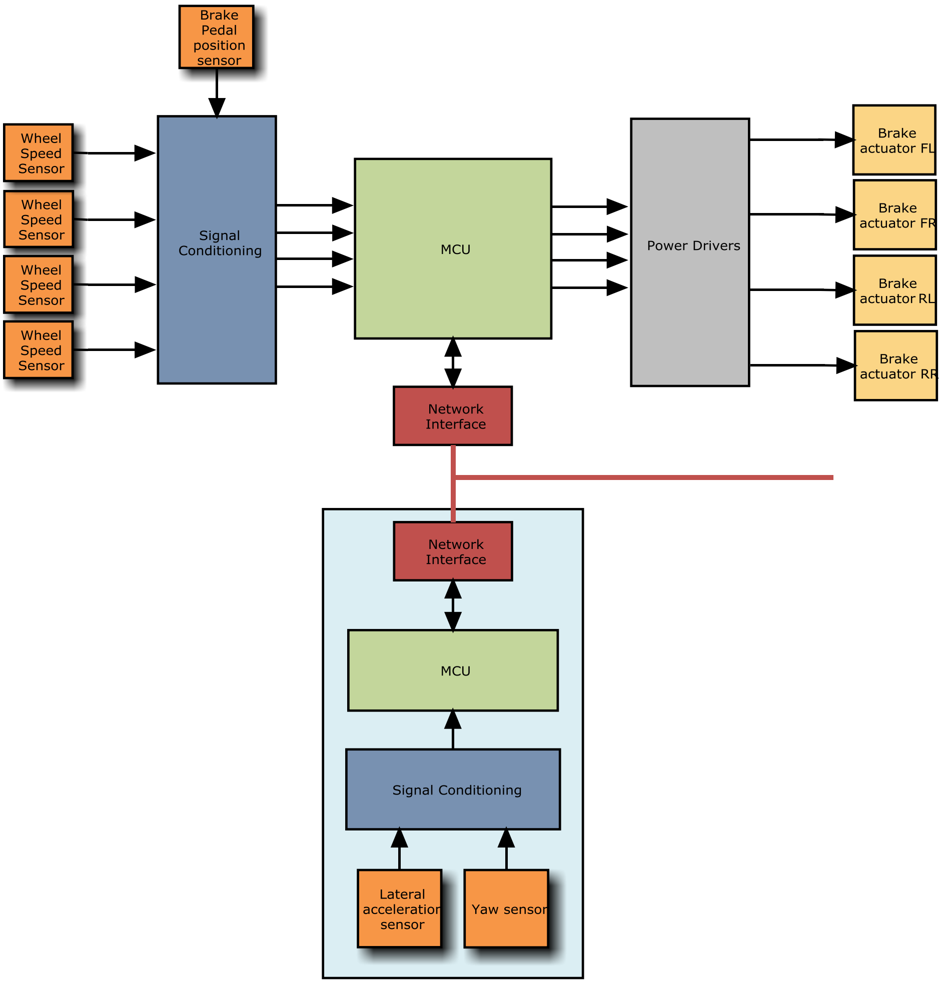


Figure 2.18 - Electronic Stability Control architecture

2.3.4 Electronic Brake Force Distribution (EBD)

EBD allows vehicles to stop in shorter distances by distributing brake force according to the distribution of weight among the vehicle [15].

Due to the fact that weight is not evenly distributed in vehicles, each wheel supports a different load. The load that a wheel has to support is also dependent on the dynamics of the vehicle. When braking in a straight line the weight shifts from the rear to the front of the vehicle while when braking during turns the weight is shifted to the outer part of the vehicle in relation to the turn. The more weight a wheel is supporting, the better grip it has and therefore the more braking force can be applied to it. The EBD takes advantage of this physical fact.

The EBD adjusts the ratio between front/rear or left/right brake forces so the braking effect is maximized. Wheel speeds are constantly monitored and, upon detection of wheel slip due to low load, brake force is increased on higher loaded wheels.

The EBD can be seen as an upgrade of the ABS system as it uses the same components and therefore only a change in the algorithm is needed to implement an EBD braking system [16].

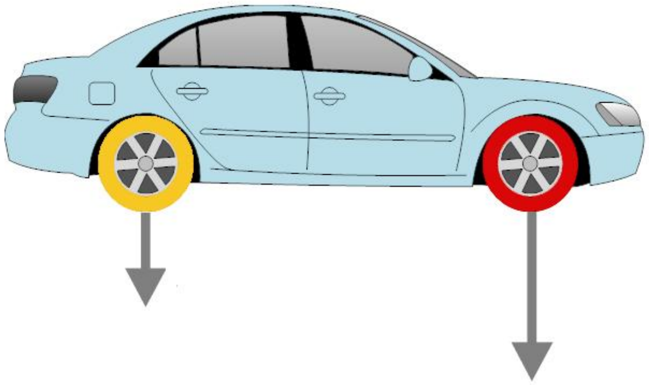


Figure 2.19 - EBD applying more brake force at the front wheels in a front engine car

2.3.5 Electronic Brake Assist (EBA)

When facing a sudden obstacle the driver has a limited time to react and press the brakes to avoid a collision. Even if the driver's reaction is promptly, the force which is applied to the brake pedal might not be enough to stop the vehicle on time. Several studies have concluded that drivers do not apply sufficient brake force in emergency situations [17]. This fact can be originated by several factors, such as emotional stress created by the unexpected situation, bad seat position and many others.

Assisted braking minimizes braking distance in critical situations by detecting emergency braking intentions and applying maximum braking force. Emergency braking can be detected as drivers tend to press the brake pedal much faster in critical situations. Analogously, when the throttle pedal is quickly released, the EBA control unit can detect this situation and apply brake force. More complex approaches consist in building a model of the driver's behavior under normal circumstances and monitor for abnormal behavior such as the situations described.

Figure 2.20 illustrates the principle of operation of the EBA. The system detects an abnormally fast brake pedal depression and outputs maximum brake force, which is afterwards modulated by the ABS.

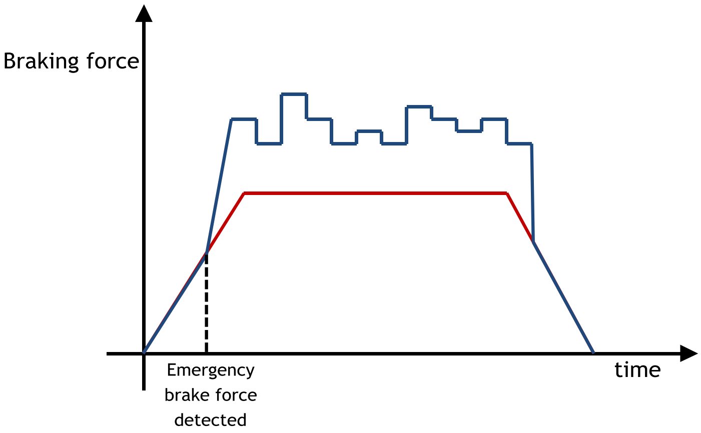


Figure 2.20 - EBA actuation

2.3.6 Architecture of Braking ECUs

All of the systems described from Sections 2.3.1 through Sections 2.3.5 are usually embedded in the same ECU. Hence, an architecture capable of serving the operation of the referred systems was already presented in Figure 2.18.

In a small minority of the studied wiring diagrams from different manufacturers, it was observed that the ESC and TCS can be implemented in separate control modules. In these cases, the interaction between the ESC or TCS and the ABS brake unit, where the BA and EBD are implemented, is done by means of a communication network. When required, these systems request braking actions to the ABS unit so its task can be accomplished.

2.4 Instrument Panels

Displaying the right information to the driver is crucial for the good handling and management of the vehicle. It permits the driver to have a better perception of his driving, adapt it according to the surrounding conditions and be aware of problems with the vehicle that can result in undesirable or dangerous situations.

In this section, the data that must be presented to the driver, its sources and how these interconnect with the instrument panel are presented.

2.4.1 Information to Display

2.4.1.1 Vehicle Speed

Drivers naturally sense vehicle speed through a combination of their sensations: their vision, engine noise, and handling feel, or road feel as it is commonly known. However, vehicles are becoming more comfortable and some of the features that contribute to a more comfortable vehicle are enemies from the drivers' speed perception. Vehicles are becoming less noisy due to a better engine/motor performance and a better cabin noise insulation. At the same time almost every vehicle is equipped with power steering or steer by wire systems (in the near future) which shades or eliminates road feel.

This means that the driver's sensorial input signals are being attenuated. In this way, drivers are becoming less likely to have a good prediction about their travelling speed. Also, drivers tend to underestimate their travelling speed which can lead to not respecting speed limits which may lead to a dangerous driving behavior [18]. Therefore, it is crucial for the driver to know its travelling speed as this information serves as feedback for its control attitudes over the vehicle.

The speed of a vehicle is generally acquired in two different ways:

1. Through a vehicle speed sensor that is placed on the transmission and connected to the motor/engine ECU.

2. By means of wheel speed sensors used in braking systems.

2.4.1.2 Motor Revolutions per Minute (RPM)

Motor revolutions per minute provides the driver with an estimation of the effort that is being performed by the motor. It enables the driver to keep that effort below its nominal value and not overload the motor.

RPM can be acquired by means of a rotational speed sensor placed in the motor shaft. This value serves as feedback for the motor control unit and thus, the instrument panel obtains its value by means of a network connection to the motor control ECU.

2.4.1.3 Battery Levels

The driver must be at all times aware of the amount of energy available in the vehicle in order to avoid unpleasant situations. This can be displayed either by means of battery level percentage or/and by an estimation of the number of kilometers. In order to do that the ECU that controls the batteries must be connected to the instrument panel ECU (directly or indirectly).

2.4.1.4 Braking Systems Information

Whenever the ABS, TCS or ESC systems are required to intervene is because the vehicle is facing possible dangerous situations. Despite these systems can avoid certain situations they cannot change the laws of physics to avoid accidents. Therefore the driver must be notified whenever these systems take actions as this is a direct consequence of road conditions and driving style. The computational elements in braking systems are aware of the driving surface and therefore can provide the driver with data that he might not be aware of.

On most of the instrument panels available, this information is displayed in the form of a brake system activity lamp(s), which will be on its *on-state* when one of the braking system features intervenes or in case of any fault detected upon diagnostic.

2.4.1.5 Tire Pressure

The display of anomalies in tire pressure is a critical matter. Lower than nominal tire pressure causes abnormal heating of the tires, which may result in tire rupture. On the other hand, higher than nominal tire pressure causes excess wear. Tire pressure management systems perform periodic acquisitions of tire pressure and by means of a network connection with the instrument panel ECU, display tire pressures and diagnostics.

2.4.1.6 Lights Status

The status of the vehicle lights is important as the driver might not be able to detect it in certain environments. During daytime and in places where the use of lights is mandatory the driver might not be aware of the lights status due to the abundant luminosity. Also, during the night the type of active lights might not be easily distinguishable depending on luminosity conditions. Therefore, the awareness of lights' status is considered to be important as lighting plays an important role in safety.

2.4.1.7 Motor Diagnostics

The driver should be notified upon detection of any failure or abnormal state on the motor. Diagnosis such as computational failure, excessive motor temperature or sensor failure (among all other critical variables) should be in the origin of possible driver alerts, in order for the driver to take appropriate actions to avoid or solve the problem.

2.4.1.8 Systems Status

When vehicles possess features like cruise control systems, speed limitation and others that might affect the control of the vehicle, the driver must be aware of these systems' status.

2.4.2 Instrument Panel Architectures

The following examples of instrument panel architectures are based on real implementations and were adapted for a better understanding of the philosophies involved. Consequently, the number and type of systems connected to the instrument panel is variable and serve as an example only. Although the following diagrams contain more components, only the systems that require its information displayed to the driver are illustrated.

In this section, two different architectures regarding two different philosophies are presented. These are represented in their pure form for a better understanding, as manufacturers often implement solutions that reflect a mixture between these architectures according to their necessities.

2.4.2.1 Point-to-point Architecture

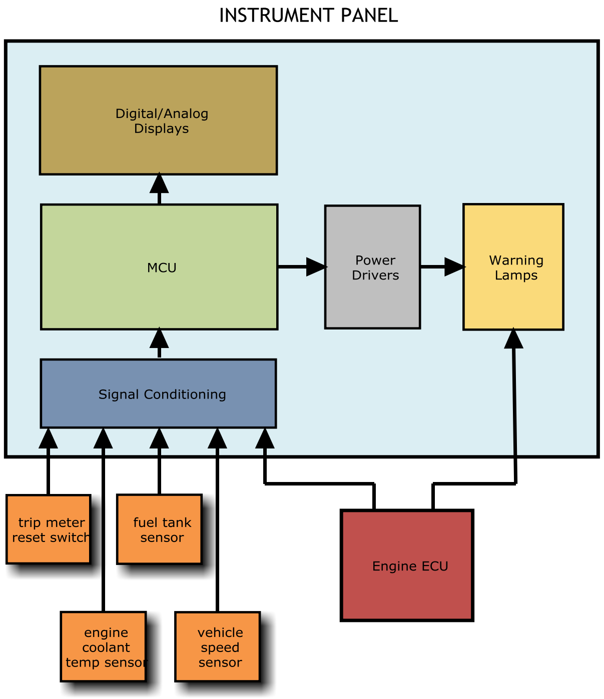


Figure 2.21 - Instrument panel point-to-point architecture example

The philosophy behind this architecture consists in hardwiring all the sensors whose variables are to be displayed to the instrument panel ECU. Sensor acquisition is performed by the instrument panel ECU, which controls digital displays, gauges and warning lamps according to the values provided by the sensors. For instance, the engine ECU provides the crankshaft sensor output to the instrument panel ECU so the value of RPM can be computed and displayed.

Warning lamps can be directly actuated by the sources of information. Systems like the supplemental restraint system, ABS, TCS, ESC, lighting systems among others, are commonly hardwired to their respective warning lamps, which are activated upon activity or diagnostic reasons. Warning lamps can also be actuated by the instrument panel ECU, when the input signal provided by the sensor is not in the form of an *on/off* state and needs to be computed. As an example, the connection between the engine coolant temperature sensor and the instrument panel ECU enables the instrument panel MCU to analyze the engine coolant temperature and actuate the warning lamps accordingly.

2.4.2.2 Networked Architecture

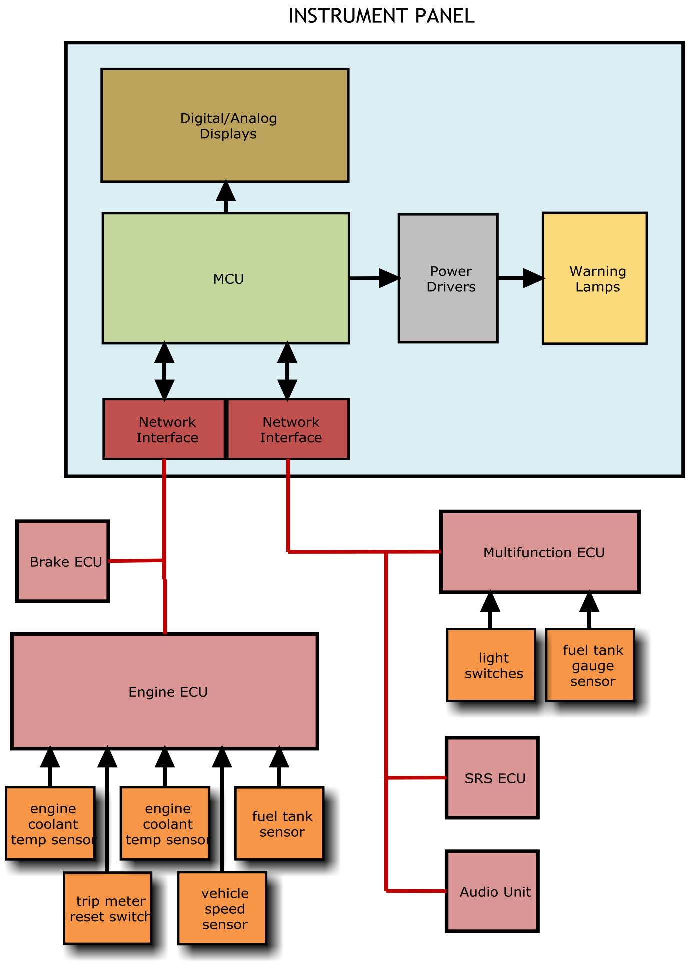


Figure 2.22 - Instrument panel networked architecture example

The philosophy inherent to the architecture described on Figure 2.22 consists on integrating the instrument panel ECU in a network connection with the sources of information.

Two different types of networks are connected to the instrument panel ECU. The first, as seen on the left part of Figure 2.22 is a high speed network where the engine ECU, brake ECU and all the dynamic controllers of the vehicle are connected. The second network at the right part of Figure 2.22 is a low speed network where components mainly belonging to the body domain are connected. Just like it was referred on the previous architecture, controllers are directly connected to the lamps as necessary.

The fuel level sensor, lighting switches and others whose values are not required by any ECUs are computed by a multifunction ECU, which transmits its values over the network to the instrument panel.

Variables of interest which have to be displayed and are produced within an ECU are transmitted over the network to the instrument panel ECU. As an example, the crankshaft position sensor is required by the engine ECU as the value of RPM is required for controlling the engine. RPM is computed on the engine control ECU and sent over network so it can be displayed to the driver.

This solution has many advantages comparing to the architecture demonstrated on Section 2.4.2.1:

1. The number and complexity of wiring is drastically reduced
2. The number of elements that may be connected with the instrument panel is only limited by the type of network
3. The complexity of the information that is displayed is higher
4. The flexibility is higher, as the information to display is not dependent on the number and type of interfaces present on the instrument panel controller.

By integrating the instrument panel ECU in a network with other systems, the ECU can capture messages that are being traded between other systems. For instance, when loss of traction is detected by the TCS, a message is transmitted by the TCS to the motor ECU to reduce torque. The instrument panel ECU can capture this message and display the TCS activity to the driver. In this way, network load and computational efforts are optimized. Additional systems can be integrated by simply connecting them to the corresponding network. Extra sensors that are required for displaying information to the driver can be connected to multifunction ECUs that are connected to the network.

2.5 Steering Systems

The steering system is responsible for transforming the driver's steering intentions into the actual change of vehicle direction. Steering systems have evolved from rather simple mechanical systems to sophisticated intelligent systems that ease the driving, provide more comfort and offer more security.

Steering systems started as purely mechanical systems in which no assistance was provided to aid the driver in steering the wheels. In these systems the driver was the unique source of the force required for overcoming the friction coefficient between the surface and the tires. When the vehicle is stopped or moving slowly, the effort demanded to the driver for steering the wheels can cause the driving experience to be quite unpleasant. The heavier a vehicle is or the largest its tires are, the more this issue is aggravated.

This situation was later overcame by power steering systems, which are available in the vast majority of vehicles sold nowadays and consist on mechanisms to assist the driver in turning the wheels by amplifying the driver's steering torque inputs [19]. Power steering systems exist mainly in three different kinds: hydraulic, hybrid i.e., a mixture between hydraulic and electric, and electric.

These systems allowed that heavier vehicles or equipped with wider tires could be easily maneuvered, despite the higher frictional forces associated with these characteristics. The mechanical details of such systems are not in the scope of this document, but a simple explanation of each these systems will aid the understanding of the factors and issues involved later in this section.

The last trend in steering systems are the steer-by-wire systems, in which on the contrary of other systems mentioned above, is based on the removal of all mechanical connections between the steering inputs and the steering actuators. Steer-by-wire concepts are described later on Chapter 4.

Four wheel steering is another concept whose popularity is gaining ground, and therefore is also referred in this section.

2.5.1 Hydraulic Power Steering

In hydraulic power steering systems, the assisting force is provided by pressurized fluids. Hydraulic fluid pressure is controlled by a pump which is mechanically coupled with the engine. Therefore, the rotation speed of the pump's rotor depends on engine speed. Figure 2.23 and Figure 2.24 illustrates a hydraulic power steering system applied in a rack-and-pinion configuration.

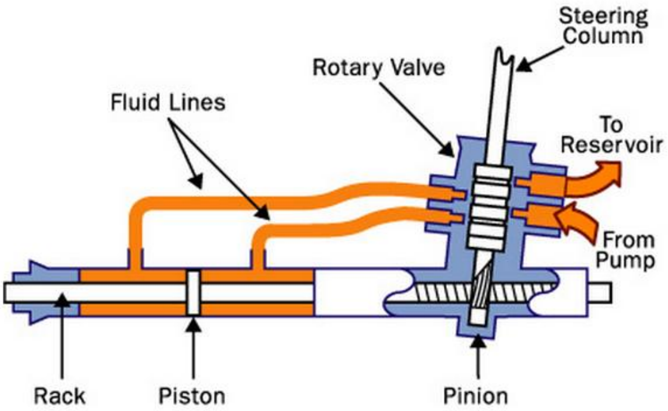


Figure 2.23 - Hydraulic power steering system applied to a rack-and-pinion configuration [20]

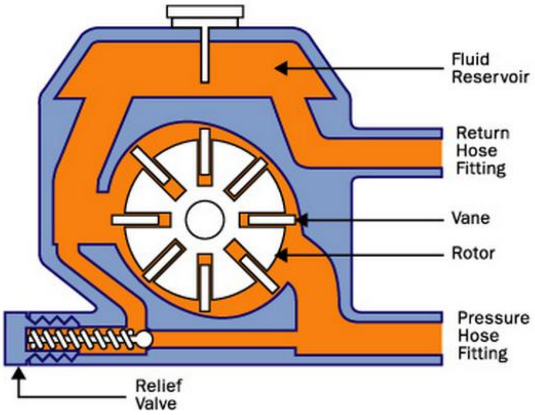


Figure 2.24 - Power steering hydraulic pump [20]

Hydraulic power steering systems are made in such a way that when the vehicle is idle, there is enough pressure for the steering to be comfortable. This has the consequence that when the vehicle moves faster, more pressure than needed is created, inducing the feeling that the steering is too soft. In order for this pressure not to raise to dangerous levels that could damage the hydraulic circuitry, a pressure relief valve is inserted the hydraulic circuit. A mechanical system that senses the steering intention is connected to hydraulic pressure valves, for enabling the system to provide assistance only when there is an intention to steer the vehicle [21].

As it can be denoted, these systems do not integrate any electronic device and were referred only for contextual reasons.

2.5.2 Hybrid and Electric Power Steering

Both hybrid and electrical power steering systems share the same principles. The difference between them resides on the source of the assisting force. On hybrid power steering systems, the assisting force is provided by hydraulic pressure, by means of an electric pump, while in electrical power steering systems the same is provided by means of an electrical motor.

When the driver intends to steer, it applies a force on the steering input device. Along with the speed of the vehicle, this torque is fed onto the power steering control ECU and the required assistance is evaluated taking these parameters into account. An example of an assisting curve can be depicted on Figure 2.25.

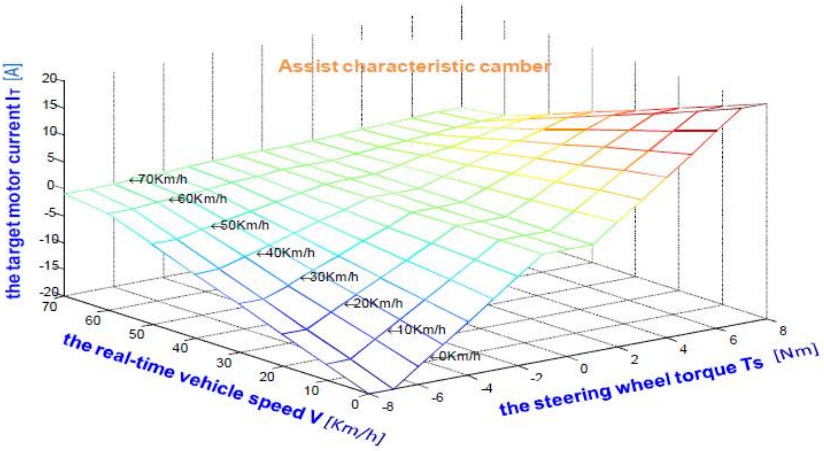


Figure 2.25 - Power steering assist curve [22]

The assisting force must be higher when the vehicle is stopped and tend to zero as speed increases. This enables the driver to have a more precise control of the vehicle.

Power steering systems are mechanically connected in such a way that a computational failure in the system does not cause the driver to lose control of the vehicle, as there is always a mechanical connection between the steering input system and the wheels. However, a faulty element can lead the force providing mechanism to develop a force when it is not supposed to. Such a situation can be dangerous and therefore, steering systems must be provided with fail safe mechanisms.

2.5.2.1 Electro-Hydraulic Power Steering

The electro hydraulic power steering system was developed with two main objectives. The first was the reduction of fuel consumption, associated with the ineffective arrangement consisting on having the hydraulic pump coupled with the engine. Secondly, extra comfort and controllability were demanded, as hydraulic power steering systems' natural assisting curve (in which the steering force rises with vehicle speed) did not offer a satisfactory behavior.

In electro hydraulic power steering systems, the hydraulic pump is driven by an electric motor and not by the engine. Therefore, the hydraulic pressure applied to assist the steering can be regulated by controlling the electric motor.

2.5.2.2 Electric Power Steering (EPS)

Electric power steering systems take advantage of electric motors to provide the assisting steering force. Its working principle is similar to the hybrid power steering system. Comparing with the other solutions discussed, EPS reduces energy consumption, the steering system's weight, provides easier and more powerful control methods [23], and is more environmental friendly due to the elimination of the hydraulic fluid [24].

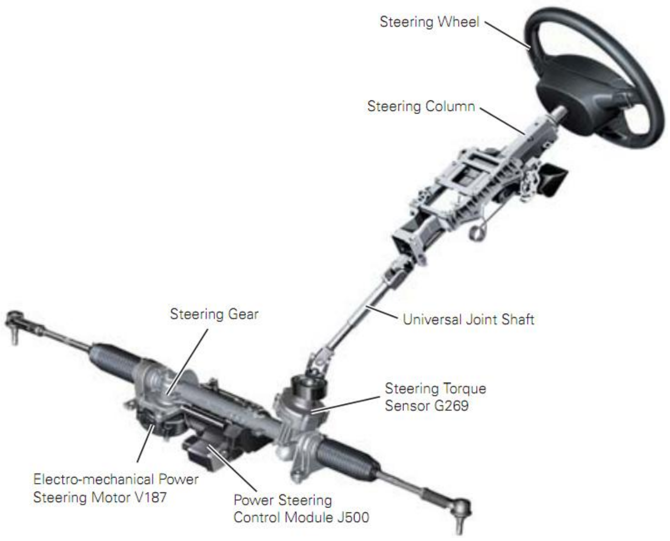


Figure 2.26 - Electric power steering [24]

2.5.3 Power Steering Architecture

In Figure 2.27 the architecture of a basic power steering architecture can be observed. Although only the basic sensors are represented, other variables can be taken in account to enhance the performance of the power steering system such as a steering angle sensor, steering speed, lateral acceleration, motor temperature among others.

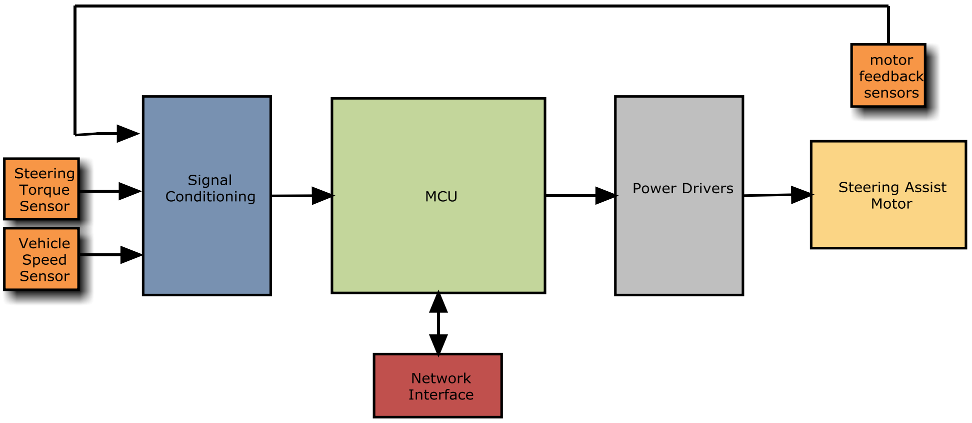


Figure 2.27 - Power steering architecture

Vehicle speed is either obtained by connecting the vehicle speed sensor to power steering MCU or by means of a network connection between the power steering control unit and the motor or brake ECUs.

The power steering ECU is commonly connected to the instrument panel ECU so that diagnostic data can be exchanged. The failure of the power steering system can have catastrophic consequences. Therefore the power steering control unit is commonly suited with fault detection mechanisms which de-energize the steering actuators in case of computational failure.

2.5.4 Four Wheel Steering (4WS)

Ackerman driving is the driving configuration of cars and 4x4 motorcycles. It consists of two wheels that do not steer in the rear and two wheels that steer in the front. Ackerman's principle relies on intersecting at all times the axis of all of the wheels in one point. In case this intersection is not observed, slippage of the wheels occurs [25].

The point where the axis of all wheels intersect is denominated the instantaneous point of curvature. Therefore, as it can be observed by Figure 2.28, inner wheels turn sharper than outer wheels in respect to the curve.

