POLITECNICO DI TORINO

Master's Degree in MECHATRONIC ENGINEERING

Master's Degree Thesis

Study and Modelling of an Electric Oil Pump and Functional Safety Analysis in Powertrain Applications

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Abstract

Nowadays, the automotive field aims to create fully electric products. For this, the components of the vehicular system have considerably changed, with the replacement of conventional mechanical components with their electrical counterparts becoming commonplace, such as the electric water pumps for cooling systems. In contrast, the adoption of electric oil pumps, while promising for enhanced efficiency, has been met with reservations due to the critical role of oil circulation in ensuring engine reliability. This study delves into this topic by conducting a comprehensive analysis of the hydraulic system within automotive contexts, focusing on electric oil pumps in electrical powertrains. This research has two main objectives: first, to analyze the hydraulic system's complexities in modern vehicles; and second, to establish a model for studying the behavior of electric oil pumps. Achieving these objectives entails formulating and evaluating an optimized system under the standards guidelines, which not only will ensure efficient oil circulation but also will address concerns related to functional safety.

This study meticulously considers diverse norms associated with functional safety and employs Failure Modes and Effects Analysis (FMEA) as a critical analytical tool to achieve these goals. By interlacing engineering principles with safety considerations, the research aims to provide insights into the reliability and viability of incorporating electric oil pumps.

Through systematic analysis and software-based simulations, this study contributes to advancing electric oil pump technology in the automotive sector. The findings shed light on the feasibility of adopting electric oil pumps and underscore the importance of developing precise control strategies that align with stringent safety standards. As the automotive industry continues to embrace electrification, this research bridges the gap between innovation and reliability, facilitating the evolution of automotive systems toward a more sustainable and efficient future.

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Primero que todo quiero agradecerle a Dios por hacer todo esto posible, por guiar siempre mi vida, dándome sabiduría y fuerzas para afrontar cada situación que se presente, no importa lo complicado o imposible que sea vean las cosas, solo con el todo es posible. Gracias Dios por todo lo que has hecho en mi vida, porque cada una de las cosas por las que he pasado, ya sean momentos de felicidad o de tristeza, me han ayudado a ser la persona que hoy soy, enseñándome que todo sucede por una razón, aunque no lo entienda en el momento, sé que todo estará bien mientras tenga mi fe en ti, enseñándome paciencia sobre todo durante este proceso de la tesis, mostrándome que las cosas son en tu tiempo y no en el mío. Sé que nunca me dejaste solo y nunca lo harás, porque esto no es el fin de un ciclo, sino parte de un nuevo comienzo, un paso más en el plan que tú tienes para mi vida.

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"Salud mi familia!"
Dominic Toretto, Fast Five

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Acronyms

FMEA
: Failure Mode and Effect Analysis

FuSa
: Functional Safety

xEV
: Electrified Vehicles

HEV
: Hybrid Vehicles

ER-EV
: Extended Range Electric Vehicles

FCEV
: Fuel Cell Electric Vehicle

PEV
: Pure Electric Vehicle

EM
: Electric Motor

ICE
: Internal Combustion Engine

ECU
: Electronic Control Unit

GB

Gear-Box

WTOC

Water Transmission Oil Cooler

LPM

Liter-Per-Minute

ASIL

Automotive Safety Integrity Levels

FTA

Fault Tree Analysis

MBD

Model-Based Design

HIL

Hardware-In-the-Loop

SIL

Software-In-the-Loop

MIL

Model-In-the-loop

PID

Proportional-Integral-Derivative

BLDC

Brush-Less Direct Current

PWM

Pulse Width Modulation

CAN

Controller Area Network

LIN

Local Interconnect Network

Chapter 1

Introduction

Transport connects people, continents, countries, cities, and cultures. For this reason, transportation is considered one of the main pillars of modern society and economy. The transport industry has risen significantly throughout the years due to the need for diverse means of transportation to surpass different situations and specific necessities.

With an increase in transportation needs, there has also been a significant rise in its damaging effects, generating substantial impacts on human health and the environment. Only in Europe, transportation is responsible for about a quarter of the total greenhouse gas emissions, according to the European Environmental Agency[1], and causes air pollution, habitat fragmentation, and noise pollution. Because of this, the interest in generating a way to damper these environmental effects has been rising in recent years. As a result, a solution has arisen in the automotive sector due to different regulations to mitigate CO2 emissions, which is the main gas responsible for the greenhouse effect.

Projects are rising behind the search for an answer to "How to reduce the carbon signature generated by light commercial vehicles?" Bringing the pursuit of full electrification in the automotive sector could be one of the solutions to this problem. A project known as "Fit for 55", the amended Regulation2019/631a proposal to make zero-emission all new vans and passenger cars registered in Europe from the year 2035[2], has been implemented in the European Union. As intermediate steps aiming to reach this goal, the new standards will require the average emissions generated by new cars to decrease by 55% and the average emissions generated by new vans to be reduced by 50% Both scenarios are expected by the year 2030, aspiring to achieve the target of Europe being climate neutral by the year 2050. The intensification of this effort as the deadline gets closer brings along the research and development of new technologies to implement in the design and production of new vehicles.

Some of these technologies could be the outcome of the edge of the vanguard research, resulting in analyzing a problem and coming out with a solution that might change the way that we previously thought about the functioning of a particular system. An example of this is the regenerative breaks used to reuse the energy previously wasted during the breaking of the vehicle and in this way that energy can be re-utilized to recharge the batteries of the vehicle, allowing it to save energy or extend their autonomy range during certain situations.

On the other hand, some solutions might be the outcome of taking previously used technologies and "modernizing" them, up to the point of improving their performance and making them able to correctly function to the new requirements of the modern industry.

An example of this could be what has been done in some vehicles with their water pumps used for the internal cooling of some car systems. Previously this pump was directly and physically connected to the mechanical rotational energy generated by the Internal Combustion Engine (ICE) with the use of belts, using its mechanical work to make the fluid circulate through the hydraulic circuit and in this way perform the task needed, nowadays, instead with the use of electric motor in vehicles, the conventional mechanical pumps have been sent to a second plane given the fact that the derived connection between the ICE and the mechanical pump done through belts or chains is no longer feasible, hence, a new generation of pumps has arrived as a solution for this problem, being this the opportunity of the ePumps to come in action. A type of pump capable of functioning leaning only on an electrical energy source and no longer depending on rotational drives, leaching on the mechanical energy produced by the ICE. The ePump would then communicate with the Electronic Control Unit of the car (ECU) to be ruled by a programmable control logic.

1.1 Project Overview

The aim of this work is to continue with the task of reaching a higher level of electrification in the automotive sector. Working alongside a company called Capgemini Engineering, with the goal of providing a solution to the needs of one of our clients, focusing on technologies that can be implemented in different types of vehicles, from passenger cars to vans, and even in heavier vehicles outside of the "light" category.

To do this, we will continue the approach previously exposed, considering a particular component, that nowadays works in a certain way, and studying it in detail to find out a way to improve its performance and update its behavior to fit the requests of the new era of electric vehicles. Following the methodology mentioned in the previous example regarding the water pump, in this work of thesis, the component chosen for the analysis is an oil pump. They might seem similar because of their analogous fluid circulation task, but the requirements for performance and reliability are quite different.

The lubrication and cooling systems are critical to ensure the correct functioning of the vehicle. Therefore, the importance of having a high reliability in the component under study, which is the core of this system, can be understood. In some electric vehicles, and also in some internal combustion vehicles, the lubrication system has an additional task besides lubricating the different components of the car: a heat exchanger can be added into the lubrication circuit to lower the temperature of the oil, which by being in contact with certain components that represent a source of heat, this liquid not only will be in charge of lubricate it but also of refrigerate it, making the importance of this system even more crucial for the right functioning of the vehicle. In fact, a failure in the lubrication system could represent a risk of damage by lack of lubrication and also by overheating, harming partially or even permanently other components or systems in the vehicle.

This high need for reliability leads to work on this problem from different approaches, focusing this project on not only making the change from a conventional mechanical pump to an ePump but also on guaranteeing that the system will be sufficiently reliable. To ensure this, the system will be fully studied starting from the architecture at the hardware level, to then proceed to find the best control logic for the system, a control logic that secures its right behavior under different possible common failures that might be present and having them to affect the performance in the minimum way possible.

This study is fully done through a functional safety analysis, following the guidelines of the normative ISO-26262. which is the functional safety regulation used in the automotive sector, by using this normative as a reference during the development process it can be guaranteed the rightful following of procedures, basing the evolution of the project in the "V" diagram for product development at system level. During this process, an FMEA analysis is also taken into consideration for the system and components following the AIAG reference manual for automotive applications to be able to obtain a system that will be reliable enough to meet the requirements needed in a commercial environment.

All these safety and reliability analyses have great importance for the development process. In fact, they guarantee that the system under consideration will be able to be used in the electric vehicles; moreover, the technology used for the electric vehicles should be used in conventional combustion engine vehicles to help mitigate energy losses and decrease fuel consumption, moving one step closer into achieving the emission goals expected by the European Union.

1.1.1 How to ensure reliability through Functional Safety and FMEA

To avoid the risks of failures that may impair the correct functioning of the system under study, the use of Functional Safety and FMEA analysis plays a vital role in every step of the development of this project.

The standard ISO-26262 titled "Road vehicles - Functional safety" is brought up as a reference for the Functional Safety analysis, being the international standard responsible for addressing potential danger caused by the malfunctioning of electronic and electrical systems installed in a production road vehicle.

Regarding some other procedures to improve the reliability of the system and its components, The Failure Mode and Effects Analysis (FMEA) is used, which is an analytical methodology with the scope of considering and addressing potential problems throughout the development procedure, doing so by generating a discussion regarding the design of a product or process, reviewing the functions and changes in the application, and the resulting risk of potential failure. This FMEA analysis follows the approach structured by the AIAG & VDA Handbook which incorporates the best methodologies and practices. By using this, we ensure to be up to date with what is currently being used by a large number of companies in the automotive sector.

1.1.2 Description of the system at the hardware level

The lubrication system of a vehicle consists, in its most basic expression, mainly of a component capable of supplying energy to a fluid, allowing it to go through an element responsible for guiding and helping it pass through the part that needs lubrication, to then finally lead to a reservoir and begin the cycle again through the circuit. In this case of study, the lubrication or refrigeration system also includes a heat exchanger responsible for decreasing the oil temperature to fulfill its additional cooling function.

The hydraulic circuit analyzed in this project refers to a real case currently in use by commercial vehicles, meaning that the different parts that compose this system, must be taken into consideration for its analysis, although they can and will be simplified during future steps of the development. These components might be filters, heat exchangers, motors, or axles depending on the particular application in use.

Another important component needed to perform this whole study is the sensor in charge of measuring the information that will later be analyzed by the controller to correctly drive the logic responsible for the behavior to meet the requirements, by constantly monitoring the conditions of the system in aspects like pressure and flow rate to ensure that a right performance is been delivered.

1.1.3 Description of the system at the software level

For the hardware components to have the right functioning and be able to fulfill the performance and reliability requirements needed for this project, there is a need for a control logic capable of managing the system's behavior, based on the information known of the components in used and the feedback supplied by the different sensors of the system

The pump is the core of the lubrication or refrigeration system studied during this project, which is why an ePump with real characteristics will be brought under the scope, analyzing its behavior and control features under real-life and commercial operational environments to correctly fit and improve its functioning methodology into this case of study

This control will be done by taking the functioning of the ePump under use and creating a characterization scheme to be able to develop an accurate model of it. Along with the integration of the data collected by the different sensors to monitor how the system behaves under all the different conditions that may occur. Doing this, we ensure to be able to implement a control logic capable of having the right balance between robustness and fast response. This logic will then be implemented into the electronic control unit responsible for managing the diverse vehicle systems.

1.2 About Capgemini Engineering

In a competitive world, companies in all sectors feel the need to accelerate their digital transformation, forcing global leaders to rethink their innovation cycle as fast as possible has become a survival factor to be able to stay ahead of the competition.

Embracing connectivity and a shift towards intelligent industries and sustainability, Capgemini Engineering as the world leader in engineering and R&D services is an integral part of the Capgemini Group, a diverse and responsible organization composed of over 340.000 team members in more than fifty countries, to achieve a sustainable future through the integration of the human energy and technology. With more than fifty-five years of heritage and expertise, Capgemini Engineering provides its clients the confidence needed to address the scope required by the innovative and fast-evolving world, helping them to accelerate their journey towards an intelligent industry, bringing a diverse set of capabilities, agile engineering, and platforms combined with an industrialized delivery model and cutting-edge technologies.

Capgemini Engineering is a company with more than 55,000 engineers and scientists in over thirty countries across the globe, in all kinds of sectors, including Aeronautics, Space, Naval, Defense, Automotive, Infrastructure, Life Sciences, Software & Internet, Communications, and more.

Providing the information and the mentors needed to develop this project, the expertise of Capgemini Engineering in the automotive sector plays a significant part in the development of this task, providing a situation based on real problems faced by its customers. With the increasing demand for fitting new requirements in the automotive industry, the opportunity for innovation arises.

Chapter 2

State-of-the-art

2.1 Powertrain

The electrification of vehicles has brought along not only a decrease in emissions generation but also a reduction in the operational complexity of several vehicle components, with the replacement of conventional mechanical elements for their electrical equivalents, increasing the simplicity of the vehicle by reducing the number of moving parts. This leads to a minor number of components needed for maintenance and the reduction of the number of elements that may cause a failure and also increases reliability.

One of the systems that benefit the most from the reduction in the number of parts is the powertrain, with a fully electric vehicle having only around twenty moving parts compared to over two hundred found in conventional. This includes the assembly of every component involved in the task of pushing forward the vehicle, from the creation of the power by the engine/motor to the delivery into the wheels on the ground. The main components in basic sets of a powertrain might include an engine/motor, transmission, driveshaft, axles, and differential, as defined by some companies and producers in the automotive sector[3]. They also reiterate the difference between a powertrain and a drivetrain, commonly seen as the same concept, but they have some differences. To simplify, the drivetrain is responsible for transmitting the power to the wheels, commonly composed of transmission, driveshaft, axles, and differentials, the same components as the powertrain excluding the engine/motor. This means that an engine/motor and a drivetrain make up a powertrain.

Technology development has produced various powertrain types and configurations based on their electrification levels to meet the fast-changing needs and demands of the market.
A study conducted by Wu et al.[4] on the powertrain architectures of electrified

vehicles (xEV), explains how we can organize them into different categories, such as Pure Electric Vehicles (PEV), Fuel Cell Electric Vehicles (FCEV) and Hybrid Vehicles (HEV), which are then divided into other five categories: micro HEV, mild HEV, etc. The measurement of the electrification level has a significant impact on the choice of an architectural design. The electrification level, typically indicated by battery voltage, stored energy, and power, determines the capacity of the electric path and the range of each xEV's energy-saving "tools". The primary characteristics and abilities of each type of xEVs are represented by these various electrification levels, some of which can be appreciated in the table 2.1. Please be aware that this review work does not include FCEV, whose architectures are essentially interchangeable with PEV and not closely related to hybrid vehicles.

	Micro-HEV	Mild-HEV	Full-HEV	PHEV	ER-EV	PEV
Idle-stop	F	F	X	X	X	X
Power assist		P	F	F	F	X
Regen-Brake		P	F	F	F	F
PEV driving			P	F	F	F
Charger				F	F	F
Voltage	12	+48	+300	+300	+300	+300
Eff. (%)	2-4	8-11	20-35	50-60	>60	>60

Table 2.1: Comparison among xEV based on their electrification level. F: full capacity; P: partial capacity; X: inapplicable. Note: Adapted from 2015 study, *Powertrain architectures of electrified vehicles: Review, classification, and comparison* [4].

These different categories of xEVs, not only differ in their capabilities but also in their architecture. With diverse requirements and tasks to perform in specific scenarios, there is also a need for a distinct architecture design in the powertrain. The main difference arises with the fundamental distinctions between HEV and PEV, where although the powertrain shares the same objective of being responsible for moving forward the vehicle, there are a different number of components involved. While the HEV consists of an internal combustion engine (ICE) working alongside an electric motor (EM) as a means to create power, the PEV relies only on an EM for this task. However, according to the configuration, they may have other components in common, such as a battery (an energy storage system), a transmission (gearbox), and a differential. If needed, there may be more than one of these components working together in the same powertrain.

In the work mentioned by Wu et al., we can also appreciate some of the most common powertrain architectures used in xEV, which will be mentioned and explained focusing on some of the main distinctions and functioning principles.

2.1.1 Architecture of a PEV

By the locations and quantity of the EM(s), the type of transmission, the number of transmission gears, and other factors, different PEV powertrain architectures can be categorized, some of the most common layouts are illustrated in Figure 2.1.

For the most elemental and most utilized architecture of PEVs, the propulsion motor, main reduction gear, and differential are frequently combined into a small package to reduce vehicle weight and installation space. This type of PEV architecture is similar to a conventional vehicle, except for the absence of a clutch and transmission. By adding a multiple-speed gearbox between the EM and differential, Figure 2.1 (a), this type of architecture can be improved, becoming more like a conventional vehicle but without a coupling device.

PEVs with two or more EMs are also possible; this flexible architecture type enables vehicles to operate in rear-wheel-drive (RWD), front-wheel-drive (FWD), and all-wheel-drive (AWD modes depending on the EMs' states as shown in Figure 2.1 (b) and (c).

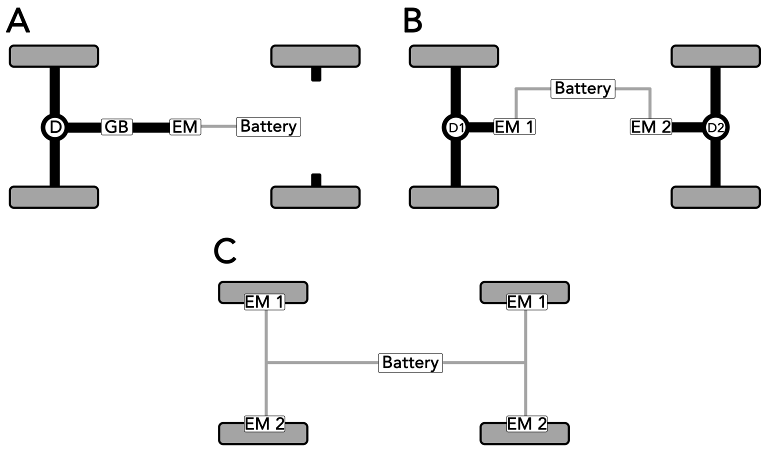


Figure 2.1: Some of the most common architectures for PEVs. Note: Adapted from the 2015 study, *Powertrain architectures of electrified vehicles: Review, classification, and comparison* [4].

2.1.2 Architecture of a HEV

There are many different hybrid electric vehicle architectures, the traditional classification method divides these architectures into series, parallel, and power-split architectures. However, hybrid vehicles refer to ICE, EM(s), coupling device(s), transmission, as well as their locations.

Series Architectures

A series hybrid, which is frequently used in locomotives, typically consists of a gasoline or diesel engine, an electric motor and generator, an energy storage system, and other components. Series HEVs have a variety of layouts, but one of the most popular is depicted in Figure 2.2

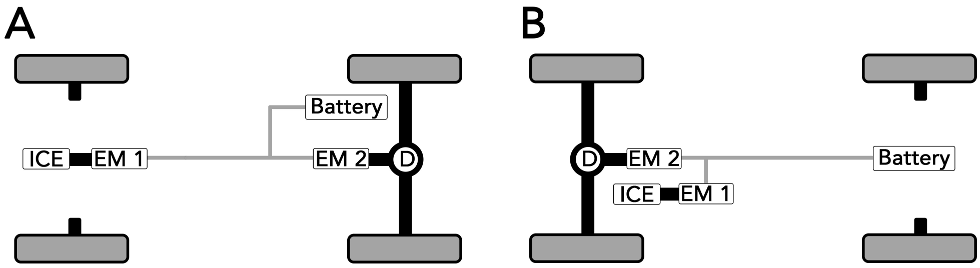


Figure 2.2: Some of the most common architectures for series HEVs. Note: Adapted from the 2015 study, *Powertrain architectures of electrified vehicles: Review, classification, and comparison* [4].

Parallel Architectures

Parallel hybrid architecture mainly comprises ICE, EM, transmission, coupling devices, battery packages, and vehicle central controller (VCC). A parallel hybrid powertrain means that the engine and electric motor are connected with a fixed speed ratio to provide driving torque to the wheel, separately or together. The EM can work as an engine booster or generator to optimize the efficiency of the ICE, according to battery state and working load.

The position of the EM relative to the other components is a crucial factor in Parallel xEV architectures, as an example we can observe in Figure 2.3(a) how besides sharing some similarity with Figure 2.3(b), architectures like the one used in (a) are only feasible for operation in hybrid as a regular HEV, while some other architectures like (b), (c) and (d) that allow operation as a PEV by disengaging the clutch and easily go back to the hybrid mode by engaging it again, in addition, we can see how architectures like (c) and (d) have a system with two independent transmissions, in the case of (d), allowing to functioning as an RWD or AWD.

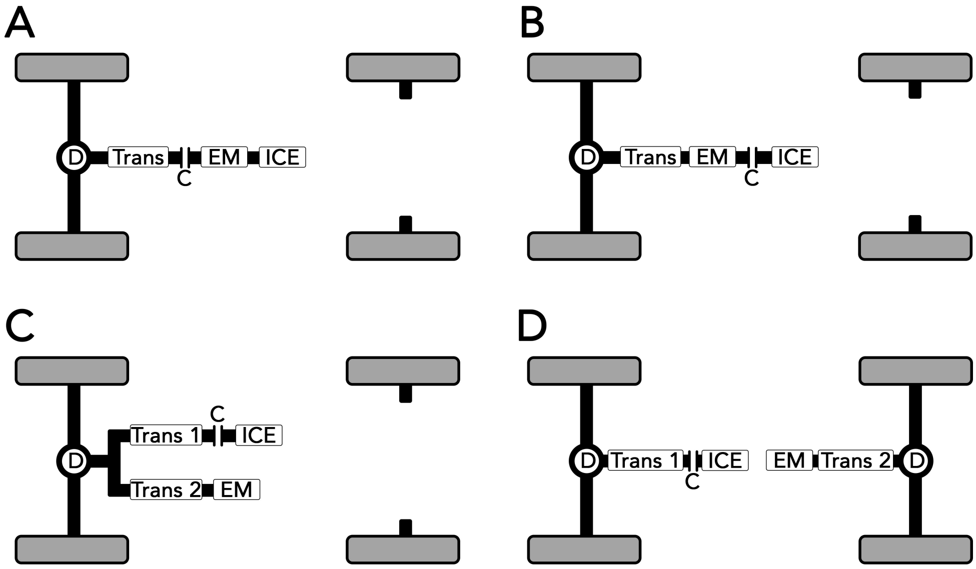


Figure 2.3: Some of the most common architectures for parallel HEVs. Note: Adapted from the 2015 study, *Powertrain architectures of electrified vehicles: Review, classification, and comparison* [4].

Power-split Architectures

The engine torque is split into two parts by a power-split device (PSD), which delivers the power to the output shaft via efficient mechanical and less efficient electric paths. A power-split hybrid powertrain is formed by a PSD, an ICE, two EMs, an ESS, and a VCC.

Since ICE can always operate efficiently, power-split xEVs can reach remarkable fuel economy improvement and currently dominate the hybrid vehicle sector. Three fundamental power-split xEV architectures are input-split, output-split, and compound-split architectures. A more complicated power split can be generated from the three fundamentals.

