POLITECNICO DI TORINO

**DIMEAS - Department of Mechanical and Aerospace Engineering**


MASTER OF SCIENCE

IN

AUTOMOTIVE ENGINEERING

Master's Thesis

# Design of autonomous steering actuator for Formula Student Driverless car


**Supervisors:**
Prof. Nicola Amati
Prof. Andrea Tonoli

**Candidate**
Sarath Babu Nagarajan
240155



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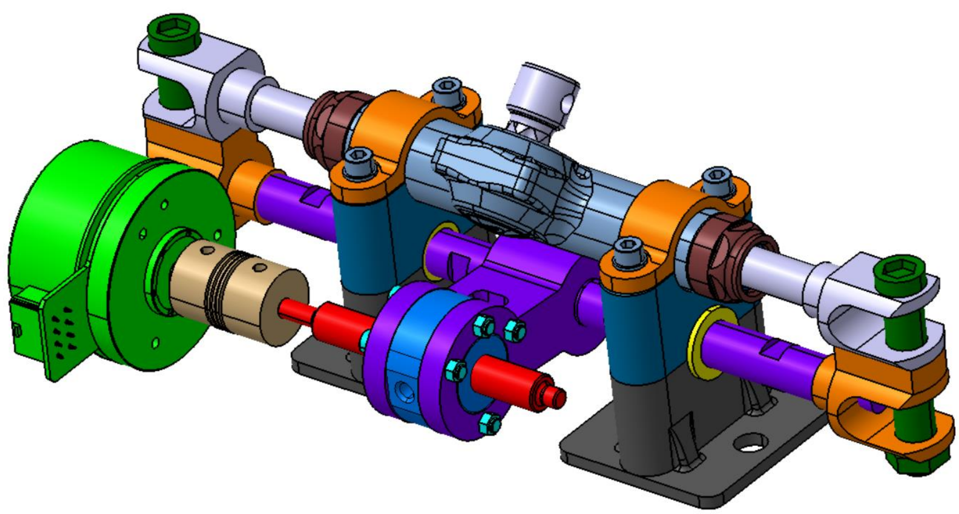
# Abstract

Formula Student is a design competition for engineering students across the world where students design and manufacture a functional prototype of a single-seater formula-car. In 2017, Formula Student Germany (FSG) was the first to introduce Formula Student Driverless (FSD) class where a Driverless Vehicle (DV) performs a series of events autonomously without any human control. The 2019 Formula Student car of Squadra Corse (SC19 – Lucia) is a fully electric car and will be converted into a Driverless Vehicle which will be steered by an electro-mechanical steering actuator controlled autonomously by an on-board controller. The vehicle's Autonomous System (AS) shall ensure that the car is being steered autonomously to have manageable handling coupled with good acceleration and braking capabilities at any given point in the test circuit. The system must also comply with the Formula Student Driverless 2020 regulations and must enable the car to perform in the various static and dynamic events of Formula Student Driverless competition.



The steering system in Desy is a custom-designed mechanical rack and pinion steering with a gear profile similar to a herringbone gear. The proposed autonomous steering system comprises of a power unit and a transfer unit. The power unit comprises a BLDC motor coupled with a planetary gearbox rigidly coupled to a ball screw shaft over which a ball nut is engaged. The ball screw and nut mechanism convert the rotary motion from the gearbox to linear motion to the ball nut. The transfer unit comprises a block connecting the ball nut and actuator link which in turn connects the clevises on the rack ends. These clevises connect with the steering tie rods

on both ends and turn the front wheels. A brief explanation about the conceptual Failure Mode and Effect Analysis (FMEA) will also be covered in the thesis.

The choice and design of actuator system is governed by several parameters such as the space constraints inside the cockpit, actuation rate of the steering to replicate driver usage, duty cycle of actuator operation, existing powerpack available in the car to power the actuator and preliminary structural analysis of the configuration through experience to name a few. Also explained in this thesis are several other design ideas, the reasons why they were not considered and why this solution is the best of them all with also the way forward in development of Autonomous Steering System for FDSV.

## Acknowledgement

To start with, I would like to thank my supervisors Professor Nicola Amati and Professor Andrea Tonoli for giving me an opportunity to work on Formula Student Driverless project. I am thankful to Angelo Bonfitto for his mentoring during the course of my thesis. I would like to thank Edoardo and the Squadra Corse team for their insightful guidance on the technical and practical aspects during each step of the project and providing valuable insights based on their experience in the team. My special thanks to my colleagues at LIM for having supported with resources and help as and when needed.

Most of all, I extend my heartfelt thanks for my family and friends who supported me academically and personally during the course of this thesis.

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# Abbreviations

AD - Autonomous Driving

ADAS - Advanced Driver Assistance Systems

AS - Autonomous System

ASMS - Autonomous System Master Switch

ASR - Autonomous System Responsible

ASS - Autonomous Steering System

BLDC - Brushless Direct Current

CAD - Computer Aided Design

CAN - Common Area Network

CFT - Cross Functional Team

CV - Combustion Vehicle

EV - Electric Vehicle

FEA - Finie Element Analysis

FMEA - Failure Mode and Effect Analysis

FS - Formula Student, 13

FSAE - Formula Society of Automotive Engineers, 28

FSDV - Formula Student Driverless Vehicle, 17

FTA - Fault Tree Analysis, 77

GD&T - Geometric Dimensioning and Tolerances, 79

ODD - Operational Design Domain, 21

R2D - Ready to Drive, 23

RPN - Risk Prevention Number, 82

RQ - Research Question, 17

SA - Steering Actuator, 36

VDA - Verband der Automobilindustrie,

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Chapter 1

# Introduction

This chapter deals with an introduction to this master's thesis. It gives a brief idea on autonomous cars, why they are considered a viable transportation option of the future, about Formula Student competition and the scope of the thesis in development of a Formula Student Driverless Vehicle (FSDV). The Autonomous Steering System (ASS) is to be implemented on the already existing electric 2019 Formula Student (FS) car '**SC19 – Lucia**' developed by Squadra Corse, the Formula Student team of Politecnico di Torino. Initially, the ideas were formulated for Squadra Corse's 2018 FS car '**SC18 – Desy**' which has a slightly different configuration but later adapted to Lucia. The cars shall be addressed as '**Desy'** and **'Lucia'** throughout this thesis in order to instil a sense of belonging and attachment to the project and the cars. The design ideas were 3D modelled in CATIA™ v5 by Dassault Systèmes. Also, the thesis will be dealing with Formula Student Germany (FSG) and Formula Student Driverless (FSD) competitions both taking place at Hockenheimring racing circuit in Germany.

## 1.1 Background

Food, water and shelter are the three basic necessities for mankind over which every civilization in the world has developed. But these necessities cannot be fulfilled if man stays in a single place. So, man started moving to different places and at some point, moving from one place to another in order to fulfil the three basic necessities became tedious. Thus, it gave rise to the invention of the wheel as it is rightly quoted 'Necessity is the mother of invention.' Over the years, necessities increased and so did the inventions. It was during the 1800s when Germany and France invented and perfected the first working models of our today's automobile. Over the span of the last 100 years, automobiles saw one of the most rapid developments in the field of transportation. Number of cars on the road increased and so did the number of accidents.

Safety thus became a matter of top priority for car manufacturers and new inventions in active safety such as Advanced Driver Assistance Systems (ADAS) and passive safety such as advanced crumple zones helped minimise road accidents and it's repercussions as they are one of the top causes of death worldwide. Research [1] states that driver-related behavioural factors contribute to the occurrence of 95% of all road accidents. The behavioural factors could be distinguished as those that reduce the capability of a driver on a (i*) long-term basis* such as aging, inexperience, diseases, drug abuse and alcoholism, (ii) *short-term basis* such as drowsiness, fatigue, acute alcohol intoxication, short-term effect of drugs, psychological stress for a short duration and most of all temporary distraction, (iii) *those that promote risk-taking behaviour with long-term impact* such as reckless driving, overestimating one's capabilities, habitual speeding and disregard for traffic rules on public roads, not using seatbelts or helmets, inappropriate driving posture (iv) *those that promote risk-taking behaviour with short-term impact* such as moderate intake of alcohol, suicidal thoughts and behaviour, intake of psychotropic drugs, motor vehicle crime.

It is apparent that the idea of developing driverless cars arose from the immense contribution of human behavioural factors towards the number of accidents happening in the world. So, the idea is to remove the human factor from the equation and theoretically, accidents will have to drop down by 95%. The most eligible candidate to replace a driver was none other than the computers. The problem lies in programming the computer to replicate the behaviour of a driver as there are numerous variables and parameters involved in developing the algorithms thereby increasing the complexity in developing a driverless car. Apart from the functional aspect, there also lies the risks involved if the system goes haywire and associating the liability in such a situation. As Rome was not built in a day, every technological development takes time to bear its fruit and most of the carmakers have unanimously agreed in developing driverless cars for the future.

While carmakers have the resources in developing a driverless car for an urban scenario for example, the academic world is also working on developing autonomous single-seater cars with the support from many consulting firms. This thesis deals with the development of a Formula Student Driverless Vehicle (FSDV) developed by the students of Politecnico di Torino to compete in Formula Student Driverless competitions and portray their skills and knowledge in making a car that could drive autonomously in a closed-circuit with manageable handling coupled with good acceleration and braking capabilities. The students of today become the engineers of tomorrow who develop safe driverless cars.

## 1.2 Formula Student

Formula Student (FS) is an international competition conducted for university students with the aim of opening a gateway for research in a wide array of engineering disciplines. The competition is based on the Formula SAE rules and guidelines [1]. The event requires the students' team to design and develop a single seater car with either a combustion or electric powertrain. The guidelines also allow the team to implement Autonomous Driving (AD) capability in an existing FS car thereby enabling them to compete in the Formula Student Driverless (FSD) competition which was initiated in 2017 and takes place at the historic Hockenheimring circuit in Germany. Starting from 2018, Formula SAE Italy & Formula Electric Italy along with Formula Student UK and Formula East have decided to follow the German event introducing a Driverless competition too.

Apart from developing a car which meets the required technical aspects, the team must also develop a viable business plan and a marketing concept for batch producing the vehicle. Focus not only lies on making the vehicle have a controllable performance in terms of ride, handling, acceleration and braking ability but also on making it inexpensive to purchase and be run by the target group comprising of amateur racers. Consideration must also be given to other aspects such as ergonomics, aesthetics and use of of-the-shelf components so that replacing components is easier. The vehicle will be judged by a jury comprising of experts from the automobile, motorsport and supply industries. The teams compete on a series of static and dynamic events for which they earn points accordingly as described in Figure 1. The team with the best overall scores from the combination of design, financial planning, marketing strategy and performance on the track will win the Formula Student Driverless (FSD) Championship.

FS enriches the teaching content of a course of study with challenging and practical experience in the fields of manufacturing and production, whilst not neglecting the practice-oriented requirements relating to profitability and market relevance. The aspects assessed by the competition correspond directly to the demands of the different branches of the industry for new product development, which is why they are not merely restricted to vehicle design. By working as part of an interdisciplinary team of students from different fields of study and expertise, the competitors learn first-hand how to combine the economic and technical goals of product development and at the same time, how to defend the solutions they themselves have developed and assert these against competing developments. [2]

As explained in Figure 1, The FSD competition is divided into static and dynamic disciplines which have sub-events the teams will have to participate in. FSD differs from FSG in the way that the competition's focus shifts from pure driving dynamics to developing an optimal adaptation of the autonomous vehicle system to the respective driving scenario. Though the events itself and the points segregation among different events may differ between FSG and FSD, the overall points are maintained the same so as to at least partially preserve the compatibility between both competition classes. It is imperative that all cars have to go through system-specific scrutineering in order to be qualified as eligible to take part in the competition. FSD requires additional checks to be completed for the autonomous features after the checks are done for the base vehicle which is either Electric or Combustion.