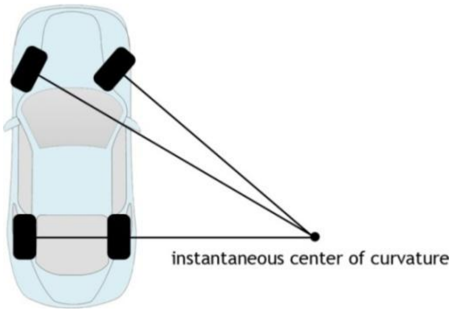


Figure 2.28 : Ackerman drive geometry

Four wheel steering can reduce the instantaneous point of curvature (21% referred on [26]) and provide more mobility to a vehicle. This is useful when the vehicle is moving slowly, so that maneuvers can be made more easily. 4WS enables the reduction of the instantaneous center of curvature by steering the rear wheels in the opposite direction than the front wheels.

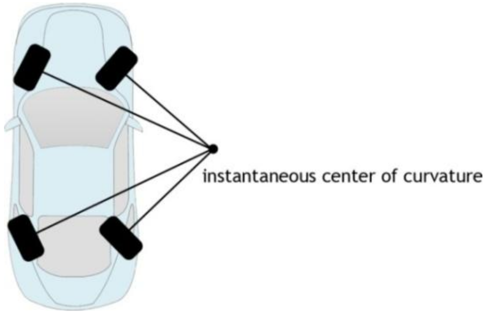


Figure 2.29 : 4WD decrease of turning radius

At high speeds, 4WS increases vehicle stability [27]. To achieve that, rear wheels steer in the same direction as the front wheels.

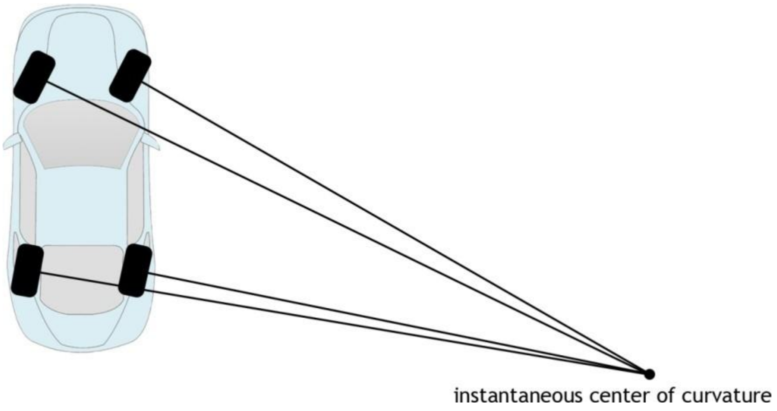


Figure 2.30 - 4WD at high speeds

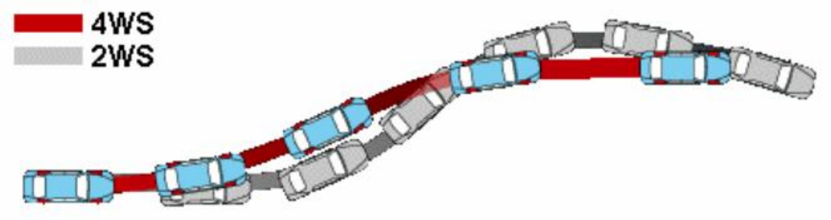


Figure 2.31 - Increased stability of the 4WS system when compared to 2WS [28]

Figure 2.32 - 4WS Jeep Hurricane [29]

2.5.4.1 4WS architecture

The four wheel steering architecture is depicted on Figure 2.33. The 4WS MCU analyses the steering wheel position and vehicle speed. After computing the desired rear wheel position, rear wheels are orientated by means of an electric motor.

The steering wheel position can be shared by the power steering ECU by means of a network connection or the steering wheel position sensor can be directly connected to the 4WS control unit.

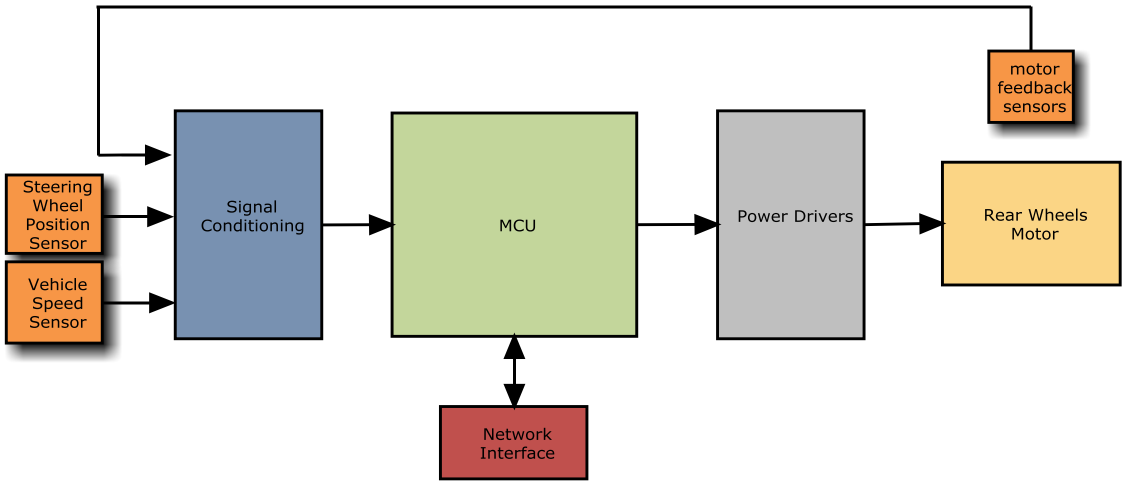


Figure 2.33 - 4WS architecture

2.6 Exterior Lighting Systems

Lights have the task of illuminating the path to the driver and to assist in evidencing the vehicle's shape, so other drivers are aware of it with the minimum possible effort. According to an issued report by the United States department of transportation, vision contributes with 90% of the information needed to the driver, hence the fact that most of the accidents happen at night, or during bad visibility periods due to poor weather conditions such as rain or fog.

The types of lights that shall be present in a vehicle and the situations that their use is mandatory varies from country to country. The various types of lights that are commonly found in vehicles are:

1. Low beam - Cruising lights that do not obfuscate other drivers and provide enough illumination for night driving
2. High beam - Intense lights that can only be used when the vehicle is not crossing with other vehicles as it produces considerable amounts of glare
3. Daytime running lamps - Mandatory in some countries. Low intensity lights that enable a better perception of the vehicle
4. Directional indicators - Blinking lights that indicate other drivers the intention in changing direction.
5. Brake lights - Give other drivers the information that the vehicle is braking
6. Reverse lights - Provide other drivers with the indication that the vehicle is driving on reverse

7. Fog lights - Provide better illumination on foggy environments

Lighting systems have been suffering a deep evolution in the past years. The lighting system is changing from being a static system, to a dynamic system that actively contributes to safety and comfort.

In this section, several emergent features regarding lighting systems are presented. The names in which these systems are known vary from manufacturer to manufacturer. Therefore, adaptations or mixes between system names are used.

This section would not be complete without a brief comment on light-emitting-diode (LED) lighting systems, due to their potential of becoming the most widely used lighting solution. LED lighting systems offer space reduction, less energy consumption, longer lasting life and faster rise to full intensity than standard bulbs. Due to the massification of its production, prices are dropping which means that it is expected that in the future the vast majority of the cars will run on led lights. Despite of what can be thought at first sight, the task of implementing LED lights on a vehicle is not trivial, due to the fact that in combustion engine vehicles the battery voltage can vary between 9 to 16 Volt. Therefore, the traditional way of driving a LED which consists in connecting a series resistor is not applicable, since variations in voltage cause variations in the LEDs' currents, which in turn will cause a variation on light intensity. Instead, buck-boost controllers are commonly implemented, which typically requires a microcontroller to generate the duty cycle signal and perform monitoring on LED's current so it doesn't exceed its rated value.

2.6.1 Automatic Lighting

Automatic lighting systems activate low beam lights upon detection of darkness or rain. This is achieved by sensing ambient light and rain through specific sensors that are connected to the lights ECU.

2.6.2 Fused Light Detection

The fused light detection system operates by monitoring the current fed to each bulb. When the lights ECU sends a signal to activate a certain bulb and no current flowing to it, it may indicate that the bulb is fused. In case of LED lights are used in series, an increase in the LED's current may also indicate led failure.

2.6.3 Dynamic Headlight Range Adjustment

Vehicle dynamic motion on the vertical axis causes the range of the headlights to change. When the vehicle is tilting forward, the range is reduced thus reducing the driver's sight. Upon forward tilt, the range is augmented, in which glare can be induced and blind other drivers. Vehicle front and rear tilting happens for several reasons: heavy load on the rear or front of the vehicle, bumps on the road or upon fast accelerations or decelerations.

The objective of the dynamic headlight range adjustment system is to grant that the vertical motion of the vehicle does not affect the headlights range.

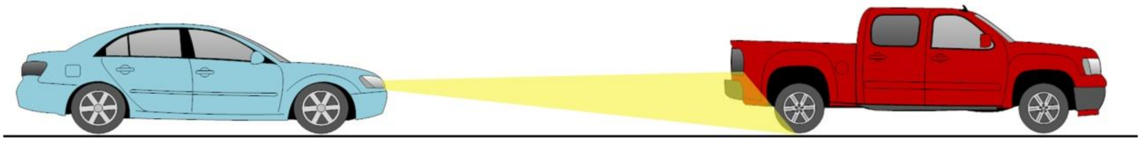


Figure 2.34 - Vehicle with headlights on

Figure 2.34 depicts a vehicle with its low beam headlights turned. Due to the flat surface of the road and the vehicle's weight distribution, the light rays are pointing down, not causing glare to the front vehicle.

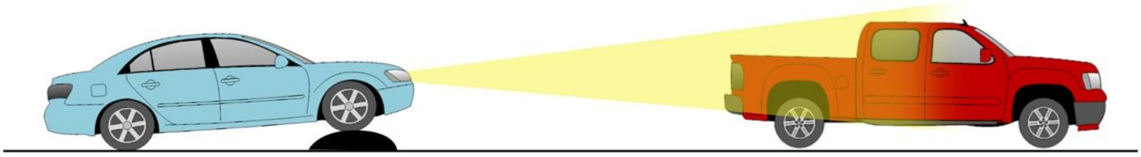


Figure 2.35 - Range of headlights increased due to forward tilt

It can be seen on Figure 2.35 that a forward tilt caused by a bump on the road increases the level of the headlights, which can cause the front driver to dazzle.

In a vehicle with dynamic headlight range adjustment, sensors monitor the vertical dynamics of the vehicle and, upon detection of front or rear tilts, the direction of the lights is adjusted, granting a constant range.

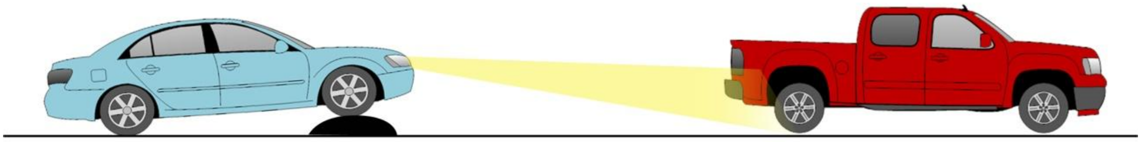


Figure 2.36 - Dynamic headlights range adjustment maintaining headlight range despite of vehicle tilt

2.6.3.1 Dynamic Headlight Range Adjustment Architecture

Figure 2.37 depicts the architecture of light system with dynamic headlight range adjustment.

Switches are responsible for acquiring the driver's commands. In some of the studied systems these are connected to a dedicated unit responsible for acquiring their state and sharing it by means of a network connection with the lights ECU.

The front and rear level sensors are responsible for acquiring information relative to the vertical dynamics of the vehicle. In some vehicles the value of these sensors is computed in another ECU which has the task of controlling the vertical dynamics of the vehicle and shared via network (dynamic suspension ECU).

Upon detection of a forward or rear tilt, the MCU which controls the lighting system request the motor controllers to assume a predetermined position.

Light intensity controllers receive commands via communications network to enable/disable the controlled lights and adjust their intensity.

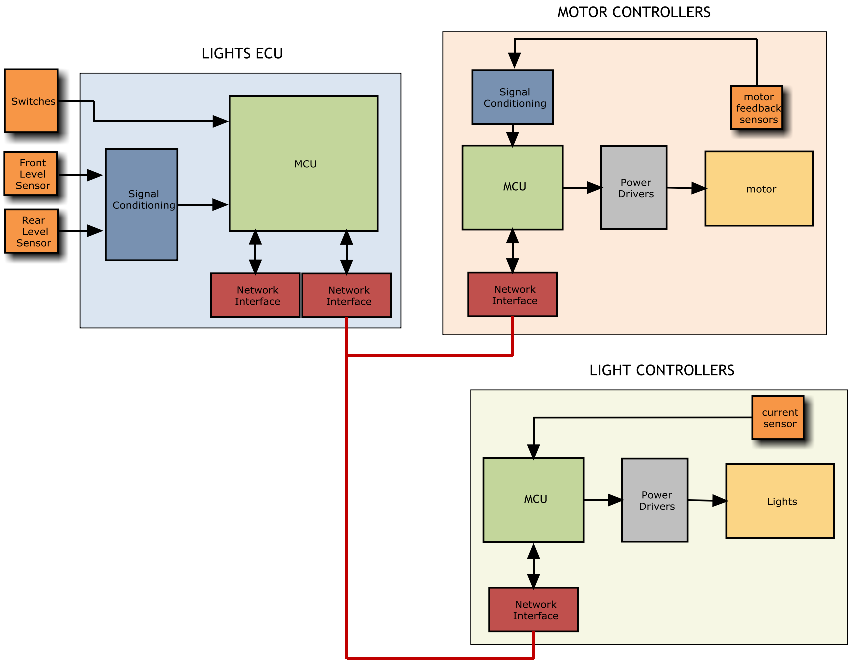


Figure 2.37 - Dynamic Headlight Range Adjustment Architecture

2.6.4 Adaptive Cornering Light

Having a good light source is not enough for the driver to have a good visibility. If lights are not pointed to the vehicle's path, the driver might not be aware of obstacles within its trajectory. Figure 2.38 depicts a vehicle turning without adaptive cornering light. It can be seen that the lights are pointing to the front of the vehicle while the vehicle is having a circular motion.

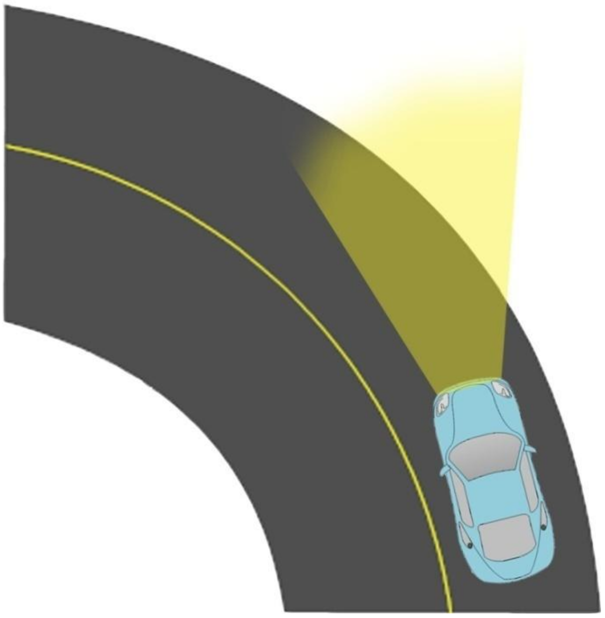


Figure 2.38 - Vehicle without adaptive cornering light system

Figure 2.39 illustrates a vehicle equipped with the adaptive cornering light system. The lights ECU analyzes vehicle dynamics and calculates where the lights should be pointed at. Electric motors adjust the determined swivel angle so the lights are always pointed to the direction of motion of the vehicle.

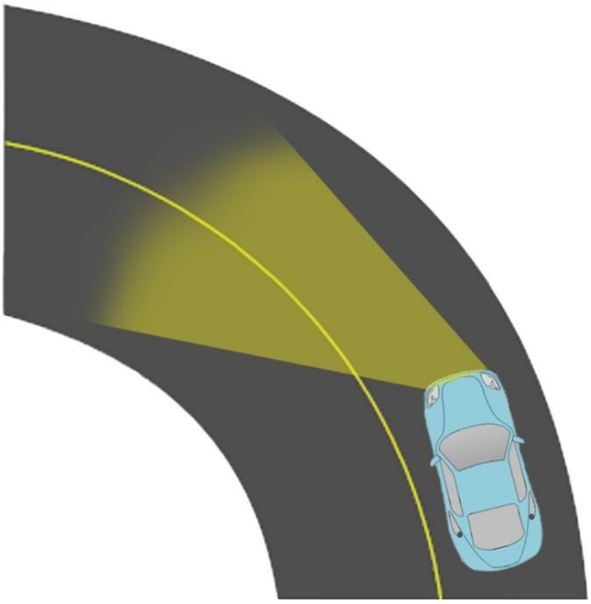


Figure 2.39 - Vehicle equipped with adaptive light cornering system

The swivel angle is determined based on three variables: vehicle speed, steering wheel position and yaw rate. The steering wheel position is used to compute the swivel angle for low speeds (typically below 40 Km/h), while for high speeds both the vehicle speed sensor and yaw rate are used to compute the swivel angle.

2.6.4.1 Adaptive Cornering Light System's Architecture

An architecture able of implementing the adaptive cornering light system is similar to that given on Figure 2.37, with the addition of motors and their respective controllers to adjust the horizontal position of the lights. The value the yaw sensor is typically shared by the brake ECU while the steering wheel angle is typically shared by the power steering ECU.

2.6.5 Camera Based Lighting Systems

This section provides a brief description of the upcoming (and already available in some high end models) lighting systems that provide extra safety and comfort. All of the systems described in this section rely on image analysis.

2.6.5.1 High Beam Assist

Several studies point out that high beam lights are rarely used even in situations when these do not cause other drivers to glare. This can be seen as a waste of illumination potential as high beam lights illuminate much further ahead, giving extra time for the driver to perceive potential dangerous situations and react accordingly.

The high beam assist system captures images of the surrounding environment such as road lights, headlights and rear lights of other vehicles and decides whether high beam lights are required or not. In case that the road light is sufficient or in case other vehicles are in risk of perceiving glare, high beam lights are disabled.

2.6.5.2 Adaptive Cutoff Line

Adaptive cut-off line system can be seen as an upgrade of the high beam assist. It has the task of optimizing the driver's visibility. A camera analyses front vehicles, and light angle is adapted so the cut-off line ends as far as possible, while not blinding the front vehicle's driver. If the system does not detect any drivers ahead, low beam lights are switched to high beam. Figure 2.40 illustrates an adaptive cut-off regulating the cut-off line according to the front vehicle.

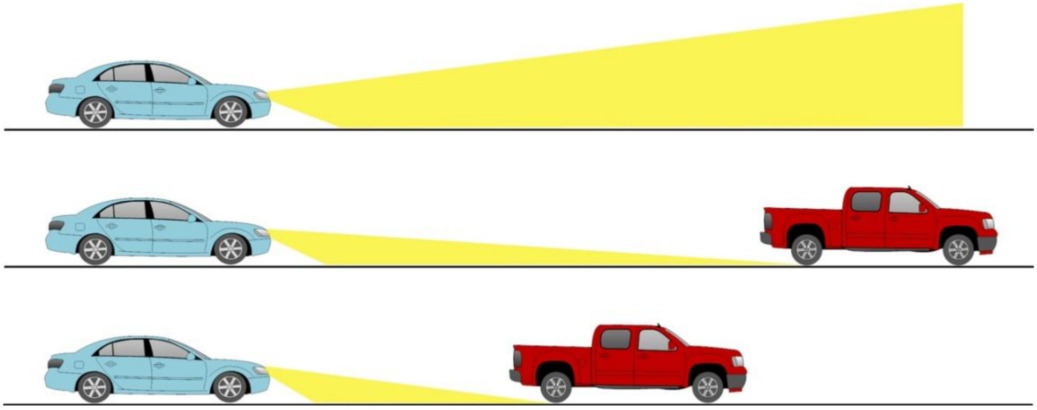


Figure 2.40 - Adaptive cutoff line

2.6.5.3 Glare Free Systems

Glare free systems are another update of the high beam assist system. With it, vehicle's can drive with high beam lights on without affecting other drivers. Glare free systems analyze the position of other vehicles and block parts of the light that can disturb other drivers.

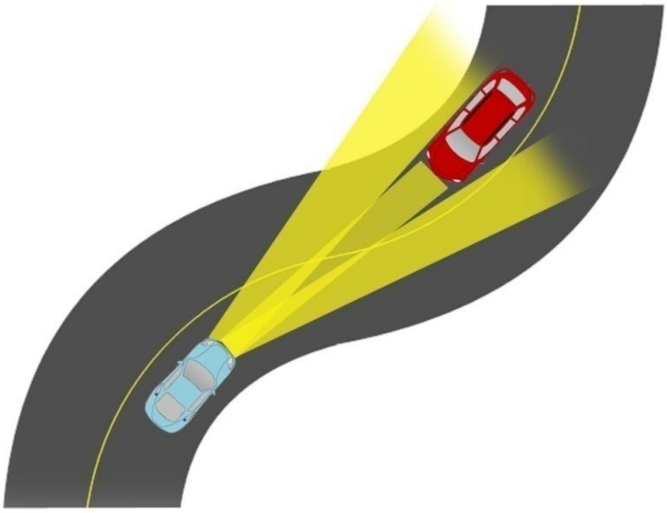


Figure 2.41 - Glare free system

In Figure 2.41 is represented a vehicle with a glare free system that controls a multiple LED light source. According to the information acquired through the analysis of camera images, the LED modules that have its light rays targeting other vehicles are pointed in a direction in which they do not induce glare on other drivers.

2.6.5.4 Marking Light Systems

While drivers might be with their attention focused on several light sources, some situations might happen that require the driver's sudden attention. Events such as a pedestrian crossing or an incoming vehicle in a crossroad might not be flashy enough to get the driver's attention. Marking light systems have the task of illuminating objects that appear suddenly, thus shifting the driver's attention for situations that might impose danger.

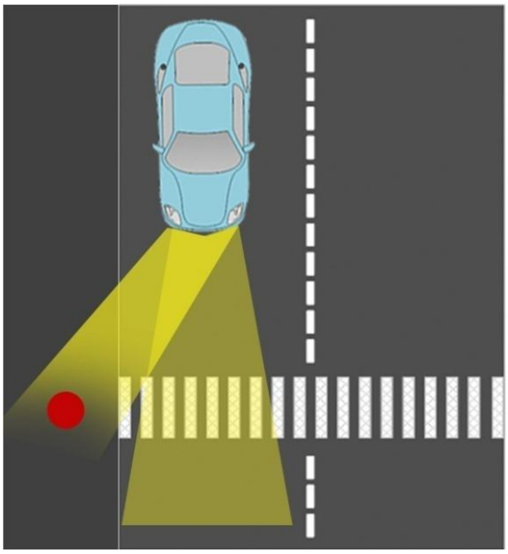


Figure 2.42 - Marking light system evidencing a pedestrian

Figure 2.42 illustrates a light marking system in action. While the vehicle is driving straight ahead, a pedestrian (represented by a red circle) is standing near the crosswalk. The marking light system identifies this situation and illuminates the pedestrian so the driver can be aware of it.

2.6.5.5 Night Vision Systems

Night vision systems take advantage of infra red light to capture what the human eye cannot. In a vehicle equipped with a night vision system, an infrared light source emits infrared light, which hits objects and reflects back to an infrared camera that is connected to an image analysis system and a monitor. The image analysis system performs routines in order to detect potential dangerous situations, and upon detection of these engages actions so the driver can be aware of it.

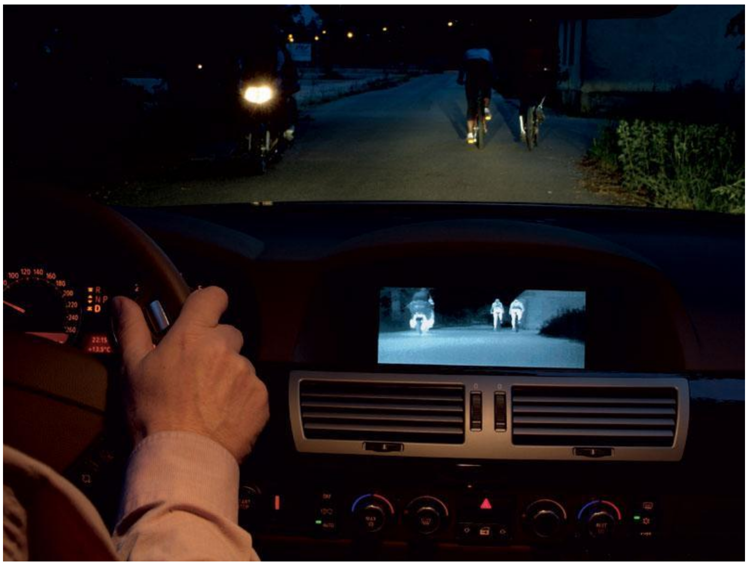


Figure 2.43 - BMW night vision system

2.6.6 Lighting Systems Architecture

Figure 2.44 depicts an architecture capable of handling all the described features. Image processing tasks are generally achieved in a microcontroller with an embedded digital signal processor (DSP) due to the high computational power required.

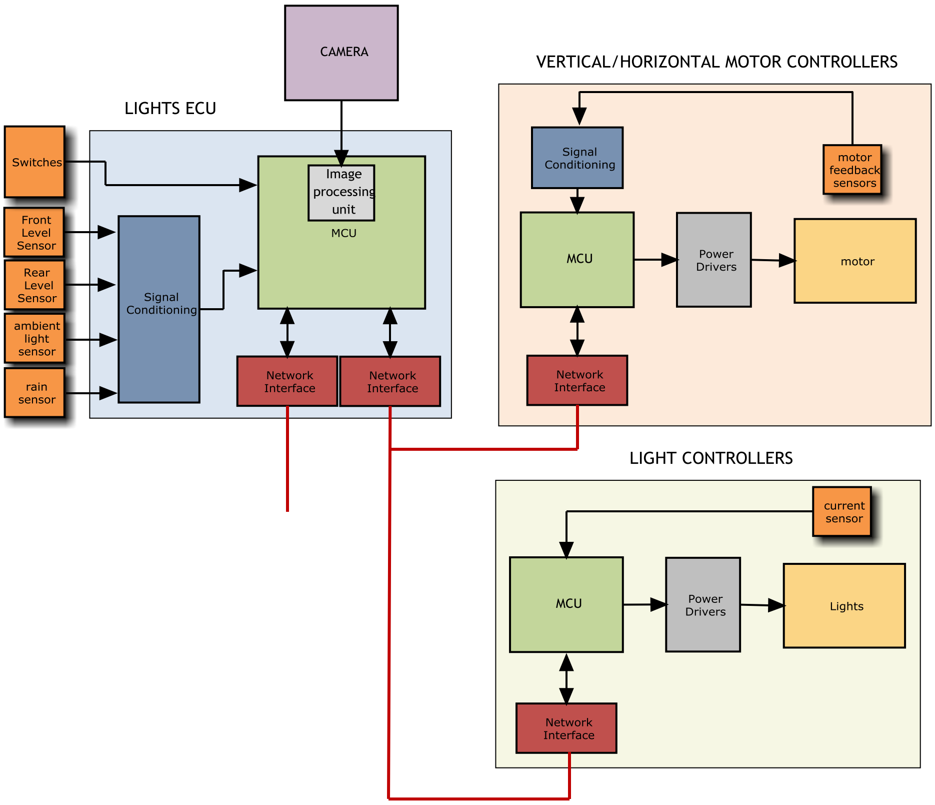


Figure 2.44 - Lighting systems' architecture

2.7 Propulsion System

In this section a brief description of electrical propulsion systems is presented. Electrical propulsion systems consist of five main elements: the motor controller, an electronic power conversion unit, the electric motor (or motors), transmission (if required) and wheels.

The motor controller determines the desired torque/speed values according to the system inputs, and actuates the power drivers in order to achieve the desired performance. The inputs to the propulsion system MCU are the throttle and brake pedals (refer to Section 2.7.1) positions and requests from other ECUs.

Among others that might arise from the systems installed in the vehicle, typical requests are torque reduction requests from the TCS system, speed setpoints by the adaptive cruise control system, or regenerative braking requests by the braking ECU. Such systems are interconnected to the motor ECU by means of a network connection. The outputs of the motor ECU and feedback sensor variables are conditioned by the type of motor used and the chosen control method. Figure 2.45 depicts an illustration of the typical architecture of an EV propulsion system.