Figure2.4(a) illustrates an input-split architecture that requires ICE, EM1, and EM2 to be connected to three ports of PSD, and the output shaft is connected with one of EM1 and EM2. At the same time, Figure2.4(b) illustrates an output-split architecture that also requires ICE, one EM, and an output shaft to be connected to three ports of PGS, and the second EM is fixedly linked to ICE. Compound-split architecture is more complicated because it contains two. For any basic power-split architecture type, several variants can be produced by shifting the locations of ICE and EMs and replacing PSD. The remaining four ports (two single ports and two compound ports) are connected to ICE, EM1 and 2, and the output shaft, respectively, as shown in Figure2.4(c)

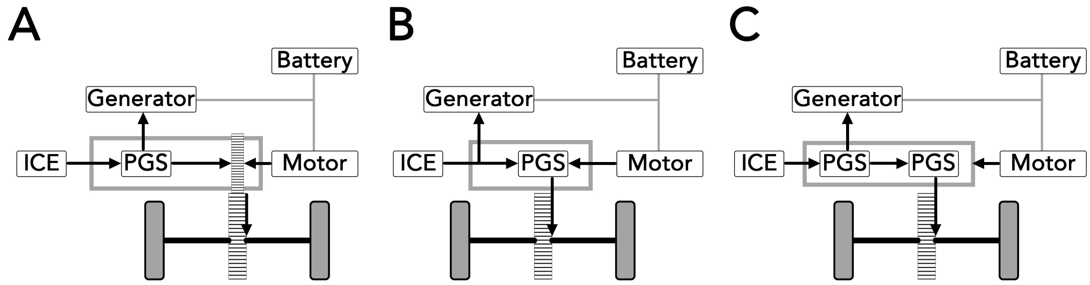


Figure 2.4: Some of the most common power-split architectures. Note: Adapted from the 2015 study, *Powertrain architectures of electrified vehicles: Review, classification, and comparison* [4].

Knowing the basis regarding the integration of electrification in powertrain architectures, and how each of their levels varies in complexity and functioning, helps us to better understand how all of them share the same basic principles despite their differences. The reason this analysis is of great importance for our project, which started as a study of the different powertrain architectures with the scope of finding how to improve their functioning in a real environment, bringing solutions to our clients.
Through this powertrain analysis, we found out that even if we focus on one particular type of architecture, some systems can fulfill their tasks regardless of the type of architecture in use by simply adjusting to some minor changes. An example of this is the lubrication/cooling system under review, which, depending on the architecture in use, might need to be responsible for a bigger or smaller number of components and might also need a bigger or smaller performance to fulfill its task. However, the basis of its functioning is still the same, as will be explained further in the project.

2.2 Lubrication System

An important aspect for understanding the scope of this project is how the lubrication system in a vehicle works in its basic form, it starts with the way that is used in conventional ICE vehicles, where this system is crucial for ensuring the smooth operation and longevity of the engine and its various components. It serves two primary functions: reducing friction between moving parts and dissipating heat generated by friction. Figure2.5 provides an overview of the basic architecture:

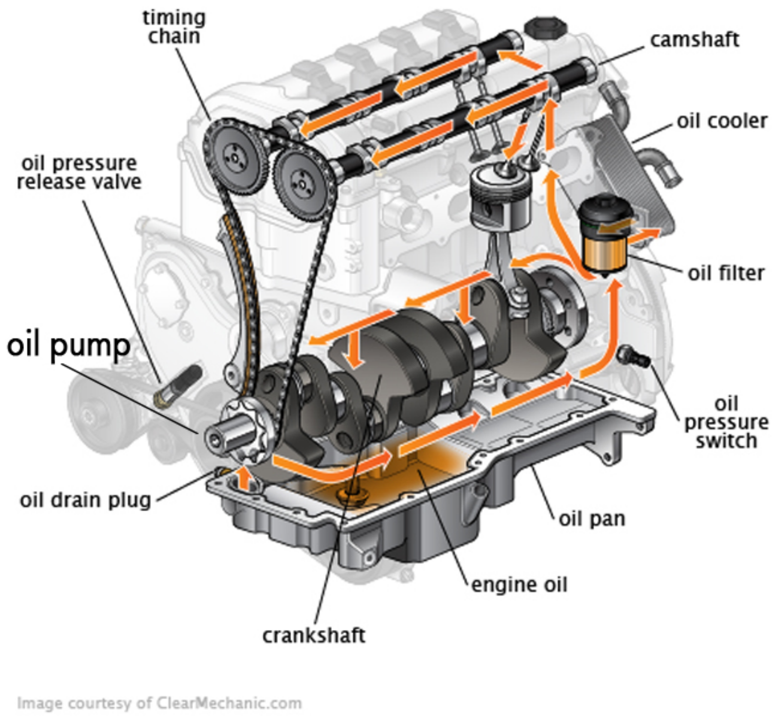


Figure 2.5: Scheme of the basic ICE lubrication system. Note: Adapted from the 2017 paper, *Oil Pumps – Heartbeat of the Engine (Part 1)* by FAI Auto [5].

Engine Oil Pan (Reservoir)

The lubrication system begins with an oil reservoir, typically known as the oil pan or sump, located at the bottom of the engine. This reservoir holds the engine oil until it is needed for lubrication.

Oil Pump

The oil pump is responsible for drawing oil from the reservoir and pressurizing it. This pressurized oil is then sent to various engine components that require lubrication. In conventional vehicles powered by an ICE, the oil pump is directly connected to the engine crankshaft, which is responsible for providing the mechanical work to make the pump rotate and initiate the circulation and pressurization of the oil.

Oil Filter

Before the oil is distributed to the engine, it passes through an oil filter. The oil filter's primary function is to remove impurities and contaminants from the oil, ensuring that only clean oil is supplied to the engine.

Oil Passages

The engine has a network of oil passages or galleries that deliver oil to critical components such as bearings, camshafts, crankshafts, and other moving parts. These passages ensure that oil reaches all the necessary areas to provide lubrication.

ICE internal components

Some of the critical components found in an ICE are the following:

- **Bearings**: Their function is to reduce friction and wear. They include the main bearings, rod bearings, and camshaft bearings.

- **Crankshaft and Camshaft**: The crankshaft, which converts linear motion into rotational motion, and the camshaft, which controls valve timing, are heavily reliant on lubrication to operate smoothly.

- **Piston Rings and Cylinder Walls**: Lubrication helps maintain a thin film of oil between the piston rings and cylinder walls, reducing friction and preventing excessive wear.

- **Valve-train Components**: The valve-train, including valves, lifters, and rocker arms, also relies on oil for lubrication. Proper lubrication ensures that these components move freely and do not wear out prematurely.

Cooling Function

In addition to lubrication, engine oil plays an important role in cooling the engine. As it circulates, it absorbs heat from various components and carries it away to the oil pan, where it can be dissipated.

Oil Cooler (optional)

Some vehicles may include an oil cooler, especially in high-performance or heavy-duty applications. The oil cooler helps to maintain optimal oil temperature by dissipating excess heat.

Return to Reservoir

After lubricating and cooling various engine components, the oil returns to the oil pan or sump to start the cycle again.
Regarding an xEV, by including some changes in the powertrain architecture, as mentioned before, we also find changes in the functioning of the lubrication system and the elements of which is composed, the addition or subtraction of components in the powertrain affects the number of components in the need for lubrication, cooling or both, as well as the way the system works. An example of these changes is the PEV, which is the main architecture analyzed in this project, the main components in need for lubrication and cooling present in this particular powertrain architecture are the transmission and the motor. Despite being an electric vehicle and not having such critical needs of lubrication as an ICE vehicle, there is still the need for an efficient scheme of heat dissipation and friction reduction in particular components. Since a PEV does not count with an ICE, the conventional mechanical connection between the engine and the pump is no longer feasible, hence the need to use a purely electrically powered pump (ePump). This pump is connected directly to the vehicle ECU, which is responsible for supplying the energy and also controls the pump's functioning characteristics, such as rotational speed, flow rate, and pressure.

Analyzing some other cases like the architecture of a HEV, the situation may become more complex, given the need to integrate the full scheme for lubrication of an ICE to the particular needs of cooling that might be found in the electric part of the vehicle. In HEV is possible to use traditional oil pumps functioning through the connection to the ICE for its lubrication. An independent water pump is used for the cooling of the engine such as in any conventional vehicle, although, HEV mostly uses an electrical water pump to avoid adding one more component that depends on the mechanical work of the ICE. Another advantage of the use of this ePump is the capability of independent control through the ECU, allowing it the possibility of an independent operation from the ICE, being able to continue cooling some components even if the engine is not running since this ePump relies only on electrical power and works under the command of the ECU, not the ICE. Additionally, HEV and PEV contain a separate cooling system for the battery pack.
Unfortunately, despite knowing the particular advantages present in the ePumps, their use has been limited in large part to water ePumps, mainly because of doubts on their reliability in systems as critics as the lubrication. This project will focus on the use of oil ePumps used in PEV for the lubrication and cooling of the eMotor and the eAxle, the use of these oil ePumps opens the possibility for its use in other HEV and ICE vehicles, approaching problems like the degradation presented

during the integration of new technologies like the start-stop systems.

2.3 Start-Stop System in Vehicles

The start-stop system, also known as idle-stop or micro-hybrid system, is an automotive technology designed to improve fuel efficiency and reduce emissions by automatically shutting off the engine when the vehicle comes to a complete stop. When the driver releases the brake pedal or engages the clutch (in manual transmissions), the engine quickly restarts to power the vehicle. This system relies on sensors to detect various parameters, including vehicle speed, brake pedal position, and battery state of charge, to determine when it is appropriate to stop and restart the engine.

2.3.1 Effects on Lubrication System

Oil Circulation

The start-stop system can affect the engine's lubrication system. When the engine is turned off, oil circulation is interrupted. This can lead to a momentary lack of lubrication in critical engine components, particularly during frequent stop-and-start cycles. The lubrication system needs to maintain oil pressure and ensure adequate lubrication during these engine restarts.

Wear and Tear

Frequent engine restarts can increase wear and tear on engine components, such as the starter motor and the crankshaft. These components must withstand the increased demands of frequent start cycles, potentially leading to earlier maintenance requirements and component replacements.

2.3.2 Effects on Cooling System

Temperature Fluctuations:

The start-stop system can result in temperature fluctuations in the engine's cooling system. When the engine stops, the cooling fans and water pump cease operation. This can lead to a temporary rise in engine temperature, especially in hot weather or in stop-and-go traffic. When the engine restarts, the cooling system must quickly bring the temperature back to an optimal range. These temperature fluctuations can put additional stress on engine components and may affect long-term durability.

2.3.3 Degenerative Effects

Among some of the degenerative effects, we can find battery replacement, over time. The vehicle's battery may need replacement sooner compared to vehicles without start-stop systems, adding to ownership costs and the environmental impact. The start-stop system relies on the vehicle's battery to power various systems when the engine is off and to restart the engine. This increased demand for the battery can affect its lifespan and performance. Many start-stop systems use advanced absorbent glass mat (AGM) batteries that are designed to withstand frequent deep cycling, even though they still degrade over time.

Although the start-stop system is intended to lower emissions and fuel consumption when driving in urban areas, it might not have a major positive impact when traveling on highways or in areas with less traffic. Moreover, one of its side effects is the increased stress that the aforementioned causes have put the engine through. While some studies concentrate on strengthening or improving the engine's physical components to withstand the extra stress, as an example we have and study made on improving the bearings by Santos et al. (2020)[6]. The ePump emerges as a way to lessen the negative effects on the engine by enabling the lubrication system to continue operating even when the ICE has stopped, allowing the oil to continue flowing, lubricating and dissipating heat for as long as is necessary.

2.4 Approach to thermal management

The proposed concept of using ePumps, shares similar basis and control methodologies with the ones found in the PEVs, however, having a powertrain that has been enhanced by electric motors and e-drive configuration, means that these electrification elements now count with electric motors or regenerative brake components integrated into this new lubrication and thermal management system for cooling applications.

There are several approaches available to satisfy the requirements of a decreasing heat rate in the different components. Regarding the eMotor, since lamination from iron losses is less common than heat generation in windings found in slots and rotors, thermal management technologies are mainly directed toward these windings, however, in some high-performance applications some special attention may need to be also addressed to other components like the transmission. In addition, automotive lubricants for electrified propulsion systems must function as an effective coolant, and reduce corrosion of copper windings among other properties. Since this type of architecture is composed of a significantly lower number of moving parts, the lubrication task is not as critical as the thermal dissipation, in contrast to the ICE, but still of great importance as in all vehicles.

It is anticipated that various technologies will be employed to tackle varying heat exchange levels. These technologies include forced air cooling, natural air cooling, indirect and direct liquid cooling, and hybrid approaches that integrate thermal conduction enhancement technologies like heat pipes, thermal paste, and phase change materials (according to Dan et al.[7]). An overview of the technologies researched for heat management is shown in Figure 2.6 below:

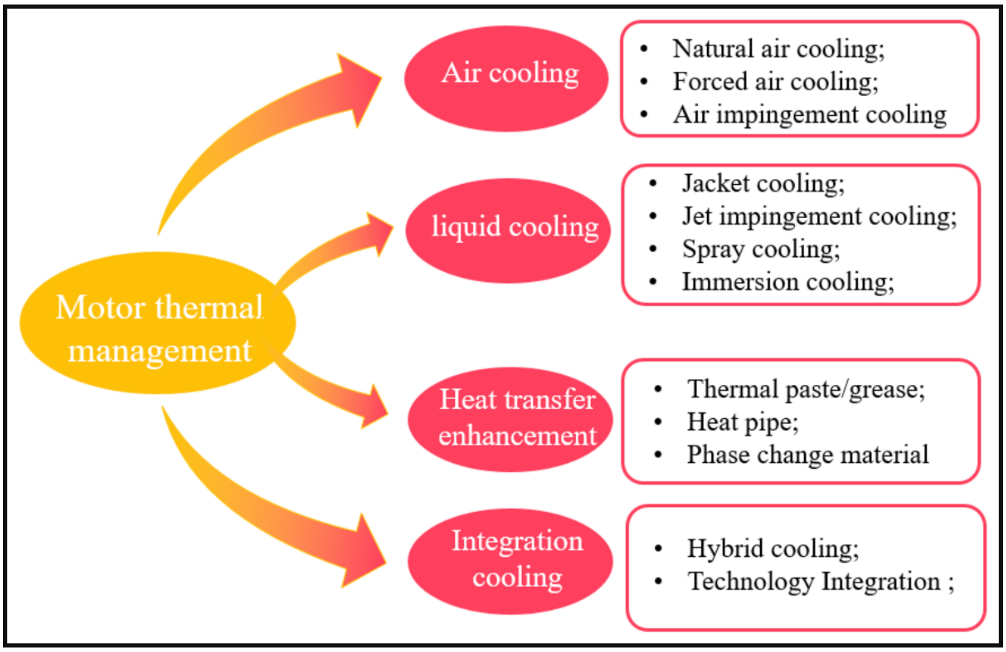


Figure 2.6: Overall thermal management technologies. Note: Adapted from 2023 paper, *Review of thermal management technology for electric vehicles.* by Dan et al. [7].

The particular technology chosen for this project is oil spray cooling, which is the one used by our client for this particular application, so this guarantees having a study based in a real environment.

2.4.1 Spray Cooling

Oil spray cooling systems are a crucial component in the thermal management of electric vehicles (EVs), ensuring that the temperature of key components, particularly the electric motor and power electronics, remain within optimal operating ranges. The use of oil as a cooling medium means that the system can efficiently absorb and transfer the heat generated by the electric motor, power electronics, and other components to the external environment.

In the basic functioning of an oil-sprayed cooling system, an electric pump circulates oil from the reservoir through a network of channels or passages to the areas that require cooling. This flow ensures that the oil continuously absorbs and transports the heat generated by the components to be dissipated externally. The pump generates the necessary pressure to keep the oil flowing smoothly through the system.

In a study made by Lim et al.[8], with the use of an experimental circuit, a description of their system is provided to contribute to a better understanding of this cooling technology. In their particular design, the heat absorbed by the cooling oil is released through the outer surfaces of the motor module, such as the housing, jigs, and oil tank, using the traveling wind of the vehicle and the radiator. The cooling oil is then sprayed to cool the motor, and this oil then absorbs internal heat before flowing back to the oil tank, passing through the housing and jigs to start the cycle again. This process is illustrated in Figure 2.7 below.

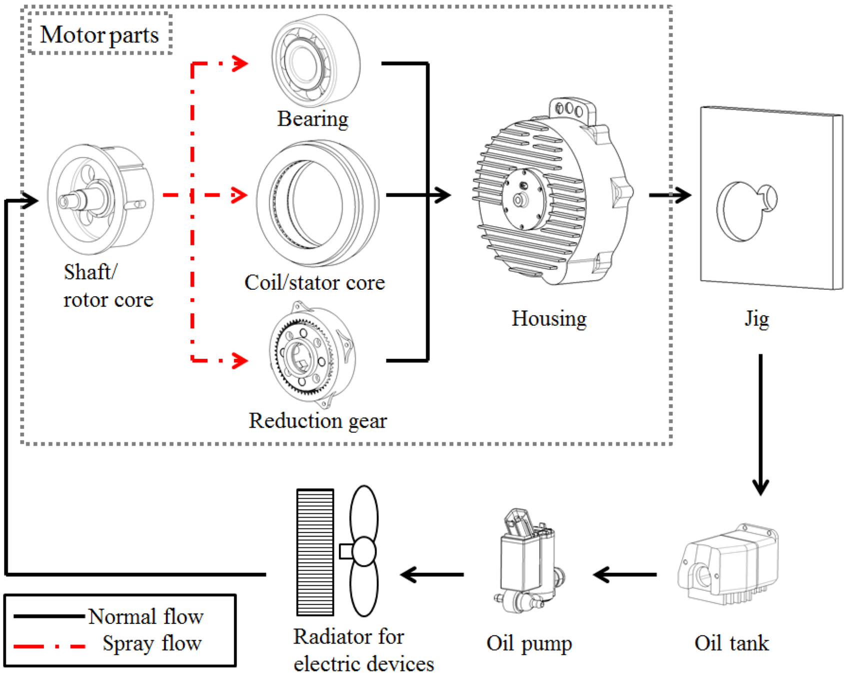


Figure 2.7: Flow circuit of the spray cooling system. Note: Adapted from the 2014 paper, *Performance Evaluation of an In-Wheel Motor Cooling System in an Electric Vehicle/Hybrid Electric Vehicle* by Lim et al. [8]

Adequate functioning of the oil spray cooling system can only be achieved through its precise control. The ePump is linked to a sophisticated control system that continuously monitors the temperature of various components. The control system adjusts the flow rate of the oil based on the data collected by modulating the speed of the electric pump. Under varying loads and environmental conditions, this adaptive control mechanism ensures that the temperature remains within the optimal operating range. This is one of the main factors in the design of this system, which is critical to its efficiency and dependability. The system should be able to keep the components at the desired temperature even under high-stress conditions like rapid acceleration or prolonged operation.

2.5 Gerotor pumps

The ePump is the heart of the oil spray cooling system since carries the responsibility for making the oil flow through the components and allowing the tasks of lubrication and cooling to be performed. Even though an ePump is electrically powered and electronically controlled, the working principles behind its functioning are similar to the conventional oil pumps found in ICE, since both of them are gerotor pumps.

Gerotor pumps are a particular type of positive displacement pump composed of internal gears. These pumps are one of the most commonly used fixed displacements due to their high operational speed, high tolerance to cavitation and fluid contamination, compactness, low cost, low number of moving parts, and some other of their many advantages, which is why they are commonly used high-pressure hydraulic systems, but, this pump also has some disadvantages, as a great dependence on its geometry, making it particularly complicated to model. This same restriction also might imply pressure limitations and fixed clearances.

As shown in Figure 2.8 by Pellegri et al.[9], the Gerotor architecture typically consists of two rotors and a body. The two rotors revolve around their axes (which are separated by eccentricity, e). This rotation causes a continuous variation in displacement chamber (DC) volume, with the number of outer rotor teeth dictating the periodicity. The suction and delivery ports provide the necessary flow to ensure the unit's displacing action.

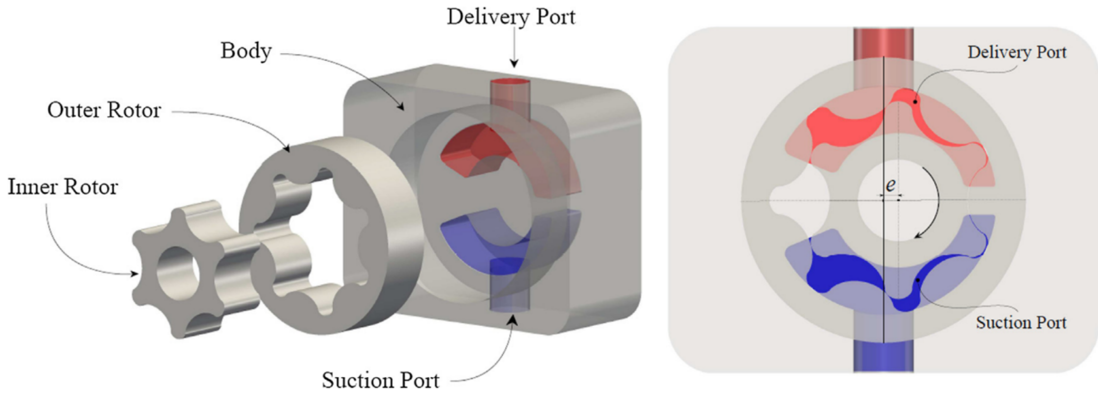


Figure 2.8: Construction of a typical Gerotor unit. Note: Adapted from 2020 paper, *A simulation model of Gerotor pumps considering fluid-structure interaction effects: Formulation and validation.* by Pellegri et al. [9].

2.6 Architecture Description

During the development of this project, we will focus the study on two particular powertrain architectures among the ones previously discussed, each one with particular schemes for the oil spray cooling system. The decision as to why to focus on these two specific scenarios is based on the particular needs of one of the clients of the company, where during the development of two separate projects, the opportunity for this study arises, bringing a chance to deliver answers regarding the similarities that can be found between different architectures, and how this opens the possibility for future research and development in the area. Due to the protection of data privacy and confidential information regarding a project in development, the name of the client among some other sensitive information can not be disclosed.

The two projects might seem quite different at first sight, but during the development of this study, similarities will start to appear. Due to the sensitivity of the exposure of some company-classified information, the first of the architectures will be referred to as a "Passenger Vehicle", which consists of an AWD powertrain, and its corresponding spray cooling system. While the second architecture corresponds to a "Heavy Duty Truck" (HD Truck), whose powertrain drives only two wheels, this is not the only difference, considering that some of the proposed spray cooling systems might also differ.

2.7 Passenger Vehicle

2.7.1 Powertrain Architecture

The powertrain used by the client for this application consists of an AWD PEV, using three electric motors to drive the four wheels, with the placement of one electric motor with a gearbox and a differential driving the front wheels, and two decoupled electric motors driving independently each on of the rear wheels, this means that there is no transmission interconnecting the wheels, allowing it work as an electronic torque vectoring differential. If needed, the full power of the vehicle can be redirected to only the rear wheels, passing from an AWD to a RWD mode.

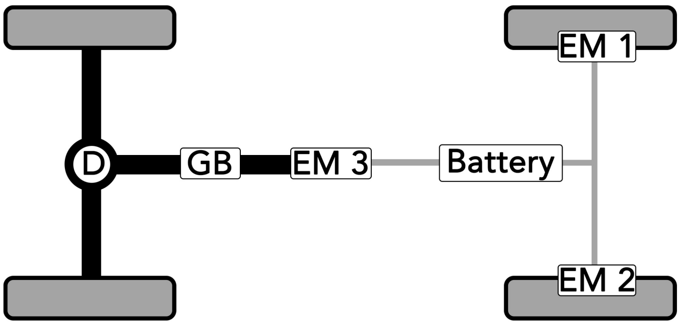


Figure 2.9: Powertrain architecture used in the Passenger Vehicle. Note: Adapted from the 2015 study, *Powertrain architectures of electrified vehicles: Review, classification, and comparison* [4].