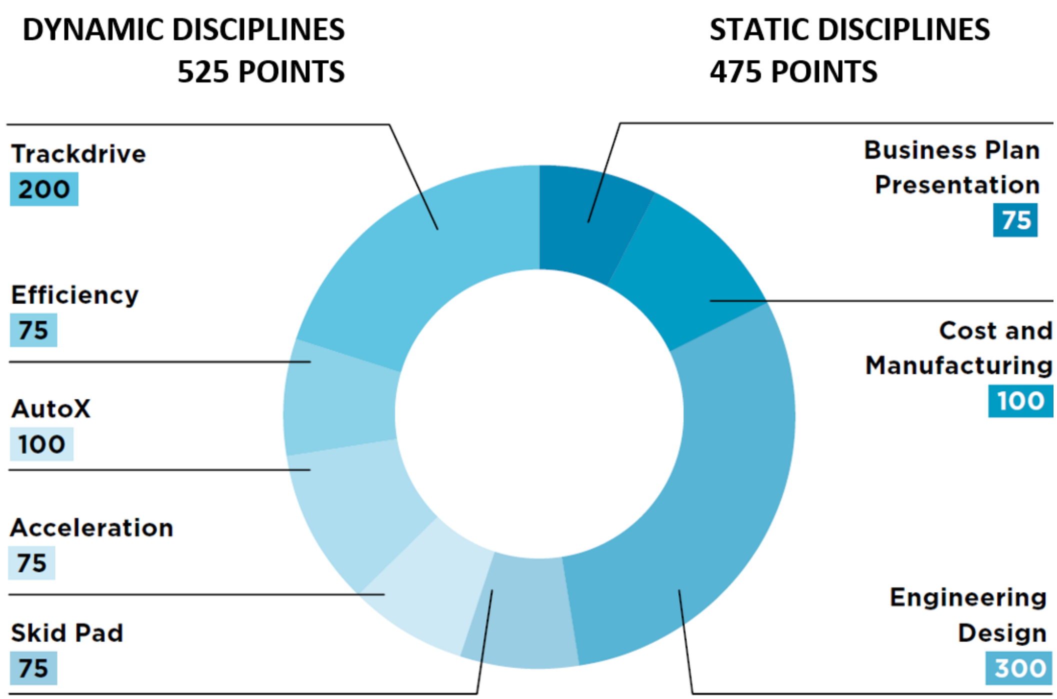



*Figure 1 : FSD competition events and maximum points*

## 1.3 Squadra Corse in Formula Student

Squadra Corse is the Formula Student team of Politecnico di Torino comprising of engineers from various disciplines who come together in making a single-seater electric Formula Student car. The team comprises of over 32 students from various disciplines of engineering such as automotive, mechatronics, mechanical, electrical, electronics, aerospace and management and also supported by professors, doctoral students and master thesis students. The following are the achievements of the Squadra Corse team in various Formula Student events across the world.

| Secured place | Event | Year |
|---|---|---|
| 1° | Formula SAE Electric Italy | 2019 |
| 6° | Formula SAE Czech Republic | 2019 |
| 13° | FS Spain Barcelona | 2019 |
| 13° | FS Spain Barcelona | 2018 |
| 3° | Formula SAE Electric Italy | 2018 |
| 3° | Formula SAE Electric Italy | 2017 |
| 2° | Design Event @ Formula SAE Czech Republic | 2014 |
| 2° | Formula SAE Electric Italy | 2012 |
| 1° | Formula EHI | 2010 |
| 1° | Formula Hybrid USA | 2010 |
| 1° | Formula EHI | 2009 |
| 2° | Formula SAE Italy | 2008 |
| 2° | Formula SAE Italy | 2007 |

*Table 1 : Historic achievements of Squadra Corse*

This year 2019 is an important milestone for Squadra Corse as they take the big step in developing a Formula Student Driverless Vehicle (FSDV) to compete in Formula Student Driverless (FSD) competition at Hockenheimring, Germany.

## 1.4 Aim

The aim of this thesis is to design and develop a working prototype of Autonomous Steering System (ASS) for Squadra Corse 2018 electric FS car Desy. This includes designing and analysing the hardware, developing the software and also designing of the controller to enable the car to steer autonomously with the help of onboard sensors. The initial developments were done for SC18 Desy and then adapted to SC19 Lucia, both being fully electric FS car. The ASS project timeline includes testing the prototype on a test bench and implementing on the vehicle for actual validation of the ASS in the car.

## 1.5 Methodology

A methodology could be defined as "the analysis of the principles of methods, rules, and postulates employed by a discipline". Methodology refers to more than a simple set of methods; it refers to the rationale and the philosophical assumptions that underlie a particular study [3]. Considering this is a practical and application-oriented project, it is prudent to understand the two different methods or methodologies involved in any type of problem solving – *Scientific method and Engineering method*.

Science and engineering could be inexplicably called as 'two sides of the same coin.' Scientists and engineers contribute immensely to the human knowledge of the world but in different ways. A scientist will ask a question and he or she develops a set of experiments to answer the question while engineers uses the engineering design process to create solutions to problems. An engineer follows the approach of identifying a specific need and analyses who needs it for what reason. Then, he or she creates a solution which meets the identified need [4].

A distinct difference between science and engineering is sometimes unclear in real life applications. So, a project may fall into the grey region where both science and engineering 'coexist', and it is fine to be so. However, it is sensible to follow the Engineering design methodology if the objective of a project is to develop a new product.

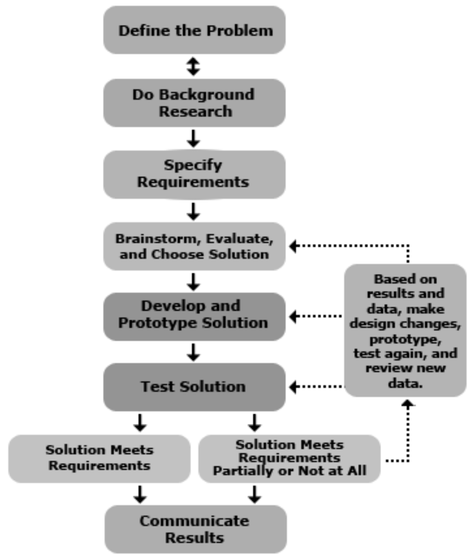



*Figure 2 : Steps of Engineering design process*

A short summary of the first four steps in engineering design process considering the development of FSDV until the design stage are presented below.

**Step 1: Define the problem**

As the famous American engineer and statistician W. Edwards Deming quotes, "*If you do not know how to ask the right question, you discover nothing*", there must be defined a set of Research Questions (RQs) which help us understand our problem more effectively and also to ensure our approach to solve it follows the rules and regulations to be adhered. A few possible RQs that could help in streamlining our research approach are as follows.

**RQ1** How complex is developing a working solution for an FSDV ASS?
**RQ2** How robust must be the ASS developed?
**RQ3** Is SC19 capable of adopting different ASS solutions?
**RQ4** How much does it cost to implement the ASS in the existing FS vehicle?
**RQ5** Does the ASS solution have a failsafe operation?

Next is to establish the '*Criteria for success'* which are the specifications a design solution must meet or the traits it must possess in order to be considered successful. These criteria are preliminary in this stage of the design and as the design develops, we will most likely find if the initial criteria require to be modified or redefined. The fact that the preliminary criteria mustn't be too specific enables a flexibility throughout the design process.

In the development of FSDV,  the preliminary criteria pertain to an initial concept of possible design solutions for the ASS such as a stepper motor with a right-angle worm gearbox attached to the steering column axially or a BLDC motor with a planetary gearbox attached to the steering column by means of a chain drive, gear drive or a belt drive. With the preliminary choices of the actuation system, an approximate level of defining the specifications is done. Like previously mentioned, it could be redefined or modified at the subsequent stages and the purpose of this phase is to have something to start the development process.

**Step 2: Do background research**

This part is very crucial to the experiment as this is where all the possible knowledge on the field of the experiment being performed could be acquired. Apart from drawing inspiration and new ideas, it is absolutely vital to know about how similar projects are done previously for two prime reasons - to ensure our project does not replicate another competitor team's design owing to legality and copyright issues as well as to avoid having wasted all the time on something which is not innovative and has already been done by someone.

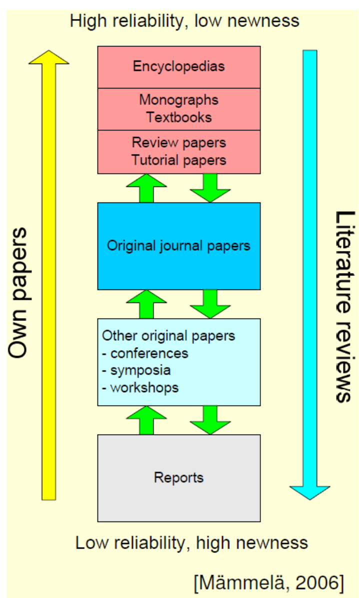



*Figure 3 : Sources for background research*

Several other university teams would have already made FSDVs and their journals and reports would be available on the internet. These documents help us understand about their DV and the reasons governing their decisions to adopt the respective systems in their DV. Benchmarking is a key player in Engineering design process.

The 21st century is a digital book and it is not an overstatement to say every information and knowledge is available on the internet. Another important upside of performing a literature study is the opportunity to combine ideas from different works and also get inspired from them and cultivate new ideas in the project. Before concluding on this, understanding who (or) what will be impacted as a result of your research and what difference you are making to the industry and the society is a key point.

**Step 3: Specify requirements**

This is the part where we begin to set foot in our project. This is, in a way, related to the different RQs we had discussed earlier. The design of a system must be made up to a predetermined specification and a part of these specifications arise as a result of answering those RQs. Another part of the specification requirements comes from the benchmark data from competitor DVs. At few places, we may not have a design specification to freeze and start working on our project. It is a prudent approach to consider the design specifications or design targets of competitor team's DVs which might enable us in realising a better car. This part of the design process has to be complete regardless of how unsubstantiated a few data might be and those could be taken care of while we progress in the project.

Considering the implementation of an ASS for a FS vehicle, the design requirements could be as follows.

**Prime mover**

- Type of prime mover
- Rated power of the motor
- Speed-torque characteristics of the motor
- Size
- Weight
- Peak current and torque of the motor
- Torque constant
- Rotor inertia

**Gearbox**

- Type of gearbox for torque multiplication
- Weight
- Reduction ratio
- Efficiency
- Moment of inertia
- Maximum output torque
- Maximum backlash

**Assembly**

- Rated power, speed and torque of the motor-gearbox assembly
- Weight of the assembly
- Dimensions of the assembly
- Inertia constant of the assembly

This is a very crucial phase as this information serve as the starting point of the development process. It is necessary that all the information gathered is as accurate as possible and a certain factor of safety has to be considered based on the duty cycle of the ASS system.

**Step 4: Brainstorm, evaluate and choose solution**

Now that we have everything needed to start the work, not everything needs to be used. With reference to the Set Theory, the information collected so far is like a universal set and we have to make subset(s) with specific information required to proceed with the design process. This is done as a team of people which not only comprises of experts in the field but also those who are not as an '*out-of-the-box'* thinking is of vital importance to a so-called '*brainstorming'* session.

The preliminary phase of doing this begins with creativity in generating new ideas that may solve the problem. Creativity is much more than just a systematic application of rules and theory to solve a technical problem. Solutions to engineering design problems do not magically appear. Ideas are generated when people are free to take risks and make mistakes. Brainstorming at this stage is often a team effort in which people from different disciplines are involved in generating multiple solutions to the problem. We start with existing solutions to the problem and then tear them apart-find out what's wrong with those solutions and focus on how to improve their weaknesses. Consciously, we combine new ideas, tools, and methods to produce a totally unique solution to the problem. This process is called 'synthesis' [5].

Once we have conceived multiple solutions for our design problem, we need to analyse those solutions and decide which solution suits the best for implementation. We apply our technical knowledge here and evaluate the proposed designs to devise solutions for each of them. We then use the results to decide which solution to implement based on an in-depth design analysis.

At this step in the design process, you must consider the results of your design analysis. This is a highly subjective step and should be made by a group of experienced people. This section introduces a systematic methodology you can use to evaluate alternative designs and assist in deciding. The analysis of design solutions could be carried out considering any or many of the following types depending upon the nature of the problem and the solution - functional, ergonomics, mechanical/strength, manufacturability/testability, product safety and liability, regulatory and compliance, economic and market analysis.

## 1.6 Scope

The final goal of developing an ASS for SC19 is in making a functional prototype car which could drive autonomously in a specified Operational Design Domain (ODD) formulated in the FSD competition. This involves developing the hardware part as well as the software part which includes developing the control algorithm and strategies with which the controller will be developed. The scope of this thesis lies in the preliminary designing of the hardware part which comprises of choosing the drive unit and the transfer unit not only confined to the kinematics and functionality but also the packaging and mounting constraints. The actuator is chosen to be equipped with a controller compatible with the CAN bus available in SC19. It also covers the preliminary conceptual FMEA of the ASS which will be taken forward in the later stages of the project and will serve as a repository of the various failures of the ASS while running on road.

## 1.7 Structure of the thesis

The thesis is arranged in a way similar to how Product Development is adopted in an industry for developing a system/component. Chapter 2 deals starts with a brief introduction about the manual steering system in an FSAE car, the architecture of SC18 and SC19 followed by the differences in their steering systems. Chapter 3 deals with the development of Autonomous Steering System (ASS) for SC19. Chapter 4 covers the conceptual Failure Mode and Effect Analysis (FMEA) of the ASS after understanding the working mechanism of the adopted solution for ASS. Chapter 5 covers the findings of the various research questions in developing ASS and the way forward in the implementation of ASS in SC19.