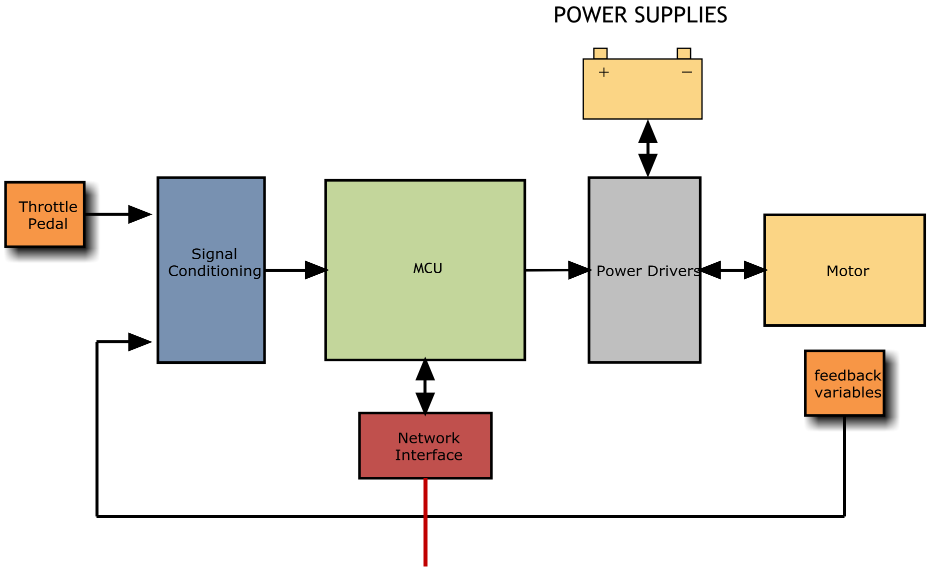


Figure 2.45 - Propulsion system architecture

2.7.1 Regenerative Braking

The electric motor has the task of converting the electrical energy provided by the batteries/ultracapacitors into the motional energy that is responsible for moving the vehicle. Also, the opposite can happen as electric motors can act as generators, proving energy back to the source. When a motor is acting like a generator, a torque which counteracts the rotation of the motor is induced. The use of this torque to aid in braking the vehicle is called regenerative braking.

Regenerative braking is important as huge amounts of energy are wasted in the form of temperature in frictional brakes, and energy is considered to be the main problem that needs to be overcome in order to make EVs commercially viable. As an example, in [30] is claimed an increase of 8-25% in EV's driving range by the use of regenerative braking and its efficiency is empowered in stop-and-go driving conditions such as in city environment. Moreover, it prevents wear on mechanical brakes.

Energy regeneration happens when the motor's back electromotive force (EMF) is greater than the voltage supplied by the power driver. In this way, instead of flowing from the batteries to the motor, current flows from the motor to the batteries. This happens when the speed of the motor is higher than the demanded speed.

Regenerative braking alone does not provide enough braking force [31]. Hence, frictional braking systems must coexist and work together with the motor ECU, which controls regenerative braking to generate the desired braking force altogether.

Only the axles/wheels that are connected to the motor/s can capture energy. When braking, in order to regenerate the maximum amount of energy, the regenerative braking force value must be the maximum value that can be provided without provoking wheel lock-up. In situations where high intensity braking is demanded, in which the amount of braking force surpasses the value that regenerative braking can provide, the remaining brake force is provided by frictional brake systems. Hence, regenerative braking relies on a strong cooperation between the motor and braking control units.

2.7.2 Cruise Control

The cruise control system enables vehicle speed to be automatically controlled. This results in higher comfort and ultimately in safety, as drivers tend to drive faster if the speed is not automatically controlled with the increase of the journey time.

Typically, it requires no additional hardware as the control can be achieved by software in the motor controller.

2.8 Adaptive Cruise Control (ACC)

The adaptive cruise control system is an enhancement of the cruise control system. Besides maintaining a constant speed when no vehicles are located ahead, the ACC measures the travelling speed of vehicles ahead, their distance and angle by means of a radar sensor and actuates the throttle pedal and brakes automatically in order to maintain a constant distance or headway time [32].

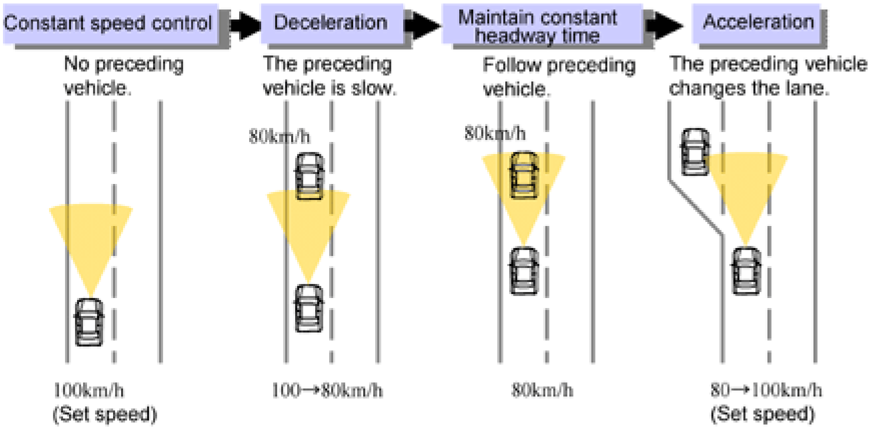


Figure 2.46 - Adaptive Cruise Control maintaining a constant headway time [33]

The adaptive cruise control is a complex system which relies not only on the radar sensor but also in values provided by other ECUs, as detecting objects alone is not enough for performing a correct evaluation of the situation.

The objects that must be considered for the adaptive cruise control operation are the ones traveling in the same lane as the vehicle. Situations where the vehicle is turning, and consequently in which front vehicles are also turning, demand the cooperation between several control units, which provide the values of interest variables such as speed of the vehicle, steering angle and yaw momentum that enable the ACC system to evaluate the situation. Such variables are also used for performing calculations when the vehicle is changing lanes, as the ACC is required to track objects on the lane in which the vehicle is moving to.

Chapter 3

In-Vehicle Networks

3.1 Introduction

This section presents the major networking solutions used by manufacturers to interconnect the systems referred in the previous chapter.

The first computational based features that were implemented in the automotive industry relied on centralized architectures, consisting of a set of sensors and actuators connected to a microcontroller.

Due to the low interaction between ECUs, in the cases that data exchanges were required, this would be achieved by means of point-to-point connections between the corresponding ECUs. Upon appearance of more complex features that demanded a strong cooperation between multiple ECUs, allied to a significant increase in the number of sensors and actuators connected to ECUs, the huge number of wires present in vehicles started to compromise their overall competitiveness: cost, complexity, reliability and weight were the major concerns [34].

Soon, the automotive market started to demand solutions that that could enable multiple ECUs to transmit data over the same transmission medium.

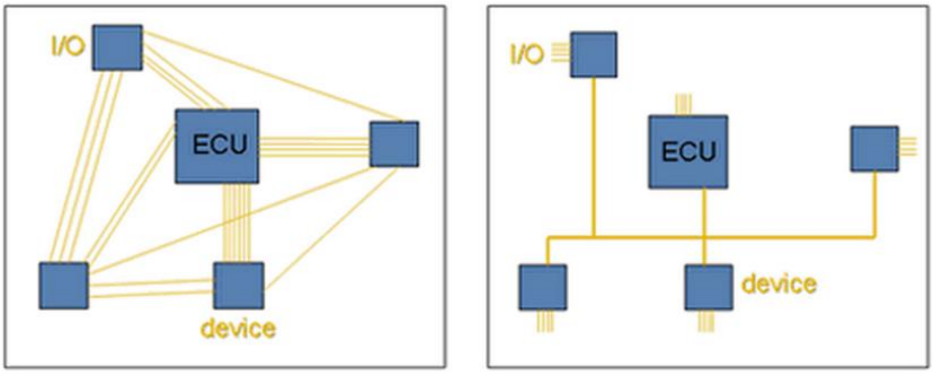


Figure 3.1 - Reduction of number of wiring by means of interconnecting ECUs in a network

Due to their importance in the automotive market, the controller area network (CAN), the local interconnect network (LIN) and Flexray are introduced with further detail.

3.2 Network Requirements for the Different Automotive Domains

The different vehicle domains discussed in Chapter 2 impose different requirements on the networks that support their operation. In [7], the following requirements are considered:

- **Fault tolerance -** the ability of the communication network to withstand behaviors that are not congruent with its specification. Fault tolerant networks embed a series of mechanisms such as bus guardians, which prevent nodes to transmit in time frames that are reserved for other nodes, and redundant hardware and software which provide error detection, confinement and recovery

- **Predictability -** the ability of a communication system to know when messages will be transmitted. Predictable communication systems are usually achieved by enforcing messages to be sent at predefined time instants or time intervals

- **Bandwidth -** the data rate supported by the network system

- **Flexibility -** the ability of the network to cope with both event and time-triggered messages, various scenarios of network load and network scalability

- **Security -** the ability to prevent unauthorized access

Table 3.1 presents the automotive domains referred on Chapter 2 and their major requirements

Table 3.1 - Automotive domains and their major requirements. Based in [7]

Subsystem	Fault tolerance	Predictability	Bandwidth	Flexibility	Security
Powertrain	YES	YES	HIGH	NO	NO
Chassis	YES	YES	HIGH	SOME	NO
Body	SOME	SOME	MEDIUM	SOME	NO
Passive Safety	YES	YES	HIGH	NO	NO
HMI/Infotainment	NO	SOME	HIGH	YES	SOME
Telematics	NO	SOME	MEDIUM	YES	YES

3.3 In-vehicle Network Classifications

The Society for Automotive Engineers (SAE) classifies the types of networks which are commonly found in vehicles according to their bitrates into four different classes that are described in this section.

3.3.1 Class A Networks

Class A networks are typically low cost networks characterized by transmission rates lower than 10 Kbps, that are used to transmit control data in the body domain [34]. Systems integrated in the body domain such as door control, climate control, seat adjustment among others, do not impose strict timing requirements or high transmission bitrates, as communications are mainly event-triggered. Examples of class A networks are the local interconnect network (LIN) and time-triggered protocol A (TTP/A).

3.3.2 Class B Networks

Class B networks operate at bitrates ranging from 10 to 125 Kbps and are mainly used to support data exchanges between ECUs to reduce the number of sensors by sharing information [6]. Low-speed CAN and J1850 are examples of class B networks.

3.3.3 Class C Networks

Class C networks are characterized by having transmission rates from 125 to 1 Mbps, and have been used over the years to integrate systems from the powertrain and chassis domain. An example of a class C network is the high-speed CAN.

3.3.4 Class D Networks

Class D networks operate with bitrates higher than 1 Mbps and are oriented for advanced powertrain and chassis systems, supplemental restraint systems, drive-by-wire systems and multimedia data [34].

Examples of class D networks are Byteflight, time-triggered protocol C (TTP/C), Flexray, Media Oriented Systems Transport (MOST) and FireWire (IEEE 1394).

3.4 Communication Networks for the Automotive Industry

To overcome the perceived limitations of the I2C and D2B networks which were used in automobiles [35], Bosch started the development of the network that would revolutionize the hole automotive industry in 1983: the controller area network (CAN). The first specifications were publicly presented in 1986 at the society of automotive engineers congress, and the protocol was widely implemented in the beginning of the 90's.

CAN was designed to be a high performance communication system to support the operation of the powertrain and chassis domain, gifted with powerful arbitration, fault detection, error confinement mechanisms, and bit rates ranging from 10 Kbps up to 1 Mbps. It is also used as the communication protocol for systems belonging to the body domain, serving as the backbone for LIN, a low cost network targeted for the requirements of the body domain. Due to its success, CAN became an international standard: ISO 11898 [36].

As new generations of vehicles started to carry more sophisticated electronic systems, along with the upcoming drive-by-wire systems, higher bit rates, strict determinism and more reliability started being demanded.

The necessity for higher bitrates is a consequence of the increase in the number, complexity and the level of interaction between the different systems within a vehicle. Bit rates up to 10 Mbps are expected to be required [37], as opposed from the 1 Mbps top bitrate offered by CAN.

The upcoming drive-by-wire systems and other critical features require levels of determinism which CAN is unable to provide as an event triggered protocol [37]. First of all, due to the fact that nodes are allowed to produce messages asynchronously, the number of collisions a frame faces with high priority frames is unknown. High priority frames with no errors might be sent by a faulty node continuously, giving lower priority frames no chance to be transmitted (the *babbling idiot* problem). Such situations can lead to the miss of deadlines of hard real time tasks as well as dangerous jitters that affect control algorithms. Furthermore, CAN does not allow a bus guardian to be implemented as a consequence of the uncertainty of when a message will be transmitted. Consequently, erroneous nodes outputting high level priority messages cannot be disabled, thus blocking the entire network.

The reliability required by safety critical systems in vehicles demands the support of a redundant transmission medium, as critical systems cannot rely on single points of failure. On its specification, CAN does not address the implementation of redundant transmission mechanisms.

Several attempts were made to overcome CAN's referred limitations. The most popular protocols that were developed in order to overcome CAN limitations were TTCAN, Byteflight and TTP [37].

Exhaustive technical analysis were performed by a group of automotive companies to discover whether any of these protocols was capable of meeting all the requirements for the upcoming generation of vehicles. It was proved that none of them could fulfill those requirements, which led to the development of a new communications network called Flexray [38]. Flexray is now starting to be adopted but its cost is still considered to be high and therefore it is still used in conjunction with CAN.

TTEthernet is also able to provide the deterministic behavior and fault tolerance mechanisms as Flexray, with the addition of supporting bitrates up to 10Gb/s. Given its potential, TTEthernet is discussed in Section 3.8.

3.5 Controller Area Network

Controller area network (CAN) is the most widely used network in the automotive industry [39]. Due to its importance, more emphasis is put on this document in the presentation of this network. Due to space and time requirements, the vast majority of details behind this protocol were omitted, given the amount and complexity of many of the questions involved. A detailed description of the protocol can be found in [40].

CAN is a multi-master protocol that uses a CSMA/CD (carrier sense multiple access/collision detection) mechanism with a non destructive arbitration concept. It is fitted with many error detection and recovery features, while granting enough bitrate to be adequate to be used as the transfer protocol between high dependability subjects of today's vehicles.

Due to the fact that the frame transmission system in the CAN protocol is based on the priority of messages to be transmitted, the CAN protocol enables its nodes to be configured to suit the necessities of real time operation, despite being an event-triggered protocol.

Therefore, CAN has been actively being used as the protocol to transfer information between engine, braking systems, power steering, among other ECUs. In [40], the following two layers of the OSI reference model are specified:

1. **Physical layer:** Description of bit timing, encoding and synchronization. It must be empathized the that the transmission medium or drivers are not specified, to give room for optimized solutions according to any application.

2. **Data link layer**
   a. MAC sublayer: Responsible for framing, arbitration, acknowledgement, error detection and signaling.
   b. LLC sublayer: message filtering, overload notification and recovery management

Gross bitrates achieved by CAN depend on the physical medium and transmission distance. Two ISO standards define the electrical characteristics, based on two different speed targets according to Table 3.2.

Table 3.2 - CAN standards

Group	Standard	Bit rate
Low speed CAN	ISO1189-3	10 Kb/s to 125 Kb/s
High speed CAN	ISO11989-2	125 Kb/s to 1Mb/s

Throughout the following descriptions the same nomenclature of the CAN 2.0 specification is used regarding bit values. The transmission medium must be in its recessive state when no node is transmitting or is transmitting a recessive bit, and in its dominant value when at least one node is transmitting a dominant value even if other nodes are transmitting recessive bits. This behavior is denominated as a *wired-and* logic.

3.5.1 CAN Nodes Interaction Model

Flexibility was one of the major concerns upon the design of the CAN specifications. Hence, to outfit each node with a physical address and route messages with the basis of that address would not provide the desired elasticity, as changing the network configuration would require the reconfiguration of all of the nodes.

Therefore, CAN nodes transmit messages in a publisher-subscriber fashion. This implies that all messages are broadcasted into the network. Upon reception of a message, each node decides whether the message is to be processed or not. This decision is based on the message identifier, placed on the arbitration field of each frame.

3.5.2 Bus Access

In a multimaster network like CAN each node is free to start the transmission of a frame. However, multiple nodes can start transferring data at the same time. CAN frames are provided with a specific field (the arbitration field) for handling arbitration between transmitting nodes.

During the arbitration phase each sender compares the value present in the transmission medium with the value that it has transmitted. In case these values do not match, which uniquely happens in the case where the node has outputted a recessive level and a dominant level was observed in the line, the sender stops transmitting, as this implies that other node is sending a message with higher priority. It is important to note that the presence of multiple senders at the same time in the same network does not destroy the content of the higher priority frame. This form of arbitration is called non-destructive.

Figure 3.2 depicts an example of the arbitration procedure between three emitting stations.

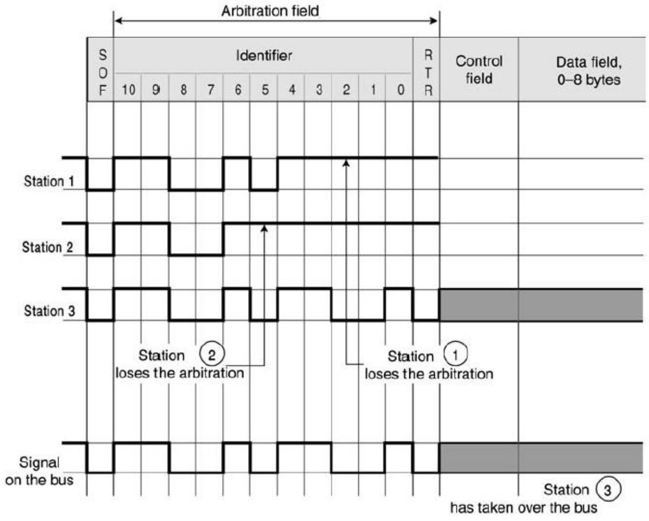


Figure 3.2 - CAN arbitration procedure in a wired-and bus [38]

The arbitration procedure implies that in a *wired-and* bus, in which the *logical one* assumes the *zero* bus value, and a *logical zero* assumes the *one* bus value, the lesser a message identifier is, the higher priority is granted to the frame.

3.5.3 CAN Frames

3.5.3.1 Data and Remote Frames

Data frames are types of frames used for different nodes to exchange data. Figure 3.3 depicts the structure of a CAN 2.0 data frame.

Remote frames are structurally similar to data frames but do not carry data, and are used to request a data frame with the same identifier.

Every time a data or remote frame is transmitted, an interframe space composed by 3 recessive bits is present.

Data and remote frames' identifiers were originally designed with an eleven bit length. However, for certain applications, this number was proved to be insufficient. CAN 2.0B specification presents an extended version of data and remote frames, using an identifier composed of 29 bits.

Both standard and extended frames can coexist in the same network, making extended frames to be an option only when it is actually needed, as the unnecessary number of extra bits in the identifier field represents extra overhead.

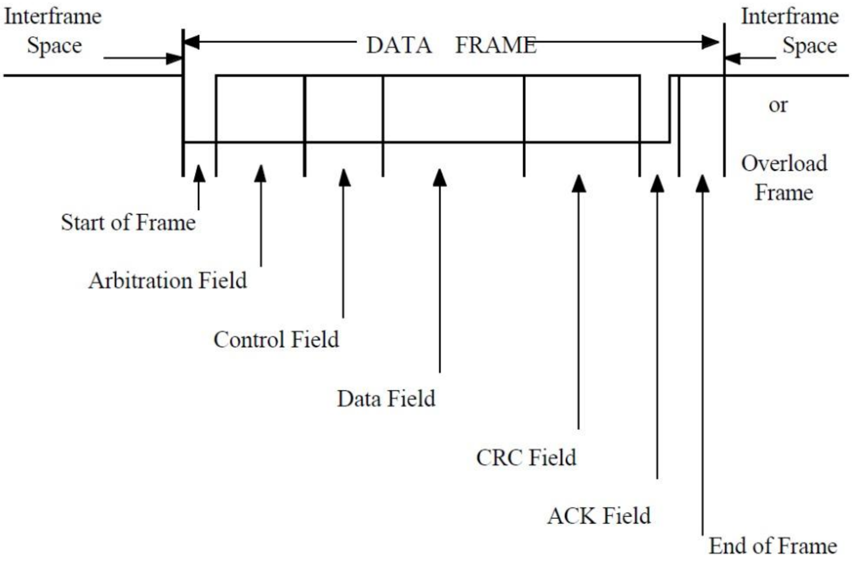


Figure 3.3 - CAN data frame [40]

<u>Start of Frame</u>

The start of frame field is composed by one dominant bit and has the task of informing all nodes that a frame is about to be transferred.

<u>Arbitration Field</u>

Bits contained in this field are the basis for the arbitration procedure already discussed. The structure of this field in a standard frame is depicted on Figure 3.4.

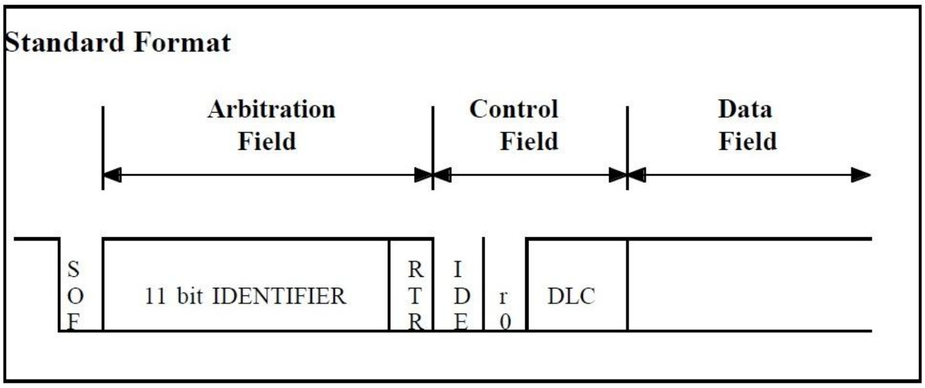


Figure 3.4 - Standard format of CAN frame arbitration and control fields [40]

In the standard frame format, the arbitration field carries the 11 bit message identifier, plus a bit known as remote transmission request (RTR). This bit signals whether the frame is a data or remote frame. Its value is dominant in the case of a data frame and recessive in the case of a remote frame. This implies that data frames have priority over remote frames with the same identifier.

The arbitration field of an extended frame is illustrated on Figure 3.5.

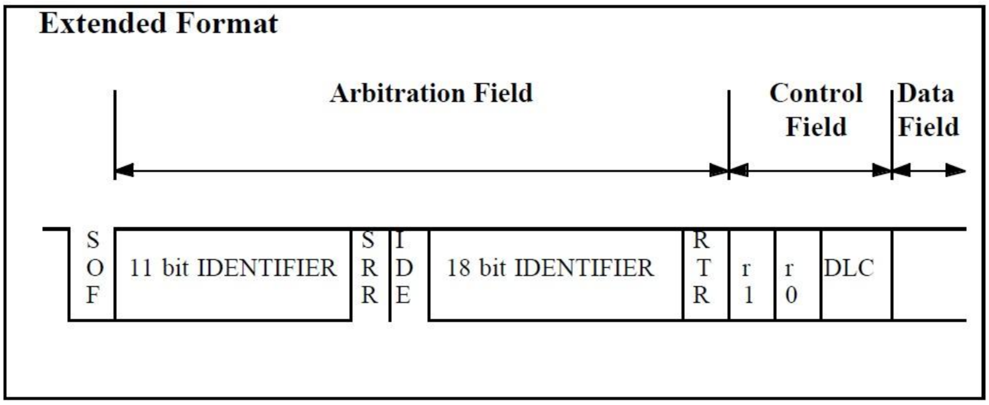


Figure 3.5 - Extended format of CAN arbitration and control fields [40]

As it was already mentioned, the identifier field of an extended frame is composed of 29 bits. The first 11 bits are denominated the base ID while the remaining bits of the identifier are denominate the extended ID.

The base and the extended ID bits are separated by two bits: the substitute remote request (SRR) and the identifier extension bit (IDE).

The SRR is recessive in an extended frame and overlaps the RTR bit in the standard frame.

The identifier extension (IDE) bit informs whether a frame is in its extended form or not. In the case of a standard frame this bit is dominant, while in the case of an extended frame this bit is recessive. In this way, when two data frames with the same base ID are sent over the network, in which one of them is in the standard format and the other in the extended format, the standard frame will gain access to the bus.

Control Field

The control fields of standard and extended frames are composed of 6 bits.

Both standard and extended frames are composed of a section named data length code (DLC) which is used to specify the number of bytes present in the data field. Due to the fact that the maximum number of bytes in the data field is 8, the DLC is made of 4 bits.

The first two bits of the control field are different for each frame. The control field of standard frames is composed of the IDE and a reserved bit (R0) for future uses, while the control field of extended frames is composed of the R0 and R1 bits, both reserved for future uses.

It should be noted that the IDE bit is present on the control field of standard frames while in extended frames this bit is present on the arbitration field.

In both types of frames, the reserved bits are sent as dominant.

Data Field

The data field is the section where the data is carried. 8 bytes can be transferred from the most significant bit (MSB) to the least significant bit (LSB).

Cyclic Redundancy Check Field (CRC field)

This section carries an error detection code discussed in Section 3.5.5.3.

Acknowledge Field (ACK)

The acknowledge field is similar in both standard and extended frames. It is composed of two sections: the ACK field and the ACK delimiter. When transmitting this field, the sender switches to listening mode, thus outputting a recessive level on the transmission medium. All the nodes in the network which received a successful frame containing no errors output a dominant level in the ACK field. This procedure informs the sender that the frame was correctly received by at least one node.

End of Frame

The end of frame field consists of seven recessive bits, which indicate that the transmission of the frame has ended.

Error Frames

Error frames are sent immediately on the next bit after the error detection. Upon detection of CRC errors, error frames are sent on the first bit after the ACK delimiter. Error frames have purposely a structure that violates the stuffing rule (refer to Section 3.5.5.2). Therefore, when an error frame is sent by a node which has detected an error, this will cause other nodes to detect a stuffing error, which will cause them to output their own error frames.

The structure of error frames is illustrated on Figure 3.6.

Error frames are composed of an error flag and an error delimiter fields. There are two kinds of error flags in the error frames: active and passive flags. The situations whether each of the flags is transmitted by a particular node is related to CAN's fault confinement strategy which is discussed in Section 3.5.6.

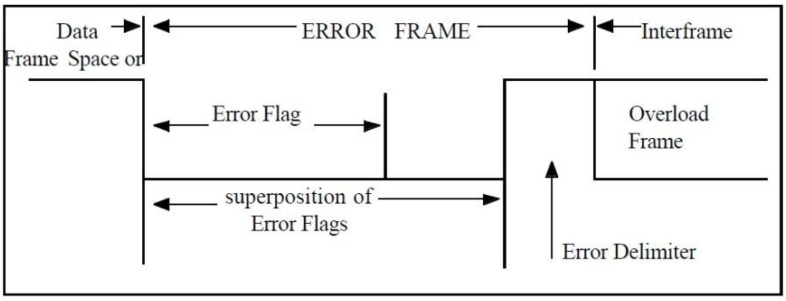


Figure 3.6 - CAN error frame structure [40]

Active error frames are composed of 6 dominant bits, while passive error flags are composed by 6 recessive bits. When a node detects a transmission error, it starts emitting its own error flag. Therefore, the error flag segment has variable size as it might represent the superposition of various error flags between nodes. This superposition will have the maximum number of twelve bits, which happens in the case of a node detecting an error after a transition from dominant to recessive, which will cause other nodes to only detect the bit stuffing violation in the sixth bit of the error flag.

After outputting an error flag, each station transmits recessive bits.

Upon detection of a recessive bit in the transmission line, implying that all of the stations are transmitting recessive bits, which in turn mean that all nodes have transmitted error flags, each node transmits seven more recessive bits. Hence, the error delimiter section is composed by eight recessive bits.

3.5.4 Overload Frames

Overload frames have the task of creating a delay between the delivery of frames so data is not lost by an overloaded node. The structure of overload frames is similar to active error frames and two overload frames can be sent consecutively by a particular node.

Overload frames consist of an overload flag and an overload delimiter, and are transmitted by any node under the following circumstances:

1. In case that additional time is required to compute last operations, the overload frame is transmitted at the first bit time of the upcoming intermission

2. Upon detection of a dominant bit at the first and second bits of intermission, or a dominant bit at the eight bit of the error delimiter, the overload frame is transmitted in the next bit after the dominant bit detected

Upon detection of an overload flag, each node outputs its own overload flag.

The overload delimiter operation is analogous to what was described in the error frame section.

3.5.5 Error Detection, Processing and Management

Due to the fact that CAN serves as the path for the exchange of safety critical messages, the protocol is equipped with several error detection mechanisms that are described in this section.

3.5.5.1 Bus Monitoring

Disregarding the arbitration and acknowledge fields, when bus access has been granted to a node, it compares the value present in the line with the value that it is outputting. In case that these do not match, a bit error is present.

3.5.5.2 Bit Stuffing

The bit stuffing method consists in having the transmitter of a frame adding an extra bit after the detection of five consecutive bits with the same value, whose value is the complement of those bits.

In this way, errors in which the node's outputs stay fixed in a dominant or recessive level are detected. Due to the fact that the CRC delimiter, ACK field and end of frame have fixed structures, these are not stuffed.

3.5.5.3 Cyclic Redundancy Check (CRC)

The cyclic redundancy check code is the rest of the division formed by treating the stream of bits since the start of frame until the end of the data field as a polynomial (with fifteen zeros added to the less significant coefficients and not stuffed) by the polynomial $g(x) = x^{15} + x^{14} + x^{10} + x^{8} + x^{7} + x^{4} + x^{3} + 1$ (BCH code). This value is sent on the CRC field.

Upon reception of a frame, the receiver calculates the CRC value of the received message and compares with the received CRC value. In case that these values do not match, a transmission error has occurred.

3.5.5.4 Message Frame Check

Transmission errors can affect the frame's structure. Hence, each node monitors messages and checks whether incoming messages respect the frame's structure. In case this structure is not respected an error is signaled.