2.7.2 Spray Cooling

The ePump is the core component of the Electric Axle's oil circuit. The Electric axle is made up of an electric motor, an inverter, a gearbox, and supplementary components. This Electric Axle in the Passenger Vehicle application includes one pump in the oil circuit of the Front Axle and two pumps in the oil circuit of the Rear Axle, as shown in Figure 2.10 below, which also illustrates its placement in the vehicle.

The ePump is installed outside the transmission, downstream of the oil sump, and is attached to the transmission housing. The oil circuit also includes a WTOC (water transmission oil cooler) to keep the transmission oil cool. A thermostatic valve that starts working in a temperature range from 80°C to 95°C can bypass the WTOC (the valve fully opened leads to complete oil flow in the WTOC). The

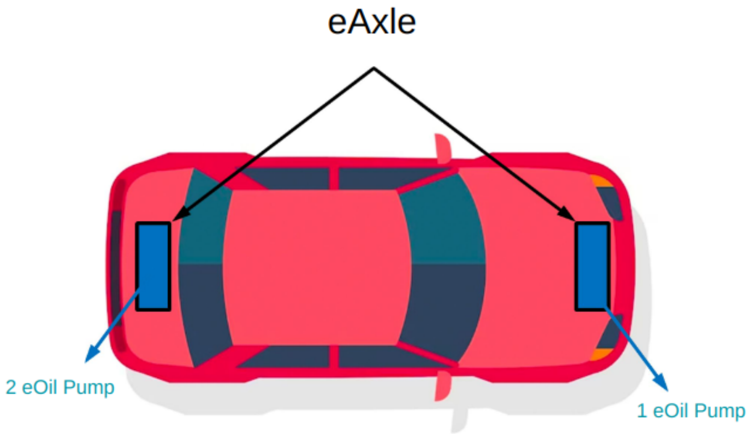


Figure 2.10: Location of the eAxle and ePumps Based on The Client Indications.

System, as shown in Figure 2.11, mounts a temperature sensor, however, there is no pressure sensor upstream and downstream of the ePump.

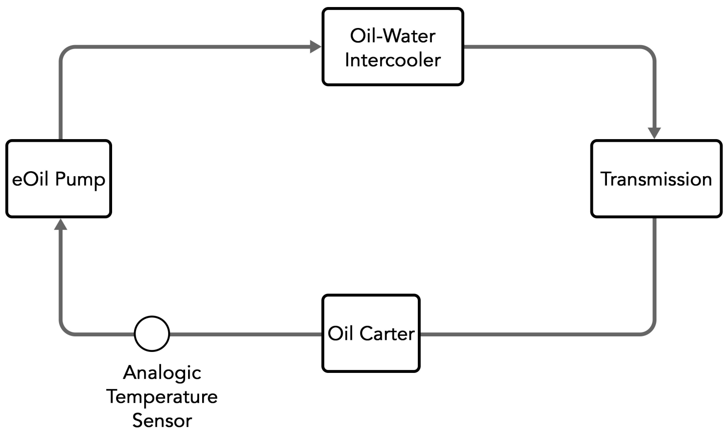


Figure 2.11: Representation of the Hydraulic Circuit Layout as Proposed by The Client.

Figure 2.12 depicts a component view of the front eAxle, highlighting in red the parts composing the hydraulic system.

Figure 2.12: Front eAxle component view. Note: Taken from Congress, G. C. (2018), *FPT Industrial Launches e-Powertrain organization; showcases E ...* GeenCarCongress. [10].

2.7.3 Operational Conditions

Oil Pump Performance

According to the technical request sent by the client to the suppliers, to fulfill the performance requirements of the system, it is needed a pump capable of working with the following characteristics.

Parameter	**Value**
Maximum oil flow	12 L/min @ Δ0.5 bar @ T = 110°C*
Minimum oil flow	10 L/min @ Δ2.5 bar @ T = 110°C*
Oil amount in the oil pan	1 L

Table 2.2: Passenger Vehicle Oil Pump Performance According to Requirements from the Client.

Environmental Parameters

In the same way, to obtain a system capable of achieving the expected performance during its functioning, it is necessary to also take into consideration the environmental conditions that the vehicle might face.

The climatic condition of transmission in the application field is referred to as the ambient operating temperature. The conditions that characterize the air

Parameter	**Value**
Min Ambient operating temp. [°C]	-40°C
Max Ambient operating temp. [°C]	+55°C
Minimum local environment temp. [°C] (at minimum ambient temperature)	-20°C
Maximum local environment Continuous Temp. [°C] (at maximum ambient temp.)	+120°C
Peak local environment temp. [°C]	+130°C
Minimum/Maximum operating altitude	-150m / 5400m
Non-operating/Storage temperature range [°C]	-40° / +60°C
Ozone (*) → Yes/No or state reference for details	YES 0 to 0.40 ppm
Dust (*) → Yes/No or state reference for details	YES
Relative Humidity (*) [%]	YES
Corrosion (*) → Yes/No or state reference for details	YES
Saline concentration in the air → Yes/No or state reference for details	YES
Pollution (SO2, NOx, CO, ...) → Yes/No or state reference for details	YES
High-pressure water washer → Yes/No or state washing condition	YES
Oil type	Gear Oil Low viscosity
Fluid base	GIII/PAO
Fluid density	0.85 kg/dm^3
Kinematic viscosity @40°C	22.8 mm^2/s
Kinematic viscosity @110°C	5.1 mm^2/s
Purity Class acc. ISO4406 (Initial)	21/19/16

Table 2.3: Environmental Passenger Vehicle Parameters According to Requirements from the Client. (*) These characteristics can be important during packing, delivery, and normal exercise.

(or any other medium) surrounding the component or system under specification in a steady state are referred to as the local environment temperature. Peak local environment temperature refers to the temperature/duration under extreme transmission working conditions that may have an impact on the component or system operating lifetime.

Parameter	Value
Continuous 100°C	100°C
Peak	120°C
Minimum	+10°C
Oil change interval	For life

Table 2.4: Passenger Vehicle Parameters: Oil Temperature According to Requirements from the Client.

2.8 HD Truck

2.8.1 Powertrain

For this application the powertrain architecture in use is not so complicated as the one used in the passenger vehicle, since in this case, we rely on only one electric motor responsible for the rear wheel drive, this EM is coupled to a gearbox and then to a pneumatically operated differential lock.

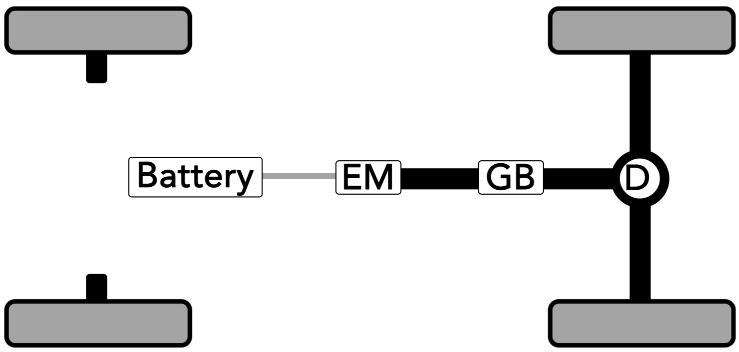


Figure 2.13: Powertrain architecture used in the HD Truck. Note: Adapted from the 2015 study, *Powertrain architectures of electrified vehicles: Review, classification, and comparison* [4].

2.8.2 Spray Cooling

This is the part where things get more complicated for the HD Truck since the spray cooling scheme has not been chosen by the client yet. However, some proposals of different circuits will be analyzed to understand their characteristics.

Layout No.1

One of the first circuits layouts considered, consisted of the use of two separate ePumps, each one responsible for independent hydraulic circuits, one in charge of the Axle, and the other of the eMotor, although, sharing the cooling system for their respective WTOCs, as can be observed in the Figure **??**, which provides a schematic view of the system. In the branch of the Hydraulic circuit responsible for the eMotor, there is also a valve in charge of limiting the max flow that goes to this component, this happens by making a bypass from the outlet of the WTOC, directly to the oil sump, this valve is represented with the yellow box.

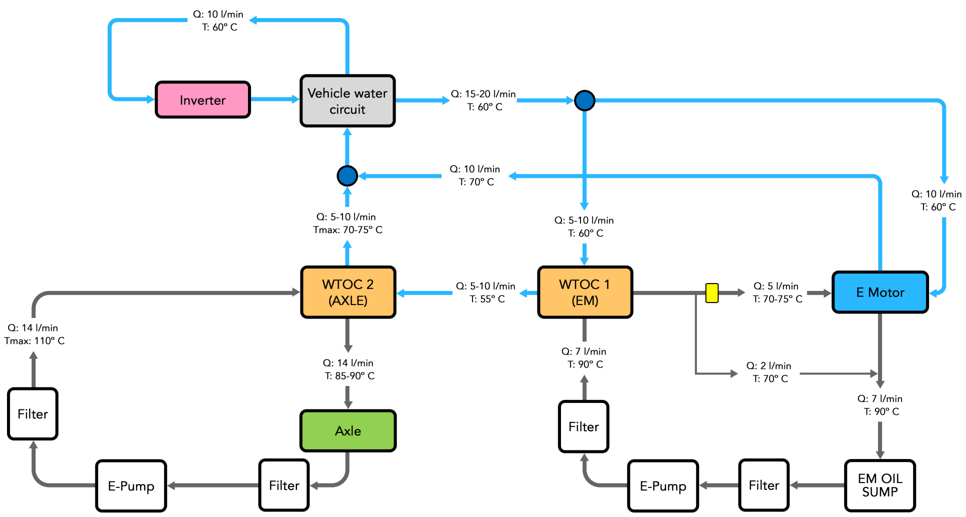


Figure 2.14: Hydraulic Circuit Layout No.1. as Proposed for The Client.

Layout No.2

The second layout, which is the one that will be taken into consideration as the project goes further, integrates both hydraulic circuits into one and uses only one pump responsible for the oil flow in the whole system, this layout also combines the two separate WTOCs of the previous layout into only one. To keep the capability of being able to control independently the flow passing through each component, whether is the Axle or the eMotor, a flow valve has been added, which by restricting the flow over one branch, allows splitting the flow as needed to match the requirements. Figure 2.15 helps us have a better understanding of the layout.

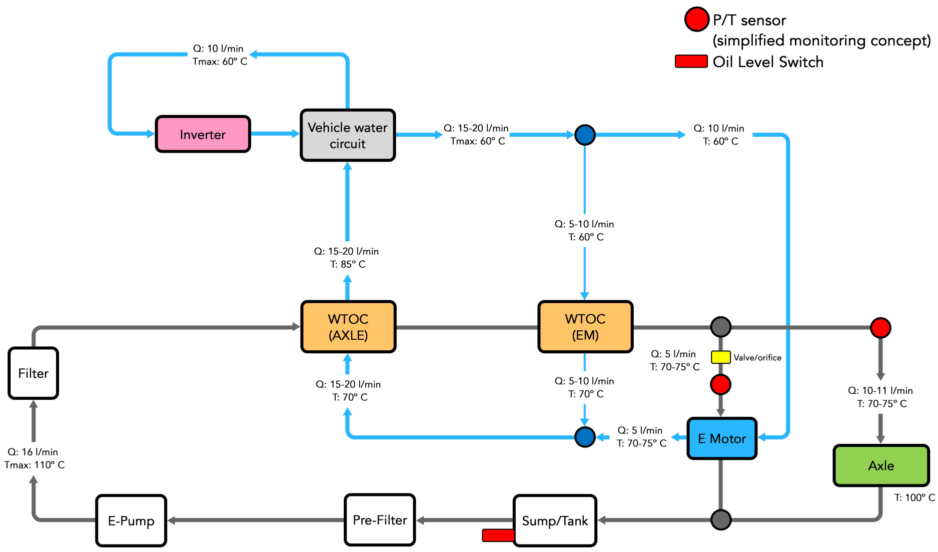


Figure 2.15: Hydraulic Circuit Layout No.2 as Proposed for The Client.

It is worth clarifying, that combining both hydraulics circuits from Layout No. 1, also means reducing the complexity of the system, the requirements of performance regarding the components to be used also increase, since we are passing to using two pumps and two WTOCs, to the use of only one of each.

2.8.3 Operational Conditions

Oil Pump Performance

Due to the two different layouts representing different performance needs in the system, each one has diverse requirements.

Regarding the first layout, two different pumps are needed to fulfill the needs of each particular hydraulic circuit branch.

Parameter	Value
Oil flow @ max nominal delivery pressure	≈ 3 l/min @ 3 barG (T_ref = 10°C)
Oil flow @ reference continuous operating pressure	> 14 l/min @ 0.7 barG (T_ref = 110°C)
Operating pressure range	0. . . 3 barG (nominal range) Min inlet pressure -0.3 barG

Table 2.5: Performance in the Axle hydraulic circuit branch in layout No. 1 According to Requirements from the Client.

Parameter	Value
Oil flow @ max nominal delivery pressure	3 l/min @ 3 barG (T_ref = 10°C)
Oil flow @ reference continuous operating pressure	> 8 l/min @ 0.7 barG (T_ref = 110°C)
Operating pressure range Min inlet pressure -0.3 barG	0...3 barG (nominal range)

Table 2.6: Performance in the eMotor hydraulic circuit branch in layout No. 1 According to Requirements from the Client.

As for the second layout, there is only one pump needed, but the performance bar has been raised for this hydraulic circuit.

Environmental Parameters

Similar to the Passenger Vehicle case, external environmental conditions also play an important role in the system

The same considerations are held about ambient operating temperature, local environment temperature, and peak local temperature as with the Passenger Vehicle.

Parameter	Value
Oil flow @ max nominal delivery pressure	≈ 10 l/min @ 2.5 barG (T_ref = 10°C)
Oil flow @ reference continuous operating pressure	>20 l/min @ 0.7 barG (T_ref = 110°C)
Operating pressure range	0...3 barG (nominal range) Min inlet pressure -0.3 barG

Table 2.7: Performance for layout No.2 According to Requirements from the Client.

Parameter	Value
Continuous 100°C	100°C
Peak	120°C
Minimum	-40°C
Oil change interval	450.000 km

Table 2.8: HD Truck Parameters: Oil Temperature According to Requirements from the Client.

2.9 Oil Selection

In the same way that the pump can be referred to as the heart of this system, the oil flowing inside the circuit can be alluded to as the blood, having a significant role to play in correct functioning and making it possible to achieve the desired performance. This fluid is responsible for several tasks, with heat dissipation being one of the most important tasks, however, by comparing its characteristics to fulfill this job, we can observe that some other fluids like water have better specific heat and thermal conductivity values, as indicated in Figure 2.16, from a study done by Tung et al[11]. This figure depicts the existing difference between the water and some other fluids.

However, unlike water, the use of this oil helps to fulfill a lubrication need in the components, protecting them from corrosion and wear, while still providing a decent heat dissipation capability.

Despite having presented three different layouts for the spray cooling system and several different pump performance requirements, the needs regarding the behavior of the oil remain quite similar, meaning that the oil needed must have the following characteristics:

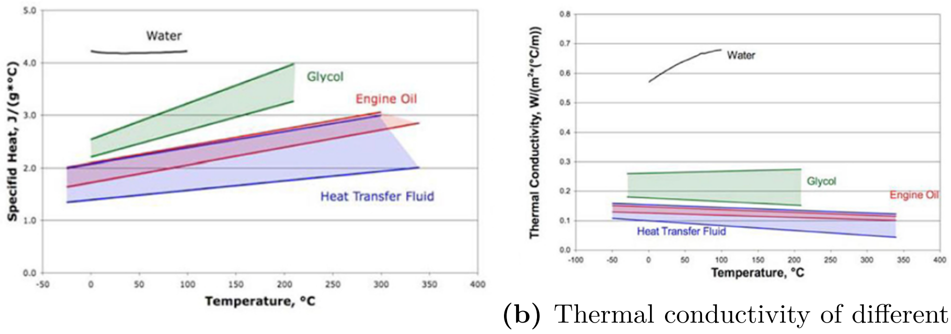
Being this a project analyzed from a real point of view means that we need to find an oil capable of fitting these characteristics between the commercial possibilities

Parameter	Value
Min Ambient operating temp. [°C]	-40°C
Max Ambient operating temp. [°C]	+55°C
Minimum local environment temp. [°C] (at minimum ambient temperature)	-40°C
Maximum local environment Continuous Temp. [°C] (at maximum ambient temp.)	+110°C
Peak local environment temp. [°C]	+130°C
Minimum/Maximum operating altitude	-150m / 5400m
Non-operating/Storage temperature range [°C]	-40° / +60°C
Ozone (*) → Yes/No or state reference for details	YES 0 to 0.40 ppm
Dust (*) → Yes/No or state reference for details	YES
Relative Humidity (*) [%]	YES
Corrosion (*) → Yes/No or state reference for details	YES
Saline concentration in the air → Yes/No or state reference for details	YES
Pollution (SO2, NOx, CO, ...) → Yes/No or state reference for details	YES
High-pressure water washer → Yes/No or state washing condition	YES
Oil type	Gear Oil Low viscosity
Fluid base	Transmission oil specs: see kinematic viscosity
Fluid density	0.85 kg/dm^3
Kinematic viscosity @40°C	24.3 mm^2/s
Kinematic viscosity @110°C	5.4 mm^2/s
Purity Class acc.	250 µm - Max admitted size of particles contamination

Table 2.9: HD Truck Environmental Parameters According to Requirements from the Client. (*) These characteristics can be important during packing, delivery, and normal exercise.

and what can be found with suppliers, two possible oils that fit these requirements were proposed, SAE 0W-30, and the SAE 10W-30. which have the following properties:

The most important property is the kinematic viscosity at 110°C, as expressed in Table2.10, which is the continuous operation temperature. The temperature



(a) Typical range of heat capacities.

(b) Thermal conductivity of different base oil types.

Figure 2.16: Note: Adapted from the 2020 paper, *Global Insights on Future Trends of Hybrid/EV Driveline Lubrication and Thermal Management.* by Tung et al. [11].

Parameter	Range
Fluid density	0.85 kg/dm^3
Kinematic viscosity @40°C	20-25 mm^2/s
Kinematic viscosity @110°C	5-6 mm^2/s

Table 2.10: Oil Characteristics Needed.

Parameter	SAE 0W-30	SAE 10W-30
Fluid density	0.8426 kg/dm^3	0.859 kg/dm^3
Kinematic viscosity @40°C	39 mm^2s	63.2 mm^2/s
Kinematic viscosity @100°C	7.4 mm^2/s	10.1 mm^2/s

Table 2.11: Reference Values for Some Commercial Oils Properties.

expressed in Table2.11 for kinematic viscosity is referenced at 100°C since is the commercial standard for technical sheets, although this value doesn't quite fit in the ideal operational range previously mentioned, we are limited by the real commercial availability of products, but despite this difference, the oil will still be able to perform efficiently in the system. This same condition is present while looking at the kinematic viscosity at 40°C, where there is a larger difference between the reference values and the required for the system, but no major affectations are done to the functioning of the system under these conditions.

2.10 Control System Basis

To efficiently perform the task at hand and be able to regulate the behavior of the pump, therefore, the oil flow through the hydraulic circuit, a control strategy is needed, here is where the control systems come into action. A control system is responsible for commanding the functioning of a component or system by the use of control loops and control logic.

The control loop can be either open-loop or closed-loop, affecting the dynamic behavior of the system, this project will be approached under a closed-loop control, which provides the possibility of having feedback from the system to ensure its right functioning in its dynamic behavior. The dynamics of the control system must be properly chosen since a balance is needed in the system response. If too quickly, it might lead to dangerous overshoots that could permanently harm the system, although, if too slow, could mean that while the system tries to reach the desired operational point, the components are being exposed to harmful operational ranges. To find a correct system dynamic behavior, a step response analysis is implemented to ensure the right balance between robustness and speed response.

2.10.1 Step Response

A step response describes the system's behavior when the input signal suddenly changes from zero to a constant value. This abrupt change in input is referred to as a step input. The step response of a control system shows how the system output, in this case, the pump speed, evolves in response to this abrupt change in input.

The transient response and the steady-state response are the two main components of the step response. The transient response is the system's initial behavior, which is characterized by the output rapidly changing toward its final value. This phase is distinguished by characteristics such as overshoot, settling time, and rise time, which reflect how quickly and precisely the system reaches its steady-state value.

The steady-state response, on the other hand, represents the system's behavior after it has stabilized and settled to a constant output value. In an ideal world, the steady-state response would correspond to the desired or expected output value for the step input.

Some of the most commonly evaluated parameters are the following: 1. Settling Time TS, which is the lag time between the application of an ideal instantaneous step input and the time when the system output arrives and stays within a specified error band. Typically, the error band under consideration is 5%. 2. Percentage Overshoot is calculated by dividing the maximum value Mpt minus the step value by the step value. 3. Steady State Error, ess, which is the deviation of the control system's output from the desired response during steady state.

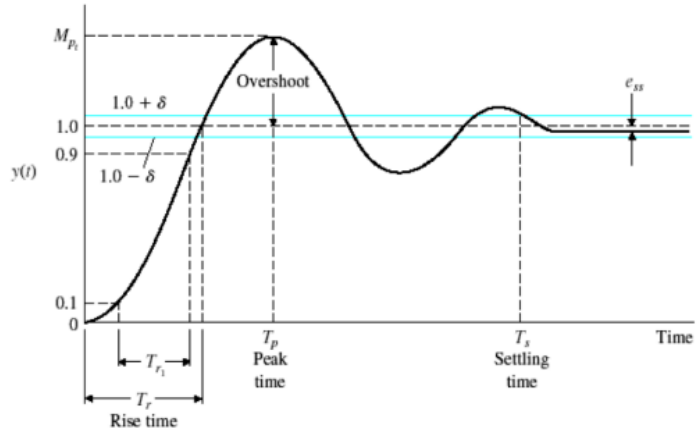


Figure 2.17: Step Response Parameters. Note: Taken from 2013 paper, *Matlab/GUI based basic design principles of PID controller in AVR* by Bayram et al [12].

Figure 2.17 illustrates the typical step response of a control system.

Chapter 3

Preliminary Design

The development of this project has followed an extensive course in the search for how to execute a deep study of a specific component accurately. As previously mentioned, this work started with the study of the powertrain, which then by the identification of commercial needs related to the client's necessities, and possibilities of further research to be carried along based on this project, a specialized focus was given to a particular element, which is the oil ePump.

During the early stages of planning for this project, the construction of a physical test bench was considered the best way to develop this study, using model-based design (MBD) as a methodology to correctly go through diverse stages that this includes, starting from the analysis of requirements and architectures until arriving to the design, construction, and control of physical components for testing under simulated conditions carried out in a laboratory.

3.1 Model-Based Design: Overview

Model-based design is an engineering methodology that involves the creation and use of dynamic models as the primary source for the design and development of complex systems, focusing on the initial creation of a mathematical or simulated model of the system under analysis before proceeding to physical implementation, saving resources and valuable time. This model acts as a virtual representation of the system's real behavior, allowing the exploration and study of different scenarios making it able to predict its performance without the need for physical variation to previously implemented systems.

The model-based design allows for a more systematic and efficient development process by allowing for the early identification of potential issues or challenges. It also enables the integration of various engineering disciplines, allowing for collaborative work and a thorough understanding of the system as a whole, this reason why this methodology has been gaining a lot of popularity in the automotive industries with the use of the commonly known as "V" model, this led to the standardization of the process to correctly implement this methodology in every case.