Chapter 2

# Steering system in SC18 and SC19

## 2.1 FSAE car's steering system and regulations

Formula Student 2020 rulebook [1] dictates a certain set of general guidelines to be adhered to while designing the steering system for FSDV. They are as mentioned below:

T2.6.1 Steering systems using cables or belts for actuation are prohibited (in Electric and Combustion vehicles with driver.) [DV ONLY] This does not apply for autonomous steering actuators.

T2.6.2 The steering wheel must directly mechanically actuate the front wheels.

T2.6.3 The steering system must have positive steering stops that prevent the steering linkages from locking up. The stops must be placed on the rack and must prevent the tires and rims from contacting any other parts. Steering actuation must be possible during standstill.

T2.6.4 Allowable steering system free play is limited to a total of 7° measured at the steering wheel.

T2.6.5 The steering wheel must be attached to the column with a quick disconnect. The driver must be able to operate the quick disconnect while in the normal driving position with gloves on.

T2.6.6 The steering wheel must be no more than 250mm rearward of the front hoop. This distance is measured horizontally, on the vehicle centreline, from the rear surface of the front hoop to the forward most surface of the steering wheel with the steering in any position.

T2.6.7 The steering wheel must have a continuous perimeter that is near circular or near oval. The outer perimeter profile may have some straight sections, but no concave sections.

T2.6.8 In any angular position, the top of the steering wheel must be no higher than the top-most surface of the front hoop.

T2.6.9 The steering rack must be mechanically attached to the chassis.

T2.6.10 Joints between all components attaching the steering wheel to the steering rack must be mechanical and visible at technical inspection. Bonded joints without a mechanical backup are not permitted. The mechanical backup must be designed to solely uphold the functionality of the steering system.

T2.6.11 Rear wheel steering, which can be electrically actuated, is permitted if mechanical stops limit the range of angular movement of the rear wheels to a maximum of 6°. This must be demonstrated with a driver in the vehicle and the team must provide the equipment for the steering angle range to be verified at technical inspection.

These are the basic parameters which are verified in the scrutineering of an FS car with driver. The additional guidelines for a FSDV include the following:

T2.6.1 Steering systems using cables or belts for actuation are prohibited (in Electric and Combustion vehicles with driver.) [DV ONLY] This does not apply for autonomous steering actuators.

DV2.3.1 Steering system actuation (movement) must only happen if the vehicle is Ready to Drive (R2D).

DV2.3.2 The steering system may remain active during an emergency brake manoeuvre while vehicle is in movement.

DV2.3.3 Manual steering must be possible without manual release steps (e.g. operating manual valves / (dis-)connecting mechanical elements) while Autonomous System Master Switch (ASMS) is switched “Off”.

**T4.2 Cockpit Internal Cross Section**

T4.2.1 The cockpit must provide a free internal cross section sufficient for the template shown on the right in Figure 4 and Figure 5 to pass from the cockpit opening to a point 100mm rearwards of the face of the rearmost pedal in an inoperative position. The template may be moved up and down. Adjustable pedals must be in their most forward position.

T4.2.2 The steering wheel and any padding that can be removed without the use of tools while the driver is seated may be removed for the template to fit.

T4.2.3 The driver’s feet and legs must be completely contained within the primary structure when the driver is seated normally, and the driver’s feet are touching the pedals. In side and front views, any part of the driver’s feet or legs must not extend above or outside of this structure.

T4.2.4 [DV ONLY] To allow for the steering actuator a reduced-height template (reduced by 50mm, shown in Figure 5) may be used for a section measuring 200mm horizontally along the template's path (compare T4.2.1).

T4.2.5 [DV ONLY] The additional space allowed by T4.3.4 and T4.2.4 may only be used for steering, braking and clutch actuators. When the actuators are removed, the standard templates must fit into the cockpit.

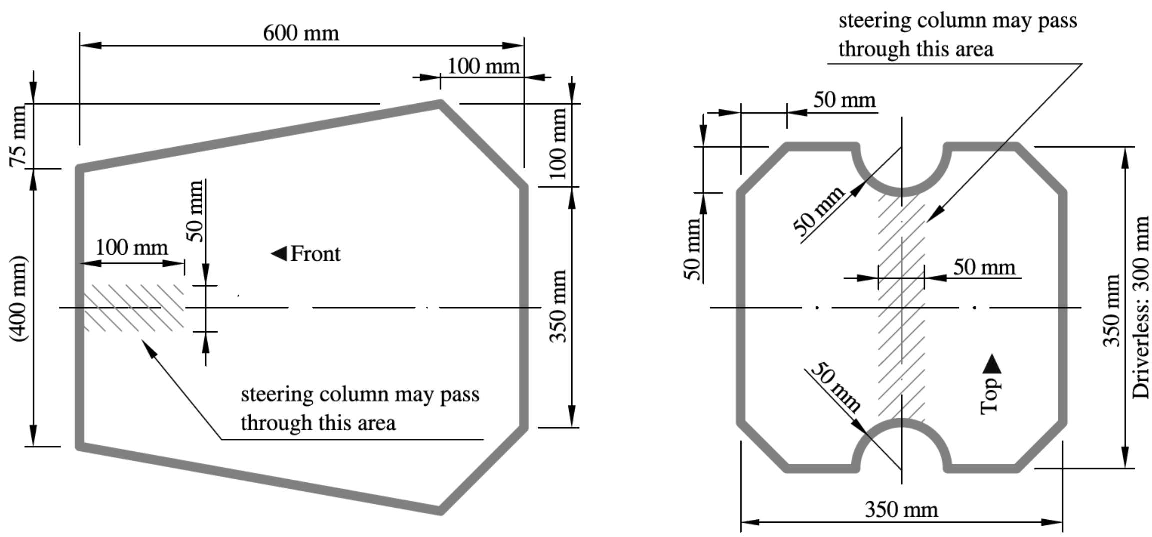



*Figure 4 : Cockpit opening template (left) and cockpit internal cross section template (right)*

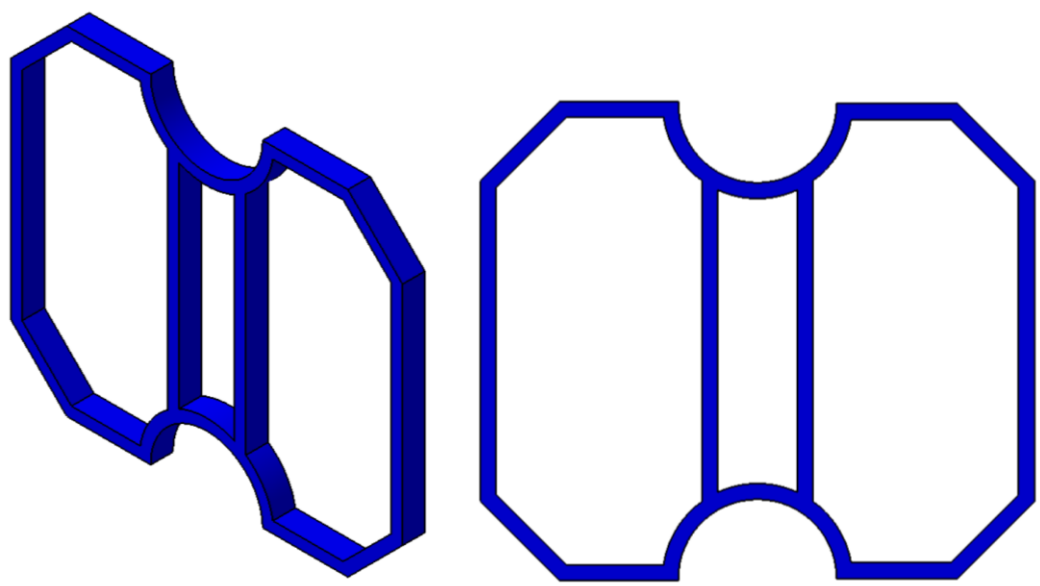


*Figure 5 : CAD model of the cross-section template for FSDV*

To summarise the regulations in simple terms,

- FSDV must function as both a DV and a vehicle with driver.

- FSDV can have “steer-by-wire” functionality for AS to replicate driver’s manual steering manoeuvre (Refer Figure 6 for the mechanism).
- The manual steering should directly actuate the front wheels through mechanical linkages.
- The entire steering system must be mechanically attached to the vehicle chassis and these connections must be visible during the technical inspection. This means bonded joints without a mechanical backup are not permitted.

The predominantly used type of steering in FS cars are the mechanical rack and pinion steering. The reason why they are most commonly adopted are due to their following advantages:

- Compact size
- Fewer parts and thus less heavy
- Precise
- Lighter
- Easy to repair and maintain

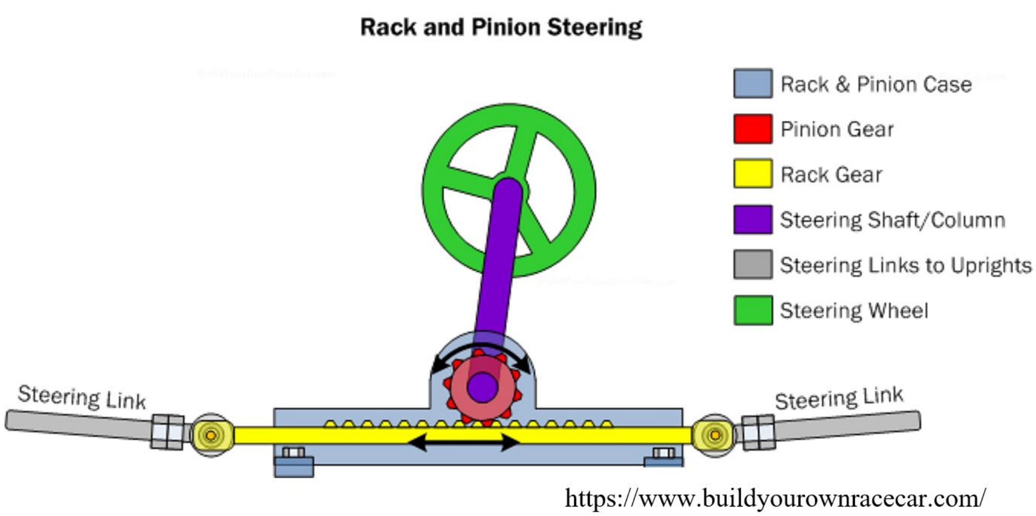



*Figure 6 : Mechanical rack and pinion steering system*

Considering the minimal space available inside the cockpit of an FS car and also power assist for steering system is not allowed for FS vehicle with driver, the rack and pinion system has to be completely mechanical without any power assist. This makes it difficult for the driver to steer owing to higher steering effort required with the absence of any power assist. This becomes an unavoidable design constraint and the entire vehicle of SC19 is built around the hard points fixed for the steering system and designed in a way to achieve a minimum possible steering effort considering every other parameter in the suspension design as well. It is apt to say the steering is the pivot around which the entire SC19 car has been built and while developing the ASS, it is important that the performance of the steering is not compromised at any cost.

## 2.2 SC18 Desy and its steering system


*Figure 7 : SC18 Desy*

The S8 Desy is the 6th electric car designed by Squadra Corse and the 4th version with outboard motors. It has 4WD layout a Lithium polymer battery pack of 7,8 kWh and 600V and AMK DD5 14 POW electric motors installed in the uprights, coaxially to the wheels. The motors reach a maximum speed of 20,000 rpm and provide 21 Nm of torque each at 8000 rpm. The car is capable of accelerating from 0 to 100 kmph in 2.75 seconds.