3.5.5.5 Acknowledgement Field

The acknowledgment of messages serves as the confirmation that a frame was correctly transmitted over the network (disregarding the unlikely event that an error might assume the form of a positive acknowledge). In case that the sender does not receive any positive acknowledgement, it can conclude that the message was not correctly transmitted and thus outputs an error frame.

3.5.5.6 Error Frames Dispatch

Error frames dispatching is discussed in Section 3.5.3.2.

3.5.6 Fault Confinement Strategy

The CAN protocol tries to minimize the effect of erroneous nodes on the network by confining their behavior. For this purpose, two kinds of counters are present in each node: one for counting transmission errors and other for counting reception errors.

Every time a transmission or reception error is detected the respective counter is incremented. On the contrary, upon successful reception or transmission the respective error counters are decremented. The increment/decrement of counters do not follow a proportional rule, as errors cause the counters to be incremented by a greater value than the decrease of its value upon detection of a successful transfer.

This provides a better perception of the fail distribution among the network as well a more strict confinement rule. Figure 3.7 illustrates the error confinement strategy:

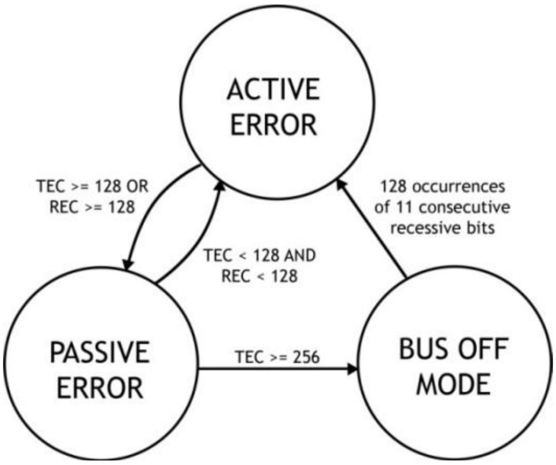


Figure 3.7 - Transitions between error states in CAN

If error counters are both below 128 the node is said to be on the active error state. Being in the active error state means that the node operates normally and, upon detection of an error, the node will output an active error flag, causing other nodes to detect this error flag.

If both counters are below 255 and at least one of the counters is above 127 the node is said to be on the passive error state. Likewise, the node will operate normally but upon detection of an error the node will output an error frame with a passive error flag, thus not interfering with the rest of the network.

Nodes enter the *bus off* mode when transmission error counters are higher than 255. In the *bus off* mode nodes are not allowed to transmit. This prevents a faulty node to block the entire network. In this state the node is not allowed to transmit, but it monitors the network as 128 occurrences of 11 successive recessive bits trigger the node back to the active error state.

3.6 Flexray

Flexray is a communication system targeted for high-speed control applications in vehicles such as advanced powertrain, chassis, and by-wire systems [41]. Flexray is able to offer bit rates up to 10 Mbps and provides the support for dual-channel communication systems, which can either be used to provide redundancy if the same frames are carried in both communication channels, or double the available bandwidth, in case that the secondary channel is used for the transmission of additional data.

Not only it does it enable bus topologies, but also other complex approaches such as active and passive stars, and mixes between these topologies to be implemented. Examples of topologies supported by Flexray can be found in Figure 3.8.

In addition to this, Flexray is able to grant bounded latencies and jitter through the aid of a TDMA based approach, a basic requirement for distributed control systems, while not leaving behind the support of event driven occurrences.

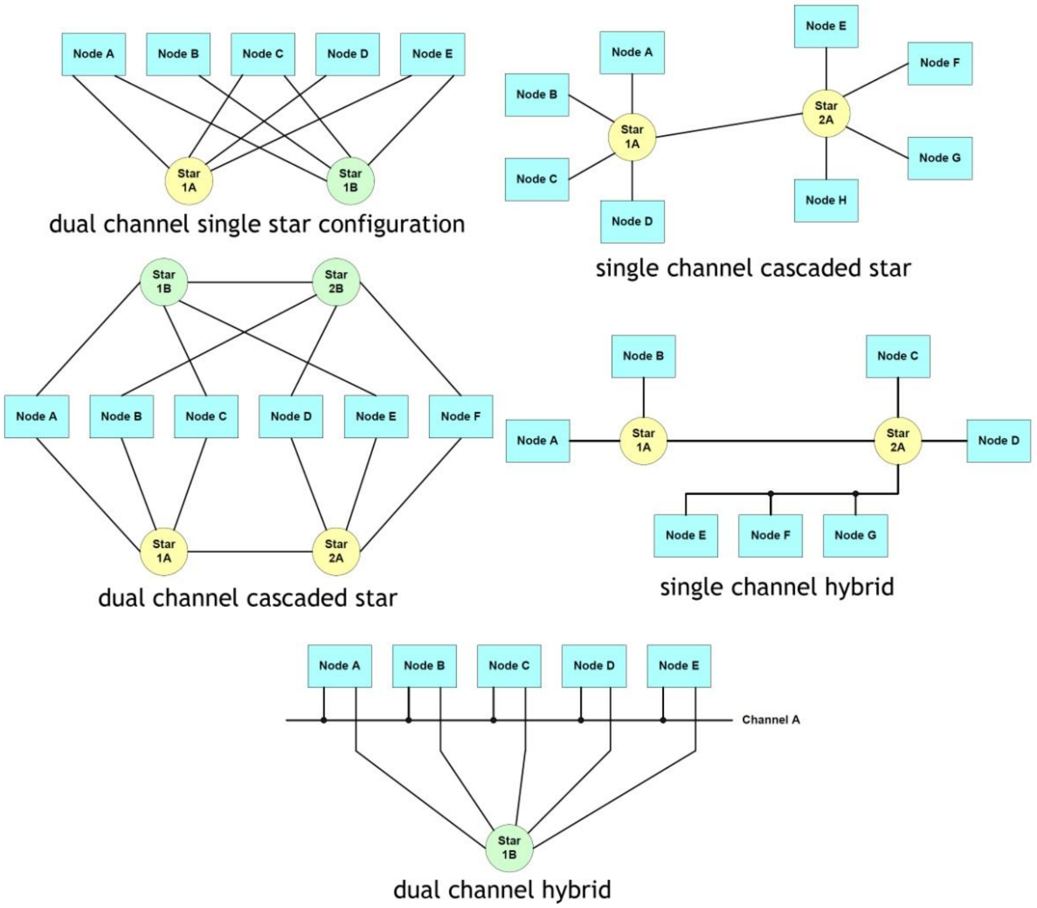


Figure 3.8 - Flexray topologies [42]

3.6.1 Bus Access

Bus access within the Flexray protocol occurs taking as basis a communication cycle where two different bus access mechanisms take place. The first mechanism occurs in a section called the static segment and is based on the TDMA approach, able to guarantee fixed latencies and jitter in which distributed control systems rely on. The dynamic segment is responsible for handling events which are not periodic in its nature. The transfer of frames within this segment is subject to a prioritizing rule based on the frame identifiers.

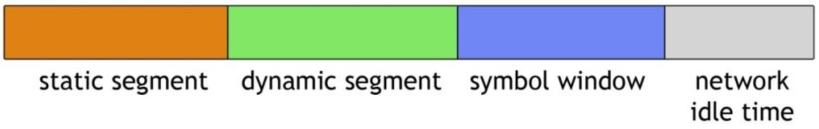


Figure 3.9 - Flexray communication cycle

3.6.2 Static Segment

The static segment is where time-triggered frames are scheduled. It is divided in an equal number of sections called slots where each frame is carried. The number of slots present in the static segment is the number of frames that are exchanged periodically.

In order to ensure that two nodes do not communicate at the same time, slots are associated with frame identifiers which cannot be shared. Allocation of the frames to the respective slots is a process done offline. To maintain the periodicity of the communication cycle, if a frame is not sent in the respective slot, other frames are not anticipated and the slot time will carry no data.

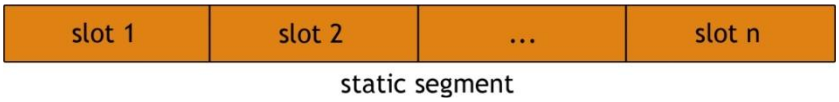


Figure 3.10 - Flexray static segment

Due to the fact that a node is only allowed to communicate in a given slot if its frame ID is associated with that slot, nodes must keep track of the current slots in order to schedule the release of its frames. This is done by means of a local variable that starts with the value 1 in the beginning of each static segment and is incremented at each slot time.

The static segment enables control loops to be implemented in a single static segment. This scheme is known as in-cycle control [43].

Figure 3.11 illustrates an example of what can be done using this technique in an ABS system.

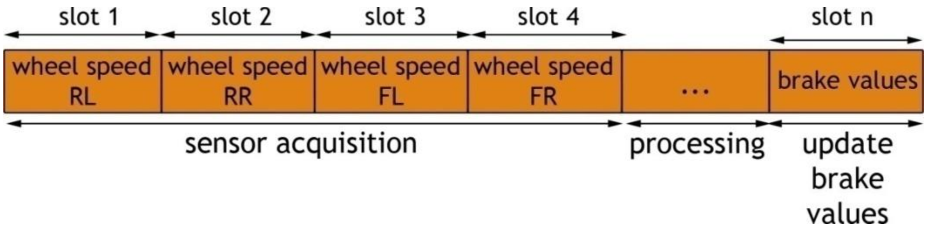


Figure 3.11 - Flexray in-cycle control

Assuming that wheel speed sensors are connected in a Flexray network, frames carrying the values of wheel speed sensors are transmitted to the ABS ECU in the first slots of the static segment. Slots after the sensor acquisition that might carry or not useful data for other processes, enable the ABS ECU to have to time to process the desired brake values. After processing the wheel speed sensors' values, the ABS ECU can share the brake pressure values with the network. This control approach enables a tighter control of the processes within the vehicle.

3.6.3 Dynamic Segment

The dynamic segment has a fixed length and is composed by subsections called minislots. Similarly to what was described in the static segment, each minislot is associated with one frame ID. If a node desires to transmit a determined frame it may only start its transmission within the associated minislot, and the access to the medium is granted until the end of the transmission, or the end of the dynamic segment. Hence, minislots grow taking the time of minislots with lower priority. Therefore, the closer to the beginning of the dynamic segment a minislot is, the higher priority a frame associated with that minislot will have.

Figure 3.12 depicts an example which contains a schematic of its minislots and associated frame IDs, in the case that no frame is transmitted within its associated minislot.

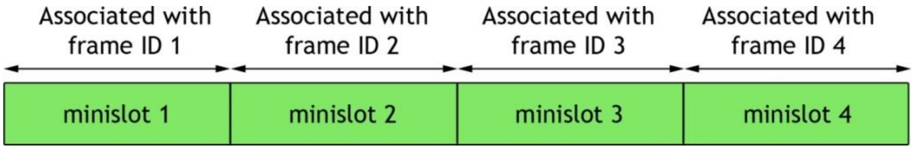

Associated with frame ID 1
Associated with frame ID 2
Associated with frame ID 3
Associated with frame ID 4
minislot 1
minislot 2
minislot 3
minislot 4

Figure 3.12 - Minislots in the dynamic segment

If it is assumed that frames 2 and 4 are to be dispatched, once the dynamic segment reaches minislot 2, the node responsible for frame ID 2 takes control of the bus and starts transmitting. As the time required to transmit frame 2 is higher than the duration of the minislot, this will cause the minislot to expand.

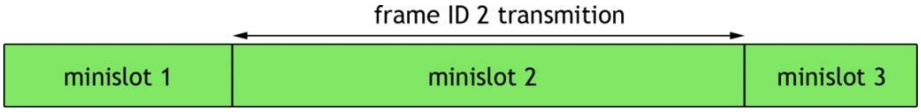


Figure 3.13 - Minislot expansion

Therefore, the dynamic segment has no time left for transmitting frame 4, which must be transmitted within the next dynamic cycle.

3.6.4 Symbol Window

The symbol window is used for the transfer of specific protocol messages, denominated symbols.

3.6.5 Network Idle Time

The network idle time is as long as the remaining time between the sum of the static segment, dynamic segment and the symbol window lengths until the communication cycle time is achieved. Clock synchronization between nodes is performed during this time. To reduce network's wasted time, this field must be kept as minimum as possible. The minimum value permissible for this segment takes into account the maximum clock deviations that might occur between nodes.

3.6.6 Flexray Frame

The Flexray frame is composed by three main sections: the header, payload and trailer segments. Figure 3.14 depicts the structure of a Flexray frame.

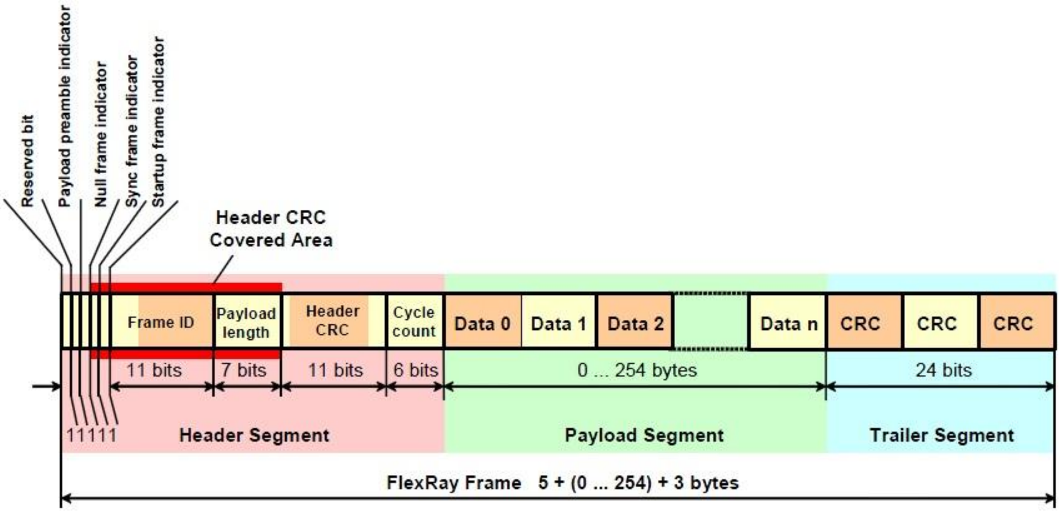


Figure 3.14 - Flexray frame [42]

3.6.6.1 Header Segment

The header segment is composed by the following bits/sections:

- **Reserved bit -** reserved for future developments of the protocol.

- **Payload preamble indicator bit -** in static frames this bit signals whether the payload field contains a network management vector at its beginning. In case of dynamic frames, it is used to indicate the presence of a message ID in the beginning of the payload field. This bit is set to zero when none of the mentioned data is present.

- **Null frame indicator bit -** indicates whether the payload field contains data or not. In case that the payload field is empty this bit is set to zero. In case that the payload field contains useable data, it is set to one. The null frame indicator bit serves as a way of providing the receiving nodes with information such as whether the transmitting node had its data ready at the time of transmission of the frame or not.

- **Sync frame indicator bit -** is set to one if the frame is a synchronization frame and is set to zero in the case that the frame is not a synchronization frame.

- **Start-up frame indicator bit -** in case that the transmitted frame is a startup frame, this bit is set to one. Startup frames are only sent by nodes during cold start. The startup mechanism is not described in this document due to its specificity. More information on the startup mechanism can be found in [42].

- **Frame ID -** identifies the content and sender of the frame. Each communication slot has a frame ID associated to it. Hence, it is not allowed for nodes to share the same frame IDs.

- **Payload length field -** carries the number of words (sets of 16 bits) in the payload field. Since the maximum number of bytes in the payload field is 254, this section comprises 7 bits.

- **Header CRC -** contains the CRC code calculated taking as basis the bits comprised between the sync frame indicator until the end of the payload length field.

- **Cycle count -** the cycle count field contains the number of the communication cycle viewed from the transmitting node's perspective.

3.6.6.2 Payload Segment

The payload segment contains the data to be transferred in the frame. It can contain from 0 to 254 bytes of data. Due to the fact that the payload length field specifies the number of bytes to be carried as a mean of words, the payload segment always carries an even number of bytes.

As it was mentioned in previous sections, the first bits of this section can either contain the network management vector in case of frames transmitted in the static section or the message ID, in the case of a dynamic frame. The inclusion of a message ID on the payload field permits nodes to filter data based on the contents of this field.

3.6.6.3 Trailer Segment

The trailer segment contains a 24 bit CRC code for fault detection. A particular note on the effectiveness of this code must be taken into account as the hamming distance offered by this code depends on the length of the payload field. For payload fields which length is less or equal to 248 bytes, the hamming distance offered by the CRC code is 6 whether in the case that the payload length is higher than 248 bytes, the hamming distance offered is 4.

3.6.7 Error Processing, Management and Transmission Security

3.6.7.1 Bus guardian

The bus guardian is a device which monitors the communication channels. It is independent from the communications controller and grants extra reliability to the system. By knowing the frame schedule of the static section, it is able to detect if nodes erroneously try to access the bus on instants where they are not allowed to. Upon detection of such situations, the bus guardian can disable the bus drivers and notify the controller.

3.6.7.2 CRC codes

The CRC code mechanism is described on Section 3.5.5.3.

3.6.7.3 Dual Channel Transmission

The multichannel ability of the Flexray protocol is able to provide even more reliability and fault tolerance to the system if the same data is carried on both communication channels. Safety critical systems might not be able to withstand the failure of the communication network. By having two distinct communication channels carrying the same data, the interruption of one of the communication channels is compensated by the non faulty channel. In case of transient faults, the redundant transmission channel is able to deliver the affected frames correctly.

The delay of one of the communication channels allows an enhancement in fault tolerance. Figure 3.15 depicts an example where frames are being transmitted with a delay under the occurrence of a transient fault in both communication channels.

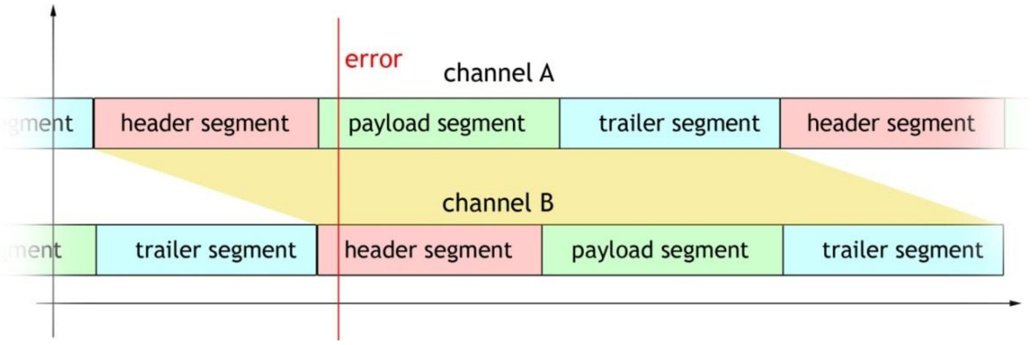


Figure 3.15 - Message delay in a two channel Flexray network

Due to the imposed delay, the error caused two different sections of the frame on each channel to be corrupted. Hence, it is possible to reconstruct the transmitted frame by utilizing the segments that have not been affected by the transient error.

3.7 Local Interconnect Network (LIN)

Different features demand for different network requirements. Vehicle systems mainly belonging to the powertrain and chassis domain demand high bitrates accompanied by powerful error detection and recovery mechanisms, as the processing of a miss value can lead to serious consequences. Because of its non criticality and low time constraints, some systems do not require the amount of functionalities and speeds that CAN or Flexray can offer. Furthermore, by implementing such functionalities in a system that does not require them, and given the fact that these functionalities are naturally associated with higher costs due to extra hardware/software components, the overall price of vehicles is raised without any added value. In order to overcome this issue, a group of vehicle manufacturers got together and formed the LIN consortium, with the objective of creating a low cost network for supporting the mecatronic elements of a vehicle such as doors, windows, heating, seating adjustment among others [39].

Local Interconnect Network (LIN) is master-slave network able to achieve bit rates up to 20 Kb/s. Its concept of operation is based on the introduction of tasks. The master node contains a master and a slave task, while slave nodes only contain slave tasks.

Many of the details presented in the LIN specification package are not discussed in this section. More information is found in [44].

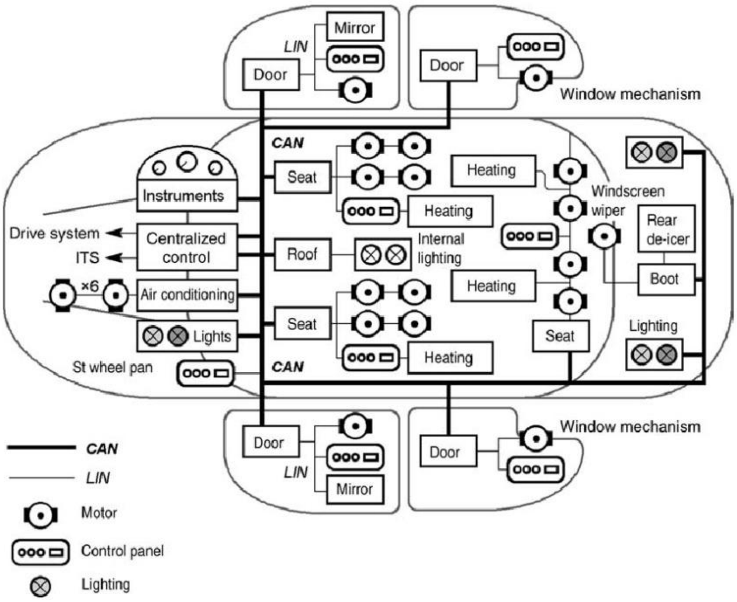


Figure 3.16 - LIN as a sub-bus of CAN [38]

3.7.1 LIN Frames

LIN frames are composed of two main sections: the header and the response field. The two sections are separated by a response space. The header is transmitted by the master task, while responses are provided by slave tasks.

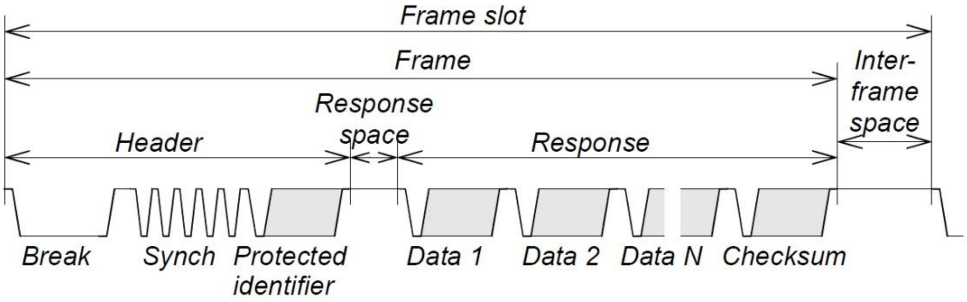


Figure 3.17 - LIN frame [44]

LIN frames are composed of the following fields:

- **Break field -** composed of at least 13 dominant bits and serves to signal all nodes that a frame transfer is about to start. This field is delimited by one recessive bit and is always transmitted by the master node.

- **Synchronization field -** enables nodes which use automatic baud rate detection to perform synchronization with the master node. In this section the master outputs the value 0x55 (1010101) so nodes can measure bit time through a capture counter and adjust their baudrates accordingly.

- **Identifier -** composed of 10 bits: 1 start bit, 6 identifier bits, 2 parity bits and 1 recessive delimiter bit. The identifier bits make it possible to address 64 possible messages. However, addresses 60 and 61 are reserved for diagnostic data, address 62 for user defined extensions and 63 for future protocol enhancements. Parity bits provide the header with a basic fault detection mechanism with 2 hamming distance. The aggregation of the identifier and the parity bits is denominated the protected identifier.

- **Data field -** consists of up to a maximum 8 bits of data. It is outputted by slave tasks in response to a given identifier.

- **Checksum -** transmitted by the slave after the data field. It serves as the fault detection mechanism for the data field. Upon arrival of the frame, the master calculates the checksum in the same way and compares with the received value to check for errors.

3.7.1.1 Types of LIN Frames

Despite that the structure of all frames is the same, the following types of frames are listed in the LIN specification:

- Unconditional
- Event triggered
- Sporadic
- Diagnostic
- User-defined
- Reserved

The difference between frames types resides in the timing and content of the data. Unconditional, event triggered and sporadic frames have particular bus access mechanisms that are referred in Section 3.7.2.

3.7.2 BUS Access

The LIN protocol follows a master-slave approach. Slaves are not allowed to transmit unless prompted. The determinism of the LIN protocol arises due to the fact that all of the communication in the bus is controlled by the master. Following its schedule table, when the master intends to cause a slave task to transmit a particular message, it outputs an header whose ID is associated with that message.

By analyzing the header's identifier and upon a positive parity check, each slave task determines whether if it is a publisher or subscriber of that particular ID. In case that the slave task is a publisher, it outputs a response. In the case that it is a subscribers, it listens to the bus so the information can be processed.

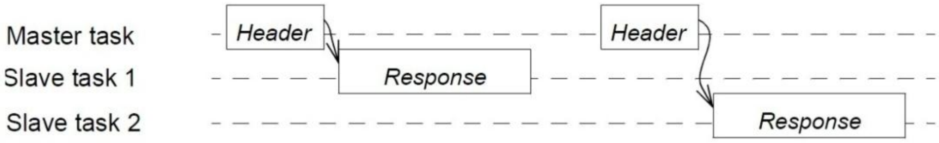


Figure 3.18 - LIN bus access [44]

The master itself can send messages (responses) to other slaves. That is achieved by placing a slave task in the master node. The slave task captures the header provided by the master task and outputs its response.

3.7.2.1 Unconditional Frames Transfer

Unconditional frames are the data carrying frames. Figure 3.19 depicts an example of three different situations upon the transfer of unconditional frames:

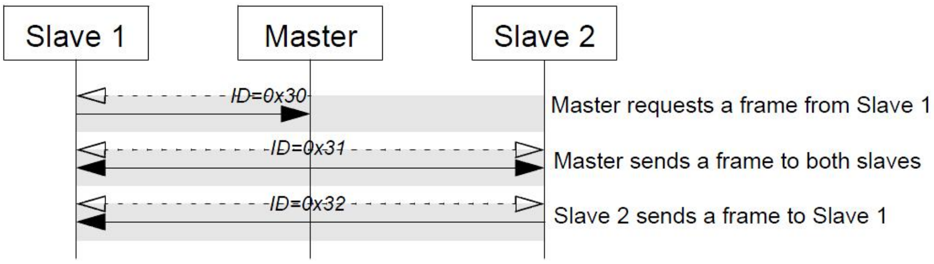

Slave 1
Master
Slave 2
ID=0x30
Master requests a frame from Slave 1
ID=0x31
Master sends a frame to both slaves
ID=0x32
Slave 2 sends a frame to Slave 1

Figure 3.19 - Unconditional frames transfer [44]

1. **Frames transfer between slave to master -** the master outputs the header whose identifier triggers the slave response. Upon reception of the header, slave 1 identifies itself as the publisher of the data and replies with the appropriate data.

2. **Frames transfer between master to slaves -** the master outputs an header whose identifier triggers the response from its own slave task

3. **Frames transfer between slaves -** the master outputs a header which will trigger slave 1 to be the subscriber of the message and slave 2 to be the publisher. Upon transmission of the frame by slave 2, slave 1 will capture and process the transmitted data.

3.7.2.2 Event Triggered Frames Transfer

Figure 3.20 illustrates an example of an event triggered transfer. The purpose of event triggered frames is to save bandwidth. This is achieved by associating multiple slave tasks to the same ID. In case that an event has occurred in a particular slave, it sends its protected ID (the ID which would be sent to query an unconditional frame) in the first data byte, so the master task can identify the node where the event has occurred.

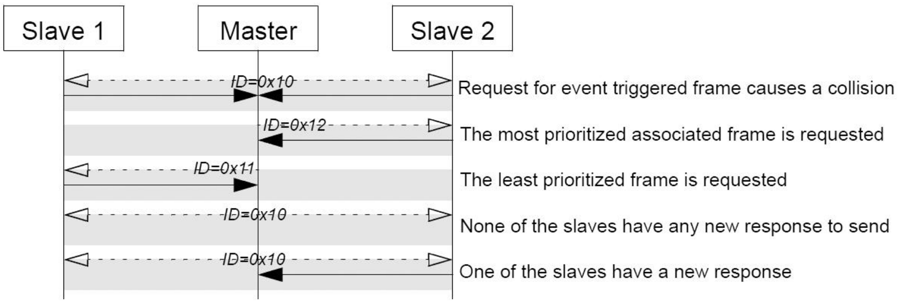

Slave 1
Master
Slave 2
ID=0x10
Request for event triggered frame causes a collision
ID=0x12
The most prioritized associated frame is requested
ID=0x11
The least prioritized frame is requested
ID=0x10
None of the slaves have any new response to send
ID=0x10
One of the slaves have a new response

Figure 3.20 - Event triggered frames transfer [44]

In case that two slaves had received an event and start transmitting simultaneous in response to the master's header a collision occurs, leading to an error. Then, according to slave priorities, the master queries them for unconditional frames.

3.7.2.3 Sporadic Frames Transfer

Although event-triggered frames might seem sporadic, the query from the master comes in a periodic schedule. Sporadic frames are used to embed a dynamic behavior in the network. Hence, sporadic headers are only sent by the master when new data was updated.

3.7.2.4 Diagnostic, User Defined and Reserved Frames

Bus access of diagnostic, user defined and reserved frames is similar to the bus access of unconditional frames. In these kind of frames, only the content of the ID and data changes.