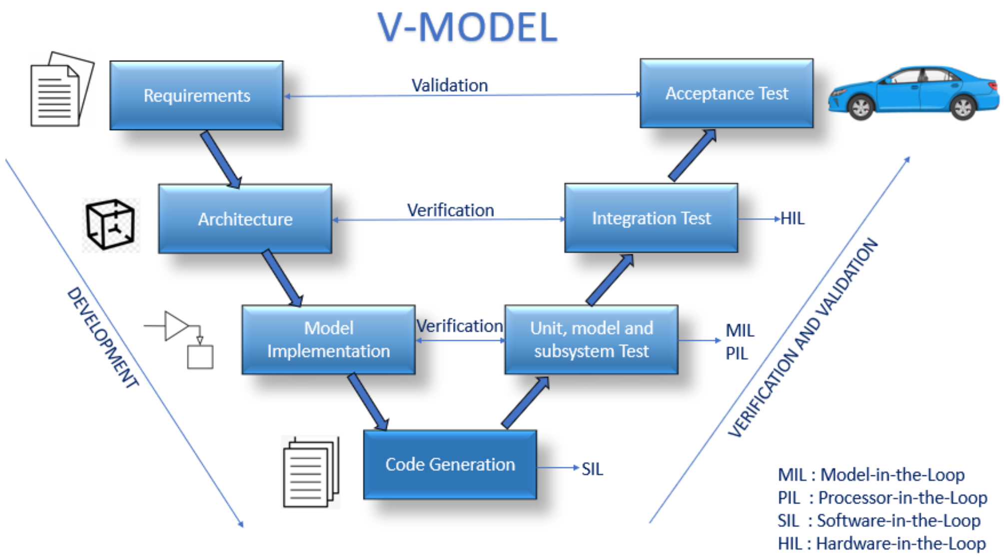


Figure 3.1: General V-Model diagram. Note: Taken from Model-Based Design (MBD) approach, by Jadhav[13].

The process is often guided by industry-specific standards, such as ISO 26262 for automotive, contrasting the IEC 61508 for process industries, or other relevant standards in different sectors. Adherence to these standards helps organizations establish a systematic approach to functional safety, ensuring that safety is an integral part of the design, development, and operation of systems and products.

The standard ISO 26262 offers a framework regarding functional safety for technological applications in mechanics, hydraulics, and some pneumatic cases. A general overview of this framework and how is integrated into the "V" diagram is depicted in Figure 3.2.

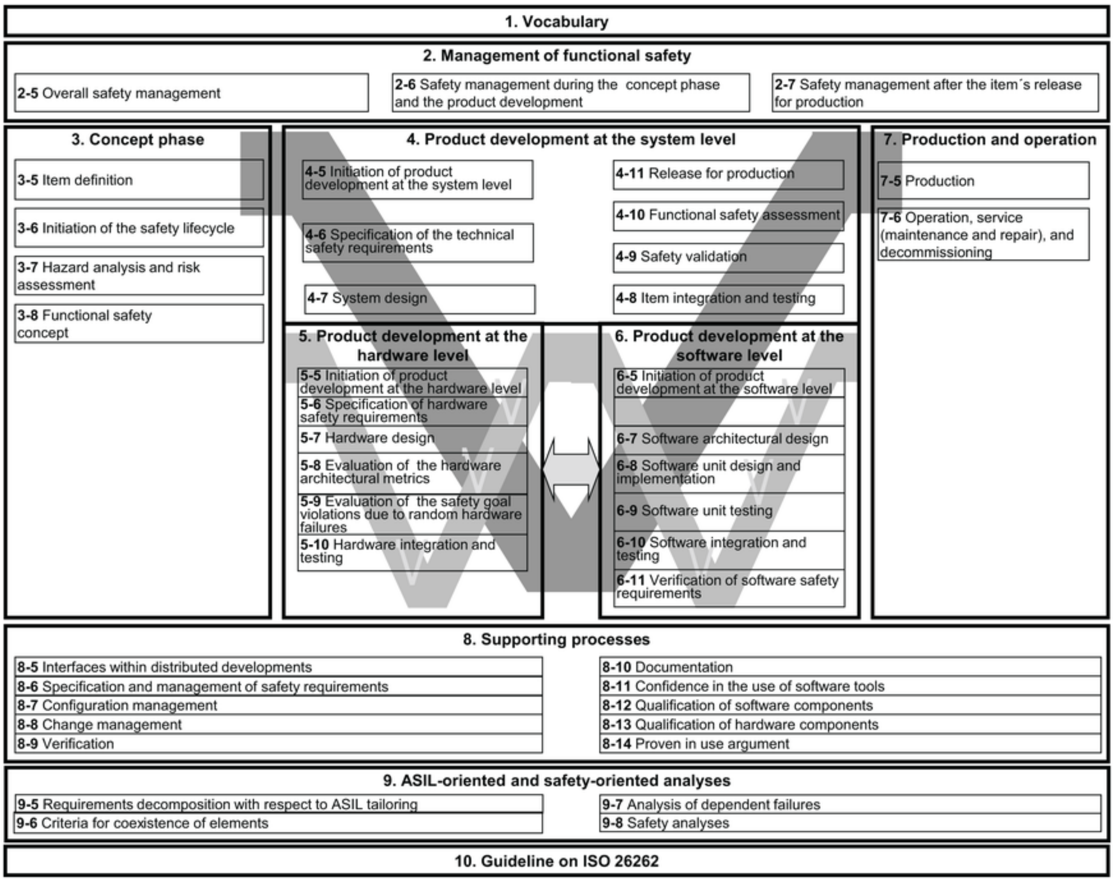


Figure 3.2: ISO 26262 Overview. Note: Taken from *ISO OBP[14].*

3.2 Design and Planning of a Physical Test Bench

To correctly proceed with this physical test bench, the planning was divided into different steps, starting with a standardization of the hydraulic circuit, moving to evaluate the necessary hardware, and finding a way to accurately control it, to then proceed to the construction and testing.

3.2.1 Hydraulic Circuit Standardization

As seen before, there are different ways that the hydraulic circuit can be arranged to perform its work, making it possible to find different circuit layouts even in the same vehicle. The reason as to why a standard hydraulic circuit layout needs to be found since to have general components and functioning allows evaluation of different arrangements, avoiding the design and construction of multiple different physical hydraulic circuits to be used during the testing of individual cases, which is not feasible due to the complexity in making several designs and also including a much larger economical cost.

Passenger Vehicle Hydraulic Circuit

We start this standardization by analyzing the hydraulic circuit layout used in the passenger vehicle, which despite having a more complex powertrain system, counts with a simpler cooling system, composed of three separate oil pumps, each one responsible for their independent flow loop. This circuit is specified in Figure 3.3, providing a closer look at the one shown in Figure 2.12.

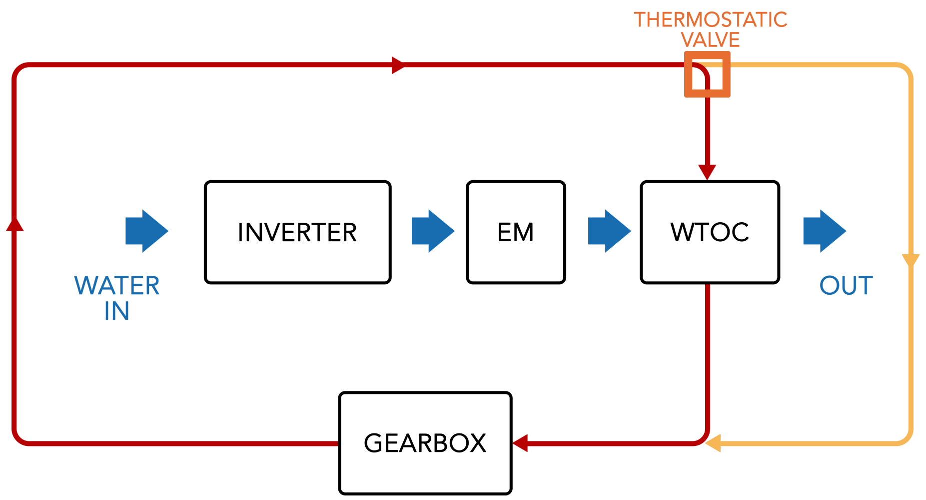


Figure 3.3: Passenger Vehicle, Front Axle Hydraulic Circuit.

This circuit is responsible only for the cooling of the front axle gearbox since the cooling of the electric motor is done by a separate cooling system that uses water. The same system is in charge of cooling the inverter, and the WTOC for the oil heat exchange, this water cooling circuit is indicated in Figure 3.3 by the blue lines, and since is not part of the oil spray cooling system will not be taken into consideration for this project. This happens also in the application of the HD Truck. There is also a lack of information regarding the water cooling system since its development is managed internally for the client, for simplification means, the WTOC will be seen as a standalone component, functioning as a heat exchanger to cool down the oil. The hydraulic circuit of interest for this project is composed of an inner loop, displayed in red, which refers to the oil flow inside the system, lubricating and cooling the front axle´s gearbox. There is also an outer loop, represented in yellow, this outer loop is controlled by a thermostatic valve, which opens and closes depending on the temperature of the oil flowing through the circuit, enabling or bypassing its flow through the WTOC. The functioning of this oil circuit for the rear axle is very similar, making it a very simple and basic oil cooling system, without any problems for its adaptation to a test bench.

HD Truck hydraulic circuit

While things were looking simple for the Passenger Vehicle oil circuit, it becomes more complex when analyzing the HD Truck layouts, but by sticking to the basic functioning principles of the system, each one of them can be simplified. Starting with Layout No.1, in Figure 2.14, we can see that the oil circuit is composed of two independent loops, each one with its pump responsible for the oil circulation, and a set of additional components like filters and WTOC, which will be also considered as a standalone component as done for the Passenger Vehicle since the water cooling system will not be taking into consideration either. By observing the two independent oil circuit loops we can appreciate that they are very similar to the inner loop found in the Passenger Vehicle, as exemplified in Figure 3.4, making it possible to adapt in a test bench with the same setup as the previous hydraulic circuit.

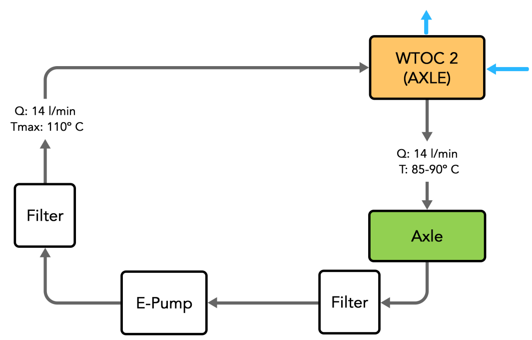


Figure 3.4: Isolation of the Axle Inner Loop in Layout No.1.

Regarding the composition found in Layout No.2, seen in Figure 2.15, some analysis and assumption are needed. We start by removing the part belonging to the water cooling system, since as mentioned before, it has no relevance to this study, this makes it easier to analyze the rest of the components, like the two WTOCs, which are connected in series between each other, which means that they can be seen as one bigger heat exchanger, this helps us to reduce the circuit by one component. A similar analysis can be done to the right side of the circuit, where we have the parallel connection between the eMotor and the axle, and the rest of the circuit, this parallel branch has a regulator valve that controls the flow that goes through the components in function of what is needed, the control of this valve does not interfere with the study carried in this project, since by analyzing the integration of both elements, eMotor, and axle, as one, being the eAxle, we can get rid of this parallel branch and synthesize it in only one equivalent component. To better understand this simplification of the oil cooling circuit in Layout No.2, the process is illustrated in Figure 3.5, having 3.5 A, representing the first part of the simplification, leading to 3.5 B as the outcome.

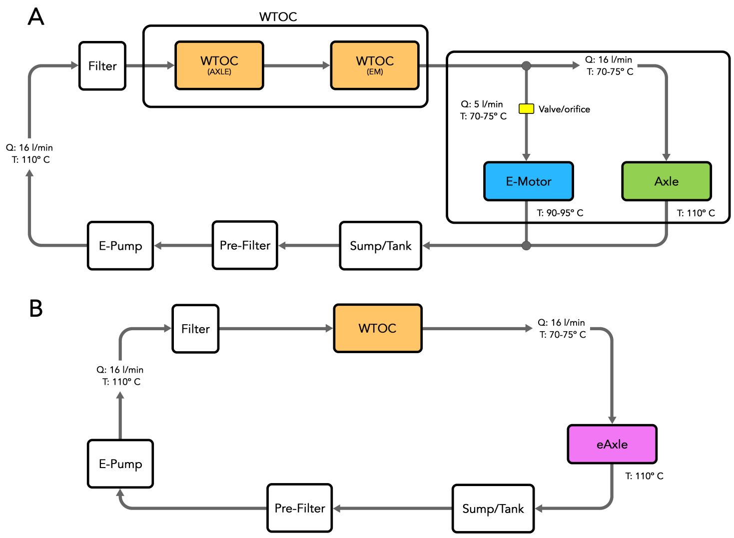


Figure 3.5: Simplification Process in Layout No.2.

We can observe now how despite starting from, apparently, different hydraulic circuit configurations, with the right use of simplification and equivalences in components, it is possible to take all these layouts into a standard one, which makes possible a general setup for the test bench.

3.2.2 Heat Management

Now that we have established the general layout to be implemented in the test bench, we need to start working on the elements of which is composed, starting with the WTOC, one of the most problematic to lead with since is a heat exchanger. To properly work with a temperature variation in the system, the integration of this heat exchanger is needed, an element capable of heating or cooling the oil to a desired point. In favor of the simplification, this feature of being able to generate a variation in the fluid temperature has been removed, limiting the system to work with a fixed oil temperature, despite how interesting an analysis with temperature variation might be, at this stage of the project is not imperative to add this feature to perform a good study, since good results can also be obtained by using a constant temperature, set at the value of continuous operation which is 110°C. The approach of using these constant values at continuous operational reference points not only helps us simplify the general circuit and optimize the use of elements but also helps us to focus on the operational range in which the vehicles will be mostly functioning, since once the vehicles are started, and the oil initiates to increase the temperature at a slow rate until reaching its continuous operation point. Under normal circumstances, there are no significant variations over long periods, due to the thermal management systems of the vehicle that are designed to keep it working at this temperature, as an example, in applications like HD Truck, where its normal use consists in long road drives for many hours, or for some city or short trips in the Passenger Vehicle.

But having a constant temperature of 110°C still means that some sort of thermal management needs to be included to raise the oil temperature and keep it stable, in the search for how to avoid this, the use of testing oils is seen as the answer for this problem.

3.3 Oil Characteristics

To avoid using the previously proposed oil, include a thermal management unit, and increase its temperature until the operational point of 110°C, a feasible option to get rid of this additional component is to use a fluid capable of behaving at room temperature with the same characteristics as its required for the oil in the system at high temperature, which means that we need to find a fluid with an approximate density of 0.85 kg/dm^3, and a kinematic viscosity @20°C at the range of 5-6 mm^2/s.

There are some fluids capable of providing this particular characteristic, some of them are Crude oil 32.6o API; Glycerine 50% water; Fuel oil 2; Diesel fuel 3D and more, but in their majority, these are highly flammable fluids, the reason some standards and normative their use in laboratories are accompanied by series of restrictions to guarantee safety, complicating, even more, the realization of a test bench.

This is where testing oils are useful, testing oils are specific types of oils used in the petroleum industry for a variety of purposes, most notably in the testing and analysis of crude oil and its products, allowing us to find an equivalent fluid to the ones previously mentioned, but unlike the others, this fluid is safe for its use in a laboratory

3.4 Oil Filter Simplification

Another important element of the system is the oil filters, responsible for keeping the fluid free of undesired particles that might induce to having harmful effects on the oil circuit, whether it can be by clogging the oil passages impeding adequate oil circulation, another scenario might be allowing unwanted micro-elements to get to sensitive components leading to possible damage over time. We can observe that alongside almost all the layouts considered, a double filter arrangement is used, by placing one filter, also referred to as "pre-filter", between the oil reservoir and the pump suction, and the second filter right at the pump delivery. This double filter configuration might seem redundant, which indeed is for the development of our final oil circuit, but for a real-life application where the vehicle is exposed to an external environment and set to operate correctly for more than thousands and thousands of kilometers before the next oil change, this kind of "redundancies" might set a difference between the actual reliability of the system. However, we are working under controlled conditions, the reason why this double filter arrangement will be replaced with only one filter located between the pump suction and the oil sump, as illustrated in Figure 3.6. this place was chosen despite being a closed loop circuit, which reduces the opportunities for external elements to get inside the system, the place with higher chances of it happening is the oil reservoir, which when opened to be filled with oil, opens the circuit to the exterior giving the chance for undesired pollution to the system to get inside the circulation loop.

3.5 Final Design and Components

To conclude this standardization process, there is still one last simplification that can be made, and this is regarding the components that represent a flow resistance in the circuit, knowing that components such as the eMotor and axle will be combined into only one becoming the eAxle, this equivalent element represents the total heat exchange and flow resistance in that branch, by applying the same analysis as done with the WTOC, and removing the thermal capabilities out of the equation, we can group everything in one big block adding some flow restriction to

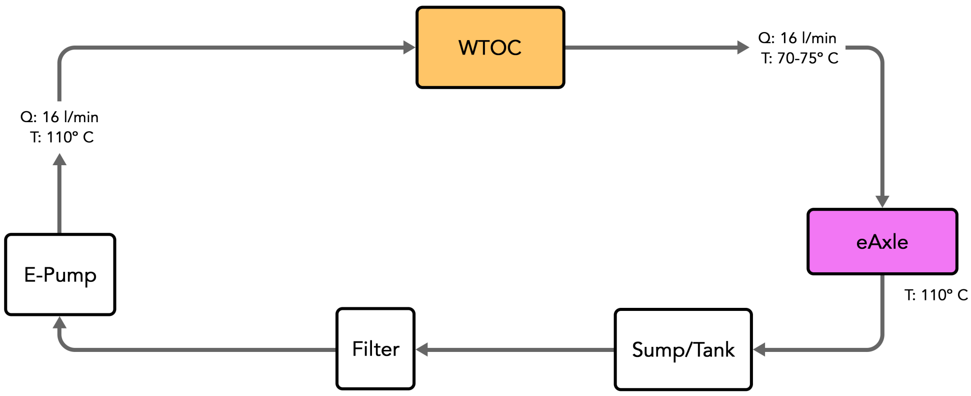


Figure 3.6: Final Placement of the Oil Filter.

the system, which can be represented in during the construction as a valve, with variable properties allowing to not be set for the particular losses of on scenario, but also being able of changing to letting us represent different cases of study. This change is depicted in Figure 3.7, where the valve can be appreciated in the yellow box under the name of "EqValve".

Now that we have reached the highest level of simplification, we are ready to describe the final oil circuit to be built, this is composed of: one oil filter; one oil ePump; one oil reservoir, or tank; and one valve, over which a test oil will be in circulation.

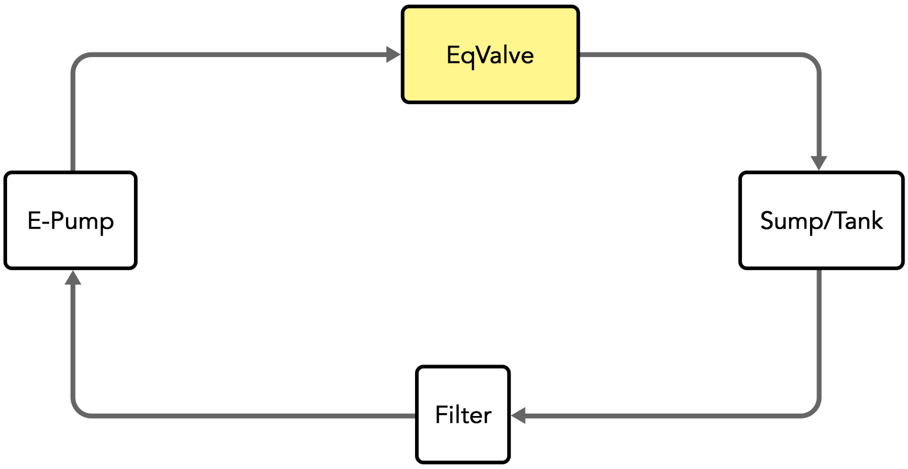


Figure 3.7: Final Model Layout.

3.5.1 Final Operational Conditions

In a similar way, as we performed integration of the hydraulic circuit architecture in the search for a general model, the differences in operational conditions between the different layouts must also be filled. Even when this may not be an extensive gap, is still important in order to have a clear sight of the system behavior, especially when related to the pump performance.

Parameter	**Value**
Continuous Operation Oil Flow	>10 L/min @ 2 bar
Temperature	T=110*
Approximate Electrical Power	110 W

Table 3.1: Operational Pump Conditions for the Final Hydraulic Circuit.

3.5.2 Components Selection

Before proceeding with the construction, we need to find the specific components that can be used to properly fit the requirements needed, having a test bench capable of studying the system at its accurate performance.

Oil Filter

For the selection of this component, we based our requirements on the ones presented by the client for the use of a filter in the vehicles, allowing us to study the behavior of the system on the test bench in the presence of a commercial oil filter that can be found in production vehicles.

- Operating Temperature: -40°C / +130°C
- Oil type: synthetic oil
  - Density at 15 °C: 0.820 to 0.860 g/cm3
  - Kinematic viscosity at 40°C: 20 to 25 cSt
  - Kinematic viscosity at 110°C: 4.6 to 7.4 cSt
- Max Oil flow: 30 lpm
- Max particle dimensions allowed: 200 um
- Max pressure difference: 0.2 bar
- Service interval: 150.000 km
- Water and dust protection: IP6K9K certification
- Salt Spray Resistance: 800 hrs

As these common requirements value commercial vehicles, the task of deciding which specific filter to acquire will be done by considering the variety in availability and prices provided by the suppliers.

Oil Pump

The selection of this component is the one that carries the biggest number of difficulties since chances of finding an electrical pump capable of working under the specific requirements of our system are limited to what can be found in the market. Acquiring one of these pumps directly from the same supplier used by the client is an almost impossible job due to the minimum order volume handled by the sellers to proceed with the purchase, making it necessary to order at least one thousand units, which is not feasible for neither of the parts. The suppliers were only taking orders for production volumes, and our project only needed one for research purposes. This restriction from the main suppliers took us to evaluate the possibility of acquisition from a third-party provider, looking for a pump sold to be used as a spare part in vehicles, this option came back with a few possible options, being an ePump from a Maserati and one from a Ferrari the ones that came better to fit our necessities, due to the significant price difference between the two pumps, the Maserati costing around 750€while the Ferrari goes for more than double the price getting close to the 2000€, going for the Maserati seems like a logical option. Being a vehicle part, the pump needs some adaptation for its use in a test bench, one of the parts needed to make it possible is an Oil Dispenser Housing, used to fit the pump alongside the oil filter, some seals, bolts, and more, increasing the total value to getting close to the 1000€line, but still with a lower price than the Ferrari pump.

However, the necessity of additional hardware needed for the adaptation to a test bench use is not the only problem that we face by purchasing a vehicle spare part, since by using a third-party provider we lose the capability of having certain information about the pump functioning, being this of critical importance for its control, considering that this pump is sell as a "plug and play" part, meaning that the control parameters, calibrations, function specifications, and more, are completely stored in the ECU, impeding us to accurate controlling the pump, since we do not know its communicating protocols, meaning that we will be purchasing a thousand euro pump that we are not able to communicate with.

By contacting different suppliers, it was possible to find a smart ePump, a practical solution being an electrical pump alongside its communication module, with the needed information about its communication protocols, allowing us to correctly connect to it and then control it this ePump, its module and other components needed for its use pushed us over the other side of the thousand lines, moving slightly closer to the two thousand euros.

3.5.3 Oil Transmission Lines

The choosing of the fluid transmission lines is done by selecting and arranging hoses and pipes with similar diameters to the ones found in transmission lines found in vehicles, the hydraulic circuit to be built was proposed to be done with the consideration of transmission lines of the standard AN10, being one widely used in the automotive sector.