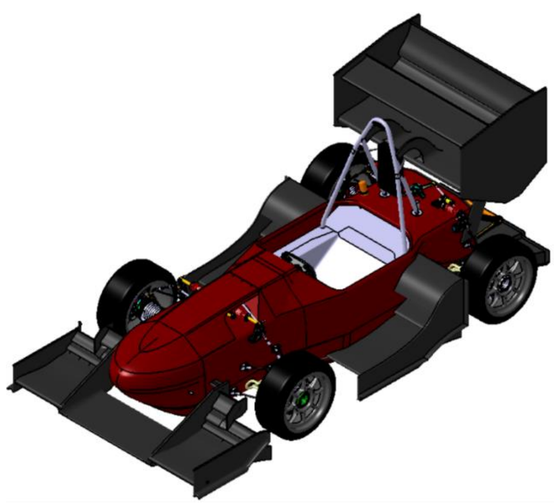


*Figure 8 : CAD model of SC18 Desy*

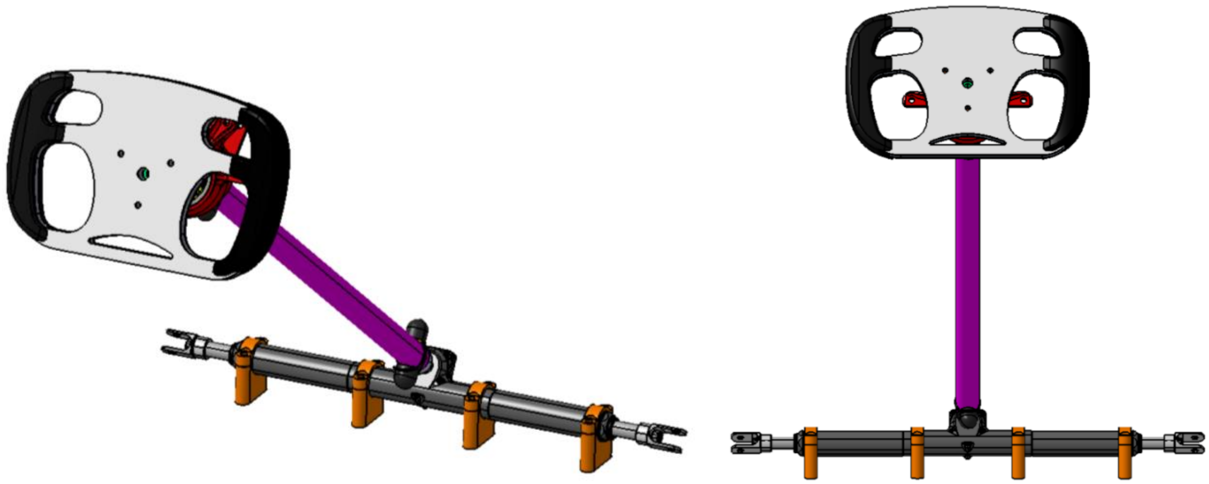


*Figure 9 : Steering system in SC18 Desy - isometric and driver's point-of-view*

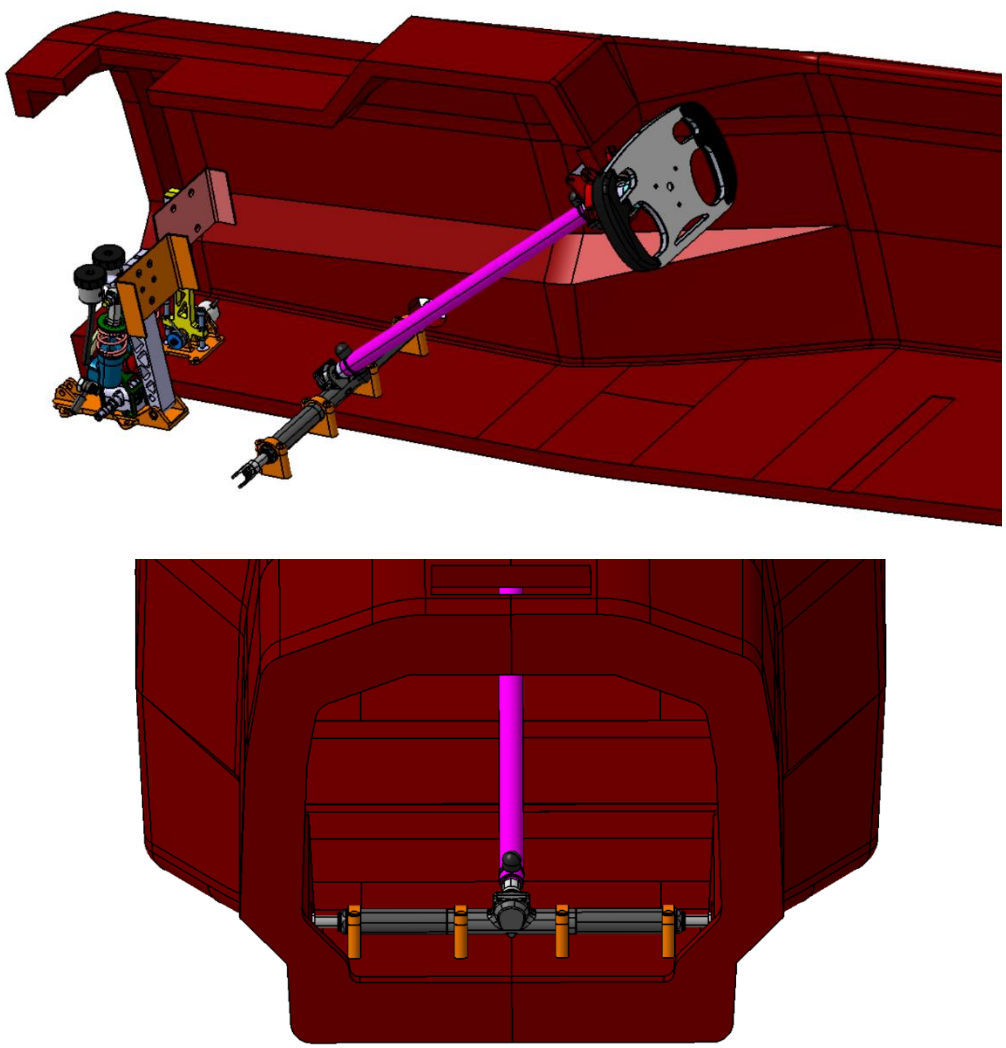


*Figure 10 : Steering system inside the cockpit of SC18 Desy*

The steering system in Desy is an off-the-shelf mechanical rack and pinion steering with a herringbone-like gear profile. Herringbone profile looks like a combination of a double helical gear of opposite hands. While looked from the top, the gears resemble the profile of a 'V' shape. It offers the following advantages:

- Not producing an additional axial load like single helical gears.
- Side thrust of one half will be balanced by the side thrust from the other half thus eliminating the need for a substantially designed thrust bearing.

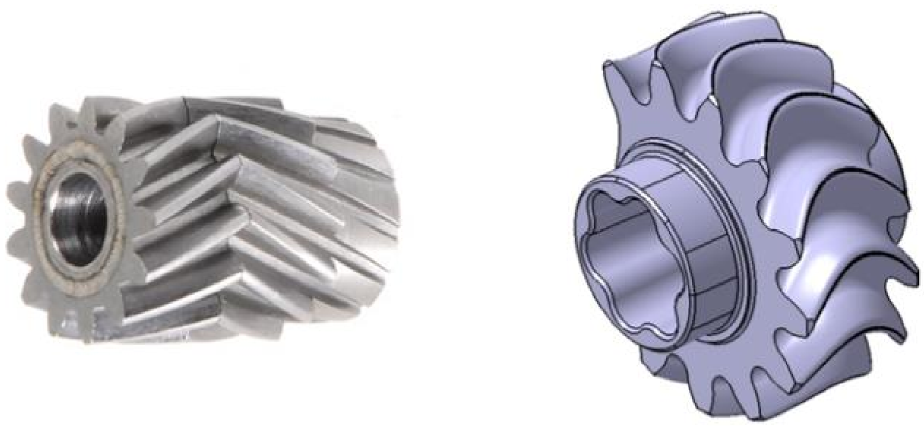


*Figure 11 : Herringbone pinion gear (left) and similar profile steering pinion of SC18 & SC19*

They however have the disadvantages of complex and expensive manufacturing. Desy's steering rack and pinion were purchased from Zedaro, a Canadian manufacturer of precision tools who have a team of FSAE alumni. They designed the '**zRack**' for FSAE cars to be sold off-the-shelf. The steering system has the following specifications: Steer ratio – 3.46:1, C-factor – 85.8 mm. The steering wheel working angle is from -90 degrees to +90 degrees. Considering the steering system is bought off-the-shelf from the supplier, there was little room for any modifications for our application and also the CAD files of the component were not available for customisation according to our requirements. Thus, it is natural that the entire car was built around the steering rack's dimensional constraints and hard points and the monocoque as well as the suspension and the other systems are built around the steering system.

*Figure 12 : zRack - off-the-shelf steering rack of SC18 Desy from supplier Zedaro*

## 2.3 SC19 Lucia and its steering system


*Figure 13 : SC19 Lucia*

The SC19 Lucia is the 7th electric car designed by Squadra Corse and the 5th version with outboard motors. The carbon fibre monocoque being the heaviest single component in the car is a completely new design in Lucia to reduce the overall weight of the car by 7.5 kg compared to the monocoque of SC18 Desy. In this regard, the monocoque cross-sectional area is reduced at the front saving considerable weight.