3.7.3 Error Processing and Management

Error detection is handled by slave tasks. It consists of analyzing frame structure, parity bits and checksum. Upon detection of an erroneous frame, the processing of that frame is aborted.

Each slave is provided with a status bit named *Response_Error*. Nodes set the *Response_Error* bit to *logical one* upon detection of transmission or reception errors in response fields. The value of this bit is sent to the master slave periodically in one of the transmitted frames and cleared after transmission. In this way, the master gets to know some information about the status of a node. In the case that a node does not reply, it is assumed that a serious error has occurred.

Due to the fact that slaves are unable to transmit data unless prompted, the signaling of errors is uniquely done after a diagnostic header has been sent by the master.

3.8 Time Triggered Ethernet (TTEthernet)

The application of Ethernet in vehicles is an interesting solution mainly due to its cost effectiveness and high bandwidth, which can reach up to 10 Gb/s, an exuberating value compared to the bitrates offered by the other discussed protocols throughout this chapter.

Ethernet's original objective was the connection of multipurpose computers in local networks. Being designed in CSMA/CD approach, it does not grant in any way that a particular node will be able to access the transmission medium in order to perform a transmission. Time constraints, determinism or fault tolerance were aspects not taken into consideration upon its design. Therefore, in its original form, Ethernet is not able to fulfill the requirements that support its integration in vehicle control systems.

TTEthernet expands the classical Ethernet to meet these requirements [45]. It achieves this by generating services on top of unchanged Ethernet. The concept behind TTEthernet is the transformation of messages from higher layer protocols into time-triggered messages without changing its content. Therefore, it can be said that TTEthernet concerns only the instants when these messages are sent.

TTEthernet permits that messages with different levels of determinism can coexist in the same network. It is possible for strict control data to be placed in the same network with media data, which does not require strict determinism but instead a defined maximum latency, or even webservices in a best effort scheme, where determinism is not required at all. Furthermore, it may achieve this while granting high levels of reliability and fault tolerance.

3.8.1 Operational Principles and Architectures

TTEthernet's basic architecture assumes the star form, in which a router is the central element. Multiple stars can be cascaded, even with segments with different bandwidths. Redundancy, which is discussed in Section 3.8.3 can also be implemented in order to achieve extra reliability and fault tolerance.

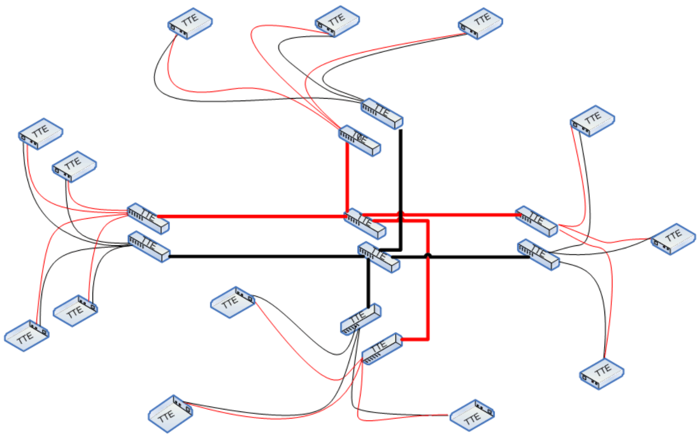


Figure 3.21 - TTEthernet redundant architecture [45]

Switches act as the core of the protocol, being responsible for the organization of incoming frames and posterior transmission in the appropriate instants, according to the predefined schedule.

The transmission of time-triggered (TT) messages requires a common sense of time between the interacting nodes. This implies that all nodes involved in the transmission and reception of time triggered frames must be synchronized. The synchronization process is quite extensible for the matters of this work and a detailed explanation of it can be found in [46].

Upon reception of scheduled time-triggered messages, switches immediately route frames to the respective network segment. Due to the fact that the transmission of these messages is scheduled offline, in error free operation the output transmission segment is always free.

Rate constrained (RC) messages are routed immediately if no TT messages are awaiting to be transmitted, and best effort (BE) messages take the remaining bandwidth. Switches have buffers for each kind of messages. In the case of high network load, the switch can notify the sending nodes that its buffer is full.

3.8.2 Types of Messages

There are three different kinds of messages that may be exchanged in TTEthernet which are presented as follows.

3.8.2.1 Time Triggered Messages (TT messages)

TT messages are messages sent by nodes at predefined instants. These messages have the maximum priority over the other types of messages, and used for exchanging strict deterministic control data.

3.8.2.2 Rate Constrained Messages (RC messages)

Not all control data requires strict determinism. A limited delay and temporal deviation can be enough to fulfill some applications' requirements. RC messages are used to carry these messages, which can vary from automotive applications with moderate timing requirements to multimedia data. The transfer of RC messages is not synchronized taking as basis a common schedule. Hence it is possible that different nodes transmit these messages at the same point in time, which may lead to queues on the switching devices, which will result in jitter.

3.8.2.3 Best Effort Messages (BE messages)

Best effort messages are the classical Ethernet messages. These messages do not rely in any of the services provided by TTEthernet and have the lowest value of priority comparing to the other kind of messages described. There is not an upper boundary on the time that will take for a message of this kind to get to the destination, or even it will actually get there. Best effort messages are transmitted in free network times between transmission of TT and RC messages, thus optimizing the use of bandwidth.

3.8.3 Reliability and Fault Tolerance

Being the central element in the network topology, switches have the ability to behave like bus guardians. Due to the fact that these are directly connected to nodes, errors can be detected and appropriate measures can be taken, such as disabling of communication drivers of the erroneous node or the masking of the error, depending on whether redundancy is present or not.

The network structure can be designed to accommodate the desired level of reliability and fault tolerance. This can be achieved by adding redundancy to the switch and to the communication channels in each node. Figure 3.22 depicts an example of a network structure offering three redundancy channels.

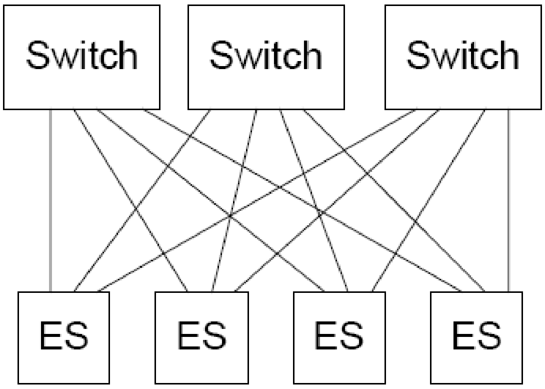


Figure 3.22 - TTEthernet multiple redundant channels [45]

Chapter 4

Drive-by-wire systems and guidelines for fault tolerant hardware design

4.1 Motivation for this Chapter

At the present moment, no vehicle available in the market employs a full by-wire scheme. Given the importance that this subject will have on the next generation of vehicles, some of the concepts behind this philosophy are presented in this chapter. The development of safety critical systems is complex and requires a profound study on the matter. However, it is possible for students to build simple dependable systems by exploring the concepts and ideas presented in this section.

4.2 Introduction to Drive-by-wire Systems

The first vehicles in the market were entirely dependent on the use of mechanical and hydraulic components. The introduction of electronic components in these systems, allowed major improvements in the automotive industry in terms of safety, economy and comfort.

X-by-wire is the designation of a field of studies that has the ultimate goal of replacing all mechanical transmission linkages by communication networks and mechanical actuators by electrical actuators [47]. The reduction of mechanical components in vehicles allows for new vehicle designs due to an increase of available space, lower maintenance, decrease assembly time and improve safety, as mechanical components like for instance the steering column are a potential deadly element to the driver in case of impact [48].

X-by-wire systems are gradually being introduced in a two stage process. The first stage is the introduction of x-by-wire systems in which mechanical backup systems are automatically activated in the event of erroneous operation. The control units that operate such systems must possess self checking mechanisms that are able to detect errors. Such units are named fail-silent units (FSU). The second stage of the implementation of x-by-wire systems is their integration without mechanical backup. By having no mechanical backup, these systems must be fault tolerant. As it will be seen, fault tolerance is achieved by means of component redundancy. Multiple FSUs working together form a fault-tolerant unit (FTU).

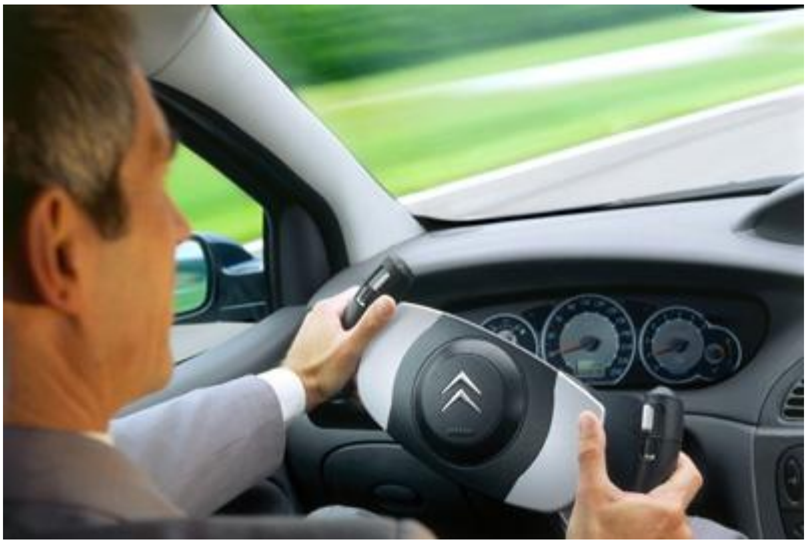


Figure 4.1 - Citroen C5 by wire: acceleration and braking integrated in the steering wheel [48]

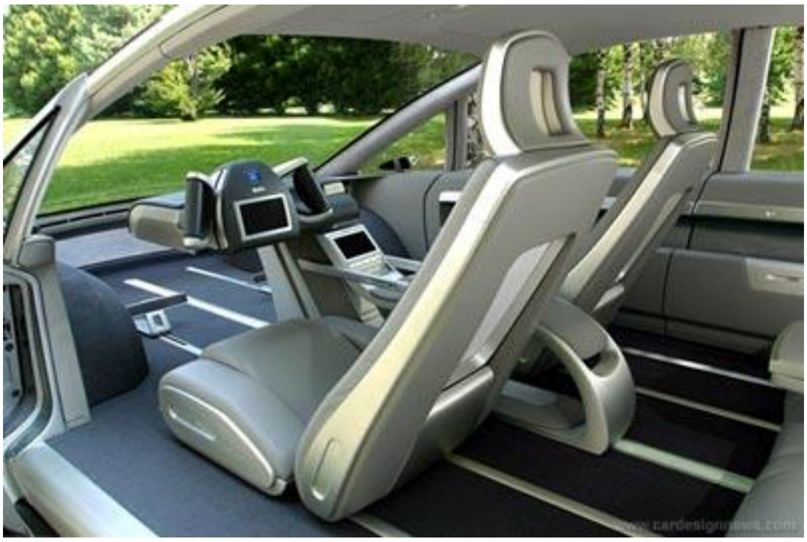


Figure 4.2 - General Motors Hy-wire concept car [49]

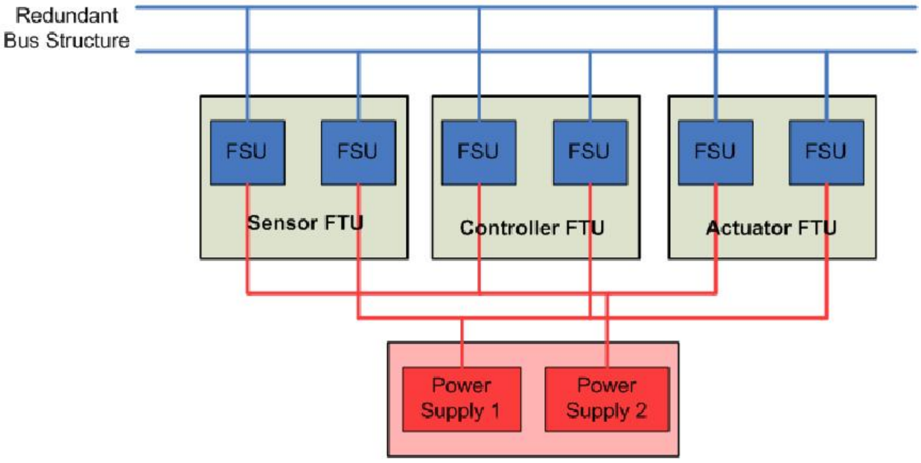


Figure 4.3 - Fault tolerant architecture [50]

Throttle-by-wire is already a reality in vehicles sold nowadays, as vehicle's modern engines are fully electronically controlled. There is no mechanical connection between the throttle pedal and the engine. Instead, sensors determine the throttle pedal position and an electronic unit commonly known as Electronic Throttle Control (ETC) actuates on the throttle based on other variables such as engine RPM, engine load, vehicle speed, temperature, atmospheric pressure among others. This permits an enhanced engine control resulting in greater performance and optimized fuel consumption which would be impossible in any other way, due to the fact that the driver as a human being is unaware of these variables [51]. Furthermore, the implementation of throttle-by-wire in the automotive industry permitted systems such as the ESC, TCS or cruise control to be implemented.

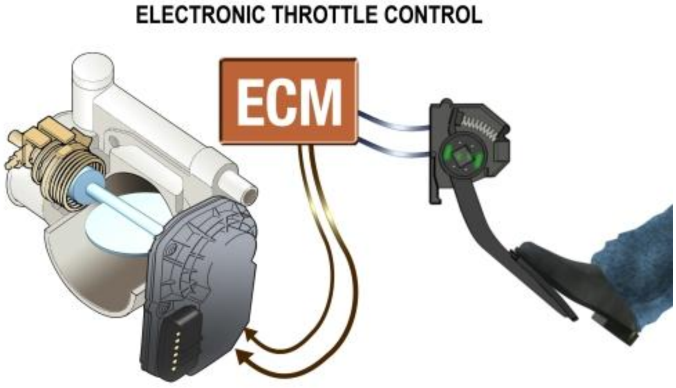


Figure 4.4 - ETC mechanism in internal combustion engines [52]

The absence of connection between the driver's inputs and the actuators in x-by-wire systems removes the so called *"road feel"*, required for the accurate control the vehicle. Hence, haptic actuators are usually added to emulate the sensations that the driver would have in a non by-wire system. The concept of haptic feedback can be further explored, as a synergy with other systems such as radars or cameras can be made to detect potentially dangerous situations and increase the driver's responsiveness and perception.

4.2.1 Obstacles on the Implementation of Drive-by-wire Systems

Braking and steering systems are good candidates to follow the *"by-wire"* trend. However, there are several objections in their way. Both the braking and steering systems are safety critical due to the fact that a faulty operation of one of such systems can lead to a loss of control of the vehicle, which can have devastating consequences. Moreover, pure drive-by-wire systems do not have safe states. Therefore, brake-by-wire and steer-by-wire systems must ensure high dependability. As it will be seen, this is achieved by means of component redundancy, which results in more complex systems, with higher development times and consequently in higher prices.

Currently, all the systems in vehicles are manufactured to operate at 14 Volt, the industry standard for automotive power buses. With the increase of electronic systems in vehicles, the current demanded to the batteries for the vehicle's operation is reaching intolerable levels [50]. For instance, if brake-by-wire systems are implemented in a 14 Volt bus and a high brake force is demanded, currents on the bus can reach astonishingly high values.

Convincing drivers that drive-by-wire systems are safe is another issue that manufacturers face, as people worry about possible electronic malfunctions that might lead to catastrophic consequences [53].

Despite all the referred drawbacks, there are plenty of research groups working in order to overcome the referred problems at is believed that the drive-by-wire will eventually become a de-facto solution in the market.

4.3 Drive-by-wire Systems

4.3.1 Brake-by-wire

In a brake-by-wire system the brake pedal is not directly connected to the brake actuators. Instead, the brake pedal position is sensed, and according to its position the brake ECU determines the amount of braking force on each wheel, taking as basis the features described on Chapter 2, and commands the actuators to develop the corresponding braking force.

In conventional vehicles, the braking features described in Chapter 2 work in parallel with the main hydraulic circuitry. By integrating them in a brake-by-wire topology, further results can be achieved, such as the improvement of stability and brake control due to use of electric motors to provide the braking force. Moreover it allows an easier implementation of systems such as the ABS, ESC or TCS, and the elimination of environmental concerns due to the removal of the hydraulic fluid [54]. Furthermore, the vibration caused in the brake pedal of conventional braking systems upon the actuation of the ABS is removed.

Two different types of brake-by-wire systems are discussed in this section.

4.3.1.1 Electro Hydraulic Brakes (EHB)

Electro hydraulic brakes are the first evolution of conventional brakes to brake-by-wire systems. These systems cannot be called pure *by-wire* systems, due to the fact that a backup hydraulic connection between the brake pedal and the hydraulic modulator exists, and is enabled in the case of erroneous operation of the brake ECU.

The brake force is generated by hydraulic means, but lacks the direct connection between the brake pedal and the hydraulic modulator under normal operation. Signals from the brake pedal sensors travel to the brake ECU, which determines the appropriate brake value on each wheel taking as basis the braking features described in Chapter 2. The determined braking values for each wheel are transferred to the hydraulic control unit (HCU), which actuates the hydraulic circuits to generate the desired braking force [50].

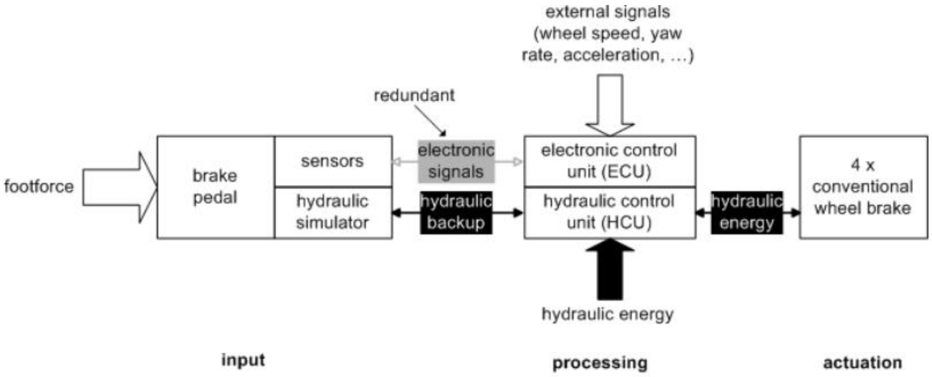


Figure 4.5 - Electro hydraulic brakes scheme [50]

4.3.1.2 Electro Mechanical Brakes (EMB)

Electro mechanical brakes reflect the pure concept of x-by-wire systems due to the fact that a mechanical connection between the brake pedal and the brake actuators is absent. The EMB operation is similar to the EHB but, instead of transmitting the brake signals to the HCU, the brake ECU transmits braking forces by wire to individual wheel brake modules placed on each wheel, which have the task of providing the determined brake force by means of electro-mechanical actuators. A scheme of electro mechanical brakes can be found in Figure 4.6:

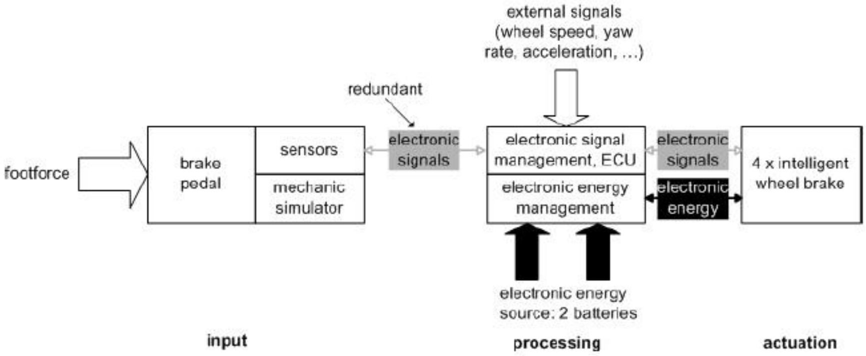


Figure 4.6 - Electro mechanical brake-by-wire [50]

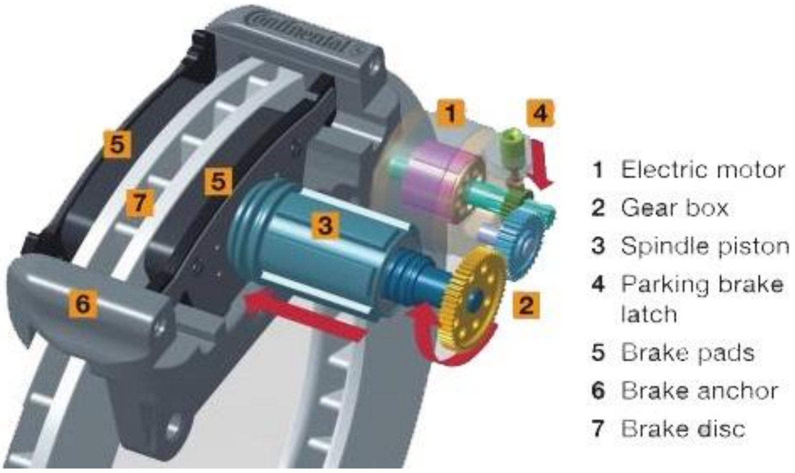


Figure 4.7 - Continental electro mechanical brake [55]

4.3.2 Steer-by-wire

Steer-by-wire expands the *by-wire* concept to the vehicle's steering system. Hence, no mechanical connection between the steering wheel and the tires exist.

Sensors placed in the steering wheel transmit its position and torque to an ECU which in turn actuates electric motors in the front axle to steer the wheels. A unit called hand wheel actuator is responsible for providing the haptic feedback to the driver [56].

4.4 Fault Tolerant Hardware Architectures Design

Many of the systems described along this document are safety critical. Being safety critical means that the failure or malfunction of such systems can lead to potential catastrophic situations such as the death of people, significant damage or loss of equipment, and environmental harm [57]. Hence, it must be assured that these systems grant appropriate levels of dependability, the level of confidence in which the system can be expected to perform its functions.

The brief discussion of the development of safety critical systems that follows takes as basis the standard IEC 61508 which addresses multipurpose safety related systems. ISO 26262 is a standard that is currently being developed uniquely for the automotive industry based on IEC 61508. Given the fact that ISO 26262 standard is not yet available [58], the classifications that follow are based on IEC 61508.

The development of safety critical systems starts by the analysis of the ways in which the target system can be the source of hazards. Hazards can be defined as situations that have the potential to cause harm to people or the environment. There are several methodologies that aid the identification of the events that lead to hazards and their consequences such as the FMEA (failure modes and events analysis), ETA (event tree analysis), FTA (fault tree analysis) among others [57]. Once the sequences of events that lead to hazards are determined, the frequency of occurrence of each hazard can be calculated.

The frequency of each hazard combined with its consequences make up what is called risk. IEC 61508 provides the classification for both the consequences, frequency and associated risk of hazards.

Table 4.1 - Risk classification according to IEC 61508

	Consequences			
Frequency	**Catastrophic**	**Critical**	**Marginal**	**Negligible**
Frequent	I	I	I	II
Probable	I	I	II	III
Occasional	I	II	III	III
Remote	II	III	III	IV
Improbable	III	III	IV	IV
Incredible	IV	IV	IV	IV

Table 4.2 - Interpretation of the various risk levels according to IEC 61508

Risk class	Interpretation
I	Intolerable risk
II	Undesirable risk, and tolerable only if risk reduction is impracticable or if the costs are grossly disproportionate to the improvement gained
III	Tolerable risk if the cost of risk reduction would exceed the improvement gained
IV	Negligible risk

Risk classification serves as basis for the determination of a safety integrity level. Safety integrity levels reflect the level of dependability of safety systems and condition not only the system's architecture but its development process.

IEC 61508 provides target failure rates for the four proposed integrity levels according to different modes of operation: a continuous mode and a low demand mode. As an example, the braking system would be considered for the continuous mode operation SIL levels, while the airbag system would be considered for the demand mode of operation. The classification on the continuous mode of operation takes as basis the number of failures per hour, while the on demand mode of operation takes as basis the probability of the system not to respond appropriately to the request.

Table 4.3 - IEC 61508 safety integrity levels for continuous mode of operation

Safety Integrity Level	Failures per hour
4	10^{-8} to 10^{-9}
3	10^{-7} to 10^{-8}
2	10^{-7} to 10^{-6}
1	10^{-5} to 10^{-6}

Table 4.4 - IEC 61508 safety integrity levels for on demand mode of operation

Safety Integrity Level	Failures per hour
4	10^{-4} to 10^{-5}
3	10^{-3} to 10^{-4}
2	10^{-2} to 10^{-3}
1	10^{-1} to 10^{-2}

IEC 61508 provides three different methods for determining the appropriate SIL level for an application, however the discussion of these methods go beyond the objectives of this document.

The main question to keep in mind is that safety critical systems must grant determined levels of safety so they can be trusted. Moreover, systems which are safety critical and were not designed with safety critical requirements, are not likely to offer the desired dependability. Therefore, it is necessary to increase their dependability, so the risks associated with the equipment malfunction are reduced to tolerable levels.

4.4.1 X-by-wire Requirements for the Automotive Industry

The x-by-wire consortium issued a report in 1998 titled "Safety Related Fault Tolerant Systems in Vehicles". Section 3.6 of the report refers to the safety requirements that x-by-wires shall obey. The referred requirements apply to steer-by-wire systems, but can serve as the basis for the development of other drive-by-wire systems. The following marks are a transcription with minor adaptations of the points discussed in that section [59]:

- Systems shall not lead to a state in which human life, economics or environment are endangered
- In the presence of faults, it is required that the system is at least able to tolerate one major critical fault without loss of the functionality, for a time long enough to reach a safety parking area
- There must be a provision to maintain safe (reduced) operation for a limited period
- A single failure of the system must not lead to a fault of the whole system
- Each of the subsystems input, process and output must be fault tolerant by itself
- Reduced functionality in the case of a failure is permissible as long as there is no risk to the safety of the driver or other traffic participants
- In case of non critical faults, the system shall maintain the full operational state but has to advise the driver
- The system must memorize the error codes of intermittent faults for maintenance
- The systems must provide information about their internal status (example: stop immediately, service required or correct operation)
- The probability of encountering any of the safety-critical failure modes shall not exceed 5×10^{-10} per hour per system

By the analysis of these requirements it can be concluded that automotive drive-by-wire systems must be highly dependable. In fact the integrity level required for x-by-wire systems is even higher than SIL 4, the highest integrity level referred on IEC 61508.

4.4.2 Increasing Dependability

The two most common ways of increasing a systems' dependability are: fault avoidance and fault tolerance [60].

4.4.2.1 Fault Avoidance

Fault avoidance is based on the concept of ensuring quality in all aspects: system design, components and their protection such as electromagnetic interference (EMI) shielding and system maintenance. The amount of extra dependability provided by fault avoidance methods is somewhat limited to the demands of safety critical systems [60].

4.4.2.2 Fault Tolerance

Given the fact that any element despite of its quality will eventually fail, fault tolerance mechanisms must be employed to ensure that no fault can result in system failure, as required by drive-by-wire design requirements. Fault tolerance is achieved by means of redundancy. The objective of redundancy is that the overall system to achieve higher reliability than the parts that compose it, and the elimination of single points of failure [60].

There are three different kinds of hardware redundancy: static, dynamic, and hybrid redundancy [57]. Static and dynamic redundancy are usually applied in drive-by-wire systems and therefore are discussed in this section.

The discussion on hybrid redundancy is left behind as it is mostly used in the aircraft industry. Hybrid redundancy reflects the combination between static and dynamic redundancy. Despite achieving the best results in terms of reliability, it usually requires a large amount of components and high complexity.

The following examples of architectures reflect simplifications of the questions involved. A more detailed approach on a solution for a brake-by-wire system is given in Chapter 5.

Static Redundancy

Static redundancy uses fault masking as its basic principle. It consists on having several elements performing the same functions in parallel and a voting mechanism which is responsible for outputting a single value out of the values provided by the units in parallel.

Static redundant systems do not perform reconfiguration upon faults. The voting mechanism can either be another device or the process itself.

N-modular Redundancy (NMR) Architectures

N-modular redundancy reflects the general concept of static redundancy. These architectures are constituted by N odd elements in parallel. In order for the voter to find an agreement, this system has to be built with at least three working units. This system is able to tolerate failures within $\frac{N-1}{2}$ different modules.

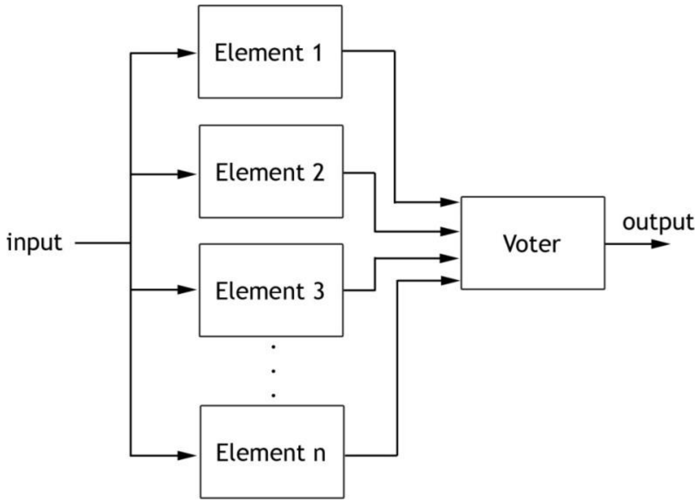


Figure 4.8 - N modular redundancy

It should be noted that although in Figure 4.8 the voter is itself a single point of failure, to achieve fault tolerance the voter itself needs to be replicated.