3.5.4 Oil Selection

Finding information regarding testing oils' properties is not a simple task due to their particular research use, making it also an expensive fluid, and difficult to find. However is always possible to find information about it, leading us to very few testing oils capable of fulfilling our needs, the one considered the best for this would be a testing oil of viscosity grade ISO 5, having a kinematic viscosity of 5 cSt at room temperature (20°C), working perfect for our project. In this case, we contacted some suppliers who provided us with the necessary information about that particular test oil.

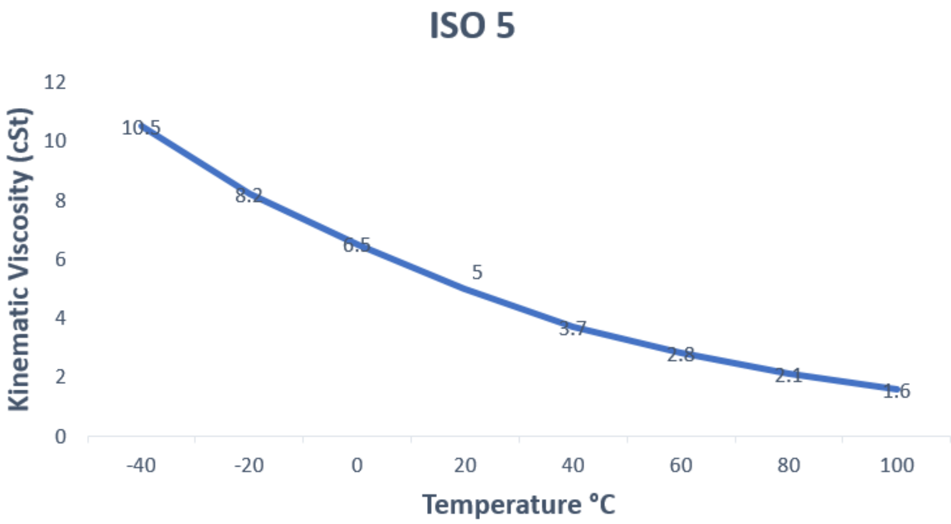


Figure 3.8: Test-Oil Characteristic Curve Generated Based on Information Provided by Suppliers.

3.6 Construction Challenges

Before proceeding to the construction of the physical test bench, it was taken into consideration if, despite all the complications that arose along the way, it was the best approach to proceed with the construction at this stage of the project. One of the many problems to come up was the long delivery time for some components like the ePump needing more than 6 or 7 weeks to arrive., or the minimum purchase volume became a problem again for elements like the oil, where while needing small quantity we would be forced to by over 30L due to the supplier's policies restricting us to buy less than their specified minimum amount, which was too high for the needs of our project. Then the constant need for different components to properly make the adaptation and installations needed, components not previously mentioned such as sealing, blots, nuts, physical space in the facilities, hydraulic sealing, and more. This led to finding a way to avoid spending thousands of euros on equipment and a few months of waiting for some of them, bringing us to consider the reach of this project under the MBD methodology and the ISO standard in use, focusing the study on the development at the software level and leaving some more room for future work to be carried out.

Chapter 4

Functional Safety and FMEA

Functional safety analysis is a systematic process that aims to identify, assess, and manage potential hazards and risks associated with the functionality of a system. The primary goal is to ensure that a system operates safely, even in the presence of faults or errors. This process is particularly important in industries where the failure of a system could lead to serious consequences, such as injury, loss of life, or damage to the environment like the automotive industry. Evaluating the reliability of system components and the system is essential for ensuring that the system meets its safety goals.

4.1 Functional Safety Analysis

The process begins with identifying potential hazards that may arise during the operation of a system. This involves considering various failure modes, environmental conditions, and operational scenarios. After identifying hazards, a risk assessment is conducted to evaluate the severity of potential consequences and the likelihood of these consequences occurring. This step often involves assigning a risk level or priority to different hazards, as an example of this, we can observe in Figure 4.1 how would be the procedure while analyzing an ABS as an example for a simple overview. While in Figure 4.2 we can appreciate some other common risks analyzed during the development of different vehicle systems.

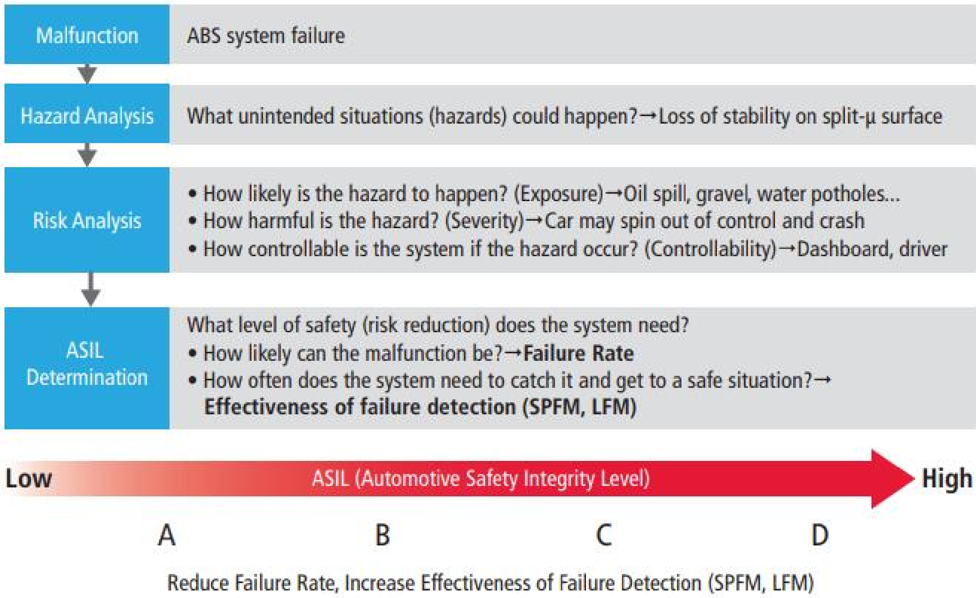


Figure 4.1: steps involved in the determination of ASIL for an Anti-Breaking System (ABS). Note: Taken from *Through the Lens of ISO 26262 Paradigm: What is Functional Safety and ASIL [15].*

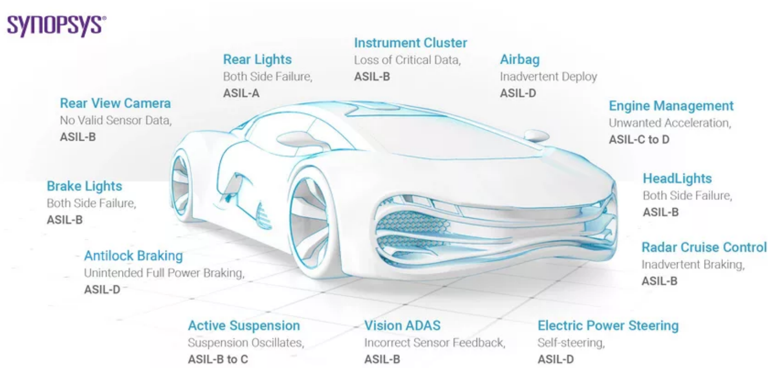


Figure 4.2: Some typical types of ASIL. Note: Taken from *What is ASIL (Automotive Safety Integrity Level)? – Overview: Synopsys Automotive [16].*

Based on the identified hazards and risk assessment, safety requirements are specified. These requirements outline the conditions and behaviors that the system must exhibit to mitigate or eliminate identified risks.

Developing a functional safety concept involves designing strategies to achieve and maintain functional safety. This may include redundancy, fault detection mechanisms, and fail-safe modes. Continuous verification and validation activities are conducted throughout the development life-cycle to ensure that the safety requirements are met and that the system behaves as expected under normal and fault conditions.

4.1.1 Normative

In the context of functional safety and system analysis, "normative" refers to aspects that are specified or required by a standard or set of regulations. Normative requirements are those that must be followed to achieve compliance with the given standard. The term is often used in the context of industry-specific standards that provide guidelines for the design, development, and operation of systems to ensure functional safety.

Normative requirements often mandate the conduct of systematic risk assessments to identify hazards and determine the necessary safety measures, where sections of standards typically address how changes to the system, whether in design or operation, should be managed to ensure ongoing compliance with safety requirements. In standards like IEC 61508, safety requirements are often assigned Safety Integrity Levels (SILs) based on risk assessments, while by following the standard ISO 26262, these requirements are referred to as Automotive Safety Integrity Levels (ASILs). Achieving the specified SILs or ASILs becomes a normative requirement for safety functions.

When performing functional system analysis, it is crucial to understand and adhere to the normative requirements specified in relevant standards. This helps to ensure that the system is designed, implemented, and operated in a manner that minimizes the risk of hazards and complies with industry-accepted safety practices. Non-compliance with normative requirements may not only compromise safety but could also impact regulatory compliance and market acceptance.

The standard ISO 26262 offers the following framework regarding functional safety for technological applications in the areas of mechanics, hydraulics, and some pneumatic cases.

Despite having this norm present during the whole development process of the project, the complete information scheme is too wide to be fully explored. Special focus will be given to some of the parts that have a bigger incidence for practical terms.

4.1.2 ASIL Analysis

The analysis of ASIL as a system for classifying the risk begins in Part 3 of ISO 26262 and gets carried along the different sections of the process. Initially, a hazard and risk analysis (HARA) assists in determining the intensity of risk of harm to passengers and property for any specific failure of a defined application at the vehicular level. This aids the project in determining the process and level of risk reduction required to achieve a tolerable risk. A subdivision into levels is also assigned, ASIL levels are ASIL A, ASIL B, ASIL C, and ASIL D. ASIL D represents the highest level of automotive hazards, while ASIL A represents the lowest. Another level, QM (Quality management level), represents hazards that do not require any safety precautions. The specification of these ASIL levels is made by engineers under assumptions based on exposure, severity, and controllability.

Exposure

Will be measured by How probable are risks to occur, i.e. the probability of a vehicle being involved in a hazard scenario that might cause injury to persons and property. E1, E2, E3, and E4 are the different levels of exposure. E1 is the least likely and E4 is the most likely.

Class	Probability of Exposure
E1	Very low
E2	Low < 1%
E3	Medium 1% - 10%
E4	High > 10%

Table 4.1: Classification of exposure probability according to ISO 26262, Part 3. Note: Adapted from *Automotive Safety and Compliance with ISO 26262 and ASPICE [17].*

Severity

Assess how dangerous the hazard is, i.e. the impact or severity of the damage to the lives of passengers and property. It is arranged in the following order: S1, S2, and S3. S1 represents minor and moderate injuries, whereas S3 represents life-threatening incidents.

Class	Description
S0	No injuries
S1	Light and moderate injuries
S2	Severe injuries, possibly life-threatening (survival probable)
S3	Life-threatening injuries (survival uncertain) or fatal injuries

Table 4.2: Classification of harm or damage severity according to ISO 26262, Part 3. Note: Adapted from *Automotive Safety and Compliance with ISO 26262 and ASPICE [17].*

Controllability

Evaluate How the system controls the vehicle in the event of a hazard, i.e. deciding the extent to which the driver or user can control the vehicle in the event of a failure. The controllability order is defined as C1, C2, and C3. C1 is easy to manipulate, whereas C3 is hard to handle.

Class	Description
C0	Controllable in general
C1	Simply controllable 99% or more of all drivers or other traffic participants are usually able to avoid specific harm
C2	Normally controllable 90% or more of all drivers or other traffic participants are usually able to avoid specific harm
C3	Difficult to control or uncontrollable less than 90% of all drivers or other traffic participants are usually able to avoid specific harm

Table 4.3: Classification of harm or damage severity according to ISO 26262, Part 3. Note: Adapted from *Automotive Safety and Compliance with ISO 26262 and ASPICE [17].*

Once the respective assumptions are made and established the appropriate hazard parameters for the system we can determine our ASIL lever according to the allocation table provided by ISO 26262, which is referenced in Figure 4.3 below.

Severity	Exposure	Controllability: C1 (Simple)	C2 (Normal)	C3 (Difficult, Uncontrollable)
S1 LIGHT AND MODERATE INJURIES	E1 (Very low)	QM	QM	QM
	E2 (Low)	QM	QM	QM
	E3 (Medium)	QM	QM	A
	E4 (High)	QM	A	B
S2 SEVERE AND LIFE THREATENING INJURIES – SURVIVAL PROBABLE	E1 (Very low)	QM	QM	QM
	E2 (Low)	QM	QM	A
	E3 (Medium)	QM	A	B
	E4 (High)	A	B	C
S3 LIFE THREATENING INJURIES, FATAL INJURIES	E1 (Very low)	QM	QM	A
	E2 (Low)	QM	A	B
	E3 (Medium)	A	B	C
	E4 (High)	B	C	D

QM (Quality Management)
Development supported by established Quality Management is sufficient.

A — **lowest ASIL** Low risk reduction necessary
B
C
D — **highest ASIL** High risk reduction necessary

Figure 4.3: Determination of ASIL level. Note: Taken from *Automotive Safety and Compliance with ISO 26262 and ASPICE [17].*

During the assignation of the respective hazard parameters of our system to correctly determine the adequate ASIL according to the indications previously explained, we analyzed the system at the hardware and software levels but making a special emphasis on the software level, and the following assumptions were made:

- The system under study is a closed loop with only a few access to external elements that could represent exposure to hazardous situations. The system is usually located inside a unified designed powertrain element providing it some protection against malfunctioning due to outer conditions. In this case, the reliability of the system to withstand a fault that could lead to a dangerous or damaging situation must be addressed and prevented through the design phase, in base on this, we can classify its probability of exposure as an E2. As long as a proper procedure is implemented during the design phase, FMEA is an acceptable methodology and the one used during this process, more information will be given further during this section. A design phase without taking into consideration this approach and methodologies increases the probability of failures in the system and generation of unsafe situations, changing the classification to an E3 or even an E4.

- Regarding the severity of the harm or damage that we could face during a failure in the system, there are some particularities, unlike other systems like ABS where a failure could lead to fatal injuries to the passengers of the vehicle due to the loss of control, in our system the most affected during a failure would be the components instead of humans lives, as long as no negligence acts are performed after the appearing of the fault (such as continue to drive normally the vehicle once a final warning is present). As far as the classification goes, this could be an S2, having important damage to components in case of failure and a prolonged use under these conditions could lead to an S3, especially when an ICE is involved, since they have a bigger dependency in the lubrication system than their electrical counterpart.

- Lastly, the controllability of our system while referring to the case of a fully electric vehicle is not much affected in case of failure, despite the system being critical for the right functioning of the vehicle. In case this ceases working the overall functioning of the vehicle allows the driver to safely maneuver until a secure stop, since even by having a complete loss in the lubrication and the cooling, the electric components can still keep working until they overheat, giving enough time to the user to correctly stop before permanent damage is made, for this scenario, we will be talking of a C1 classification. However, in the case of an ICE vehicle, a failure in this system represents a critical state by reducing the response time of the driver significantly due to the crucial role that this system plays for all the moving parts of the ICE, making it more difficult to control the vehicle to a secure stop, in accordance to the gravity of the failure we could be having a classification between C1 to C2.

Summarising the assumptions made during the analysis to assign a proper ASIL level, we can say that the system under study counts with an exposure level of E2, a severity of S3, and a controllability of C2, increasing its reliability by taking into consideration it's functioning under the most critical circumstances, allowing it to also be used in ICE vehicles. This results in an ASIL-A, as can be seen by using the previously mentioned Figure 4.3.

4.1.3 Part 4: Product development at the system level

Part 4 of ISO 26262 focuses on the system-level aspects of product development in the context of functional safety. It provides guidance and requirements for the development of safety-related electrical and/or electronic (E/E) systems within road vehicles. As seen in Figure 4.4, which provides a simplified view of this section.

The standard addresses key areas such as:

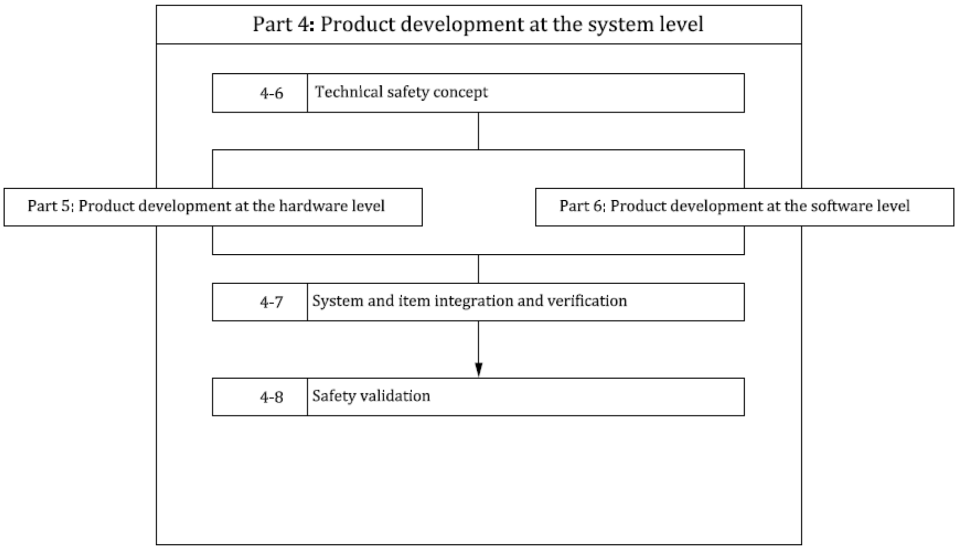


Figure 4.4: Product development at the system level Note: Taken from *The functional safety mirror [18].*

Product Development at the System Level

, Focusing on the description of the concept phase and the system-level requirements, specifying the activities required for the development of safety-related systems.

Technical Safety Concept

, which emphasizes the development of a technical safety concept to address safety goals and requirements.

System Design

specifies the functional safety requirements and offers guidelines for the architectural design of the system.

Hardware and Software Design

explains how to design system-level hardware and software components while keeping safety regulations in mind. Sections 5 and 6 of the respective approach are linked for a detailed analysis of the development at the hardware and software levels.

Safety Validation

describes the procedures for item integration and testing that are involved in validating safety requirements at the system level.

Functional Safety Assessment

directs the system-level safety evaluation before it is put into production, along with any supporting procedures that are pertinent to the creation of new products.

Release for Production

at last. covers production and operation-related topics, such as the drafting of safety plans. includes advice on how to run and maintain safety-related systems, as well as how to handle system modifications over the course of their lifetime.

4.1.4 Part 6: Product development at the software level

This part of the standard addresses the development of safety-related software and provides guidelines and requirements for ensuring functional safety in software components within automotive systems. This structure is summarised in the "V" diagram illustrated in Figure **??**. This process starts with establishing the **Software**

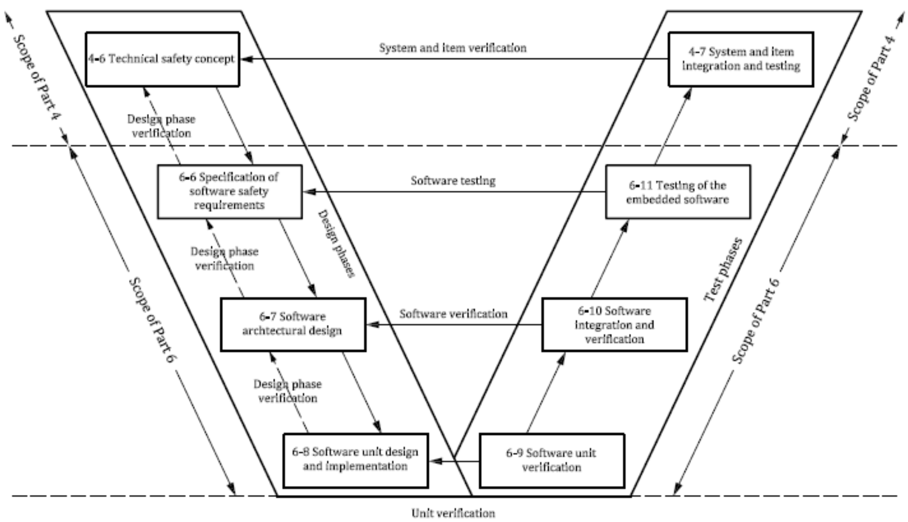


Figure 4.5: Reference Phase Model for the Software Development Note: Taken from *Freedom from interference FFI [19].*

Safety Requirements for specifying safety requirements for software; followed by **Software Architectural Design** providing guidelines for the architectural design of safety-related software; then proceeding to a **Software Unit Design and Implementation** of individual software units, ensuring that safety requirements are met; **Software Integration and Testing** includes the testing and integration of software components to guarantee appropriate operation and adherence to safety regulations; **Software Verification** Specifies the activities and processes for verifying that the software meets the specified safety requirements; **Software Testing** provides guidelines for evaluating safety-related software to make sure it operates correctly in various scenarios; **Software Integration Testing** explains how integrated software components are tested to ensure that their overall behavior and adherence to safety regulations are met; lastly, **Verification of Software Safety Requirements** focuses on validating safety-related software to make sure it meets the required safety standards.

4.1.5 Part 8: Supporting Processes

This part offers detailed instructions for guaranteeing road vehicle systems' functional safety. Opening this section we have a basic overview of the procedures that must be followed in order to achieve functional safety; the standard explores the **Specification and Management of Functional Safety Requirements**, highlighting the value of having a separate system for managing safety. It emphasizes how important methodical management techniques are to properly supervise functional safety aspects. A crucial part of the life-cycle of safety-critical systems, preserving the integrity and consistency of safety-related elements, is covered in the **Configuration Management** section of the standard. The **Change Management** section that follows focuses on the management of modifications to the hardware, software, system, or functional safety concept. This component is essential to make sure that the overall safety is not jeopardized by any changes. It then emphasizes **Verification**, highlighting how crucial it is to confirm that safety standards are fulfilled at various phases of development. This guarantees that the safety objectives are met at every stage of development. Subsequently, the topic of **Documentation** is discussed, highlighting the importance of gathering and preserving pertinent safety data over the course of a product's life cycle. This guarantees that crucial safety information and judgments are methodically documented and made available. **Validation**, the following section, discusses the validation procedures required to verify that safety standards are met and the system operates as intended. For the ultimate validation of functional safety, this step is essential.

4.1.6 Part 9: ASIL-Oriented and Safety-Oriented Analysis

Part 9 of ISO 26262 explains how each component and item in the road vehicle system is assigned an Automotive Safety Integrity Level (ASIL). To then be given instructions for determining and defining safety requirements following the established ASIL, describing the best way to do a qualitative hazard analysis to find possible risks and the ASILs that go along with them.

To do so, this part discusses the creation of safety-related items, such as confirmation measures and ASIL allocation considerations, explaining the fault tolerance analysis, which is essential for determining the quality of how well the safety measures reduce the impact of faults. Covers the examination of hardware and system metrics to guarantee that safety standards are fulfilled, giving instructions on how to compute safety-related probabilistic metrics, such as those related to arbitrary hardware failures, in this way providing general instructions for carrying out safety analyses that stress the value of a systematic approach. In addition, this explains how to analyze the likelihood of dangerous events using the Fault Tree Analysis method.

This part also includes a technique for ASIL customization in the concept and development stages, which is ASIL decomposition. This provides the opportunity to make advantageous architectural decisions by having enough independent architectural elements. During the process of allocating safety requirements for these independent elements we get a chance to implement safety prerequisites twice, and to assign a potentially lower ASIL to (some of) these decomposed safety requirements. The initial ASIL is inherited by the redundant requirements and the architectural elements if they are not sufficiently independent. The standardized decomposition scheme is depicted in Figure 4.6.