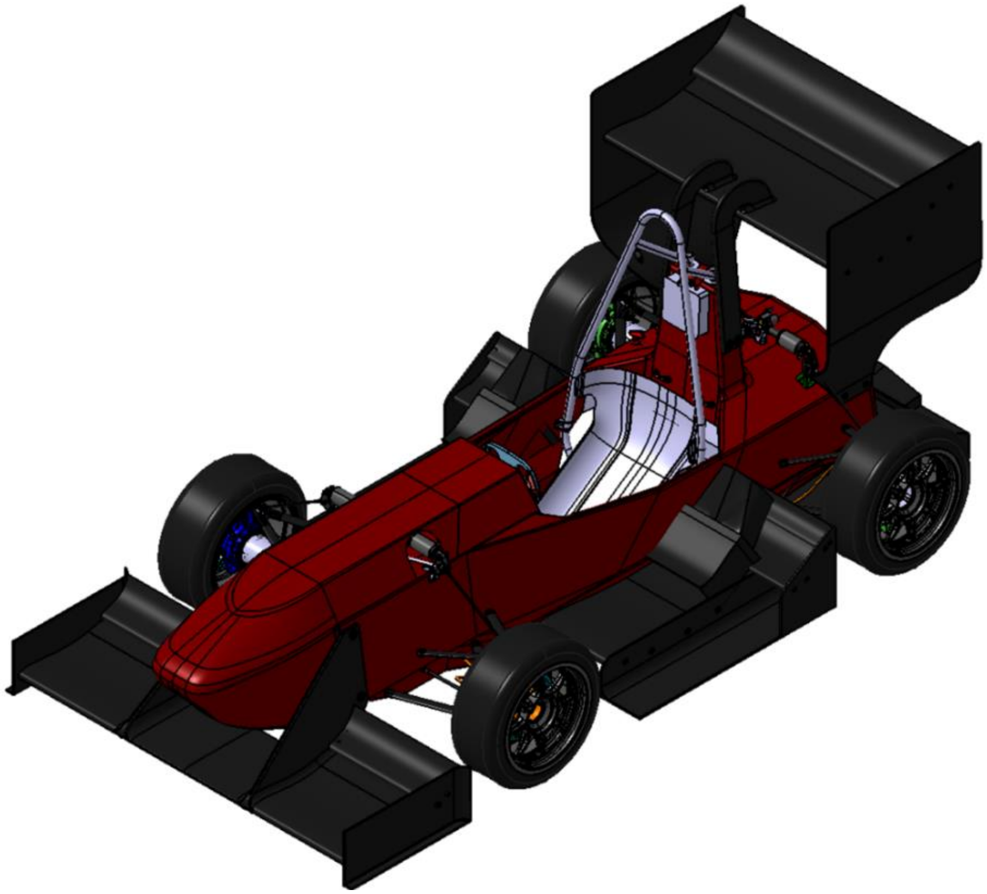


*Figure 14 : CAD model of SC19 Lucia*

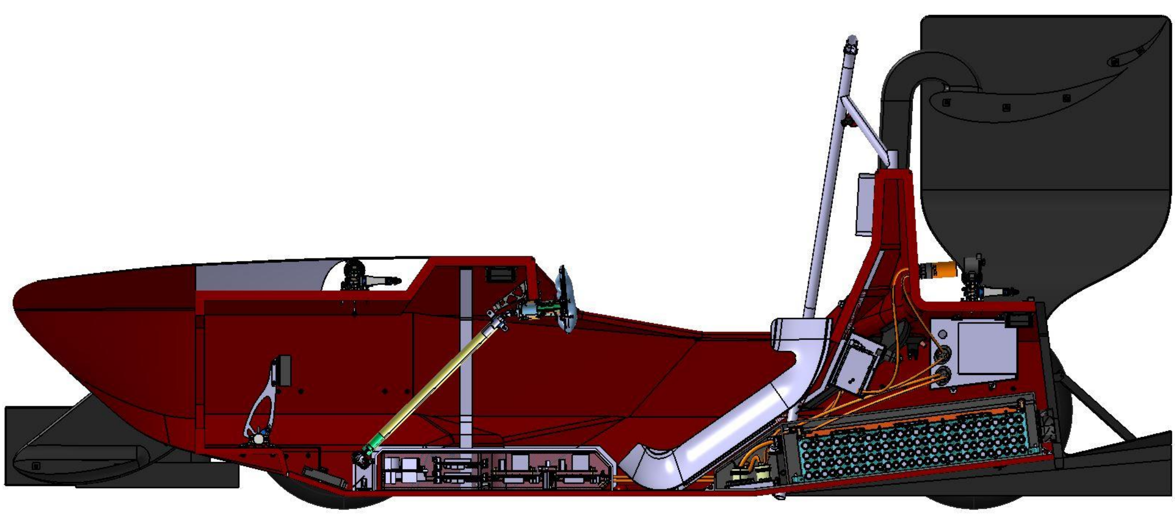


*Figure 15 : Longitudinal cross-section of SC19 Lucia*

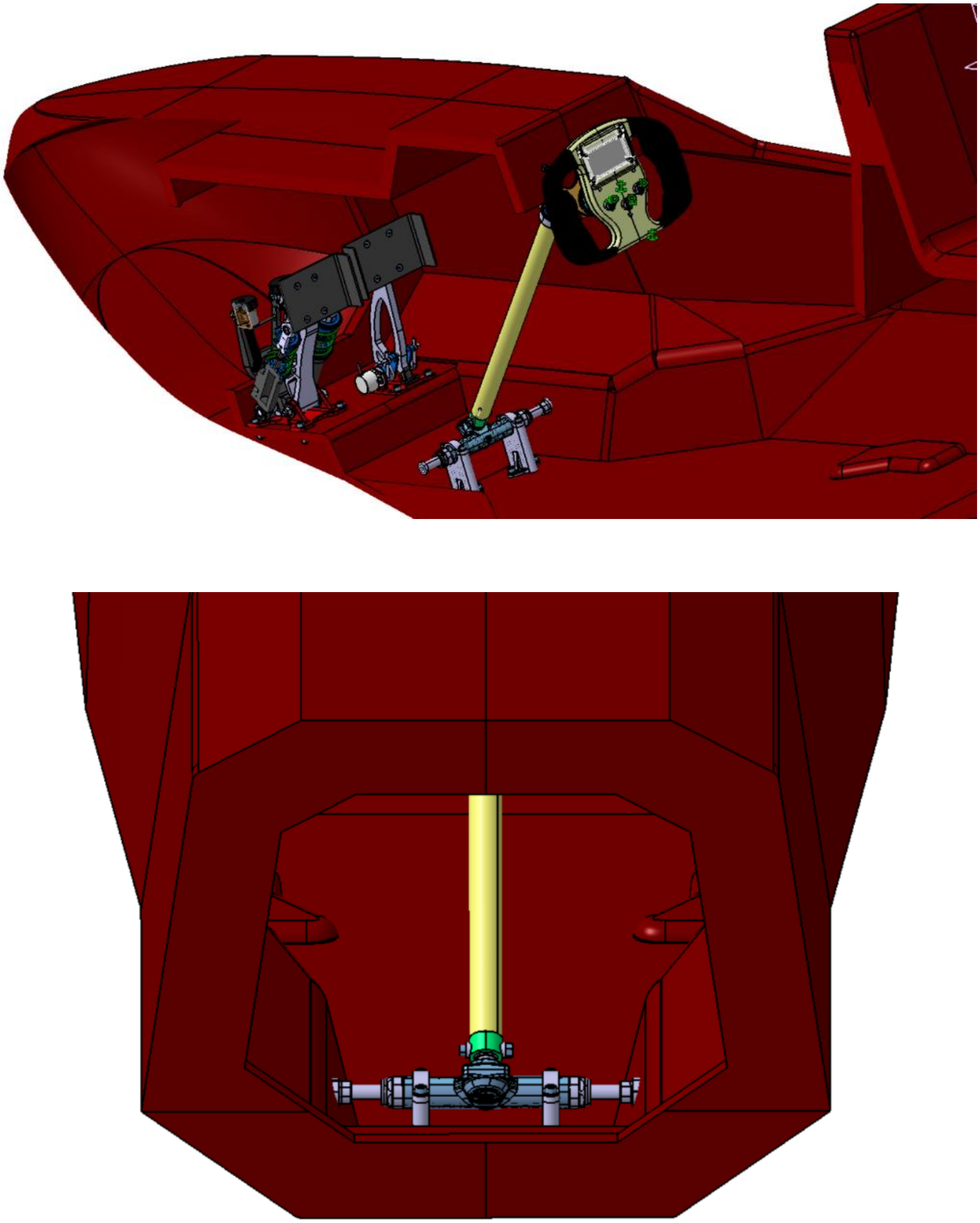


*Figure 16 : Steering system inside the cockpit of SC19 Lucia*

The steering rack is equipped with a rotary position sensor that measures the angular position of the pinion (or the steering wheel) and this will be an input signal for the ASS controller.

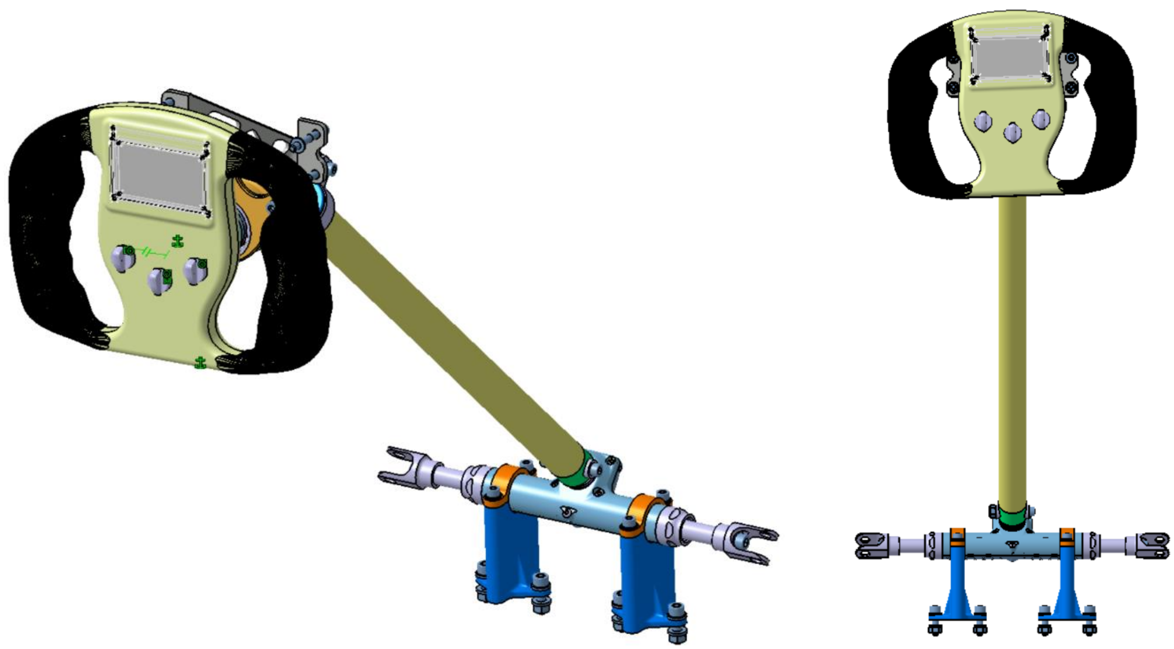


*Figure 17 : Steering system in SC19 Lucia - isometric and driver's point-of-view*