The output of a voter can be computed in several ways such as the majority, median, mean among others.

Figure 4.12 depicts this philosophy applied in the acquisition of the steering wheel position. Three sensors are working in parallel (Triple Modular Redundancy) and the steering controller performs voting over the three values provided by the sensors.

The voter can also be the process itself, as Figure 4.9 depicts.

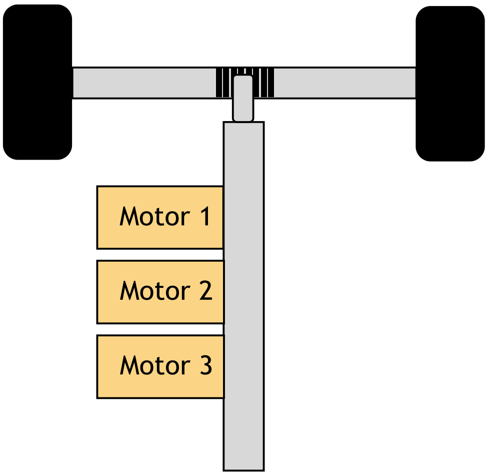


Figure 4.9 - Static redundancy applied to steer-by-wire

Figure 4.9 illustrates this concept applied to a steer-by-wire system by adding three or more motors in series to control the steering torque. In the event of failure of one of the steering actuation modules, the system would operate in a degraded mode but it would be possible to control the vehicle and lead it to a safe state.

Dynamic Redundancy

Static redundant systems rely on a high number of parts to achieve fault masking, which can lead to intolerable costly solutions. On the other hand, dynamic redundant architectures rely on fault detection mechanisms and system reconfiguration to employ fault tolerance.

Despite of requiring more processing power due to required fault detection mechanisms, the number of elements required for fault tolerant operation is decreased. In fact, dynamic redundancy can be achieved with two units. Under fault free operation, processing spare elements do not generate outputs but can either be actively processing information (hot standby), or be with limited activity (cold standby).

Upon detection of a faulty element, the system is reconfigured to substitute the faulty element by a spare element. During the reconfiguration phase the processes are uncontrolled, hence it must be evaluated if the reconfiguration time can or not lead to potentially dangerous situations. The choice whether to use hot or cold standby spare units conditions the system's reconfiguration time, which is less in the case of hot standby.

Standby Spare Architectures

Standby spares are the most basic form of dynamic redundant architectures. In this scheme, only one unit is actively producing outputs. In case that a fault is detected, the faulty unit is removed from operation and substituted by a spare element.

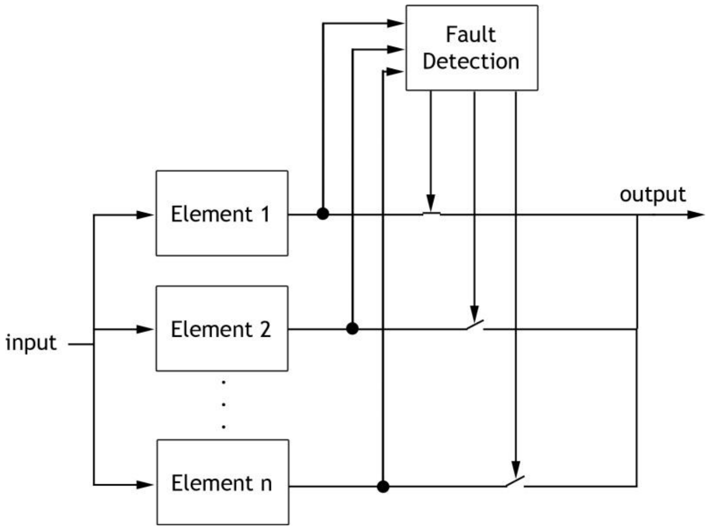


Figure 4.10 - Standby spare architecture concept

The concept of standby sparing can be applied to the steering motors of a steer-by-wire system as the example on Figure 4.12 suggests. In this example the steering control module is responsible for controlling motors that steer the wheels. Sensors provide the feedback of the motor's behavior into the steering control module. Upon detection of a faulty motor, the steering control module de-energizes the faulty motor and controls the spare motor.

It must be noted however that the steering control module needs itself to be fault tolerant with the risk of erroneous commands being sent to the steering motors.

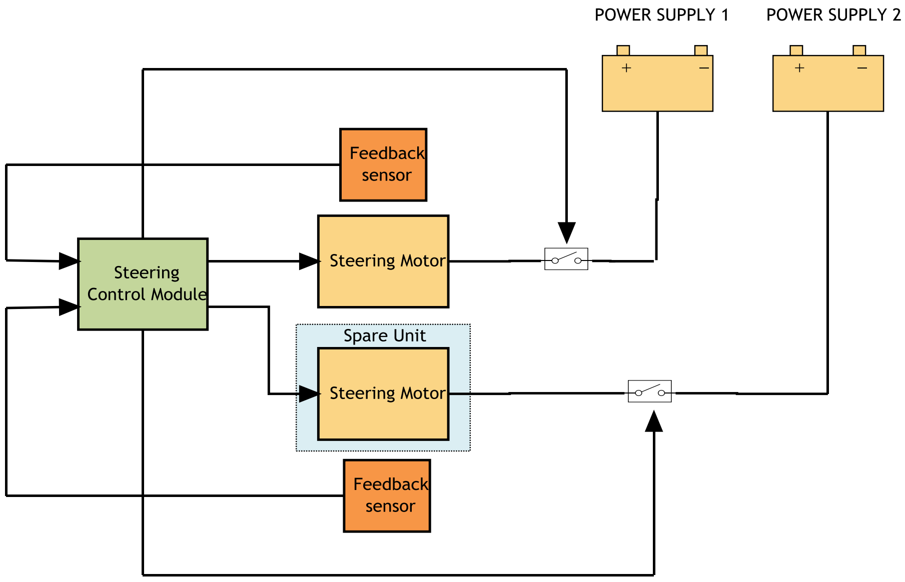


Figure 4.11 - Standby sparing applied to steering actuators

The same idea can be applied to steer-by-wire systems as Figure 4.12 suggests. A steering controller is checked by a dedicated unit. Whenever a fault is detected on the active steering controller the checker element requests the spare unit to assume control.

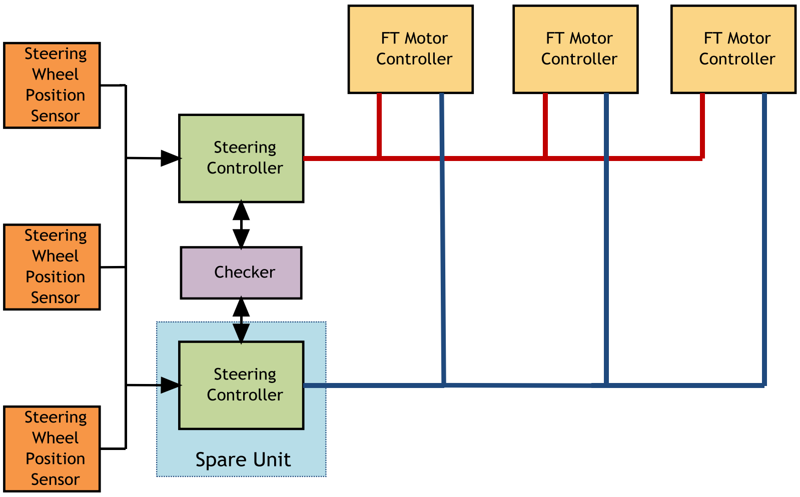


Figure 4.12 - Standby sparing applied to brake-by-wire

Pair and Spare Architecture

Standby spare architectures have a major drawback: if the active unit produces erroneous but plausible outputs, the faulty operation might not be detected. Pair and spare architectures correct this drawback by having two units working in parallel over the same inputs. The outputs are then compared and, if in case of disagreement extra units are called to operate. Therefore, pair and spare architectures require at least three units. Although more costly due to the extra hardware requirements, this unit grants even higher levels of dependability.

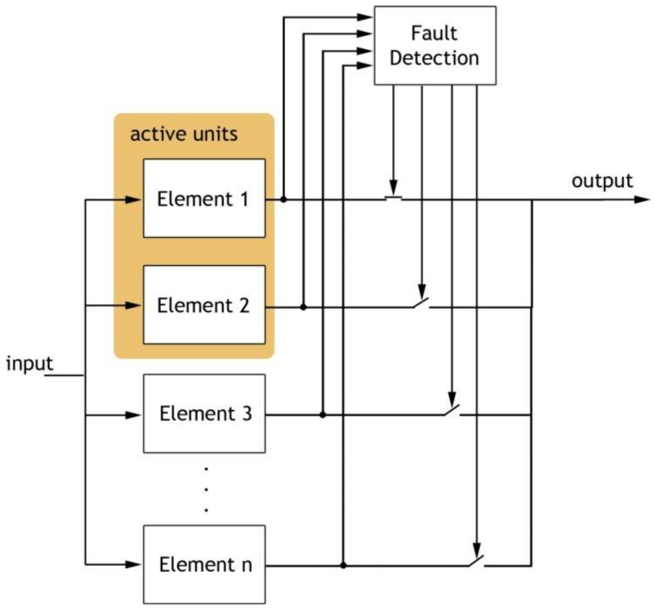


Figure 4.13 - Pair and spare architecture

Figure 4.14 depicts the pair and spare philosophy applied to the a set of sensors in a brake-by-wire system. Two sensors are actively being compared by the brake controller. When the brake controller finds a disagreement between the two active sensors it enables an extra sensor, checks which of the active sensors is faulty and excludes it.

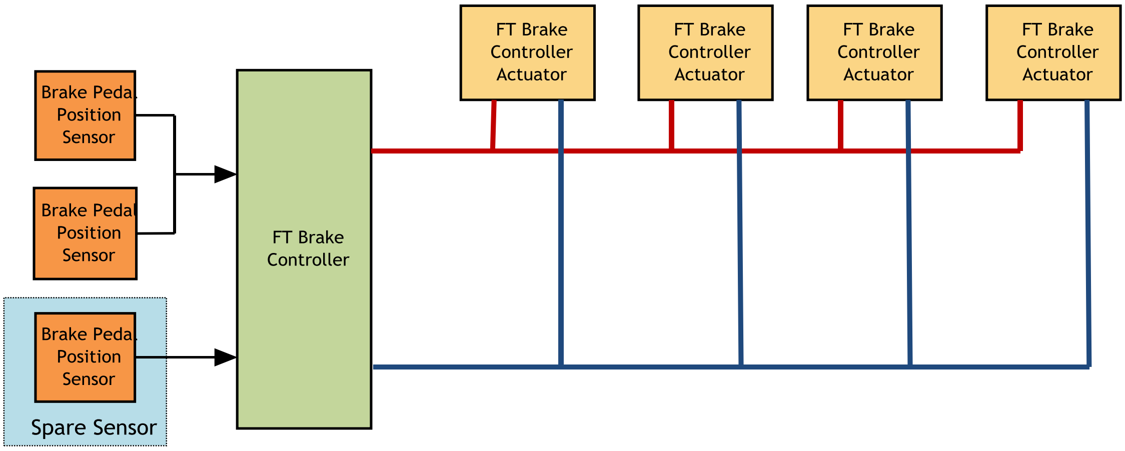

Brake Pedal Position Sensor
Brake Pedal Position Sensor
Brake Pedal Position Sensor
Spare Sensor
FT Brake Controller
FT Brake Controller Actuator
FT Brake Controller Actuator
FT Brake Controller Actuator
FT Brake Controller Actuator

Figure 4.14 - Pair and spare architecture applied to brake-by-wire

4.5 Fail Safe Units

Some systems might not be able to withstand an erroneous operation with the risk of the of occurrence of a catastrophic event. In such cases, the erroneous operation must be detected and the system must be lead to a safe state.

The braking and steering features which were discussed in Chapter 2 have the ability to cause potentially dangerous situations in case of erroneous operation. An incorrect brake operation by the ABS, TCS or ESC has the potential of affecting the stability of the vehicle. Similarly, erroneous steering assistance provided by power steering systems have the potential to cause the driver to lose control of the vehicle. Therefore, it must be granted that these systems fail in a safe way. Failing in a safe way in systems which have mechanical backup is achieved by making computational units to stop producing outputs. Units that behave in this way are denominate fail safe units.

Two main hardware strategies that rely on multiple cores can be applied to detect failures and lead the system to a safe state: a master/checker approach and a comparative duplication mechanism.

4.5.1 Master/checker Approach

The master/checker approach consists on having a main microcontroller be periodically checked by another microcontroller, typically with less computational power for the sake of cost saving. Upon detection of erroneous behavior by the checking unit, measures are taken to prevent the master from producing outputs.

4.5.2 Duplication with Comparison

Duplication with comparison consists on having two microcontrollers performing the same operations and comparing the outputs. The two microcontrollers can run the same software or employ different software versions, in which case software faults can also be detected.

In any case, if the outputs from both microcontrollers do not match, the system is lead to a safe state.

4.6 Hardware for Safety Critical Systems

As more dependability is being demanded to computational units, manufacturers are now offering on-chip solutions to meet the requirements of safety standards [61].

Some of the most popular features are presented in this section.

4.6.1 Integrated Voltage Regulators

Improper voltage fed to the microcontroller can lead to unexpected behavior and consequently, to faulty operation. Integrated voltage regulators have the task of feeding a constant voltage to the microcontroller components regardless of the voltage fluctuations in the source.

4.6.2 Voltage Monitors

Voltage monitors supervise the voltage fed to the microcontroller and engage safety measures in case of high or low voltage detected.

4.6.3 Memory Protection Unit (MPU)

The memory protection unit is a hardware feature that splits the physical memory into several slots, and assigns different rights to each of the memory accessing entities (CPU, communication interfaces etc..), preventing overlapping, unauthorized access and protecting memory sections.

4.6.4 Error Correction Code Protected memories (ECC)

In ECC memories data is stored with additional redundancy so its accuracy can be tested when saving or retrieving data from the memory. Several mechanisms can be employed in protected memories such as parity bits, duplication codes, checksums, cyclic redundancy check codes among others. Some of the coding mechanisms allow corrupt data to be recovered, at the cost of higher overhead.

4.6.5 Clock Monitoring Units

Clock monitoring units check for deviations on the generated clock frequency. In the case that the clock frequency deviates from a determined threshold, safety measures are engaged.

4.6.6 Peripheral Components Replication

Component replication enables the outputs from components such as analog to digital converters, counters among others to be compared. In case of non matching outputs between two redundant units, microcontrollers or special safety related units are signaled so safety measures can be carried.

4.6.7 Watchdog Timers

Watchdog timers are special safety related timers with the goal of ensuring that the supervised unit is actively performing its operations. The supervised unit periodically resets the watchdog timer value. In the case that the watchdog reaches its maximum value, which may happen in case of erroneous operation in the supervised unit, safety measures such as resetting the microcontroller are carried. Watchdog timers are able to detect not only hardware lack of response or overload failures but also software faults, in which programs may fail to reset the watchdog timer due to erroneous operation.

4.6.8 Dual Core Microcontrollers for Safety Applications

In safety dual core microcontrollers the processors and other critical components are replicated in order to attain higher integrity levels. Figure 4.15 depicts the block diagram of the Freescale MPC564xL microcontrollers family, designed specifically for the needs of automotive safety related systems.

The replicated elements are bounded by redundancy checking units, whose aim is to supervise the consistency between the two sets of replicated units. Every time a disagreement between the outputs of the replicated modules is observed, the redundancy checker signals the fault collection and control unit (FCCU), which in turn enables safety measures depending on the nature of the detected fault.

The processors from dual core microcontrollers can be configured to operate into two distinct modes: the lock step mode (LSM) and the decoupled parallel mode (DPM).

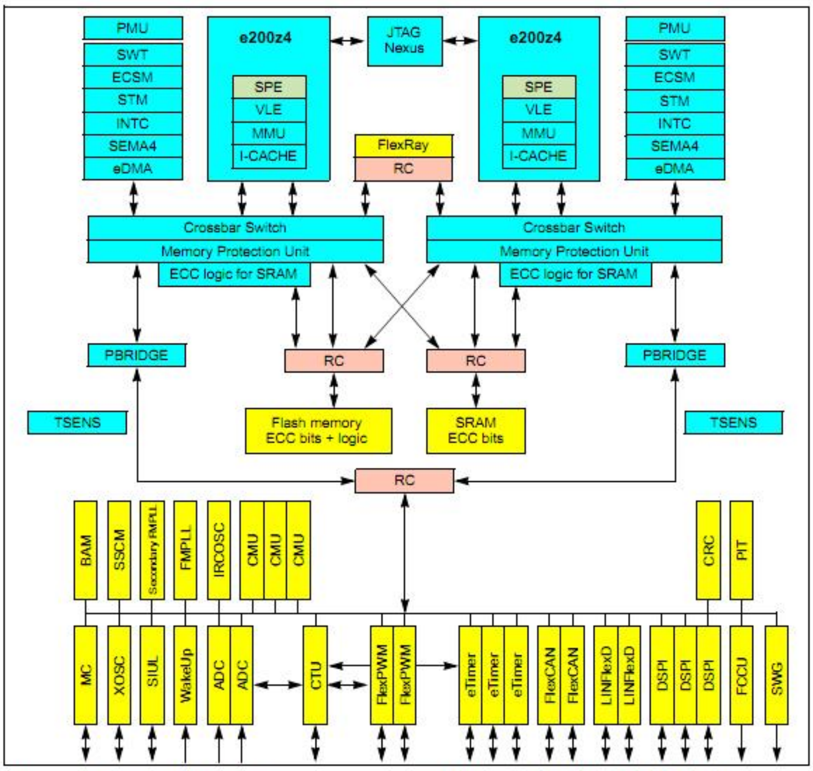
4.6.8.1 Lock Step Mode (LSM)

In lock step mode the two processors operate synchronously. The same instructions are executed at the same by each of the processors. The outputs of both processors are compared by hardware and in case of deviation the system is lead to a safe state.

In this way, failures affecting one of the processors are widely detected and signaled in short amounts of time, without any software intervention.

4.6.8.2 Decoupled Parallel Mode (DPM)

In the decoupled parallel mode, processors work independently. Hence, no hardware fault detection is possible without the implementation of specific fault detection software. Software fault detection mechanisms using the DPM are described in [62].



ADC	– Analog-to-Digital Converter
BAM	– Boot Assist Module
CMU	– Clock Monitoring Unit
CRC	– Cyclic Redundancy Check unit
CTU	– Cross Triggering Unit
DSPI	– Serial Peripherals Interface
ECC	– Error Correction Code
ECSM	– Error Correction Status Module
eDMA	– Enhanced Direct Memory Access controller
FCCU	– Fault Collection and Control Unit
FlexCAN	– Controller Area Network controller
FMPLL	– Frequency Modulated Phase Locked Loop
INTC	– Interrupt Controller
IRCOSC	– Internal RC Oscillator
JTAG	– Joint Test Action Group interface
LINFlexD	– LIN controller with DMA support
MC	– Mode Entry, Clock, Reset, & Power
PBRIDGE	– Peripheral bridge
PIT	– Periodic Interrupt Timer
PMU	– Power Management Unit
RC	– Redundancy Checker
RTC	– Real Time Clock
SEMA4	– Semaphore Unit
SIUL	– System Integration Unit Lite
SSCM	– System Status and Configuration Module
STM	– System Timer Module
SWG	– Sine Wave Generator
SWT	– Software Watchdog Timer
TSENS	– Temperature Sensor
XOSC	– Crystal Oscillator

Figure 4.15 - MPC5643L block diagram [63]

Chapter 5

Architecture Definition

In this Chapter, the concepts and ideas explored in previous chapters are put together to form a conceptual architecture for the backbone architecture of the vehicle. Afterwards, a proposed architecture for the braking system is explored in detail, along with the algorithms which support the correct behavior of its hardware elements.

The objective of the development of the FEUP's EV is not the creation of a vehicle to be driven on the public road. Instead, the main goal of this project is the development of a vehicle that can be designed and assembled by students taking in consideration the price of components and availability, the students learning curve and the knowledge obtained in the various courses along their academic career. Therefore, the proposed architecture does not include most of the de-facto solutions present in most of the commercially available vehicles.

Most of the systems described in this document are too complex to be developed by a single working group in a reasonable amount of time. In order for this project to be feasible by students, the proposed architecture is based on the idea of isolating the boundary of each feature up to the maximum degree possible. This means that functionalities that would normally share a single ECU (like for instance most of the discussed braking functionalities) must be divided to form a network of less complex control units. In this way, students will not be restrained on the use of a particular hardware/software platform and are free to make their own decisions.

However, given the fact that multiple dependencies between functionalities and systems exist, it is not possible nor practical for all functionalities/systems to be completely independent. Several functionalities, such as the TCS which relies both on the brake and motor ECUs operate in a distributed fashion. Therefore, in order for the implementation of distributed algorithms to be possible, the software specification on each module must include a set of services that allow the interaction between ECUs. Global awareness of variables that might interest several ECUs should also be provided. These issues should be solved by means of appropriate software and middleware specification.

Although the main focus of this work is hardware, brief references to software have to be made to aid the explanation of concepts behind the proposed architectures.

5.1 High Level Architecture

The following set of requirements were considered for the definition of the proposed architecture:

1. Networks interconnecting vehicle systems must be within those which are lectured in the students curricular plan, or be congruent with the students learning curve
2. It shall be possible for students to easily integrate their systems with any other systems present in the vehicle
3. The architecture must be scalable
4. Network components shall be inexpensive

From these requirements, CAN and Ethernet were considered to be viable options to serve as the communication backbone for the EV. However, as it is discussed in Chapter 3, CAN's 1 Mb/s bandwidth might impose limitations on the system's scalability. Hence, to give room for the maximum number of systems to be integrated Ethernet shall be used as the communication backbone for the EV.

Figure 5.1 depicts the high level view of the proposed architecture. This architecture consists on having the main systems discussed in Chapter 2 connected to each other on a star topology by means of an Ethernet switch.

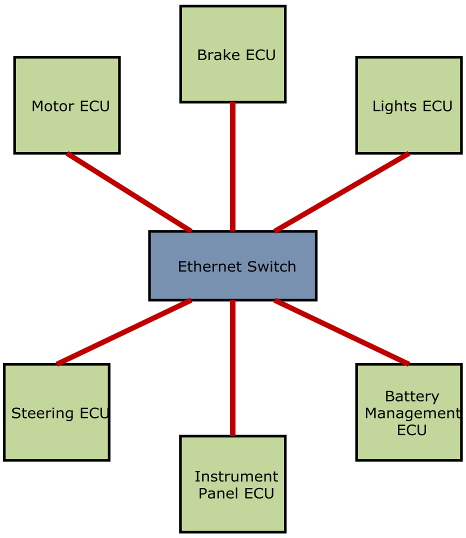


Figure 5.1 - High level view of the proposed architecture

It must be noted however, that if the bandwidth required for the various systems to exchange data is less than 1 Mbps, CAN is considered to be a viable solution to serve as the backbone for the EV. Instead of a star topology, all the systems would be simply integrated in a bus topology. This solution allows for real-time behavior of distributed control algorithms, at the cost of requiring a study on the schedulability and CAN priority assignment of all frames that are expected to be exchanged.

5.1.1 Architecture Limitations

Ethernet was not tailored to support the exchange of data in real time. Hence, it cannot provide the desired level of determinism required for the operation of systems which rely on data exchanges between multiple ECUs.

The fact that that the switch is a central element connecting all ECUs implies that its failure will lead to the failure of all the features which rely on data exchanges between multiple ECUs. Hence, the failure of the switch will eventually lead to the failure of systems such as the ACC, power steering, TCS, ESC, instrument panel among others. In order for this issue to be minimized, such systems must be provided with software mechanisms which detect the failure of the Ethernet switch and engage safety measures such as vehicle speed limitation, so the driver can lead it to a safe state.

5.1.2 Data Exchange between ECUs

Certain functionalities require the knowledge of variables that might not be produced within the ECU where the feature is implemented. Vehicle's speed for instance, is a variable that can be either produced on the motor or brake ECUs and is required by functionalities that operate in other ECUs such as steering, lights and instrument panel ECUs.

A possible solution for this issue that would also allow the integration of additional systems with minimum effort, would be the transmission of several variables of interest in a publisher/subscriber pattern. This would allow for a scalable solution which permits the integration of additional systems that require those variables in a plug-and-play fashion.

A deep study regarding the functionalities to be implemented must be carried in order to determine all the variables of interest to be published. The following tables depict several examples:

Table 5.1 - Motor variables of interest

Variable	**Potential Subscriber(s)**	**Function**
Vehicle Speed	Instrument Panel ECU	Vehicle speed display
	Brake ECU	Wheel slip detection
	Steering ECU	Steering assist force adjustment
	Lights ECU	Adaptive Cornering light function
RPM	Instrument Panel ECU	RPM display
Motor Torque	Brake ECU	Electronic Stability Program, Traction Control System
Motor Temperature	Instrument Panel ECU	Motor Temperature Display

Table 5.2- Lights ECU variables of interest

Variable	**Potential Subscriber(s)**	**Function**
Lights status	Instrument Panel	Light Status display

Table 5.3 - Brake ECU variables of interest

Variable	Potential Subscriber(s)	Function
ABS, TCS, ESC, EBD and BA activity	Instrument Panel ECU	Activity display
	Adaptive Cruise Control	Adaptive cruise control disable
	Cruise Control	Cruise Control disable
Brake activity	Adaptive Cruise Control	Adaptive cruise control disable
	Cruise Control	Cruise Control disable
Brake Diagnostics	Instrument Panel ECU	Diagnostic Message Display
	Motor ECU	Speed limitation upon bad diagnostic
Yaw Momentum	Lights ECU	Adaptive Cornering Light Function
Lateral Acceleration	Lights ECU	Adaptive Cornering Light Function

Table 5.4 - Steering ECU variables of interest

Variable	Potential Subscriber(s)	Function
Steering Wheel Position	Brake ECU	Electronic Stability Program
	Lights ECU	Adaptive cornering light

5.1.3 ECU Services

In order for the development of distributed functionalities to be possible, ECUs must be accept service requests from other units. Moreover, the existence of services makes it possible to enhance functionalities by taking advantage of the cooperation between different ECUs. This section provides some examples of services and synergies that can be developed.

5.1.3.1 Steering ECU

Yaw Request Service

Whether the steering system is a power steering or a steer-by-wire system, it is possible to generate vehicle yaw momentums by steering the wheels. A service provided by the steering ECU that would generate a desired amount of yaw momentum would be valuable for enhancing the safety of the vehicle.

ABS Synergy

When braking in split friction coefficient surfaces, the ABS induces asymmetrical brake forces which induce a yaw moment on the vehicle.

A synergy between the steering systems and the braking system would enable an enhancement on the vehicle's response to the induced yaw. By knowing the braking force on each wheel, the induced yaw can be easily calculated. The braking ECU could then request the steering ECU to develop a counteracting yaw that would compensate for the ABS induced yaw.

ESC Synergy

The effectiveness of the ESC can be further enhanced by taking advantage of the yaw generated by the steering system

Autonomous Driving

The creation of a yaw generating service would allow the implementation of autonomous driving systems such as automatic parking, collision avoidance and autonomous driving.

5.1.3.2 Brake ECU

Brake Force Request Service

A brake force request service would allow other control units to request the brake control unit to develop a determined brake force.

Such service is required for the implementation of the adaptive cruise control system.

Collision avoidance systems automatically actuate the brakes in case of a eminent collision. Thus, a brake force request service is also mandatory for the operation of such systems.

Autonomous driving functionalities also require a brake force request service.

5.1.3.3 Motor ECU

Torque Request Service

A torque request service would allow ECUs to request a determined torque that would be provided by the propulsion system.

This service is required by the TCS and the ESC.

Speed Request

A speed request service enables the definition of a target setpoint speed by other ECUs. It is required by the operation of the cruise control, adaptive cruise control and autonomous driving systems.

Speed Limitation

Upon detection of a critical system failure, a service that would inhibit the driver from exceeding a pre determined speed would enhance vehicle safety. For instance, the failure of one or more of the wheel braking modules would impose a limitation of the vehicle's speed, which would allow the remaining brake modules to compensate more easily for the faulty module.

5.1.3.4 Lights ECU

Emergency Light Activation

An emergency lights activation service would allow a safety enhancement of the vehicle and its occupants. Several situations could lead to a request of this service:

- Detection of a critical fault in any of the vehicle's systems, such as braking, steering or propulsion systems
- Emergency braking detected by the BA system
- Impact detection
- Collision avoidance system

5.1.3.5 Instrument Panel

Message Display Service

This service would offer the possibility of any ECU to display messages to the driver such as diagnostics, notifications among others.

5.2 Braking System Architecture

This section presents the proposed braking architecture for a brake-by-wire system to be developed in the EV project by students.

Commercial braking systems usually have all of the functionalities described on Chapter 2 implemented in a single ECU. A braking system encompassing all of the described functionalities in a single ECU is considered to be an extremely complex system. Given the impracticability of such a system to be developed by a single working group during the duration of a semester, it was decided to grant each feature a dedicated control module as Figure 5.2 depicts.

The presented architecture is conceived with the objective that any of the components inserted in the architecture, cannot in any way cause the complete loss of the brakes or the ability to provoke the loss of vehicle control.