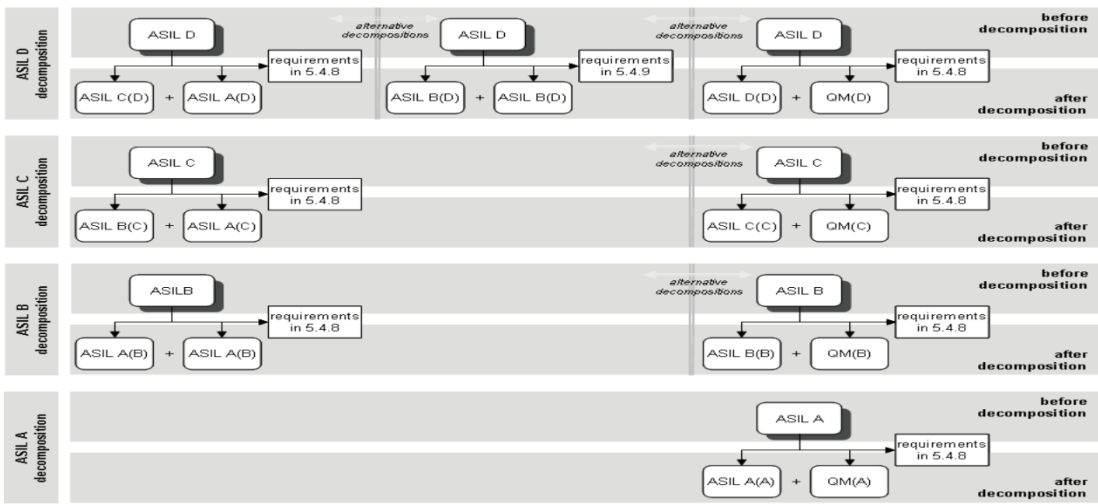


Figure 4.6: ASIL decomposition scheme. Note: Taken from *The Automotive Standard ISO 26262, the Innovative Driver for Enhanced Safety Assessment & Technology for Motor Cars [20].*

For our case under study, we have assigned an ASIL-A level, which is ranked as the lowest in functional safety, for a system as critical as this one to have such a low rating hazard level we have to count on a properly designed system capable of reducing the risk down to that level. An ASIL-A shall not be decomposed, except when needed, like in this case where to address the analysis of the system in the most complete way possible we have proceeded with decomposition as represented in the previously mentioned Figure 4.6, having a system, analyzed under 2 fronts, one has an ASIL-A(A) and as a QM(A).

Regarding "Quality Management," the QM level indicates that all risks that have been evaluated are acceptable from a safety standpoint (even though the manufacturer may wish to address them from a customer satisfaction standpoint). As a result, safety assurance controls are extra, and standard quality management procedures are adequate for development. To ensure this, additional analyses are made to properly evaluate the system at a level of acceptable risk and leave further revisions as a part of the general quality process during production.

4.2 FMEA

FMEA, which stands for "Failure Mode and Effects Analysis", is a systematic method for evaluating the potential failure modes of components within a system, assessing the effects of those failures, and identifying measures to prevent or mitigate these failures.

We complement the FMEA concept by linking it with the AIAG VDA 7-Step FMEA, in Figure4.7, which is a detailed methodology developed jointly by the Automotive Industry Action Group (AIAG) and the German Association of the Automotive Industry (VDA). The AIAG handbook emphasizes the great importance of FMEA analysis as an efficient technique to prevent or reduce failure by addressing them in the early stages of the design, evaluating and managing risks in product design and manufacturing processes.

Planning and Preparation

This first step entails laying the groundwork for the FMEA. It entails establishing the goals and parameters of the analysis, putting together a cross-functional team, and obtaining pertinent data such as design specifications and client expectations. By guaranteeing that all required resources and expertise are available, this step sets the stage for an exhaustive and efficient analysis.

Figure 4.7: AIAG VDA 7-Step FMEA. Note: Taken from: *AIAG VDA 7 Step FMEA. Planning & preparation. Results documentation [21].*

Structure Analysis

In the second phase, the emphasis is on comprehending the parts and arrangement of the system, subsystem, or process under study. This is accomplished by identifying every component covered by the FMEA and drawing block diagrams or process flowcharts. A thorough grasp of the system and its elements depends on this structural overview.

Function Analysis

Finding the purposes and specifications for every element found in the structure analysis is the third step. As part of this, each component or process's intended functions must be defined, along with any performance requirements or anticipated results. Through this step, the alignment of the analysis with the intended functionality of the system is ensured.

Failure Analysis

Potential failure modes for every component are identified in the fourth step, along with their causes and consequences. This entails enumerating all potential failure modes for each element and figuring out the reasons behind and consequences of each failure. Understanding the system's vulnerabilities requires completing this step.

Risk Analysis

The risk connected to each failure mode that has been identified is assessed in this step. It entails evaluating each failure mode's potential occurrence, detection difficulty, and impact severity. These risks are quantified using tools such as the Risk Priority Number (RPN), which helps to prioritize efforts to mitigate risk.

Optimization

This step focuses on creating plans to mitigate risks that have been identified. This entails making recommendations for steps to reduce or eliminate high-risk failure modes. These steps could include tweaks to the process or design, more testing, or the addition of new quality controls. Improving the system's dependability and safety requires taking this crucial step.

Results Documentation

Documenting the analysis and overseeing the improvement actions' implementation are the last steps. This entails tracking the implementation of the action plan and updating the FMEA in an organized manner as needed. This step guarantees that the system's safety is continuously enhanced and that the insights obtained from the FMEA are effectively utilized.

All these steps of AIAG VDA have been previously addressed during the development of this report, and due to how extensive it would be to correctly integrate the description and proper documentation of this seven-step analysis, we will proceed directly to analyze some of the possible failure modes and actions needed to mitigate or eliminate their effect.

4.2.1 Failure Analysis: Causes, Effects, and Actions Taken

During the analysis of the possible failures that could be present in the system, we have divided them into two different types; those that can be addressed at the hardware level and the ones managed at the software level. For the first kind of failure type, not much focus will be given since we will limit the reach of this project to a software level. Some of these failure modes include diverse physical malfunctioning such as a broken pipe or a faulty fitting that might lead to a leak, generating a fluid loss, leading to a pressure drop and ultimately impeding the system to properly work. These kinds of leaks could happen due to a diverse amount of factors, from general wear in some components, accidents including external perturbations like unexpected impacts that generate cracks, or even poor quality control during the production stage that leads to an unsatisfactory assembly of the components.

Some of these problems that are generated at the hardware level can be solved by adding some redundancy or backup components, and even can be managed from a software level. In this case, we will especially focus on the ones related to the failure in different sensors that might interfere with the accurate reading of the conditions of the systems, making it difficult or even impossible to know their state. In this way, they impede the proper functioning of the vehicle without having enough information to generate a warning to the user allowing him to take the needed actions to prevent hazardous and damaging situations.

We can start this analysis by referring to the final system architecture previously mentioned in Figure 3.7, which will add a sensor capable of measuring the pressure and temperature of the oil, the position where this sensor is placed is of vital importance for the correct acquisition of information over the system that then will be processed by the ECU for it uses whether it is for the control of the ePump of the generation of warnings in cases of a failure. During the initial stages of the design, the position of this sensor was proposed to be between the filter and the pump, before its suction port as indicated in Figure 4.8, this place was chosen by the clients since is a very common place for the use of this kind of sensor in the automotive industry, this position so often used that is very expected to find vehicles with an oil filter housing prepared for the connection of this sensor.

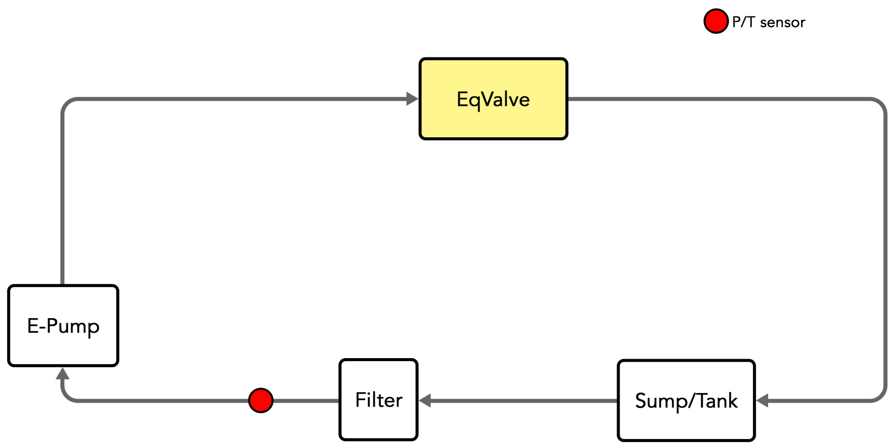


Figure 4.8: Initial placement of the P/T sensor.

Placing the sensor in that particular position doesn't allow us access to perform measurements of important information such as the output pressure of the pump or the temperature in other parts of the system. Knowing this information is not critical during the production phase and once the system is fully tested for its adequate functioning since is just assumed the correct operation of the pump is based on the calibration parameters and performance requirements based on the extra information that the ECU might have available from others vehicles systems such as internal temperature sensors in the electric motors. However for our case study and especially for our aim of increasing the reliability of the system, we can not only count on the assumption of acquiring information coming from other car systems, especially regarding the knowledge of the operation pressure of the pump, since the P/T sensor placed in the suction of the pump is incapable of giving us the information of how much is the pressure supplied but our pump, this sensor is mounted in the low-pressure side giving us only information of the oil once it has passed through the whole system and has come back to the reservoir tank, depriving us of valuable information during the development of this study and analysis of its performance.

To correctly measure information about the pressure and temperature from the discharge port of the pump, a sensor is needed in that area, but the information received from the other sensor is also valuable so the simple action of just moving it to a different location is not enough for this case, so the solution considered has been to add an extra sensor at the discharge port, allowing us to have more information about the state of the system regarding the temperatures and operational pressure of the pump and the system. The addition of this new sensor can be seen in Figure 4.9.

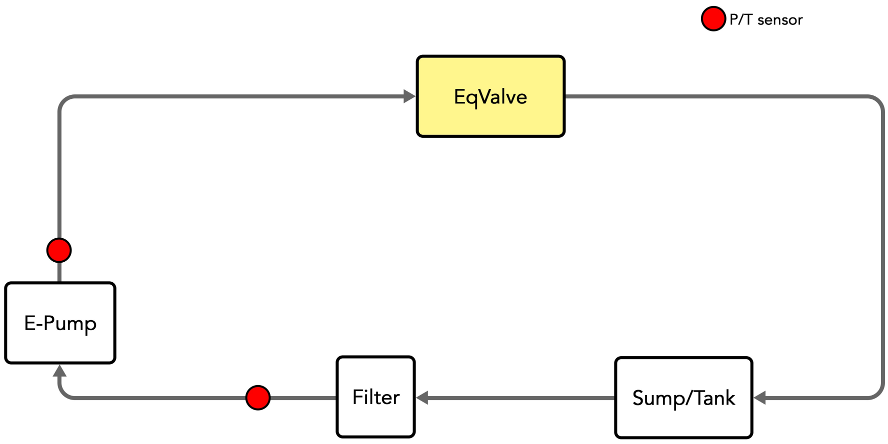


Figure 4.9: Double P/T sensor.

The addition of this second P/T sensor not only gives us more information about the system but also allows us to have a certain sense of redundancy regarding these instruments, which despite taking their measurements in different positions, provide us enough information to be analyzed in case that one of them presents a failure, increasing the so desired reliability in the system.

One disadvantage of the P/T sensors is that in the case that a failure is present in the pump and this component ceases working, it would be hard to obtain an immediate status of this problem since the information acquired depends on two different parameters such as the pressure and the temperature. In case of a full stop in the pump, there might still be some pressure in the system, meaning that the sensor will still measure a pressure value and this will keep being the case until the condition changes taking some time for the failure to be detected. The same thing happens with the temperature, for this parameter to be measured and correctly understood as the detection of a pump stop failure, some time will be needed until the temperature continues to increase or decrease up to the point where is out of operational parameters. A solution that can be implemented to obtain a more reliable system would be the addition of a Flow Rate sensor, unlike the previously discussed sensors, in case of a full stop of the pump this also means that the circulation of the fluid inside the hydraulic circuit has also stopped, since no component completes the cycle and forces it to recirculate. This ceases of flow will then be detected in a much faster way allowing the to opportunity inform the

ECU and take action to prevent further damage. The Flow Rate sensor will then be located before the input port of the tank, as indicated in Figure 4.10.

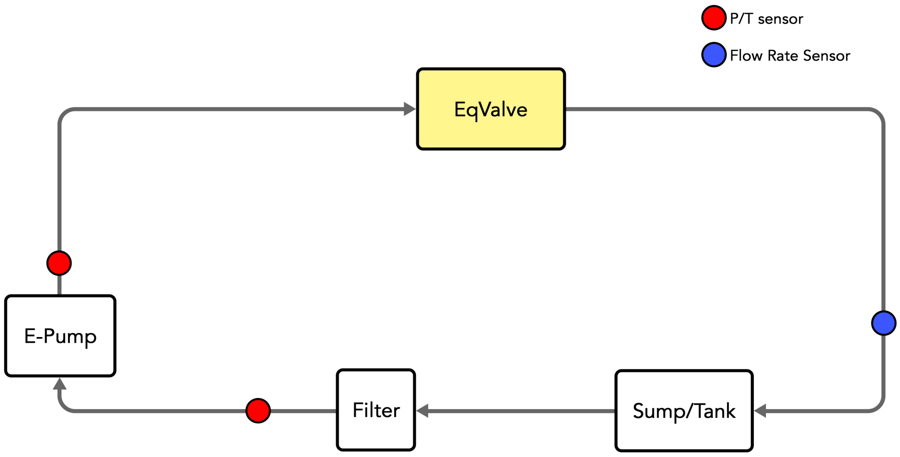


Figure 4.10: Integration of the Flow Rate sensor.

The inclusion of these sensors not only provides an extra level of reliability at the hardware level by adding redundancy to the system but also amplifies the possibilities of accurate control and diverse kinds of solutions at a software level.

Chapter 5

Modelling of the System

5.1 Model-Based Design: In-Depth

Delving into the details of MBD allows us to get into the main steps of this methodology, although it should be clarified that the specific stages may vary according to the particular application at hand, and in dependence on the product development level, different paths might need to be taken, as seen over the V diagrams and procedures previously mention during the FuSa analysis. However, in general cases, this procedure commonly includes the following stages for software development:

Requirements Analysis

In this initial stage, an understanding of the documentation and the requirements of the system under analysis is done. Collecting information about the intended functionality, performance, and constraints that the system must face.

System Architecture Design

At this stage, the goal is to create a high-level design that summarizes the software system's structure, components, and behavior, allowing the development of a preliminary design for the computational model construction.

System Modeling

System Modeling consists in the creation of a mathematical model based on a chosen architecture capable of representing the system studied. This model can be made by using several amount of techniques, whether it is just done by a simple graphical representation using block diagrams or state machines, to more complex ones as mathematical models composed purely of equations.

5.2 ePump and Components Modelling

The ePump is the main component of the hydraulic circuit. We need to generate a computational model that allows us to carry along a simulation for a better understanding of its functioning in the presence of the existing architecture. We should also be able to accurately control the behavior of the model and obtain the desired performance of the system under study. The rest of the components are also of great importance, but during this part of the project, we will focus on the specific characteristics regarding the ePump model. The modeling of some other elements will also be depicted.

As mentioned before, there are several ways to develop a model. We will mainly consider two of them while looking for the best way to properly simulate the pump behavior.

5.3 Model Approach No.1

Referring back to the previously mentioned study carried out by Pellegri et al. (2020)[9], they developed their model for a simulation of a gerotor pump consisting of different modules. Instantaneous volumes and porting areas are assessed using a numerical geometric model; fluid dynamics is assessed using a lumped parameter fluid dynamic model in conjunction with loading, journal, and micromotion modules; lubricating interface analysis is carried out by an advanced CFD-Gap module, where CFD stands for Computational Fluid Dynamics; contact torque losses are assessed by an elastohydrodynamic lubrication contact module.

Except for the CFD-Gap Module, all of the simulation model's modules run simultaneously as it evaluates the force and instantaneous flow characteristics using CAD drawings as input. This methodology is illustrated in Figure 5.1.

This modeling methodology for the gerotor pump might seem like an overkill by expanding its scope in a large area as is the case for CFD. Still, we can observe how this modeling process starts with a geometry analysis of this component. This approach is up to some point very similar to the one used by MATLAB in their example about how to model, parameterize, and test a gerotor pump, (*Gerotor Pump - MATLAB & Simulink - MathWorks Italia*, [22]). The gerotor pump, the load system downstream of the pump, and the inlet system upstream of the pump make up the flow circuit in this model. The pressure drop upstream of the pump is represented in the inlet system model through a combination of pipes, bends, abrupt changes in area, and an orifice representing a filter. The same representation is used for modeling the pressure drop across the heat exchanger, and orifices at the entry to the stator and rotor, in the load system.

During the development of this model, the use of MATLAB and Simulink

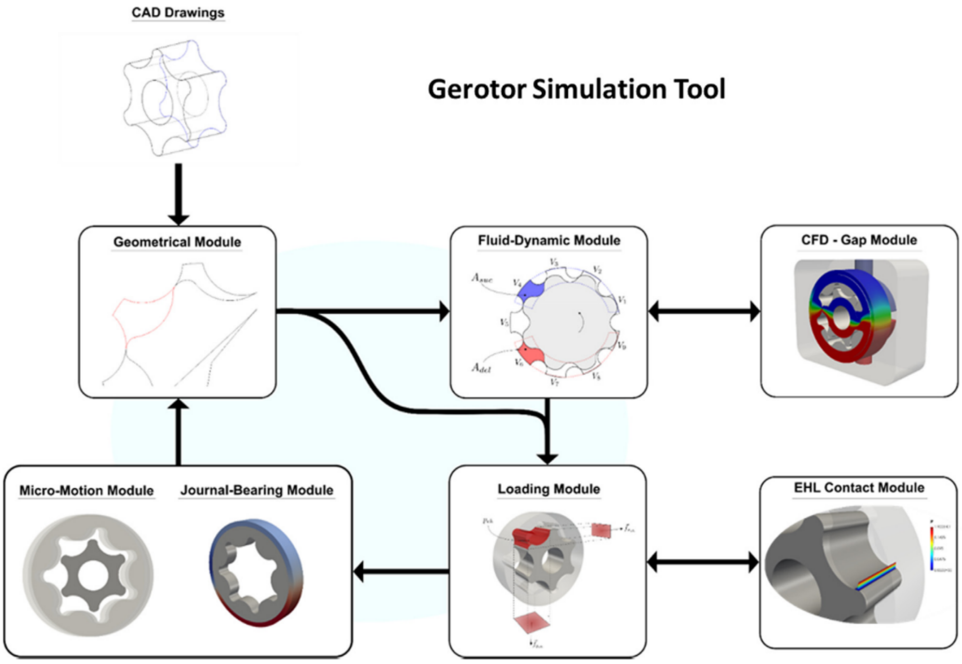


Figure 5.1: Different Model Types and Stages for a Gerotor Modelling and Simulation. Note: Adapted from 2020 paper, *A simulation model of Gerotor pumps considering fluid-structure interaction effects: Formulation and validation.* by Pellegri et al. [9].

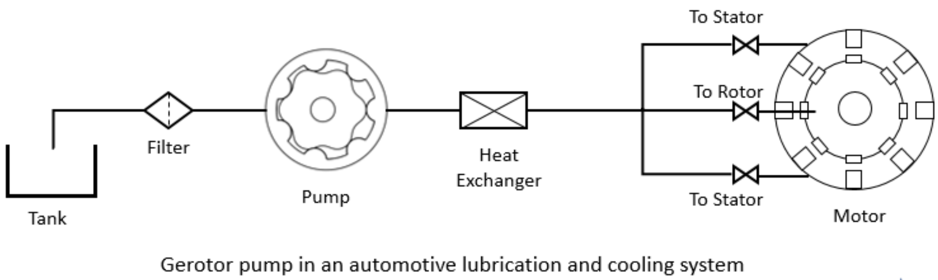


Figure 5.2: Scheme studied by MathWorks. Note: Adapted from *Gerotor Pump. by MATLAB & Simulink - MathWorks Italia [22].*

is essential, especially focusing on the implementation of Simscape, which is a tool that allows us to create models of multi-domain physical systems inside a Simulink environment. By using this tool, we can properly describe and simulate an interaction within the computational and physical representation of the components under study, allowing us to work with different domains in a combined way, which is needed in this case to adequately combine the rotational (physical domain, represented with the color green), the hydraulic (which domain is represented in color blue as an isothermal liquid) behavior of the system and then being able to observe it from a computational point of view.

Gerotor pumps are composed of an inner gear called the "driving gear" and an outer gear called the "driven gear," which are mounted on a rotating shaft that is modeled as an angular velocity source. In this model methodology, a trochoid curve's geometry is used to determine the inner gear teeth profile of the pump under consideration. The outer gear teeth profile is equal to the inner gear teeth profile's reciprocal. Given that the cyclical volume variation between the teeth of the mating gear set serves as both a delivery mechanism and a continuous source of volumetric flow, a gerotor pump is classified as a positive displacement pump.

There are several sub-volumes or chambers that make up the liquid volume between the mating gears, as seen in Figure **??**, which shows how by going deeper into the block that composes the modeling of the gerotor pump these different chambers are considered. This model also considers the gap created by tip leakage between the chambers as a result of teeth clearance connecting these chambers to one another, this clearance is important during the design of the pump since this helps avoid contacts between the inner and outer gear. as seen in Figure 5.4. This clearance generates face leakage, which is a type of leakage flow due to the connection in volumes of the inlet and outlet ports. The volume of the chambers changes as the pump rotates, and port area profiles connect the chamber volumes to the ones of the inlet and outlet ports. Equal numbers of variable-volume liquid chambers and outer gear teeth are present.

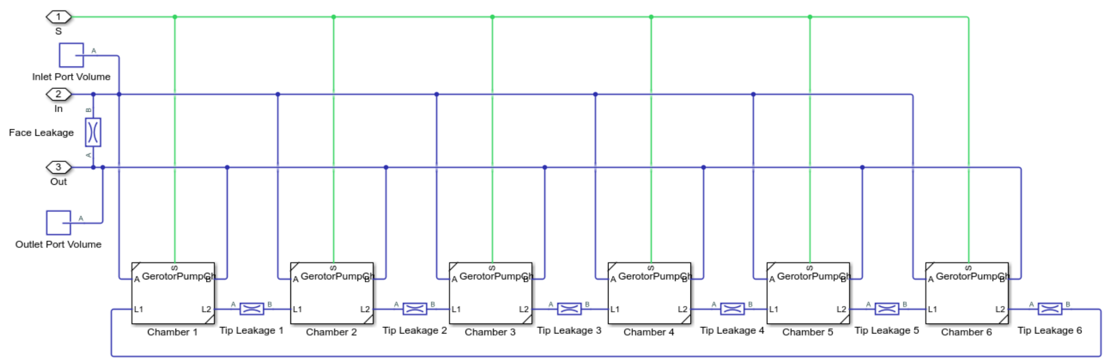


Figure 5.3: Modeling of the inner chambers and leakage of the gerotor pump by MathWorks. Note: Adapted from *Gerotor Pump.* by MATLAB & Simulink - MathWorks Italia [22].

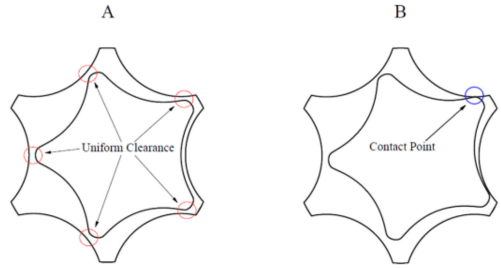


Figure 5.4: Difference between the presence of a uniform clearance (A) and a contact point (B). Note: Adapted from 2020 paper, *A simulation model of Gerotor pumps considering fluid-structure interaction effects: Formulation and validation* by Pellegri et al. [9].