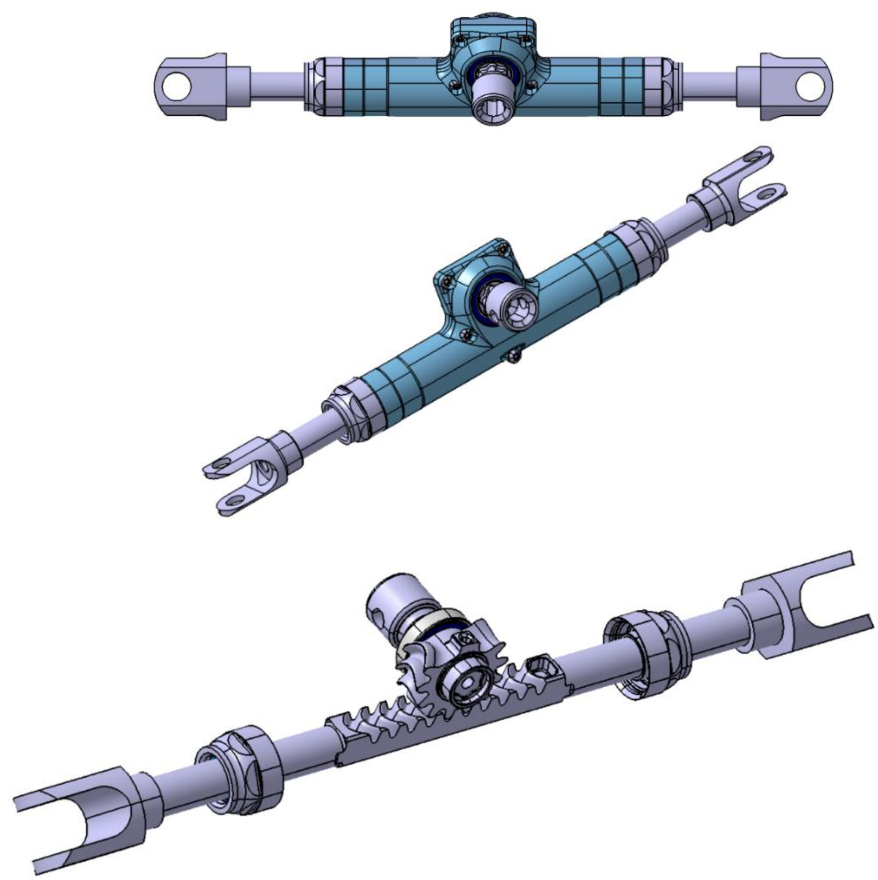


*Figure 18 : Customised steering rack of SC19 Lucia*

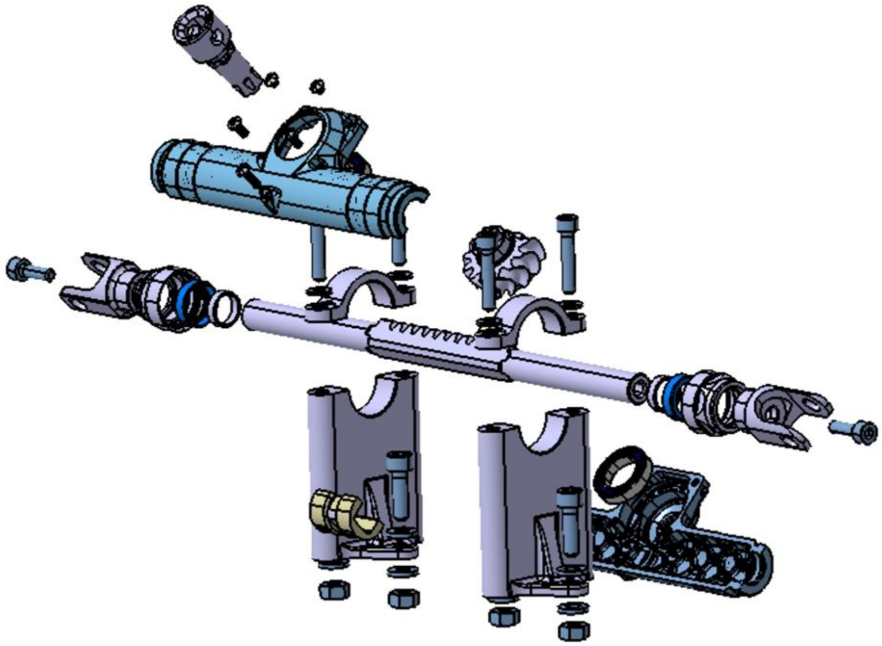


*Figure 19 : Exploded view of the steering rack components - SC19*

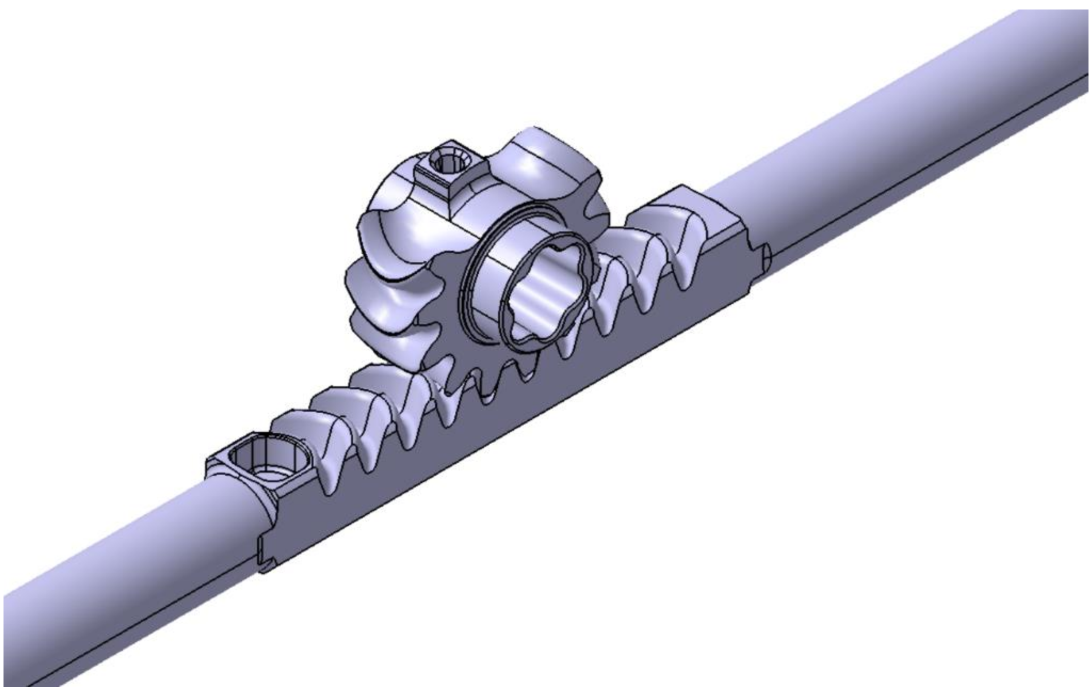


*Figure 20 : Rack and pinion - SC19*

Chapter 3

# Autonomous Steering System (ASS) for SC19 Lucia

## 3.1 Concept of ASS and its working logic in an FSDV

The purpose of an Autonomous Steering System (ASS) in an FSDV is one of the main features required to be added to the already existing FS vehicle with a human driver. In an FS vehicle, the driver is in control of the environment and perceives the route he/she has to drive in a particular event of the competition. The FSD competition is all about removing the driver from the car and making the car perform equally good or better than how a driver would drive in the specified event. Logically, computers have a faster response times compared to a human and this becomes more important when considering a driver who falls under any of the behavioural factors listed earlier in the background of this thesis. Under those circumstances, the driver becomes more vulnerable to himself/herself as well as to the others around him. The steering system is equally responsible for handling of a vehicle effectively during an accident avoidance manoeuvre by restraining the vehicle's lateral dynamics to be within the stable handling region while performing relatively aggressive manoeuvres. The quicker is the steering response, the quicker an unstable car will be able to escape from an accident-causing situation.

The FSD competition is one such initiative to develop autonomous cars capable of driving safely without a driver and it gives university students opportunity to understand the various criteria and parameters involved in developing such a vehicle. As far as the competition is concerned, the ASS as well as the Autonomous System (AS) of the vehicle is designed, developed and programmed to function only on specific test and environment conditions or ODD. In an FSDV, the role of an ASS is to also work in tandem with the brake system and if necessary, the drive train in order to execute an accident-avoidance manoeuvre which aims at bringing the unstable car to a safe stop. In FSD competition, this includes the yaw control of the vehicle during an emergency stop when the vehicle tends to have a higher yaw rate due to uneven braking forces on the different wheels (considering the ASS is connected to the LVMS and the ASMS.) The below picture gives a schematic explanation of the states and state transitions the AS must implement when the FSDV is in different modes.

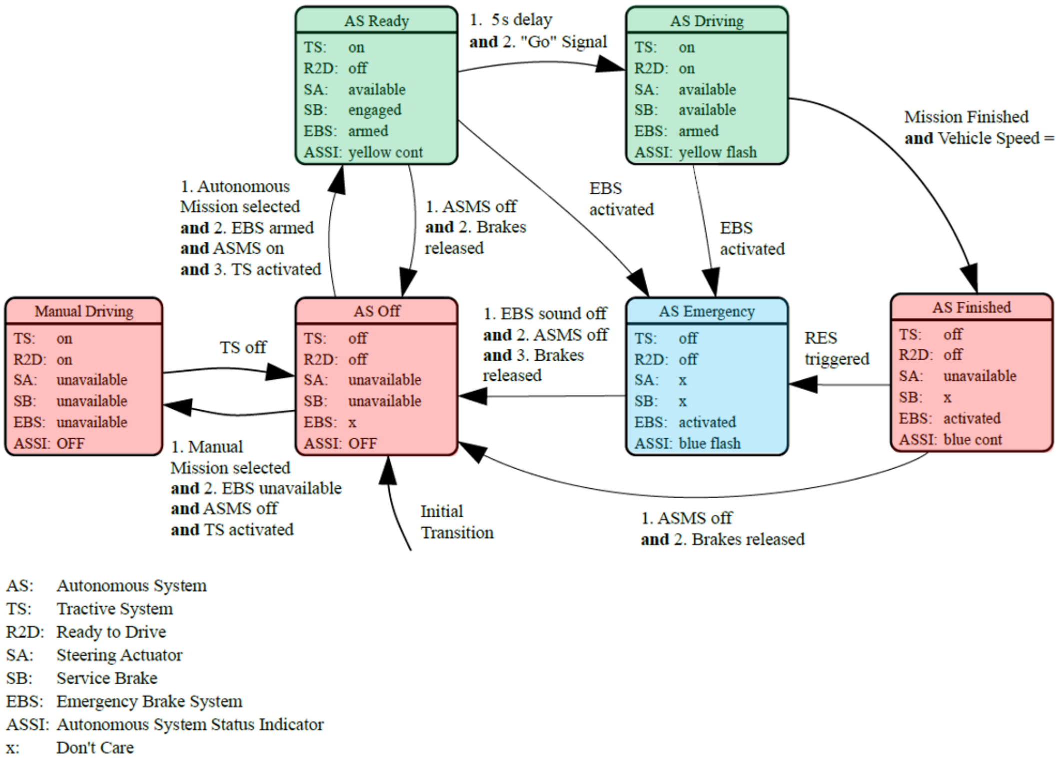



*Figure 21 : Autonomous System (AS) state machine - FSD 2020*

As far as the ASS is concerned,

- The Steering Actuator (SA) must be available (shaded in green in Figure 21) when
    - the ASMS is turned ON and the vehicle is ready for driven autonomously
    - the vehicle begins to drive in autonomous mode (Vehicle speed ≠ 0 kmph) after the GO signal is given by the Remote Emergency Switch (RES) which is a wireless controller operated by the Autonomous System Responsible (ASR)
- The Steering Actuator (SA) must be unavailable (shaded in red in Figure 21) when
    - the autonomous driving event is completed (ASMS is 'ON' and Vehicle speed = 0 kmph)
    - ASMS is turned to 'OFF' condition from 'ON' condition (after the completion even before starting of an autonomous driving event)
    - manual driving mode is selected

- The Steering Actuator (SA) availability does not matter during the state of AS Emergency (shaded in blue in Figure 21). This state transition happens when there is an emergency situation and the RES is triggered which causes the Emergency Brake System (EBS) to engage. While the EBS engages, it is not mandatory for the ASS to be available according to DV2.3.2 of the FSD 2020 regulations [2]. If required, the ASS can be programmed to counter steer the vehicle when there is uneven braking among the wheels while EBS is engaged. Due to this, the vehicle tends to have a higher yaw rate and the steering can counteract this phenomenon and assist in bringing the car to a stable and safe stop.

When it comes to the operating torque/force of the steering actuator, the different autonomous driving modes have a different requirement from the steering actuator. The following steering modes can be considered for an FS car equipped with an ASS:

- **When vehicle is at rest** – during this condition, the wheels are straight and not rolling. There exists a condition of maximum static sliding friction while trying to turn the wheels and also the vehicle is at rest whose inertia is of no advantage in turning the wheels. Consequently, the steering effort is very high.
- **When the vehicle is at motion** – once the vehicle has started to roll, it has overcome the static friction and is subject to dynamic rolling friction which is way lesser than the former. Added to this, the vehicle’s inertia while in motion makes steering a lot easier.

The controller receives the input signals from the different vision sensors onboard the FSDV and plots a 2-dimensional trajectory the vehicle must follow in order to finish an event. This trajectory serves as the input for driving the FSDV along the track. The trajectory is made up of 2-dimentional vector points and the vehicle is supposed to drive along those points at the defined vehicle speed and direction. Depending upon this input, the ASS will actuate the steering system to turn the FSDV in following the plotted trajectory.

Considering these, the controller could be programmed to actuate the steering only when the vehicle speed is not equal to zero. By doing this, we can avoid overloading the steering actuator in turning the wheels while the vehicle is at rest and also, it reduces the power requirement of the steering actuator thereby giving the possibility of having it compact and less heavy.

## 3.2 SC18 Desy vs SC19 Lucia

Though SC19 Lucia may be derived from SC18 Desy, they have significant differences in their architecture and layout. Lucia is designed with several improvements in each system compared to Desy based on design improvements, innovations and past experiences.