Due to the fact that all elements belonging to the braking system are safety critical, all modules are built with two redundant elements.

The brake pedal position module is responsible for the acquisition of the brake pedal position sensors and the transmission of the brake pedal position over the network to the interested entities.

Each wheel is provided with a brake actuator module, which receives the brake pedal position from the brake pedal position module and braking requests from the ABS, TCS and ESC modules, and command the actuators to generate the desired braking force.

The ABS, TCS and ESC modules capture wheel speed values made available by the wheel speed acquisition module and the brake pedal position value, compute the required interventions and, if necessary transmit braking requests to the brake actuator modules.

The gateway is the element responsible for providing the interface between the modules and exterior systems. It enables outside systems to request braking services (ACC or autonomous driving), and enables modules from the braking system to output diagnostics and request services such as torque reduction or speed limitation.

The internal structure of these modules and several algorithms that grant the appropriate behavior of the hardware are discussed with further detail over the next sections.

The proposed architecture is based on the principle that although the functionalities are separated throughout different modules, the entire braking system is seen as one from the exterior systems. This is important for the following reasons:

1. The braking system architecture can be modified according to the students' needs without having to reconfigure the exterior systems.
2. It enables the replacement of this architecture with a single chip system that can be developed by any student or research group without any modification on the higher level network.

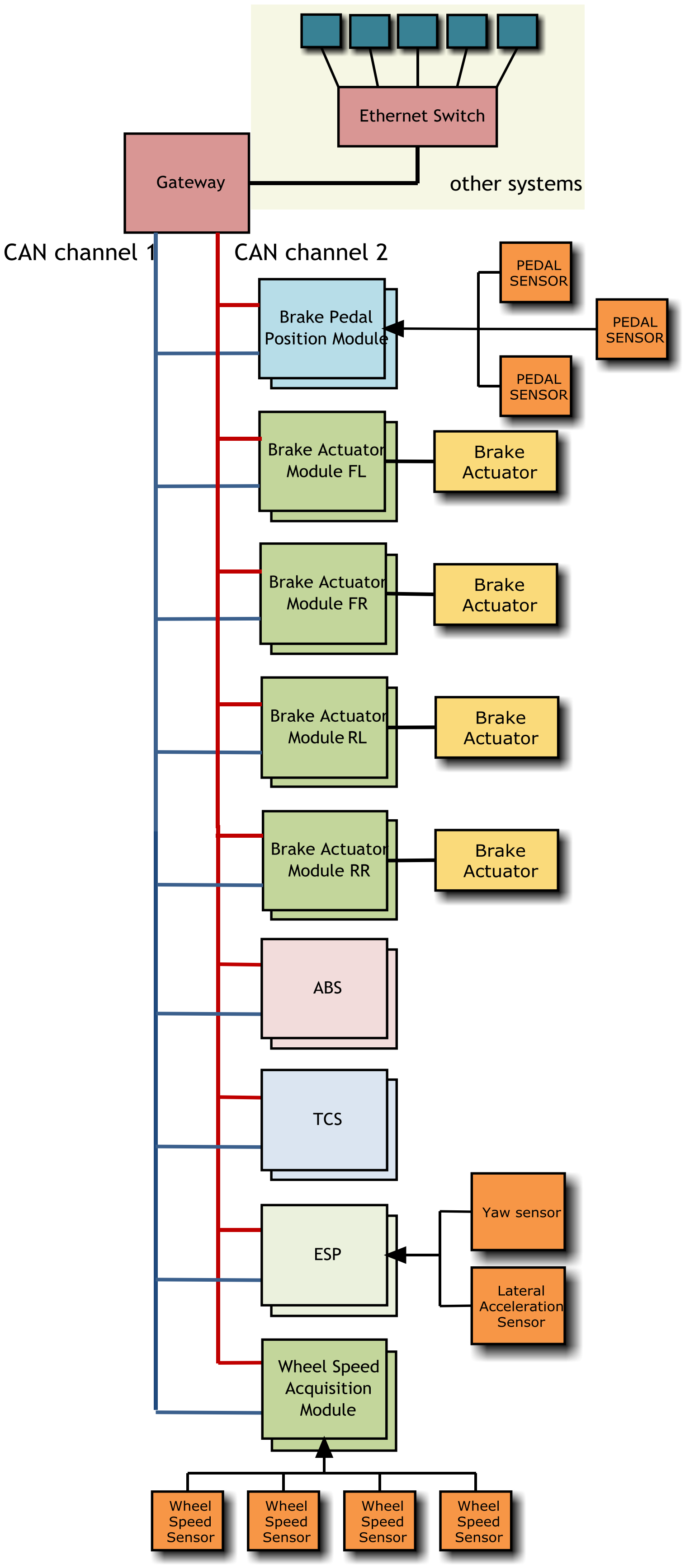


Figure 5.2 - Braking system architecture

5.2.1 Braking Architecture Network Proposal

When implemented in a single ECU and due to hard real time requirements, braking functionalities must be scheduled by a real time operating system. By having them distributed into different hardware modules it is not enough to provide a real time operating system for ensuring deterministic responses. The communication network must be itself deterministic, otherwise it can jeopardize the efficiency of distributed control algorithms and the meeting of hard real time deadlines.

Choosing an appropriate network for the braking system requires a deep study of each individual feature to be carried, so that timing requirements can be specified. Due to the fact that this work serves as the first introduction to the EV project, the requirements for these systems are not yet known. Therefore, at this moment it is impossible to ensure that the proposed networking solution is able to meet the timing requirements of such functionalities.

Given the impossibility of taking the functionalities' timing requirements into account, the specification of the networking solution uniquely considers the feasibility of this architecture.

As it was discussed in Chapter 3, deterministic, multi-channel and high speed network would be required for the braking system, such as Flexray, TTP/C, or TTEthernet. However, given its cost and the required time for students to get familiarized with such protocols, it is not realistic to propose such solutions. Despite a detailed study on the timing constraints of each feature being required, CAN appears to be a good networking solution to be applied in this academic project for the following reasons:

- It enables the definition of priorities between messages
- It is possible to guarantee the scheduling of periodic messages
- It is taught on the available courses
- It is present in many low cost microcontrollers available in the market
- It is a widely adopted solution in the automotive industry for control applications - proven efficiency
- It provides a low cost implementation
- It is robust

However, safety critical elements cannot be dependent on a single transmission medium, as its failure would lead to the loss of the brakes. Therefore, it was decided to provide the proposed architecture with redundant transmission mediums.

5.2.2 Gateway

The internal structure of the gateway is illustrated on Figure 5.3. The gateway is divided into three distinct modules: the main element, and elements 1 and 2. Units shall be connected internally by means of dedicated transmission channels as Figure 5.3 suggests.

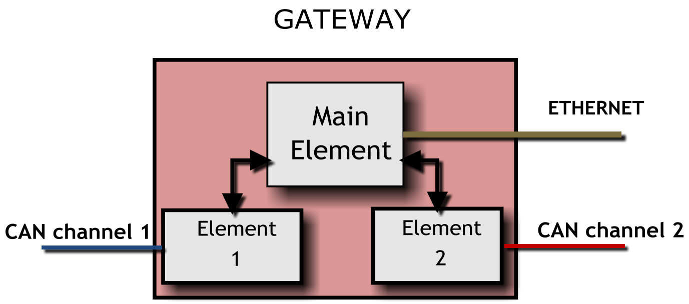


Figure 5.3 - Gateway

The main element is responsible for routing messages between the exterior systems and the braking modules, by means of elements 1 and 2.

Elements 1 and 2 are responsible for providing the interface between the main element and the braking system modules. The introduction of elements 1 and 2 prevent that a single unit connected to both communication channels can cause both network channels to fail, which would result in brake loss.

5.2.2.1 Routing Messages From Exterior Systems

Upon arrival of an Ethernet package into the main element, the main element has the task of transmitting its content to elements 1 and 2, which in turn will transmit the content as CAN messages to the respective CAN channel. All messages transmitted by the main element to Elements 1 and 2 shall be provided with error detection mechanisms, to prevent that a faulty main element can cause elements 1 and 2 to jam both CAN channels.

The format of incoming messages from exterior systems can assume two distinct forms.

The first, consists in embedding CAN messages inside Ethernet frames. This enables the main element to extract the CAN frame from the received Ethernet frame, and transmit it directly to elements 1 and 2. This approach requires the assignment of CAN identifiers to be done globally.

The second method consists on having transmitters to send data encapsulated into pure Ethernet frames. Upon reception of an Ethernet package, the main element is required to assign an identifier to the received data according to its content, and transmit it to elements 1 or 2.

5.2.2.2 Routing Messages from the Braking Systems

Due to the fact that not all frames exchanged in channels 1 and 2 are to be delivered to exterior systems, elements 1 and 2 require the knowledge of the frames that must be delivered to exterior systems, to after transmit them to the main element.

Messages transmitted by elements 1 and 2 can arrive to the main element in distinct time instants. Therefore, a time frame in which messages are considered to be valid must be defined. This prevents that a safety procedure might be engaged in case of transient faults.

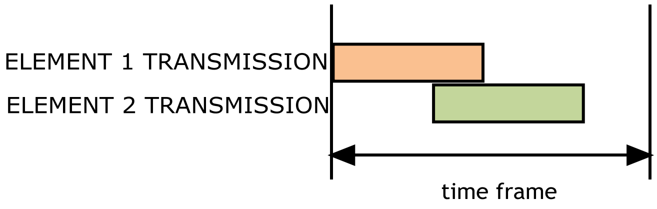


Figure 5.4 -Time frame of messages delivered to the main element

Upon reception of a frame from elements 1 or 2, the main element shall start counting the time frame. If the second frame is received in the mean time or the time window expires, the main element proceeds the transmission to the Ethernet segment according to Table 5.5.

Table 5.5 - Output of the main element according to incoming messages

Element 1	Element 2	Main element Output
C_A	C_A	C_A
C_A	I	C_A
I	C_A	C_A
I	I	$Fault\ diagnosis$
C_A	C_B	$Fault\ diagnosis$

where:

$C_A, C_B : error\ free\ message$
$I: erroneous\ or\ null\ message$

5.2.3 Brake Pedal Position Module

The brake pedal position module consists of two elements which operate independently and synchronized. Each brake pedal position unit has the task of acquiring the value of a redundant set of brake pedal position sensors, compute one value out of the measured values by means of a software voting mechanism, and output the brake pedal position to the interested entities. The brake pedal position shall be sent periodically, so faults within this module can be detected by other units. Despite in Figure 5.2 and Figure 5.5 three sensors are represented, any number of sensors can be connected to ensure the desired level of dependability and any of the techniques presented on Chapter 4 can be applied.

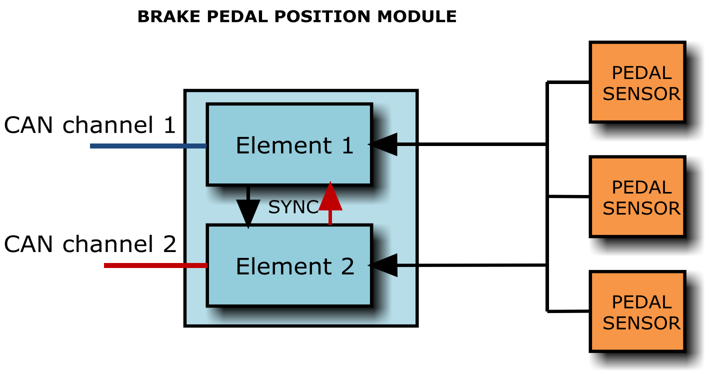


Figure 5.5 - Brake pedal position module

5.2.3.1 The Necessity of Synchronism

If both elements operate unsynchronized it can happen that the sampled value of the sensors can differ significantly, as Figure 5.6 illustrates. The faster the driver presses or releases the brake pedal, the higher the difference will be.

Fault tolerant software mechanisms that operate in the brake actuator modules can interpret the difference between both values as a fault, with the aggravation of being unable to distinguish which of the elements is providing the erroneous value. In such a situation, the brake output module would not be able to perform a correct decision on the brake force to produce.

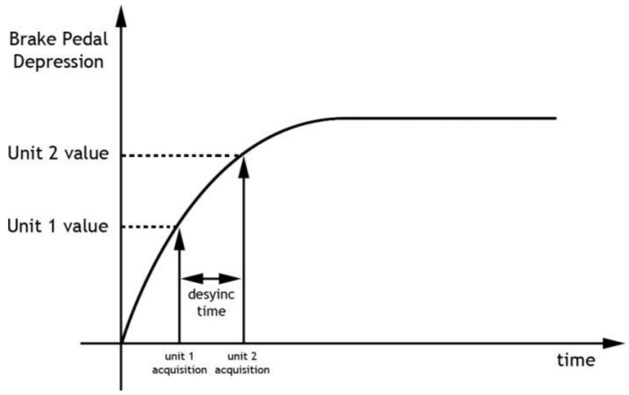


Figure 5.6 - Unsynchronized units

By synchronizing the acquisition time between both units, the system minimizes the deviation between the acquired values in both units.

A Simple Synchronism Method

A simple synchronism method which can be easily built by students, only requiring two digital ports on the microcontroller and two wires connected as Figure 5.7 illustrates.

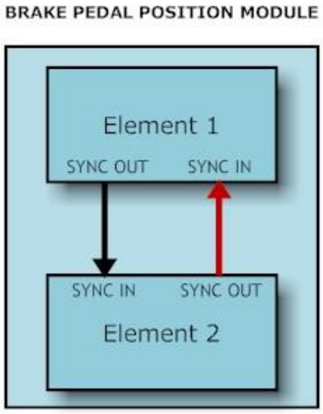


Figure 5.7 - Synchronism diagram

The synchronism algorithm consists on the idea that each element must expect a change on its sync in port after changing its sync out port. After two level changes the two units are synchronized. The algorithm is presented on Figure 5.8.

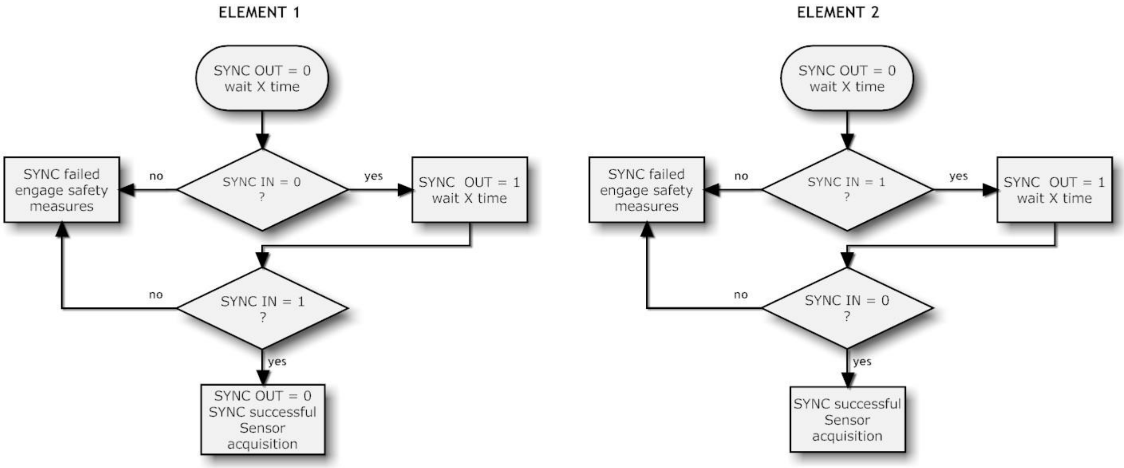


Figure 5.8 - Synchronism algorithm

If any component of the synchronism mechanism becomes faulty, such as digital ports or wires, its operation becomes unavailable. To reduce the negative effects of the lack of synchronism between the two elements, the sample rate and network dispatch of each element can be raised and safety measures such as speed limitation should be carried.

5.2.3.2 Plausibility Tests on the Brake Pedal Position

To avoid erroneous brake pedal values to be transmitted to other modules, plausibility tests on the brake pedal position sensors should be performed. Plausibility tests should be performed before the voting mechanism, so faulty sensors do not influence the result of the brake pedal position.

This section provides some examples of plausibility tests that can be performed to detect faulty sensors

Range Testing

Range testing relies on the fact that the brake pedal position must be within a range of plausible values. For instance, if it is considered a depressing value between 0 and 100 percentage, a negative value or a value above 100 would indicate a erroneous operation.

Furthermore, if for instance the analog to digital converter responsible for acquiring the sensor values with a 10 bit resolution, values higher than 1023 would also indicate a erroneous operation.

Derivative Testing

Derivative testing relies on the dynamics of the driver pressing the pedal. The pressing of a brake pedal follows a natural curve, with a maximum physical variation. If the rate of variation is exceeded it might indicate an erroneous value and the value provided by the sensor can be excluded.

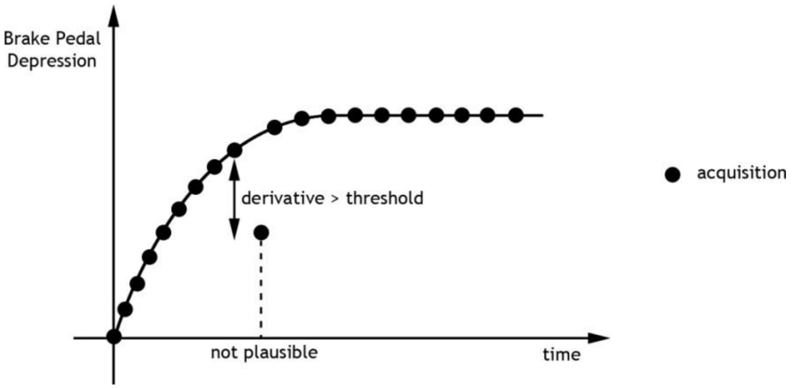


Figure 5.9 - Brake pedal depression dynamics

Threshold Testing

A threshold test can be applied for the exclusion of faulty sensors in the following way:

1. Calculate the average/median of all sensor acquisition values
2. If one sensor differs from a predetermined amount from the average/median, this sensor is excluded and marked as faulty

5.2.3.3 Elements Operation

The operation of the braking system cannot be dependent on a single brake pedal element, as its failure leads to the loss of brakes. Hence, it is advisable to provide each element with self checking mechanisms. Whenever it is considered that an element is faulty, the driver must be notified and vehicle's speed should be limited.

It should be noted that as both elements operate independently, it is possible that both can transmit different brake pedal positions. However, as it was mentioned, the dynamics of a driver pressing or releasing the brake pedal follows a natural curve, and therefore, the receiving modules can detect and choose which value is plausible by performing the appropriate tests, and after notify the driver and request for vehicle's speed limitation.

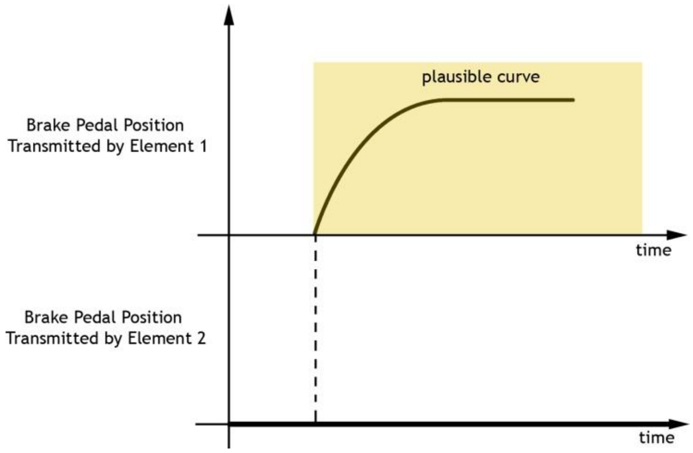


Figure 5.10 - Fault detection by observation of a plausible brake pedal depression

Figure 5.8 illustrates the suggested algorithm for the brake pedal position elements operation.

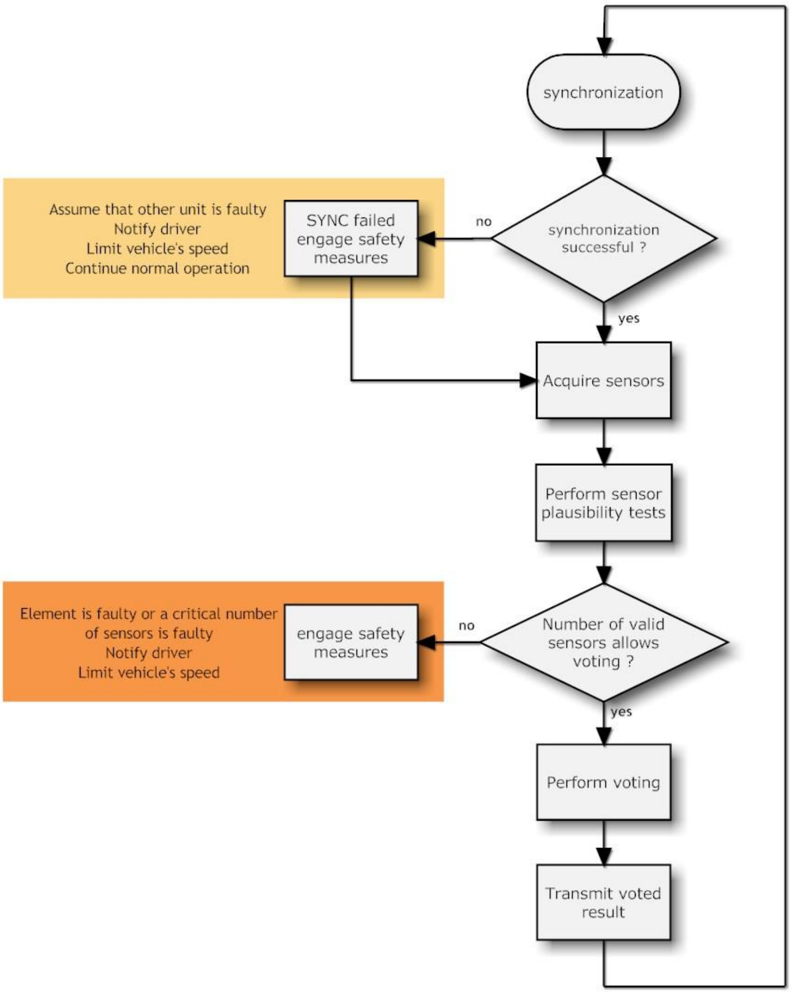

synchronization
synchronization successful ?
no
yes
SYNC failed engage safety measures
Assume that other unit is faulty
Notify driver
Limit vehicle's speed
Continue normal operation
Acquire sensors
Perform sensor plausibility tests
Number of valid sensors allows voting ?
no
yes
engage safety measures
Element is faulty or a critical number of sensors is faulty
Notify driver
Limit vehicle's speed
Perform voting
Transmit voted result

Figure 5.11 - Brake pedal position module algorithm

5.2.4 Wheel Speed Acquisition Module

It would not be practical to connect wheel speed sensors to all of the requiring functionalities. Therefore, a extra unit named wheel speed acquisition module was added. Wheel speed values are made available in the network channels by this module.

The calculation of vehicle dynamics taking as basis erroneous wheel speeds values may affect the stability of the vehicle as the ABS, TCS and ESC systems can perform erroneous brake requests taking as basis wrong wheel speed values. Therefore, it must be granted that wheel speed values are always correct, or no wheel speed values are transmitted over the network.

Many of the architectures and philosophies presented in Chapter 4 can be used to overcome this issue. The simpler method consists on the replication in a duplication with comparison topology of the computational elements of the wheel speed acquisition module. This method consists on having two redundant units performing the same operations and comparing results. If a disagreement between the two units is found, the entire module is considered as faulty. Upon this situation, diagnostic messages would be sent by the error detecting unit(s) and their operation would be ceased.

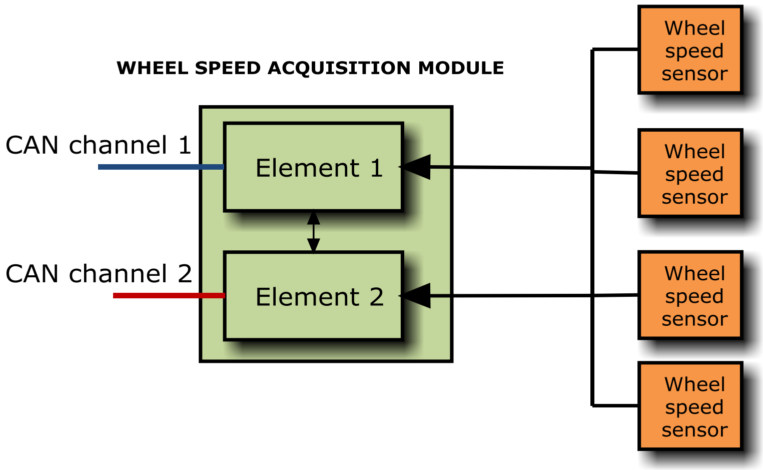


Figure 5.12 - Wheel speed acquisition module

To ensure that the transmitted wheel speed values are always correct, the wheel speed acquisition module should be composed by two elements which compute the values of wheel speed sensors at the same instants, perform plausibility tests on the acquired sensor values, and exchange the values with the other redundant unit. Congruence tests have to be made to check whether the values acquired by both elements are in consonance. This can be done by means of threshold tests, which check whether the differences between wheel speeds vary from a determined range which is considered faulty. If congruence is verified, a voting mechanism is performed between the two units so the same wheel speed values are transmitted to the respective CAN channels.

Similarly to what was discussed for the brake pedal position module, wheel speed sensors require redundancy so faults within a sensor can be detected or compensated.

In case of disagreement between the results, the module is considered faulty. As the ABS, TCS and ESC modules are unable to operate without the knowledge of wheel speed values, the driver should be notified.

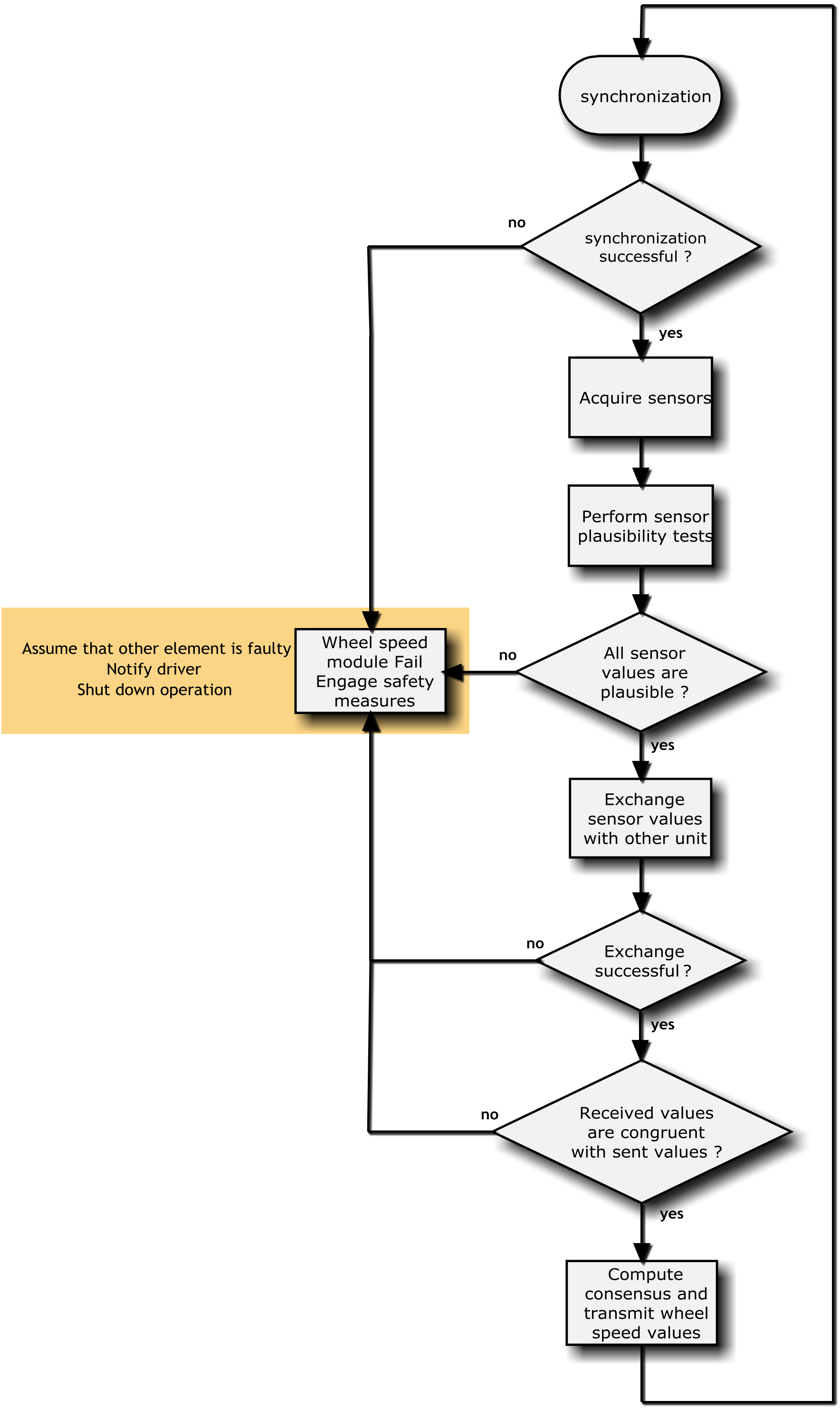

synchronization
synchronization successful ?
no
yes
Acquire sensors
Perform sensor plausibility tests
All sensor values are plausible ?
no
yes
Assume that other element is faulty
Notify driver
Shut down operation
Wheel speed module Fail
Engage safety measures
Exchange sensor values with other unit
Exchange successful ?
no
yes
Received values are congruent with sent values ?
no
yes
Compute consensus and transmit wheel speed values

Figure 5.13 - Algorithm for ensuring fail safe behavior of wheel speed acquisition modules

5.2.5 ABS, TCS and ESC Modules

The ABS, TCS and ESC have the ability of causing catastrophic situations by requesting erroneous brake services to the actuator modules. Therefore, these units must grant a fail safe behavior, which means that upon failure, no brake requests are allowed to be sent by these units.