As we can see, the geometrical characteristics of the pump play an important role in its modelling, especially while performed by using this methodology, which in pour particular case provides a series of limitations.

5.3.1 Model Description and Limitations

To model the variation of each chamber volume with shaft rotation, the gear set's geometrical parameters are necessary. Once the geometrical parameters are known, the volume profile or variation in the volume of any chamber with shaft rotation can be generated as seen in Figure 5.5, where a custom Simscape component is used to model a variable-volume liquid chamber represented in green. The derivative of volume for the corresponding chambers with the rotation angle can also be obtained. These two profiles must be provided directly to properly customize the model according to the desired functioning, and are necessary for the simulation of the model in addition to being derived from geometrical parameters. This chamber is connected to two mechanical rotating conserving ports in order to compute the isothermal liquid port and angular velocity.

Each liquid chamber's isothermal liquid ports are additionally connected to an inlet port orifice and an outlet port orifice. The inlet and outlet port opening areas to which the chamber is exposed during pump rotation are represented by these orifices, which are modeled using a different custom Simscape component. These ports are shown in the same Figure 5.5 with the blue of their respective domains. This component is connected to two isothermal liquid ports and one rotational angle port. The appropriate variation must be applied in the inlet and outlet orifice areas for any chamber that has a rotating shaft.

This same strict geometric dependency in its parameters, which allows the model the possibility of delivering an accurate and reliable representation of the component behavior in a real physical environment, is the same characteristic that

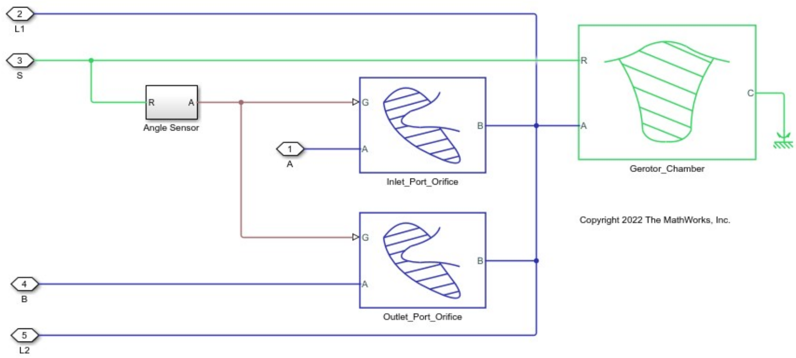


Figure 5.5: Modeling of the inner chambers and orifices according to the geometry parameters of the gerotor pump by MathWorks. Note: Adapted from *Gerotor Pump.* by MATLAB & Simulink - MathWorks Italia [22].

limits its use in our case of study since the high detail in the geometric information of the pump is not available. During this project, we use the data provided by the client and its respective suppliers for the system under development, but the amount of information that we are able to access is limited by what the suppliers are willing to share. For them, the release of this particular knowledge is highly sensitive, since comprehending the intrinsic geometry of the pump will make it possible to be duplicated in its construction. The reason why, due to the lack of information it was almost impossible to properly fit this representation of the gerotor pump model into our particular needs, having massive differences in the performance and the construction of the pump, making it difficult to adapt the representation in hand to the component desired by the client.

Even by trying to fit the equations of the model, it was impossible to properly fit the model to our component, needing to know some basic information that if not given by the suppliers, should be measured from a real component or making necessary a whole design of a pump to properly assume and obtain feasible values. The measurement approach was the one chosen by Pellegri et al. in the referenced paper, where they performed different measures with the use of metrology software to generate the needed CADs of the pump in order to accurately represent the geometrical parameters needed for the prediction of the leakages, chambers, and more. Regardless, in our case, this is not a feasible option over this stage of the project, due to the reasons previously explained about the difficulties in the acquisition of a physical component.

However, this model still provides us some guidelines for future steps of the project that will continue to be performed outside the scope of this report, but for now, the focus is given to analyzing the behavior of this representation besides the differences with our system, one of the main ones being the number chambers,

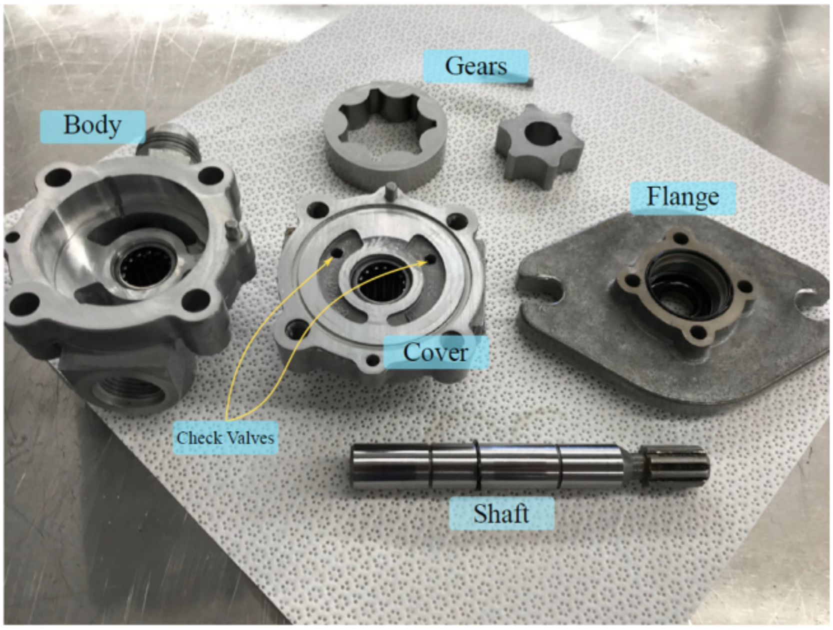


Figure 5.6: Physical gerotor pump decomposition performed by Pellegri et al. Note: Adapted from 2020 paper, *A simulation model of Gerotor pumps considering fluid-structure interaction effects: Formulation and validation.*. by Pellegri et al. [9].

this model is based in a pump with six chambers, which is a design commonly used for this component, however, our system opted for the choosing a component particularly designed for this application with four chambers instead. Regarding the additional components of the hydraulic system, the model analyzed by MATLAB considers some elements such as the heat exchanger, some accessories, and more, which are useful to observe its representation in a computational simulation environment. This information is kept in mind for the development of the model as a load in the hydraulic circuit for the components that are represented in the EqValve. (which are the WTOC, eMotor, and Axle, as previously explained).

5.3.2 Model Behavior and Characterization

To analyze the behavior of our final model in a simulated environment, this is represented in Simulink by adapting the gerotor pump for its functioning with our particular architecture, in Figure 5.7 it can be observed how the system works in a way that by performing a change in the angular velocity of the pump by stimulating the rotational source, we can control its performance in the delivery of flow and pressure. Analyzing this model one can see how it behaves at different

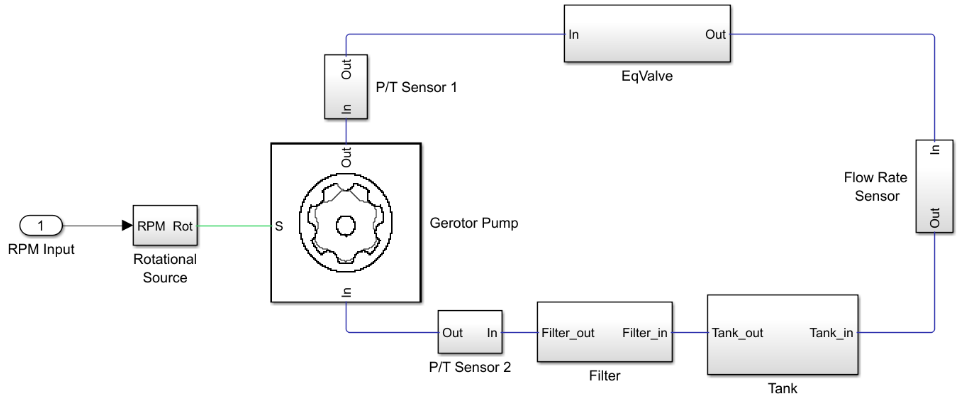


Figure 5.7: Final Model Simulink representation. Integrating the gerotor model with the final model architecture.

speeds, allowing us to characterize it. To properly understand how this system performs under diverse performance requirements. This characterization process can be appreciated in Figure 5.8.

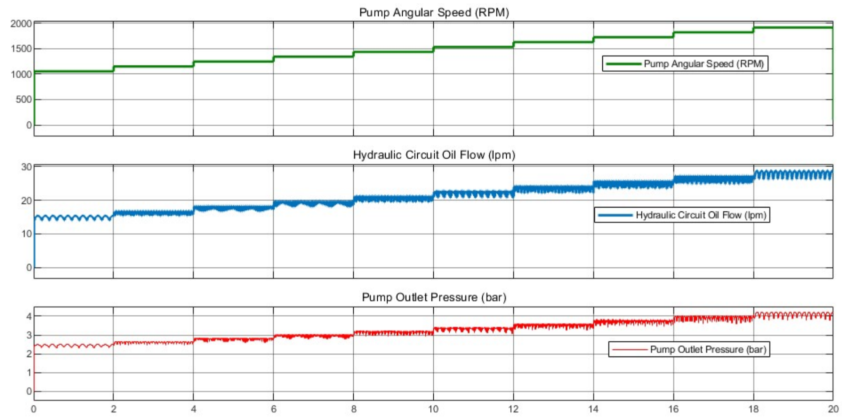


Figure 5.8: Characterization Process.

This characterization is done by generating a series of step increases over an input signal of RPM to the pump shaft, starting from around 1000 RPM, up to close the 2000 RPM, these values were chosen by looking at the pump performance and trying to keep it into the operational range of our system while adapting it to obtain the desired behavior within the system present.

During this characterization process, we can see how the system behaves in an almost completely linear way to the RPM input, However, something concerning arises while looking up close to the information measured by the sensors, in Figure

5.9 we can observe the presence of some harmonic oscillating disturbances that increase in magnitude and frequency as the RPM increases. This oscillation could be acceptable up to some point since the system could physically deal with this, but in our quest for accurate and reliable control of the system, the oscillation provides a significant change in the magnitude that should be adjusted for the controller in order to provide precise response, this variation in value occurs in such high frequencies at high speeds that could result in a faster computation time needed than the one capable of being done by the controller, which is of 0.01 seconds for this system.

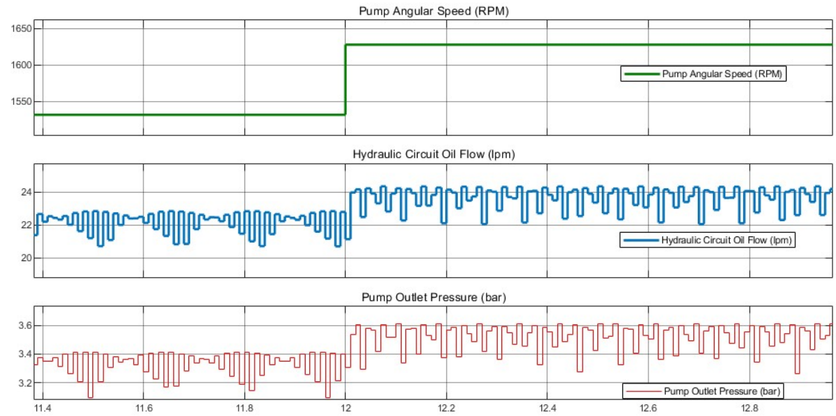


Figure 5.9: Presence of Oscillating Disturbance.

This presence of the oscillation in the system is a characteristic of this pump that depends directly on the geometry of the component, and as stated before, all the aspects related to the geometry represent a bigger challenge due to the lack of information. This ultimately provides a system that can not be completely accurate, but only up to some point, where performing the fitment of the existing data and trying to fill the gaps of information with the one belonging to another system is not feasible as an option to completely rely on.

5.4 Modeling of Additional Components

Based on the Simscape representation made in Simulink, it was possible to use some of the work from Model Approach No.1 and fit it to our particular needs, more specifically in the representation of the filter, the tank, and the components that conform to the EqValve, allowing us to validate the right assumption of one equivalent component responsible of representing a group of elements of the system.

5.4.1 Sensor Signal Discretization

An important aspect to take into consideration is the combination of components of different domains in an integral system, where we perform measurements of physical signals, behaving in a continuous time regime, with the use of digital elements, working in a discrete-time, this means that the fluidity and similarity of the measurements depend of the sample time of the system and the component. This is an important feature since this sample time is responsible for the particular shape of the oscillations visible in Figure 5.9, To correctly model this, one needs to use a triggered subsystem in charge of enabling the value obtained according to the sample time specified, which is 10ms in our system, This sample time indicates that every 0.01 seconds, the controller will acquire the information measured by the sensors and also perform the logical computations needed for the proper functioning of the system.

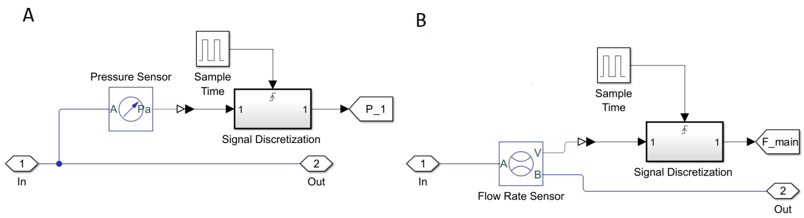


Figure 5.10: Signal Discretization.

In Figure 5.10, we can observe how this discretization is performed in the P/T Sensor and in the Flow Rate sensor, where the triggered subsystem is located right before the tag that carries the value measured. As seen by the blue color representation, the system is a physical component, meaning that must always behave in a continuous time domain, therefore, it can not be discretized but only the measurements taken upon him, just like it happens in real scenarios. Another important clarification is that despite being a P/T Sensor, only the pressure measurements are relevant at this stage of the project since, as previously explained, we are working under constant temperature assumptions, the reason why the library of isothermal components is the one used during this project, instead of the one corresponding to thermal liquids.

5.4.2 Filter Model

For the modeling of the filter, located at the suction port, a subsystem is created to group all the respective components that conform the upstream of the gerotor pump, as depicted in Figure 5.11. An orifice that represents a pressure drop across a filter, bends, abrupt area changes, and pipes are all used to model the inlet system. These elements are responsible for the pressure drop upstream of the pump. This particular representation is based on Model Approach No.1 developed by MATLAB.

Figure 5.11: Filter Subsystem Representation According to MATLAB & Simulink.

5.4.3 EqValve Modeling and Validation

Regarding the modeling of the EqValve used in the final layout of the model under study, the representation of the components made by MATLAB & Simulink, Figure 5.12, was used as a starting point during the generation of our model for this element.

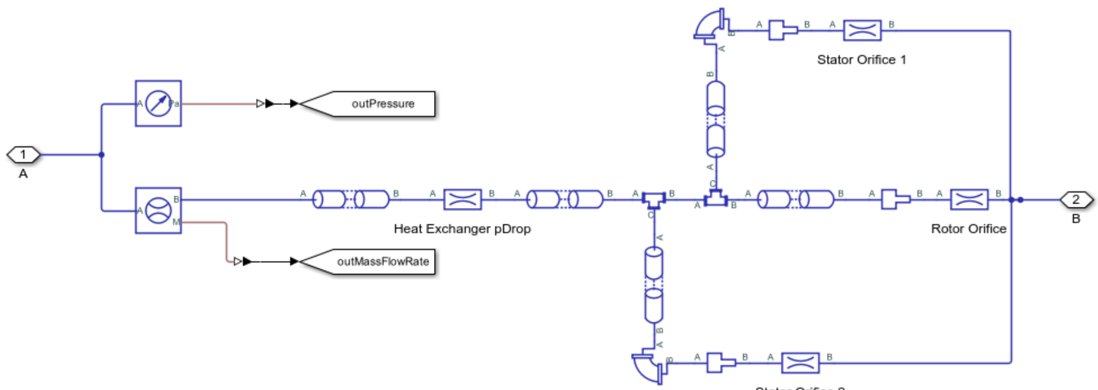


Figure 5.12: Modeling of the Load Components Conforming the Hydraulic Circuit by MathWorks. Note: Adapted from *Gerotor Pump.* by MATLAB & Simulink - MathWorks Italia.[22]

Following the reasoning previously exposed during the third chapter, it is accurate to approach the idea that the blocks representing individual elements, such as the eMotor; the Axle; and the Heat Exchanger (WTOC), as depicted in Figure 5.13(A). It is equivalent to the use of only one block capable of integrating the accumulative load in the system in order to simplify its architecture, as seen in Figure 5.13,(B).

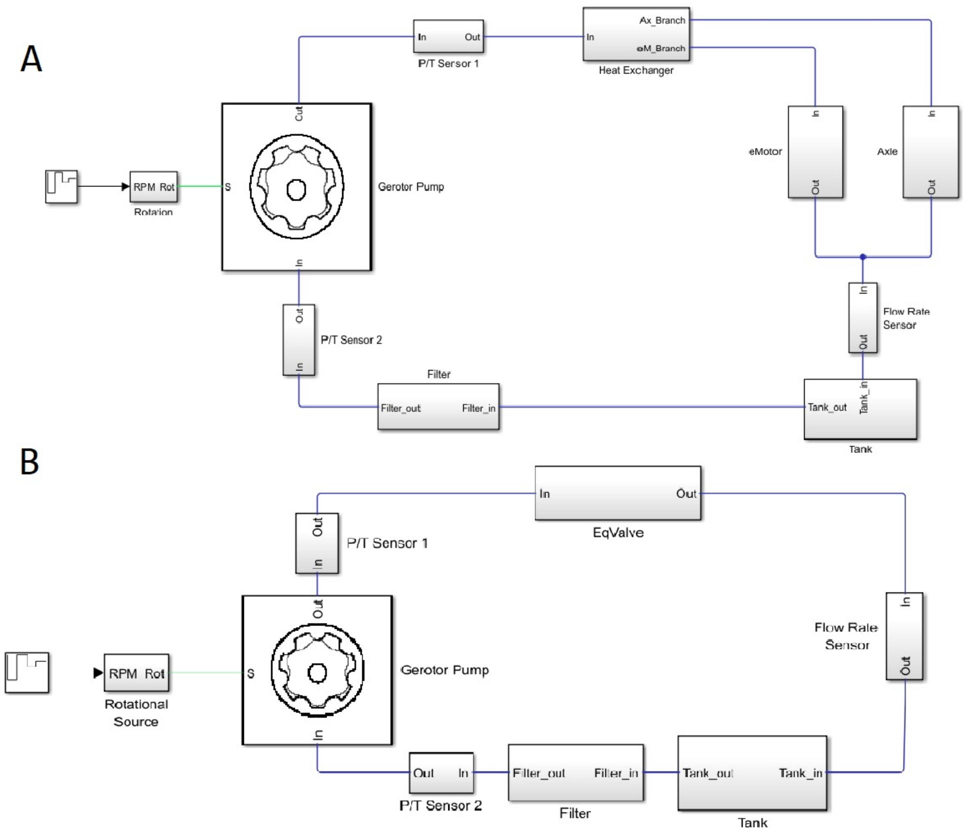


Figure 5.13: Generation of the EqValve Block Based on Individual Components.

While performing a decomposition and behavior analysis of the individual components seen in Figure5.13(A). In order to validate the architecture simplification, the detailed view of each component that will be regrouped into the EqValve is provided in Figure5.14, being (A) the WTOC, (B) the eMotor, and (C) the Axle. Some additional measurement instruments are added to properly acquire the information needed for the analysis. However, these instruments have no further incidence outside this section, reason why they are not included in FMEA analysis or in the discretization of their signals.

5.5 Model Approach No.2

To properly describe and model our pump, there is a need to break the dependency link to the geometric information required, so instead of relying exclusively on known theoretical concepts, one can find a way to build models through the analysis and learning of patterns from data. This is where the data-driven model design

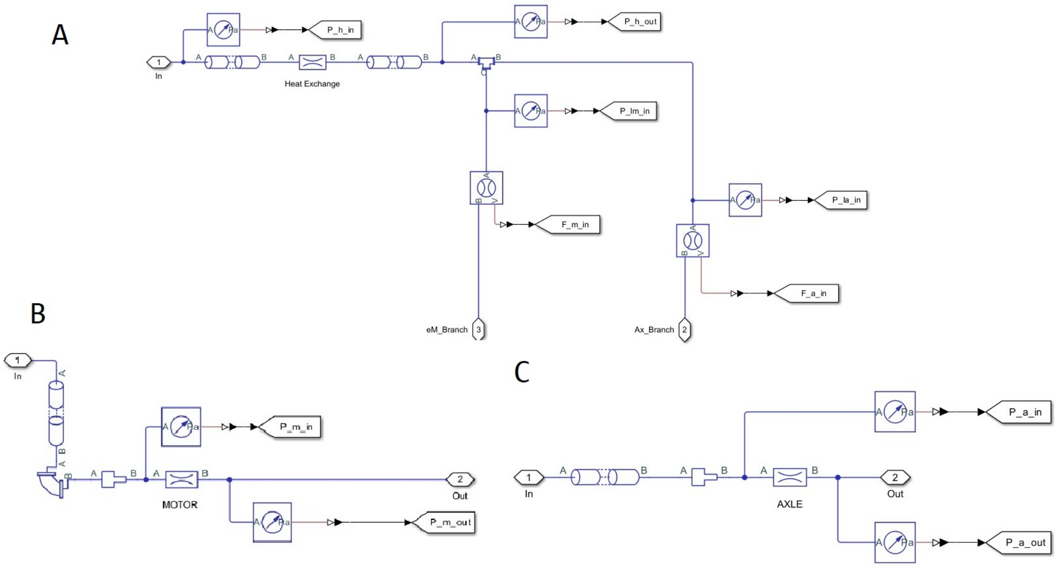


Figure 5.14: Representation of the WTOC (A), eMotor (B), and Axle (C).

could bring a solution, which allows us to use information regarding the behavior of the pump during its operation as a way to provide details about the basic performance of this component under an experimental testing condition made by the supplier of this component.

5.5.1 Data-Driven Model Design

In the field of modeling and simulation, data-driven model design is a novel approach where the main goal is to derive knowledge and insights from empirical data in order to create models. Compared to traditional theory-based modeling, which mainly relies on accepted scientific and mathematical principles, this approach is different. Data-driven modeling makes use of methods like artificial intelligence, machine learning, and statistical analysis to find relationships, patterns, and trends in data sets that theoretical models may not be able to fully or immediately explain.

Complex system modeling can be accomplished pragmatically and effectively with data-driven model design, especially when lookup tables are used. This design methodology relies heavily on lookup tables, which provide a simple and direct way to add empirical data to models. Encapsulating real-world observations and measurements in a format easily utilized for computation, they are essentially structured data sets from which values can be retrieved based on input parameters.

The first step in the procedure is gathering and preparing the data, which is then arranged into these tables. These tables can show a variety of relationships, like how a system component reacts to different operating circumstances. In our example, an oil pump's lookup table might include information derived from operational or experimental data that correlates with the pump's speed, pressure, and flow rate.

Lookup tables have various benefits when used in data-driven modeling. It eliminates the requirement for substantial mathematical modeling and enables the inclusion of intricate, non-linear relationships. This method saves time and lowers the level of expertise needed to fully comprehend the underlying physical processes. It also offers a high degree of flexibility; tables can be added to or updated in response to new data, which lets the model develop and get better with time.

However, using lookup tables exclusively has its drawbacks. The caliber and extent of the data utilized to generate the tables have a significant impact on the model's accuracy and comprehensiveness. Inaccurate models can result from incomplete or biased data, so rigorous validation and testing against real-world scenarios are essential. Moreover, lookup table-heavy models might have trouble extrapolating outside of the data range that is available, and sophisticated interpolation techniques might be needed for the best results.