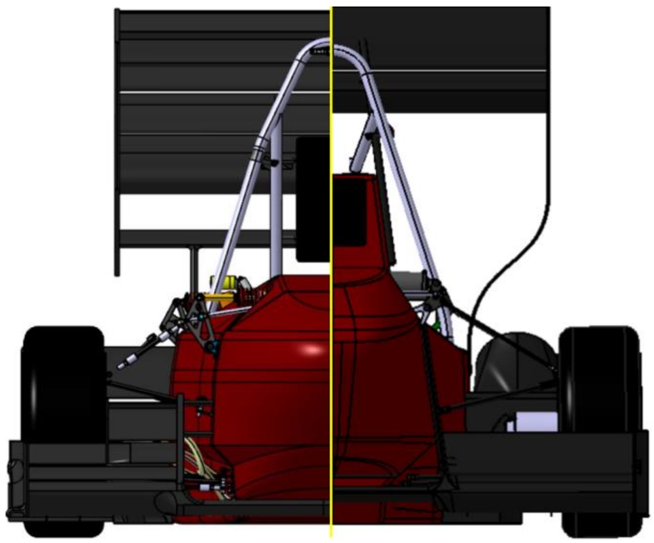


*Figure 22 : Front view of SC18 Desy (left) and SC19 Lucia (right)*

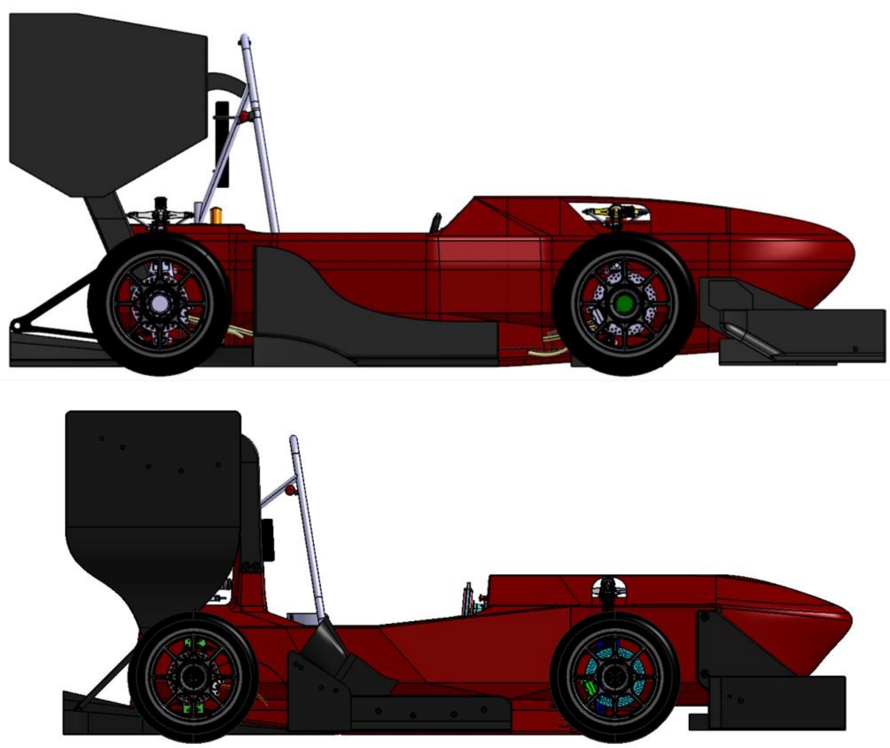


*Figure 23 : Side view of SC18 Desy (top) and SC19 Lucia (bottom)*

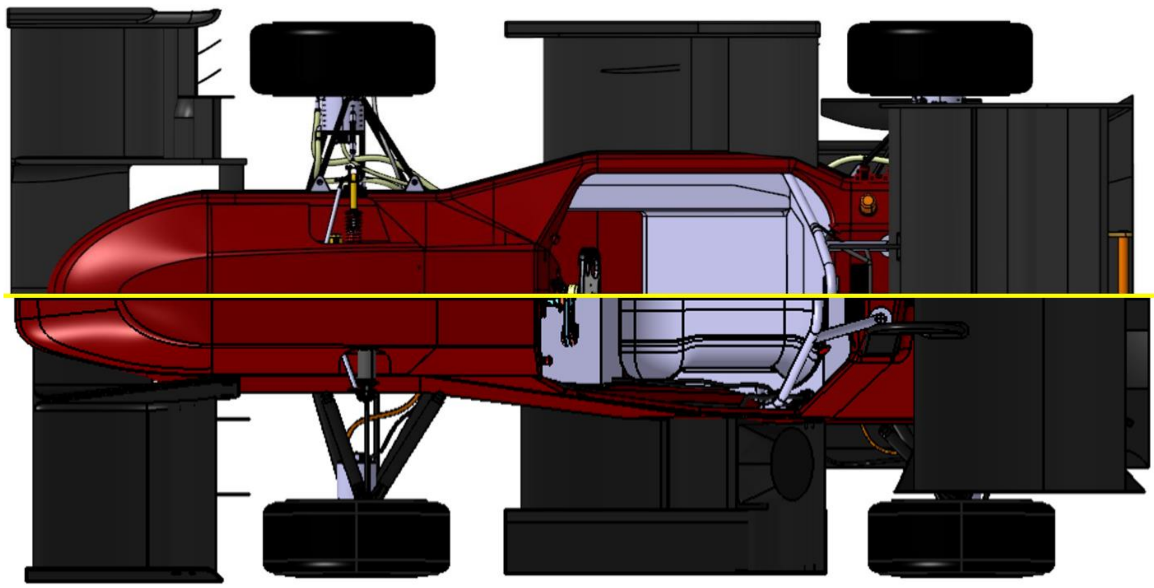


*Figure 24 : Top view of SC18 Desy (top) and SC19 Lucia (bottom)*

As far as this thesis is concerned, focus shall be on those system changes which affect the steering system. The following are the components and design parameters which differ between Desy and Lucia pertaining to the integration of the ASS into the existing steering system:

3.1 **Monocoque** – the width of the monocoque in the Y axis at the YZ plane of the steering rack is reduced from 385.4 mm by 160 mm to 225.4 mm. The monocoque was redesigned to fulfil the following targets:

- Performance targets
    - Mass reduction
    - Torsional stiffness
    - Improve aerodynamics
    - Improve dynamics
- Functional targets
    - Improve packaging
    - Ergonomic design

3.2 **Steering rack** –the steering rack supplier Zedaro had stopped producing the zRack for FSAE cars and the company made the CAD models of the zRack open-source giving the advantage of customisation as per our requirements. In this regard, the rack length in SC19 Lucia is reduced by 160 mm (from 442 mm to 264 mm refer Figure 27) owing to the decreased frontal cross-sectional area of the monocoque in the YZ plane of the steering rack. This design change has given rise to a reduced volume inside the cockpit for integrating our steering actuator assembly.

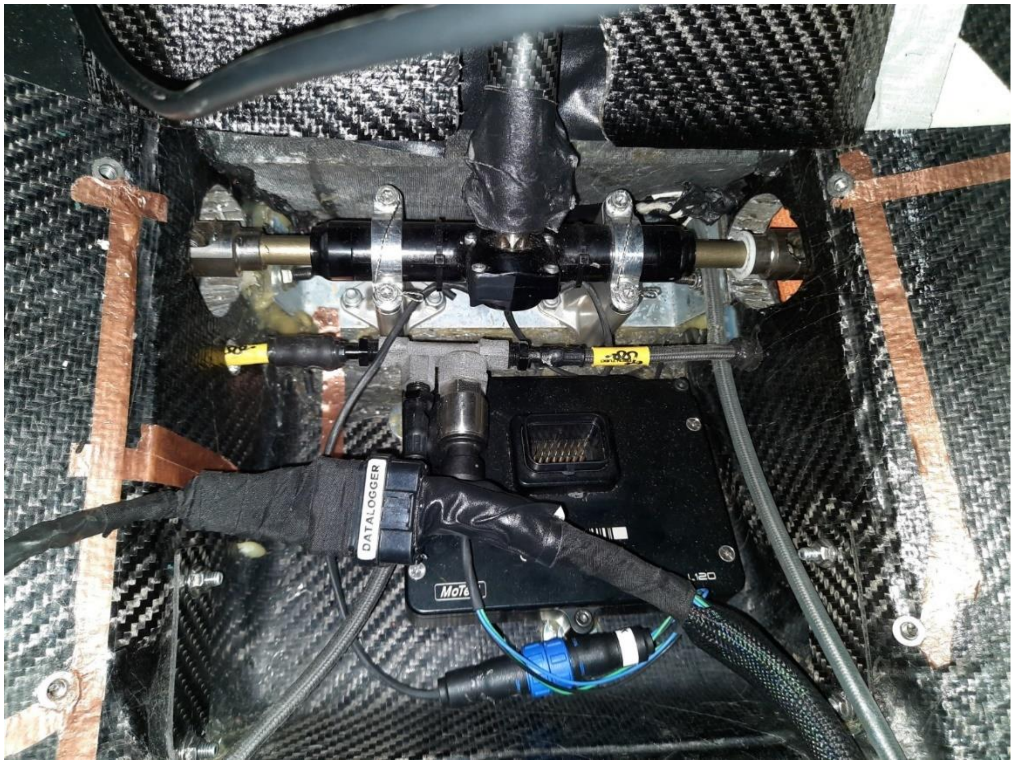



*Figure 25 : Steering rack inside the monocoque in SC19*

SC18 has a Hooke's joint connecting the steering wheel to the steering column. It is the most common type of joint for angular power transmission between the input and the output. However, since the steering column is made more inclined to the horizontal in SC19, it also increases the angle between the input and the output ends of the cardan joint thereby causing a higher fluctuation in transmission ratio i.e., the ratio between output speed to input speed. Upon analysis, it was observed that it does not cause any deterioration in terms of handline difficulties and performance of the car. In SC19, the orientation of the steering wheel is made more vertical to the driver and the steering column is more inclined to the horizontal as the steering rack is on a much-lowered surface of the monocoque compared to the pedal box as shown in Figure 35.

Since the hardpoints of the steering cannot be changed, the next best solution is to add a double cardan joint which has a constant transmission ratio even at higher angles but at the expense of larger space requirement, higher cost, increased complexity, requires additional support and also had failed while performing a test and currently, SC19 is equipped with a single cardan joint.