Similarly to the wheel speed acquisition module, ABS, TCS and ESC modules are constituted by two redundant elements which perform the same calculations and compare the results before transmitting brake requests.

However, if both elements would compare the results of a brake force request only when an intervention was required, a disagreement in the brake forces to request could be found, and no intervention would be outputted. This could result in a dangerous situation in which the driver would only be aware on a faulty unit when its intervention would be required.

Therefore routine checking mechanisms are mandatory. A suggested mechanism which can be applied in the ABS, TCS and ESC modules when no intervention is required, consists on performing calculations over the received wheel speed values and the comparison between the obtained results from both elements. A simple calculation in the form of:

$$C = WS_{FL} \times k_1 + WS_{FR} \times k_2 + WS_{RL} \times k_3 + WS_{RR} \times k_4 \tag{10.1}$$

where:

$C: checking\ parameter$

$WS_{FL}: wheel\ speed\ of\ front\ left\ wheel$

$WS_{FR}: wheel\ speed\ of\ front\ right\ wheel$

$WS_{RL}: wheel\ speed\ of\ rear\ left\ wheel$

$WS_{RR}: wheel\ speed\ of\ rear\ right\ wheel$

$k_1, k_2, k_3, k_4: constants$

would allow the detection of a faulty element within the module.

Figure 5.14 depicts a generic algorithm which will ensure the fail safe operation of the ABS, TCS and ESC modules.

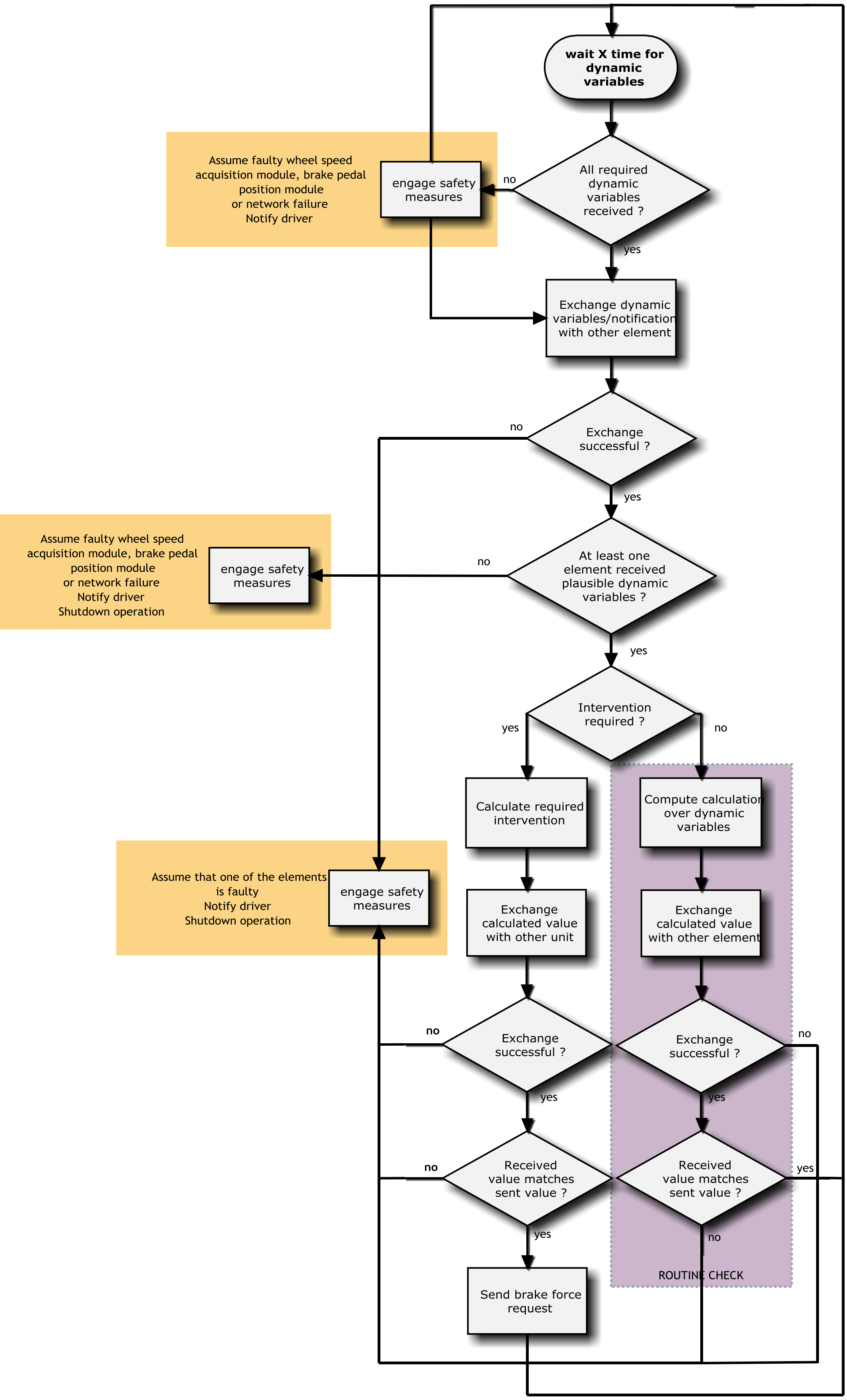

wait X time for dynamic variables
All required dynamic variables received ?
no
yes
engage safety measures
Assume faulty wheel speed acquisition module, brake pedal position module or network failure Notify driver
Exchange dynamic variables/notification with other element
Exchange successful ?
no
yes
At least one element received plausible dynamic variables ?
no
yes
engage safety measures
Assume faulty wheel speed acquisition module, brake pedal position module or network failure Notify driver Shutdown operation
Intervention required ?
yes
no
Calculate required intervention
Compute calculation over dynamic variables
Assume that one of the elements is faulty Notify driver Shutdown operation
engage safety measures
Exchange calculated value with other unit
Exchange calculated value with other element
Exchange successful ?
no
yes
Exchange successful ?
no
yes
Received value matches sent value ?
no
yes
Received value matches sent value ?
yes
no
ROUTINE CHECK
Send brake force request

Figure 5.14 - Algorithm for achieving fail safe operation applicable to the ABS, ESC and TCS systems

5.2.6 Braking Actuator Modules

Braking actuator modules are responsible for receiving braking requests and effectively actuate the brakes to generate the required braking force. Brake requests are received periodically by the brake pedal module, and sporadically by other units such as the ESC, ABS, TCS, ACC and other implemented systems as required. Several brake requests can be sent at the same instants by these units. Such issues have to be dealt with appropriate software specification.

5.2.6.1 The Safe State of a Brake Actuator

The braking actuator modules are responsible for actuating directly on the brake actuators. Although it was mentioned in Chapter 4 that a brake-by-wire system does not have a safe state, the difference between the safe state of the entire braking system and a single brake actuator must be understood.

When designing fault tolerant architectures, one of the most important things is that its safety must be self-sustainable. Thus, during this discussion we exclude the hypothesis of intervention from the Electronic Stability Program in case of vehicle destabilization provoked by erroneous brake actuation.

A faulty braking actuator module can cause two distinct situations: performing an unsolicited brake force and the contrary, not performing a solicited brake force. The former situation can lead to catastrophic situations such as the loss of vehicle control, as the creation of an unsolicited brake force creates an undesired yaw moment. In case of occurrence of the latter situation, a yaw moment is also generated but with the advantage that the effects of a non braking wheel can be detected and compensated. It must be kept in mind that brake compensation can only be performed up to a certain brake force. However, if we consider that the odds of a brake actuator failing at the same instant that the driver performs an emergency braking, the non braking state can be considered the safe state of a braking actuator.

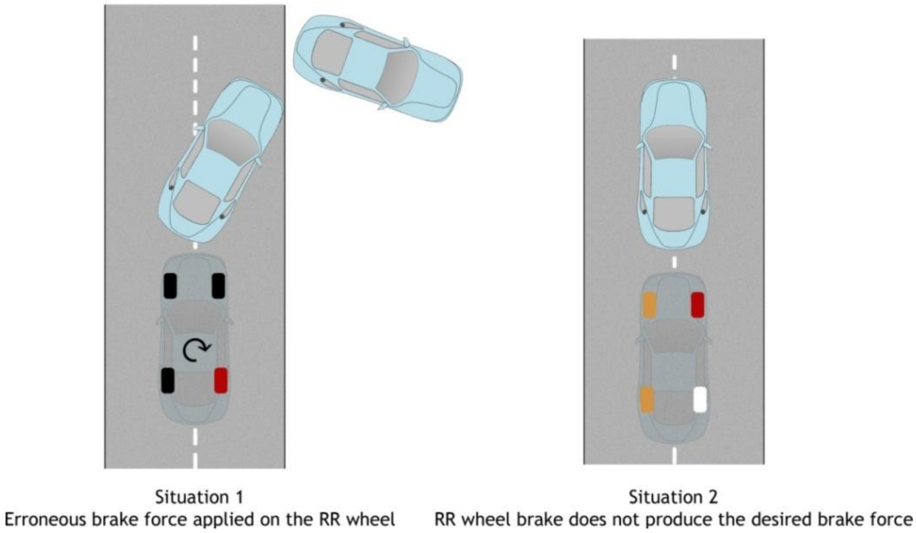

Situation 1
Erroneous brake force applied on the RR wheel
Situation 2
RR wheel brake does not produce the desired brake force

Figure 5.15 - Erroneous operation of the brake actuator

5.2.6.2 Braking Actuator Modules Operation

Similarly to the wheel speed acquisition module, ABS, ESC and TCS modules, the brake actuator modules are constituted by two elements working in a duplication with comparison topology. Although both elements perform the same calculations, only one element commands the actuator. Upon abnormal behavior from either the actuator or any of the elements, the detecting element de-energizes the actuator and engages safety measures.

A more detailed view of the braking actuator modules and the interacting units is seen on Figure 5.16.

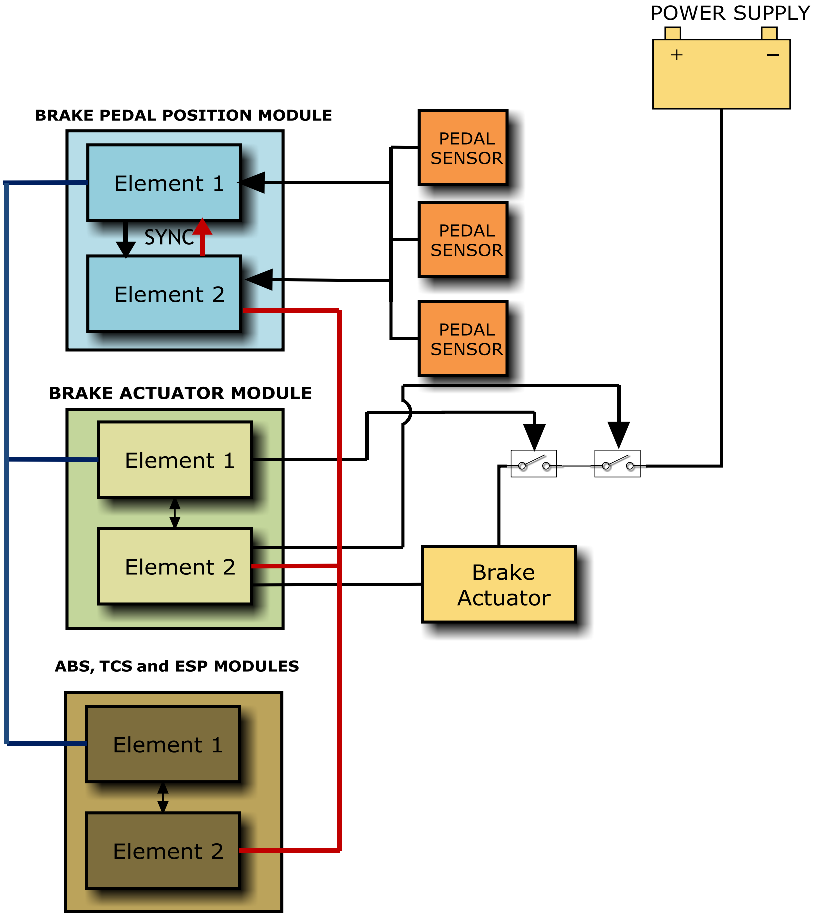


Figure 5.16 - Detailed view of brake actuator module connections

Figure 5.17 depicts an algorithm that ensures the fail safe behavior of the brake actuator modules when performing brake requests upon reception of the brake pedal position.

The algorithm for performing brake request from units such as the ABS, TCS and ESC is similar to that described in Figure 5.17, but in case that both elements receive different brake requests, the command shall be ignored as this implies that a fault has occurred in the ABS, TCS or ESC modules. Upon such situation, a diagnostic message should be sent.

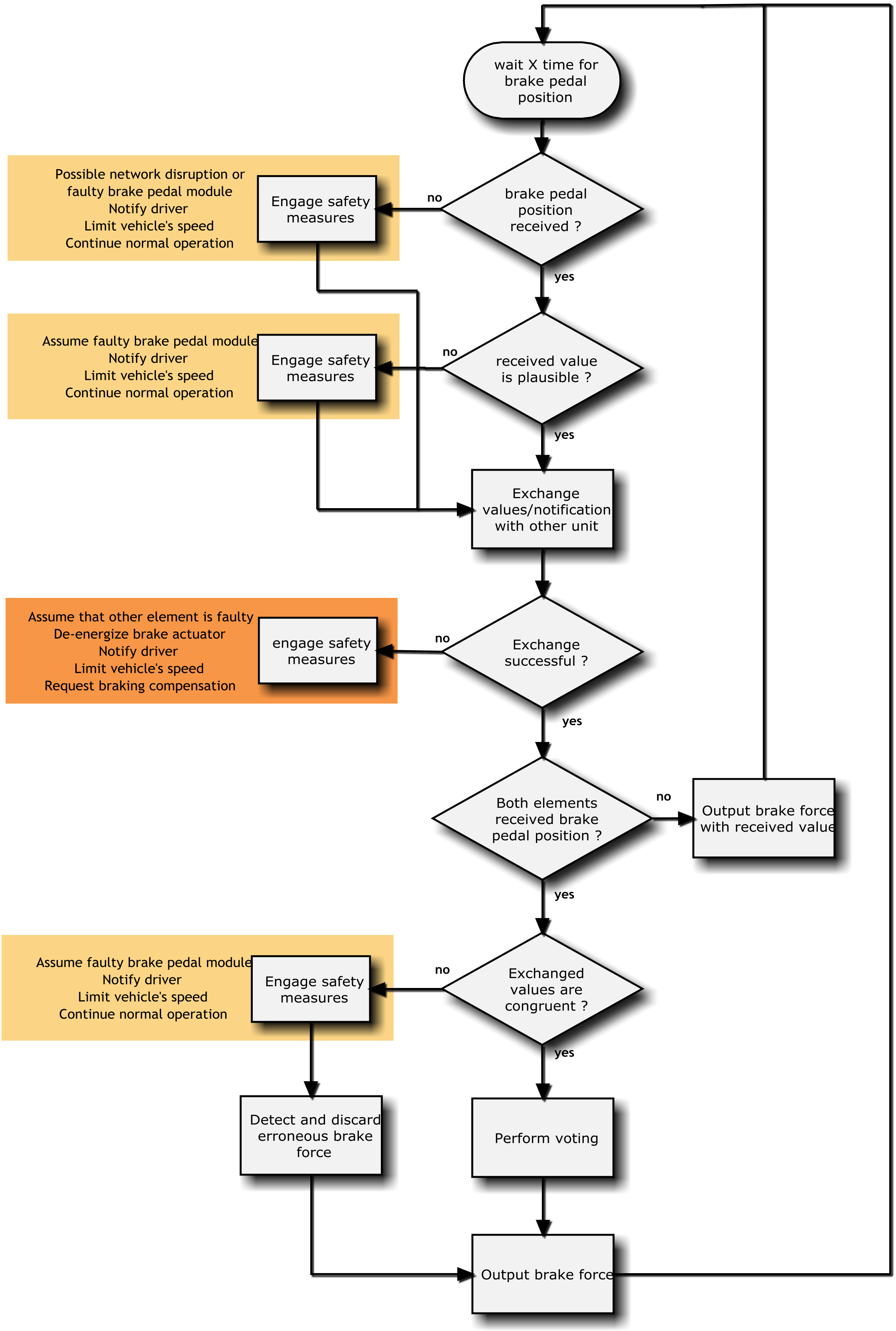

wait X time for brake pedal position
brake pedal position received ?
no
yes
Engage safety measures
Possible network disruption or faulty brake pedal module
Notify driver
Limit vehicle's speed
Continue normal operation
received value is plausible ?
no
yes
Engage safety measures
Assume faulty brake pedal module
Notify driver
Limit vehicle's speed
Continue normal operation
Exchange values/notification with other unit
Exchange successful ?
no
yes
engage safety measures
Assume that other element is faulty
De-energize brake actuator
Notify driver
Limit vehicle's speed
Request braking compensation
Both elements received brake pedal position ?
no
Output brake force with received value
yes
Exchanged values are congruent ?
no
yes
Engage safety measures
Assume faulty brake pedal module
Notify driver
Limit vehicle's speed
Continue normal operation
Detect and discard erroneous brake force
Perform voting
Output brake force

Figure 5.17 - Algorithm which ensures the fail safe of brake actuator elements

5.2.6.3 Wrap Around Testing

Once the controller outputs the appropriate signal to generate a certain brake force, it cannot be expected that the actuator will actually perform the desired brake force, as faults can occur in the actuator and on the interfaces between the controller and the actuator. Therefore, it must be tested at all times that the desired brake force is actually being generated. This implies that there must any kind of feedback between the controlling and the actuating units. On the impossibility of measuring the brake force directly, several indirect analytical ways can be performed such as:

1. Measuring the current applied to the actuator (current proportional to torque)
2. Observing wheel speed when brakes are applied

The suggested algorithm is illustrated in Figure 5.18.

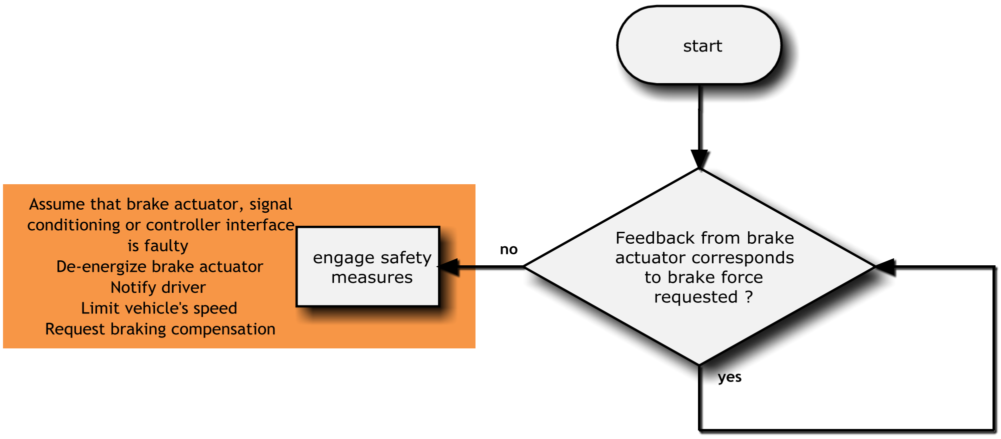

start
Feedback from brake actuator corresponds to brake force requested ?
no
yes
engage safety measures
Assume that brake actuator, signal conditioning or controller interface is faulty
De-energize brake actuator
Notify driver
Limit vehicle's speed
Request braking compensation

Figure 5.18 - Algorithm which checks if actuator behavior corresponds to desired behavior

5.2.7 Power Supplies

The connection of all controllers and actuating units on the braking system to the same power supply would result in loss of the brakes in case of power outage. The ideal situation is to provide each component of the system with a dedicated power supply. Due to unfeasibility of such idea, due to cost, complexity and available space, and following the same philosophy of reducing the number of components on the maximum while granting safety, the minimum number of power supplies suggested is two.

Both elements from the brake pedal position module must be powered by different power supplies, as the failure of a single power supply would lead to brake loss, given the inability of the brake pedal position to be transmitted to the actuators.

Due to the fail safe behavior of the ABS, TCS, ESC and wheel speed acquisition modules, these can be powered by the same supply, as a power outage on any of the elements will cause the whole modules to stop working due to the comparison mechanisms for fault detection.

To minimize the effects of power outage on vehicle dynamics, brake controllers/actuators belonging to the same side of the vehicle cannot be supplied by the same power source. The fundaments of this idea can be visualized on Figure 5.19, which depicts undesirable situations in all power configurations.

Situation 1 reflects a situation that happens upon power outage of the brake actuators when two brake actuators from the same side are connected to the same source. In this situation, if the driver is pressing the brake pedal and the power supply fails, a yaw momentum is generated, which can cause the driver to lose the control of the vehicle.

Although in situations 2 and 3 the available brake force can be diminished, the failure of the power source does not induce an undesired yaw.

The diagonal configuration on figure two has the potential of providing additional brake force comparing to the front/rear power supply configuration. For instance, if the vehicle is heavier on its front side, rear wheels cannot perform as much brake force as front wheels. Hence, in case of a power outage on the front brake wheels, the available brake force will be diminished. In case of the diagonal arrangement, if the front wheel provides more braking force and if a steering yaw compensation service is available, the effects of the generated yaw can be reduced, while the brake force is increased.

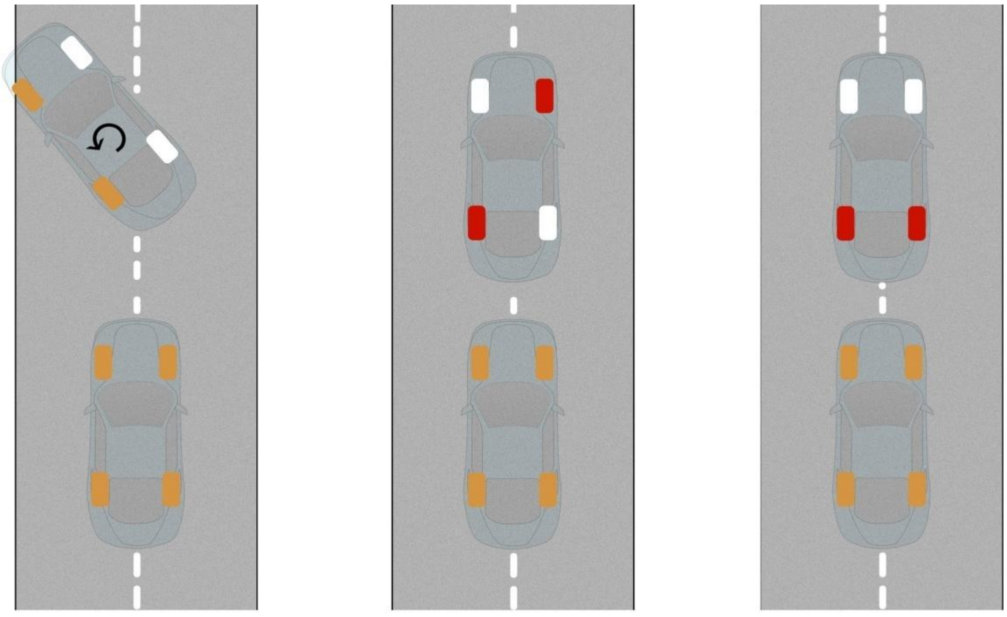


Figure 5.19 - Different responses from the vehicle according to different configurations of power supplies upon power outage

5.2.8 Braking System Fault Analysis

This section provides a brief overview of the types of faults than can occur within the braking system, the respective consequences and its effect on brake control. The following tables summarize the concepts and ideas that have been discussed throughout this chapter.

Table 5.6 - Gateway fault analysis

Component	Fault	Consequence	Brake loss
Main Element	Component fail or power outage	• Braking system unable to interact with exterior systems • TCS and ESC unable to operate	No
	Erroneous messages transmitted to elements 1 and 2	• None: erroneous messages detected by elements 1 and 2 and not transmitted to braking modules	No
Elements 1 or 2	Component fail	• None: interaction with exterior systems is done by means of non faulty element	No
	Power outage	• Braking system unable to interact with exterior systems • TCS and ESC unable to operate	No

Table 5.7 - Network channels fault analysis

Component	Fault	Consequence	Brake loss
CAN transmission medium 1 or 2	Communication channel mishap	• None: units are able to communicate by means of redundant transmission medium	No
	Network jam by any unit connected to the channel	• None: units are able to communicate by means of redundant transmission medium	No

Table 5.8 - Brake pedal position fault analysis

Component	Fault	Consequence	Brake loss
Element 1 or 2	Component fail	• None: brake pedal position is transmitted by other element	No
	Erroneous brake pedal position transmitted	• None: receiving modules detect erroneous brake pedal position and consider the value sent by the redundant element	No
	Power outage	• None: brake pedal position is transmitted by redundant element which is not affected by power outage	No
Sensors	Erroneous value provided	• None: fault detected by plausibility tests or natural curve and masked by voting mechanism	No

Table 5.9 - ABS, TCS and ESC modules fault analysis

Component	Fault	Consequence	Brake loss
Element 1 or 2	Component fail	• Module unable to operate: detected by redundant element	No
	Erroneous brake request transmitted	• Required intervention not performed: brake actuator modules detect discrepancy between the two received brake requests and do not perform any intervention (very unlikely due to routine checks)	No
	Power outage	• Module unable to operate	No

Table 5.10 - Brake actuator modules fault analysis

Component	Fault	Consequence	Brake loss
Element 1 or 2	Component fail	• Loss of brake force provided by the controlled actuator: detected by redundant element, which can request brake compensation	Limited
	Power outage	• Loss of brake force provided by the controlled actuator	Limited
Brake Actuator	Component fail	• Loss of brake force provided by the actuator: erroneous behavior detected by brake actuator elements and actuator de-energized	Limited

Table 5.11 - Wheel speed acquisition module fault analysis

Component	Fault	Consequence	Brake loss
Element 1 or 2	Component fail	• ABS, TCS and ESC unable to operate: detected by redundant element	No
	Erroneous wheel speed values calculated	• ABS, TCS and ESC unable to operate: detected by redundant element	No
	Erroneous wheel speed values transmitted	• None: ABS, TCS and ESC modules detect discrepancy between the two received values	No
	Power outage	• ABS, TCS and ESC unable to operate	No
Wheel speed sensors	Erroneous value provided	• ABS, TCS and ESC unable to operate	No: fault detected by plausibility tests or natural curve and masked by voting mechanism

Table 5.12 - Power supply fault analysis

Component	Fault	Consequence	Brake loss
Power Supply	Component fail	• All elements connected to power supply fail • Loss of brake force provided by actuators powered by the faulty power supply	Limited

Chapter 6

Conclusions and Future Work

6.1 Conclusions

Throughout this work, several functionalities that are usually found in modern vehicles and which have the potential to be developed along the various courses available have been identified, and their operation and hardware architectures have been documented. Despite the intent of providing this document with more information about the computational platforms that are used by manufacturers to implement the described features, the lack of information resulting from the fact that such information represent trade secrets, made it impossible for providing this document with such data.

The most widely used communication networks in the automotive industry have been studied and documented, which will allow students to understand the concepts and their applicability on the projects that will be developed. Although TTEthernet is not actually used in the automotive industry, its capabilities and features granted it a spot in this document due to its potential of becoming the future solution for the problems that the new generation of vehicles will face.

During this study, it was found that many efforts are being put together by manufacturers for the implementation of drive-by-wire systems. Although it was not on the objectives of this work, it is my belief that this document would be incomplete without a brief reference to the concepts of this emergent philosophy. Not only the drive-by-wire systems were referenced, but also some guidelines and techniques that will enable students to develop their own solutions.

The architecture and ideas that were proposed in Chapter 5 for the braking system, enables that a system which is usually integrated in a single module to be developed by several working groups. Despite being conceptualized taking as basis a network protocol that was not designed with the intent of being implemented for safety critical applications, the proposed architecture and algorithms that support its operation are able to achieve a fair amount of dependability, which is required for a system whose malfunction can lead to catastrophic consequences.

6.2 Future Work

As it was mentioned in Chapter 5, Ethernet as a the communications backbone for the EV does not guarantee in any way the desired level of determinism which is required for the distributed control algorithms that will depend on it. This issue could be solved by the creation of a middleware layer that would allow the different systems within the vehicle to exchange data in a TDMA scheme, based on the Ethernet infrastructure.

The proposed architecture for the braking system requires a detailed study on the timing requirements of each feature, so the schedulability of all the messages that are expected to travel within both CAN channels can be proved.

Being the EV an academic project, it is expected that the architecture of the systems installed will change over time. To avoid constant reconfigurations on the devices that are expected to communicate, a middleware layer which would hide the details of the hardware architecture would be a valuable asset.

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