5.5.2 Model Construction

In order to properly represent the system behavior in a simulated environment, we use experimental data provided by the supplier of the pump. This data provides information about the pump's behavior under different situations, focusing on Flow Rate [lpm] and Power [W] response while changing the operational pressure of the system and its input angular speed. This information is then analyzed in order to create a functioning map capable of feeding the data needed to the lookup table responsible for representing the system. To accurately describe our system behavior four maps were generated, each of them depending on two variables. The first of them, Figure 5.15, is responsible for providing the RPM needed in the function of the Flow Rate and the Pressure, the same values that also dictate the power needed according to the second map, Figure 5.16. These first two were generated by using a linear interpolation methodology, and are linked to another two validation maps, this time generated with the most complex cubic spline interpolation, depending on these previously output values, which now are the ones that help predict if under these conditions of angular speed and power, we are actually obtaining the desired Flow Rate and Pressure, Figure 5.17 and Figure 5.18 respectively. This described link between the different maps can be observed in Figure 5.19, which provides the integration of the maps with the use of Simulink lookup table blocks. A saturation block is also used to prevent obtaining a value outside the operational range of the system.

For the generation of the maps, we take the data from our suppliers regarding the behavior and performance of a pump capable of fitting our needs, more specific

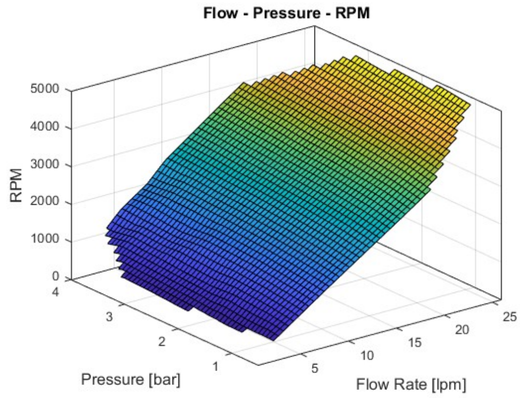


Figure 5.15: RPM as a function of Flow Rate and Pressure.

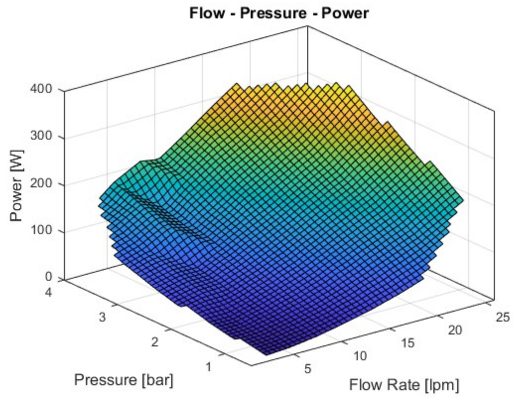


Figure 5.16: Power as a function of Flow Rate and Pressure.

information about the data and the computational processing cannot be shared due to confidentiality. The information is then analyzed to properly prepare the surface data over which a linear or cubic interpolation fitment will be applied, to then proceed with the generation of a mesh taking into consideration the operational range of the system.

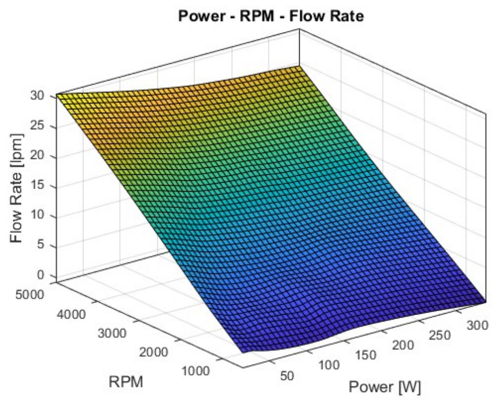


Figure 5.17: Flow Rate as a function of Power and RPM.

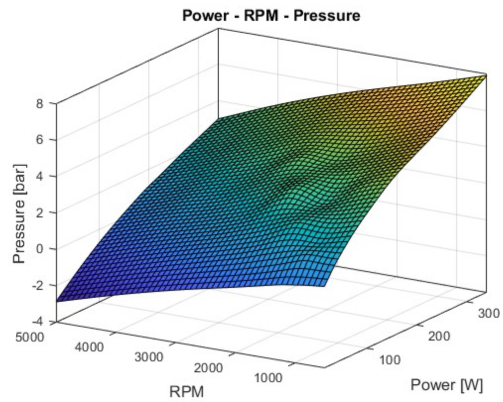


Figure 5.18: Pressure as a function of Power and RPM.

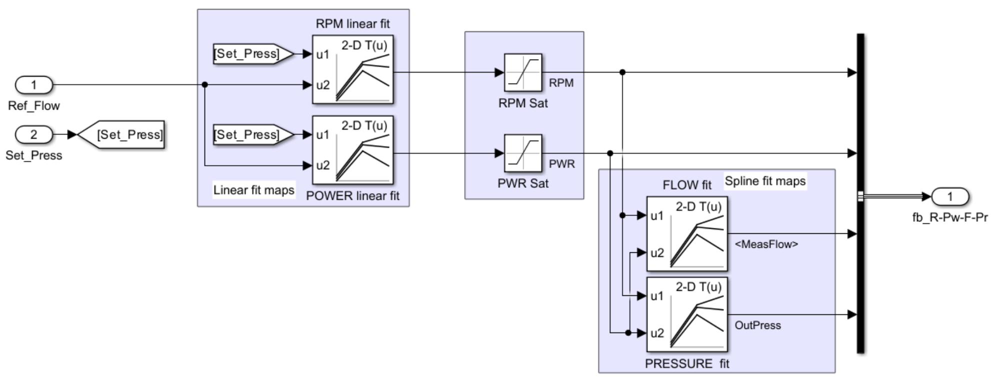


Figure 5.19: Integration of the Maps into Simulink Lookup Tables.

Chapter 6

Communication and Control of the System

Once we properly understand the functioning and behavior of the system, we can proceed to look for a way to control it. In order to accurately determine the overall expected functioning of the system we need to focus on the core component of the hydraulic circuit, which is the ePump as previously mentioned. This component is responsible for generating an oil circulation in the system, and also for managing the pressure and flow rate at which this oil will be flowing inside the circuit. Having a Component capable making circulating a fluid under controlled conditions in order to properly reach the desired values of operation, is crucial for the adequate functioning and reliability of the system, therefore, it can be understood the importance of this stage of the project.

While controlling a pump, we are able to determine the condition of the fluid being pumped, limited by the performance and capabilities of the component. A gerotor pump, functions based on the rotational energy supplied to the inner gear, as previously mentioned in section two, by controlling this rotation (angular speed of the shaft), we are able to directly affect the pressure and flow rate of the fluid delivered into the system. In conventional vehicles and other applications where the oil pump is directly connected to the ICE, the rotational speed of the pump shaft depends on the rotation of the engine crankshaft due to its physical-mechanical connection. However, in an ePump, this connection does not exist, so there is the need for a motor that provides the needed rotation to the pump shaft. this motor is usually a Brush-Less DC (BLDC) motor that is integrated into the ePump housing, normally included in commercial ePumps and practically being part of "one" same component.

Controlling the angular speed of the pump depends on the way that the manufacturers of the ePump integrate the BLDC in the construction of the ePump as a component, more specifically in the communication protocol integrated into this one. There are a diverse number of ways that the pump can communicate with the main ECU of the vehicle, among the most common are the Pulse Width Modulation (PWM), the CAN (Controller Area Network) bus, and the LIN (Local Interconnect Network) bus.

6.1 Pulse Width Modulation

One technique for regulating the speed of electric motors, such as ePumps, is pulse width modulation. To change the amount of power supplied to the motor, it modifies the electrical signal's duty cycle. By varying the length of the "on" pulse within a set signal frequency, the speed of the ePump can be adjusted. Speed increases with longer "on" pulses and vice versa, Figure 6.1. This allows basic ePump speed control based on preset parameters or straightforward sensor inputs.

Even though PWM is useful for basic speed control, it isn't sophisticated enough to adjust to changing engine demands, particularly in complex systems like those found in electric or hybrid cars. Additionally, the integration of PWM modules into ePumps provides some other limitations, one of them being the lack of two-way communication for diagnostics, having only a tachometer output as an RPM feedback signal.

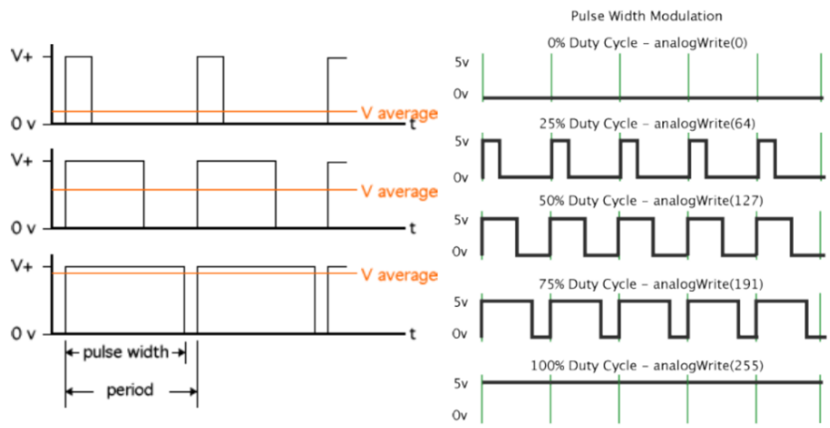


Figure 6.1: Pulse Width and Duty Cycle variation. Note: Adapted from *Design-Build-Code: Engineering Projects* [23].

6.2 Smart Pumps

Through the integration of more complex sensors and control algorithms, smart ePumps go beyond basic PWM control. Modern sensors built into Smart ePumps track a number of variables, including temperature, flow rate, and fluid pressure. Even though PWM is useful for basic speed control, it is not sophisticated enough to adjust to the changing engine demands, particularly in complex systems like those found in electric or hybrid cars. Complex algorithms are used by these ePumps to dynamically modify their operation in response to engine demands in real-time, maximizing efficiency and performance. Smart ePumps are capable of communicating with other vehicle systems for predictive maintenance and diagnostics in addition to operational control, this communication is done by protocols like CAN or LIN. Figure 6.2 provides the component view of a commercial smart ePump, highlighting the different parts, including its internal ECU and the signal plug for CAN connection in this particular model.

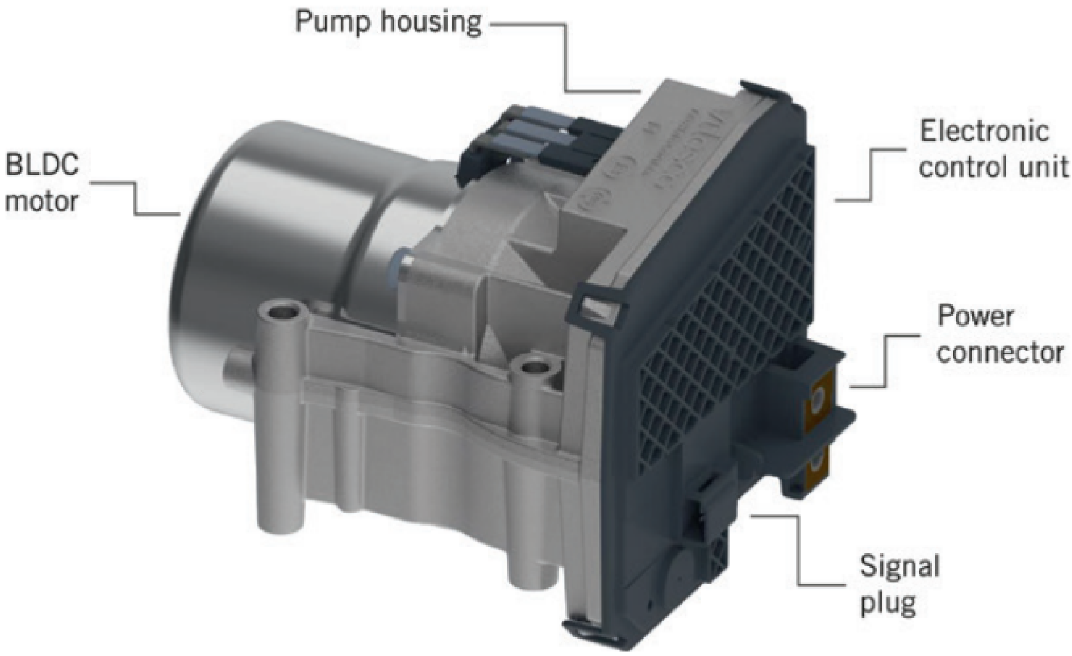


Figure 6.2: Component View of an ePump by *Vitesco Technologies* [24].

By performing in a more capable and efficient way, allowing for an improvement in the control of the system, while at the same time providing the possibility of data acquisition for diagnostics and improving reliability, it is clear why this is the path to take, and the one that many other companies are setting their eyes on.

6.2.1 Selection of the Communication Protocol

Knowing that for powertrain applications, the choice of a smart ePump is the path to take, the only matter in hand is to select which communication protocol to use, whether it is CAN or LIN the one that fits better with the system requirements.

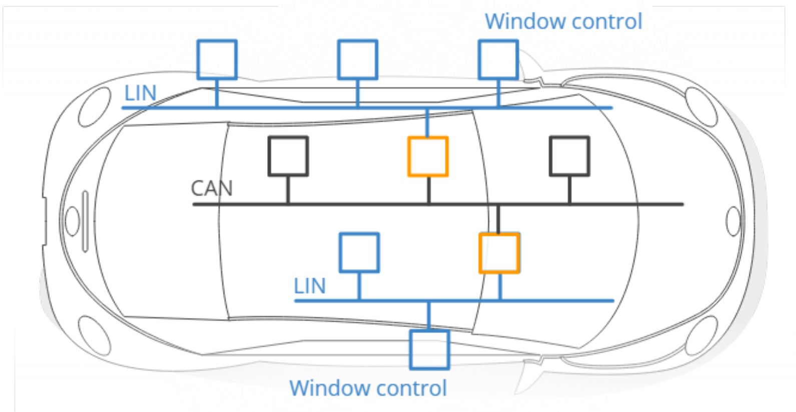


Figure 6.3: CAN and LIN as Communication Protocols in a Vehicle. Taken from 2021 Electronics [25].

CAN Protocol Overview

CAN is a powerful vehicle bus protocol, created to let micro-controllers and other devices talk to one another inside a car without the need for a host computer. A multi-master serial bus architecture is used by this protocol, it follows that every device on the network has the ability to communicate with every other device. This is illustrated in Figure 6.4

Although they can change, data transfer speeds normally go up to 1 Mbps (megabit per second). In order to preserve signal integrity over longer network lengths, the speed may be reduced. CAN controls message priority through non-destructive arbitration. Priority is assigned to messages with smaller identifier fields, guaranteeing that important messages are delivered first.

This protocol includes advanced error detection techniques, such as in-frame checks, bit stuffing, and bit monitoring. CAN also possesses error counters in network nodes designed to minimize the effect of a malfunctioning node on the network as a whole. When these counters surpass predetermined levels, the node will go into a "bus off" state.

The CAN network allows a large number of devices, including sensors, actuators, and control units, to be connected. Adding more nodes to the network is a simple

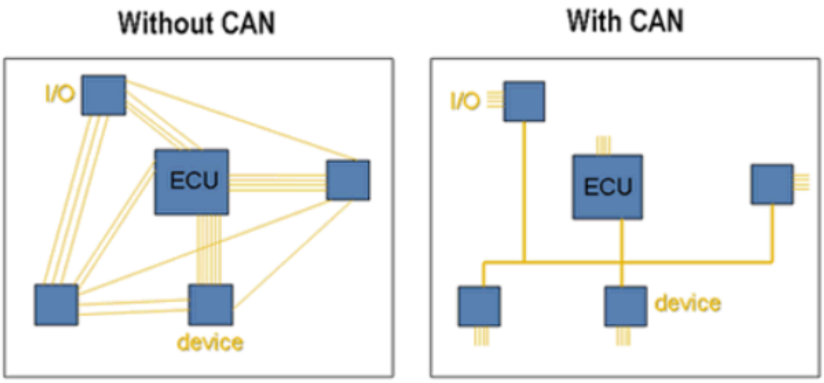


Figure 6.4: Effect of CAN on Automotive Application Note: Taken from: *CAN Bus Protocol - 10 Minute Lesson* [26].

way to expand it without making major infrastructure changes. However, the addition of a large number of nodes may difficult to ensure the integrity of the network. This protocol is used in cars to connect sensors, actuators, and electronic control units (ECUs) for a variety of systems, including airbags, ABS, engine control, and more.

Due to its capacity for fault confinement and error detection, this protocol counts with a high reliability. Another of its advantages is the reduced wiring, since multiple signals can be sent over a single bus, resulting in a physical installation with a reduction in complexity and weight. One advantage that is particularly important for our system, besides the reliability, is the capability of use in a situation where real-time data transfer is necessary.

LIN Protocol Overview

Most commonly used in automotive applications, LIN is a low-speed, serial communication protocol that is inexpensive. It is an adjunct to the faster and more intricate CAN protocol. LIN was created mainly to manage basic devices in response to the increasing expense and complexity of automotive networks. It is intended to facilitate communication between actuaries and smart sensors or between different automotive subsystems.

LIN operates with a configuration of one master and several slaves. Multiple slave nodes are under the control of a single master node. Up to 20 kbps (kilobits per second) is the typical data rate for LIN, which is adequate for less important communication tasks. Compared to systems like CAN, it frequently uses a single wire (plus ground), which lowers wiring complexity and cost. LIN lacks the complex error handling and fault confinement mechanisms found in CAN, even though it has error detection with the use of checksums, which are a basic form of error detection included in each message frame. In vehicles, it is frequently used to operate the seats, windows, mirrors, rain sensors, and other less important features.

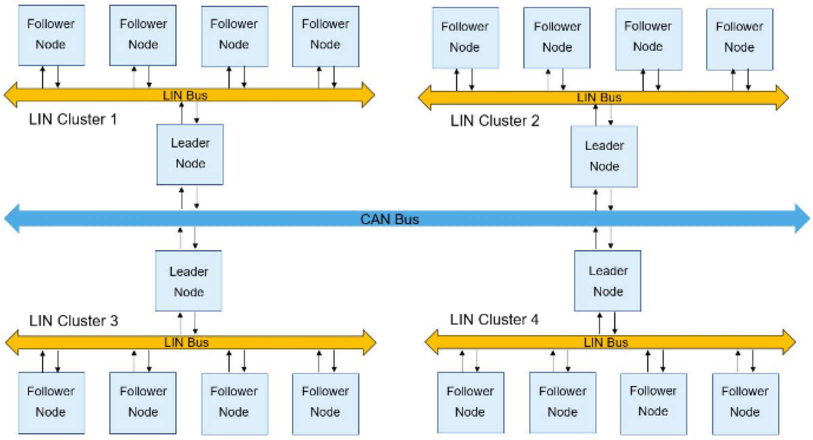


Figure 6.5: LIN in a Vehicle Note: Taken from *Local Interconnect Network (LIN)*, 2023 [27].

Final Decision for the Smart Pump Communication Protocol

According to their particular characteristics, CAN is a reliable, fast communication protocol primarily utilized for vital automotive systems, having a higher fault tolerance and can handle large amounts of data compared to LIN, which is a more direct, economical protocol appropriate for less important vehicle functions. Though slower than CAN, it works well enough for basic tasks, which is not the case at hand. The capabilities of CAN to process more extensive quantities of data at a faster speed, make it appropriate for critical systems, leaving LIN to be used in non-critical applications. The reason why CAN is frequently preferred for the integration of a smart ePump into the powertrain cooling and lubrication system. It is appropriate for crucial engine operations due to its robustness and higher data transmission speeds.

6.3 Control Overview

Once we have defined the way that the smart ePump will communicate with the other components, we need to address how this information is managed in order to properly control the behavior of the ePump.

Using a smart ePump simplifies in great measure the task at hand since this component possesses an internal ECU capable of performing the necessary computations without needing to connect directly to the main vehicle ECU. This internal control unit takes the reading from the sensors as an input to properly calculate the rotational speed needed in the pump for delivering the fluid under the desired conditions.

This process is linked to the behavior obtained while interacting with the model represented in Figure 5.19, which represents the performance of the pump. During the design of the system, it has been specified some operational points regarding the conditions of the hydraulic circuit. These are responsible for dictating how the system should function, and depend on what kind of disturbance his operation should vary.

During continuous operation, the system should operate under a constant pressure of 2 bar, and a minimum flow rate of 10 lpm, where is established according to the pump performance that the power used should be approximately 110 W. In the presence of a distribution, the system should be able to continue operating under acceptable conditions, being the control in charge of keeping the system in check and regulating the angular speed of the pump to properly adjust the system to the desired conditions.

During this control, it is crucial to count with a closed-loop control scheme capable of having feedback from the model to accurately monitor in real-time the conditions of the system. However, as part of the general behaviors of real-life systems, whenever a change is imposed it is never instantaneous. This is because there is always a delay, especially while analyzing hydraulic circuits where the variation of conditions depends on a series of effects like the pump motor reaching the desired speed, the oil flow resistance through the system, and more. The knowledge of this delay is crucial to properly control the system, especially while performing a simulation since the conditions of the delay must be known. The delay must be introduced into the model while during a real-life event, this delay can be measured. This is one of the biggest limitations for developing an accurate control during this stage of the project since we are facing a lack of data available regarding the system response. Although we have some information related to the delays given by measurements taken during testing system phases by the suppliers, this information is not yet complete. The lack of information leaves a significant absence of data since what we have obtained is not enough to perform accurate simulations.

The control methodology has been studied and tested up to some extent preparing for the arrival of the new data in order to continue with the project, but a complete control logic will have to wait until later stages of development of the project.

Chapter 7

Conclusion and Future Work

One important aspect of this study relates to the way the project is being performed, from the moment it was planned, and how this one evolved throughout the different stages of development. Starting from the analysis of the general functioning, to then proceed with focusing on a particular component. Not leaving aside the way in which this should be addressed, with the implementation of different standards and methodologies that validate the right procedure, for proper compliance of requirements in a commercial environment, allowing to perform an extensive analysis with the certainty of having handled all needed conditions demanded by the automotive sector in the area of functional safety and the system reliability.

Summarizing what we have achieved during this stage of the project, we have been able to identify and isolate a situation that allows us to solve a problem and improve the status of a system regarding its reliability. Addressing it from different angles, such as the architecture of the hydraulic circuit, the selection of the critical components, the way they should be controlled or managed, and making special focus on the FuSa and FMEA, following their respective norms and guidelines to ensure correct compliance with the commercial standards.

This study sets a cornerstone for a much larger project that will continue to be carried out in the company beyond the reach of this report. Setting the basis and fundamentals regarding the system functioning, architecture, components, reliability, and behavior. By analyzing the system and carrying forward the design of what started as a physical test bench, we now count on a proper model designed while taking into consideration the system requirements and limitations, paving the way for further steps to be performed, and expanding the project until it reaches the final goal.

The first thing that should be addressed when continuing with the project would be to solve the complications that were presented for us, such as the lack of data in case is desired to create a new model for simulation analysis; or the long delivery times from the suppliers, combined with the high costs and the construction challenges previously mentioned.

There are some different approaches that can be taken to proceed with the project and move forward with the next steps. One option is to continue in a simulated environment. But this time, moving outside of the continuous operation conditions and introducing changes in the oil temperature due to diverse and more extreme scenarios. Another option would be to continue under the same conditions, but this time proceed to the physical construction of the system, in order to properly evaluate the real behavior, and at the same time, have access, through the use of measurements, to some of the non-available data that might help fill the gaps found during the modeling process. Ultimately, being able to have an integral test and simulation environment capable of studying the behavior of this component in every scenario and a simple integration of the change of components to properly test other elements as different pump performances or different load conditions: All this being done through a software level, with the integration of a more complete computational model, working alongside the its physical representation, performing studies containing different types of test and parameters variations.

Appendix A

Appendix

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