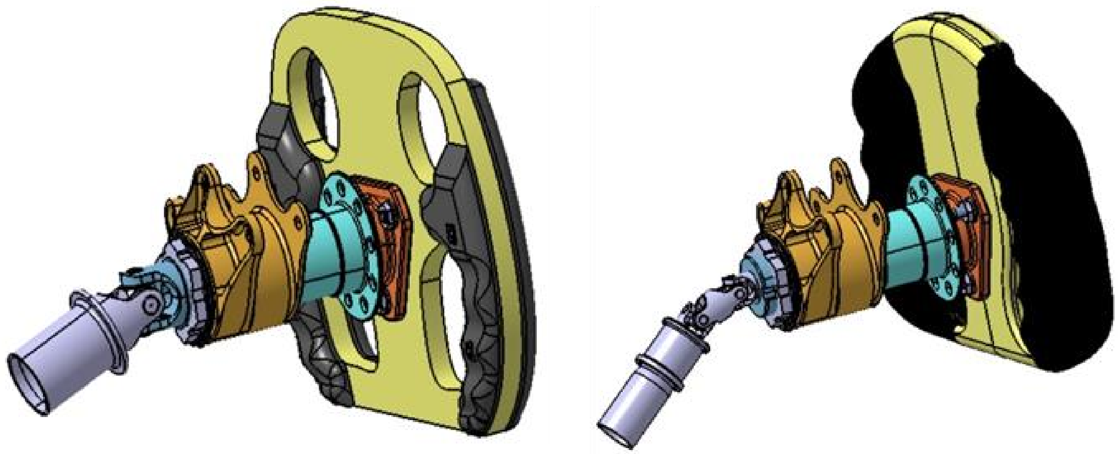


*Figure 26 : Single Cardon (left), double Cardon (right) – SC19 Lucia*

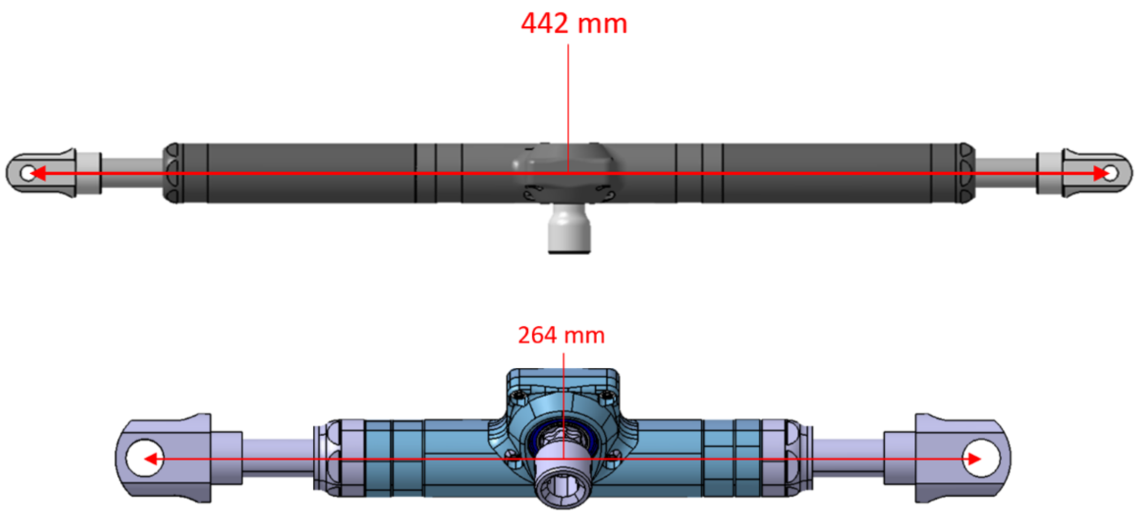



*Figure 27 : Length of steering rack - SC18 Desy (top) and SC19 Lucia (bottom)*

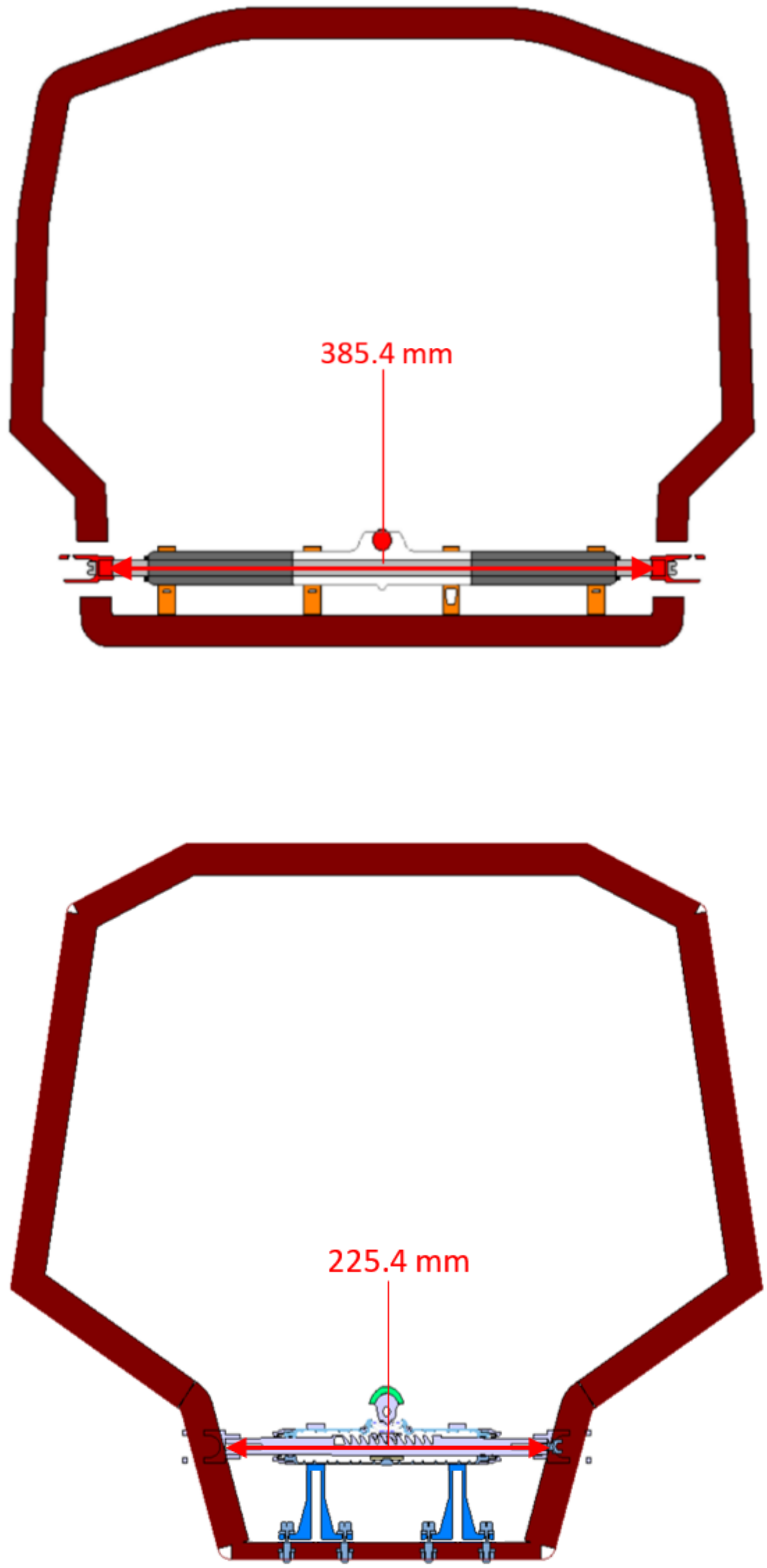



*Figure 28 : Width of the monocoque at steering rack plane in SC18 (top) and SC19 (bottom)*

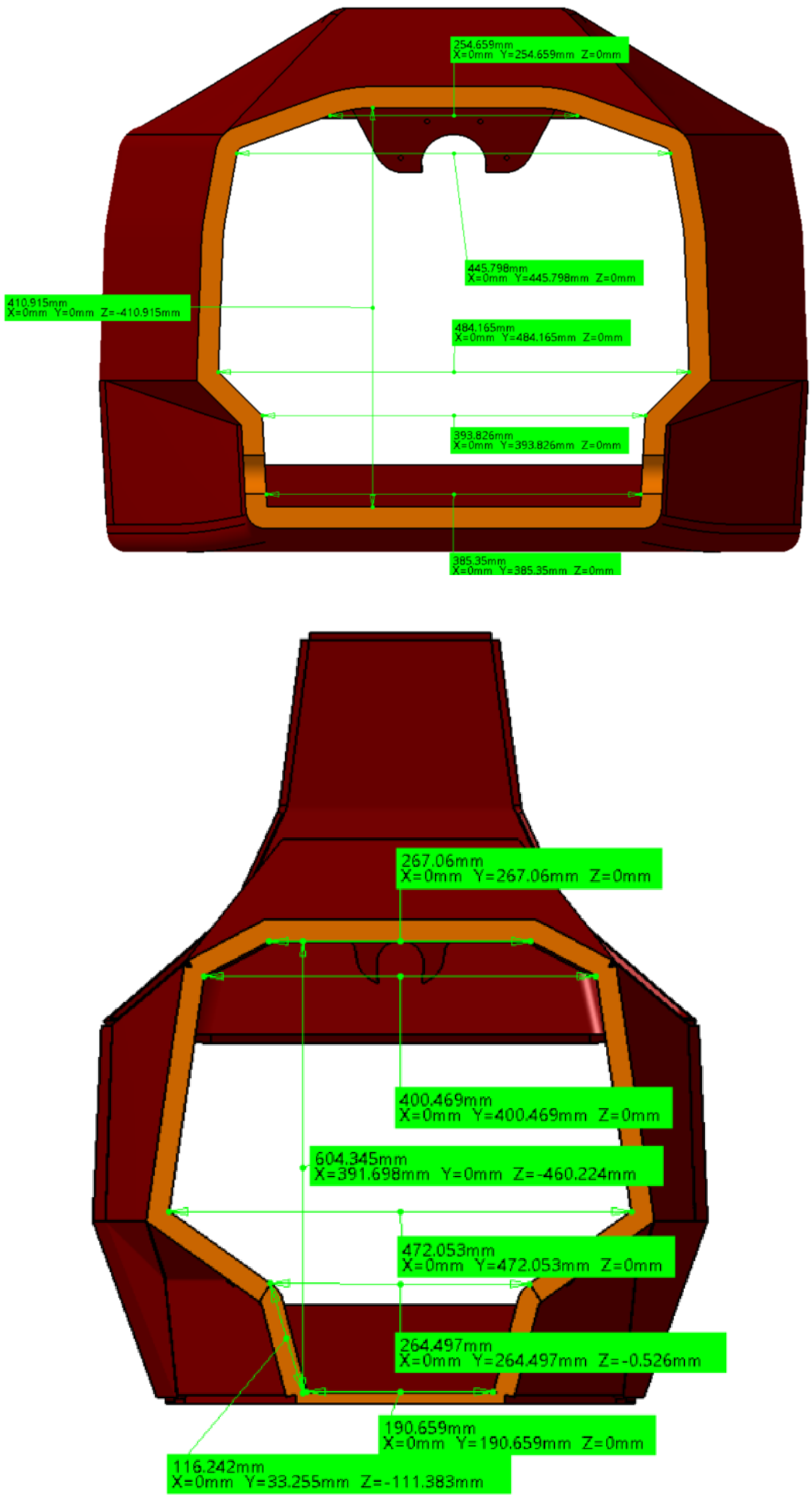



*Figure 29 : Anterior YZ plane cross-sections of SC18 (top) and SC19 (bottom) monocoque*

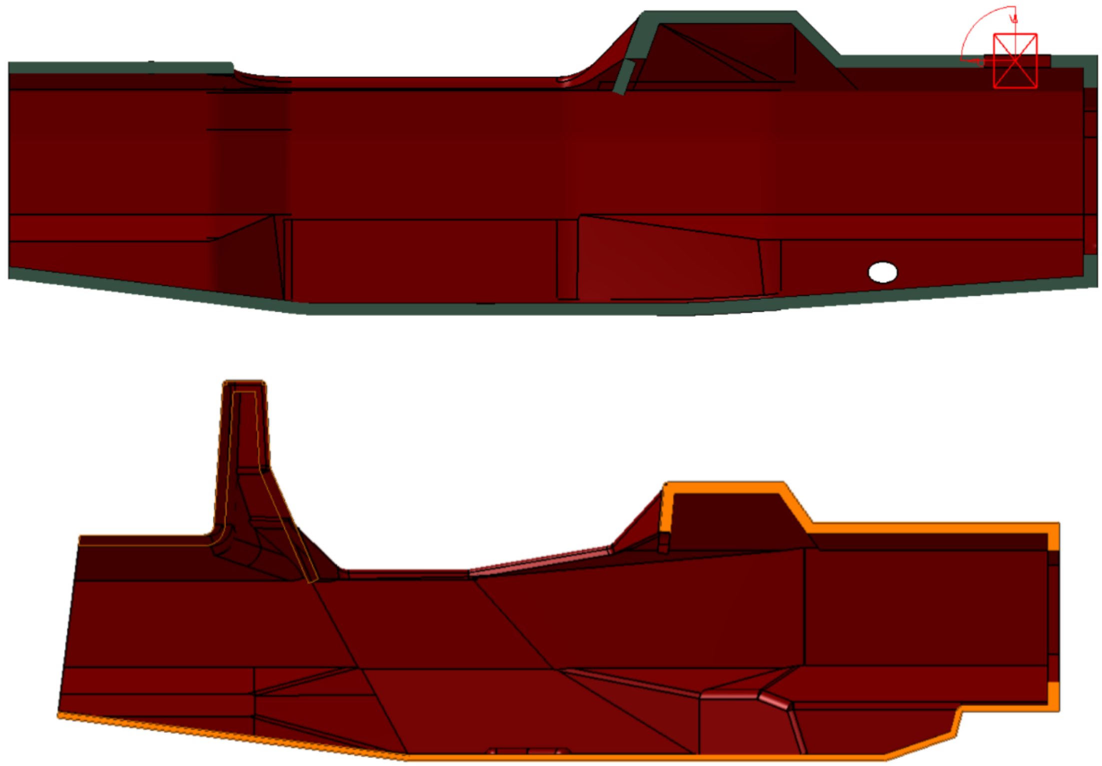


*Figure 30 : XZ plane cross-sections of SC18 (top) and SC19 (bottom)*

## 3.3 Types of actuators

As discussed earlier, the idea of ASS is to mimic or replicate a driver's steering of a car. These actuators could be *hydraulic, pneumatic* or *electro-mechanical*.

- A *hydraulic actuator* will work like a hydraulic power-assist steering system and will be able to provide the required actuation since it is a proven and practical technology. However, there exists an immense lack of space inside the cockpit and it is impractical to have a hydraulic actuator which comprises of a hydraulic pump driven by a motor, the supply and return oil lines, pressure regulator, control valves and the mounting of these components. Thus, it is not possible to adopt a hydraulic actuator for ASS.
- A *pneumatic actuator* on the other hand is quite compact and has less components compared to the hydraulic actuator. But the problem lies in the precision of the actuation required for our application. Pneumatic actuators are predominantly used in applications which involve moving from one extreme to the other extreme between two points. Our

application involves discrete movements within the working range and thus, a pneumatic actuator is not the right choice.

- *Electro-mechanical actuators* convert electrical energy to mechanical energy. They are predominantly of two types: *linear actuators* and *rotary actuators*. Both the actuators are driven by an electric brushless DC motor or a stepper motor which gives a rotary output. The linear actuator gives a translational or linear displacement output while a rotary actuator gives a rotational output. The main choice of actuator depends on the transfer of motion from the input to the output, power requirements, the orientation of the final driven component and the orientation of the driving actuator considering the space and mounting constraints to name a few. Both the types of actuators come in a diverse spectrum of sizes and specifications so that a user can precisely choose the type of actuator for his/her application.

A typical brushless DC motor has a speed-torque characteristic as shown in Figure 32. It is evident that the speed and torque characteristics are inversely related to each other and thus, it is required to choose a motor such that our application lies within the continuous operating range of the motor for most of the duty cycle of operation. Our target is to achieve a steering actuation from left lock to right lock (-90 degrees to +90 degrees in SC19) in 1 second (or lesser) and this converts to a steering actuation at the wheel at roughly 30 rpm. The steering system of SC19 has a C-factor of 85 mm, the same as that of SC18 which means for every $360^O$ rotation of the pinion, the rack translates by 85mm. Considering the total steering wheel rotation is $180^O$, the rack travel is around 42.5 mm. This sets the target specification of our actuator actuate the steering wheel at 30 rpm or higher (for a rotary actuator) or the steering rack at 42.5 mm/sec or higher (for a linear actuator) and it has to be remembered that this actuation time includes the time to overcome the inertia of the system, accelerate to the required speed from zero ($t_a$), holding there ($t_c$) and decelerating to zero ($t_d$). This follows a trapezoidal speed-time profile as shown in Figure 31. It is required that the actuator's duty cycle of operation lies predominantly in the continuous operation zone (refer Figure 32).

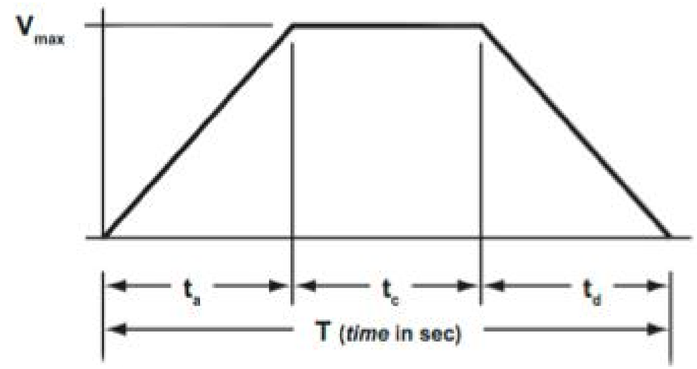



*Figure 31 : Trapezoidal speed-time profile for linear motion systems*

Also, the power requirement must also be considered in order to ensure the powerpack available in the car already can sufficiently power the actuator as well. Otherwise, it may lead to taking a complex step in adding an additional battery pack to drive the actuator.

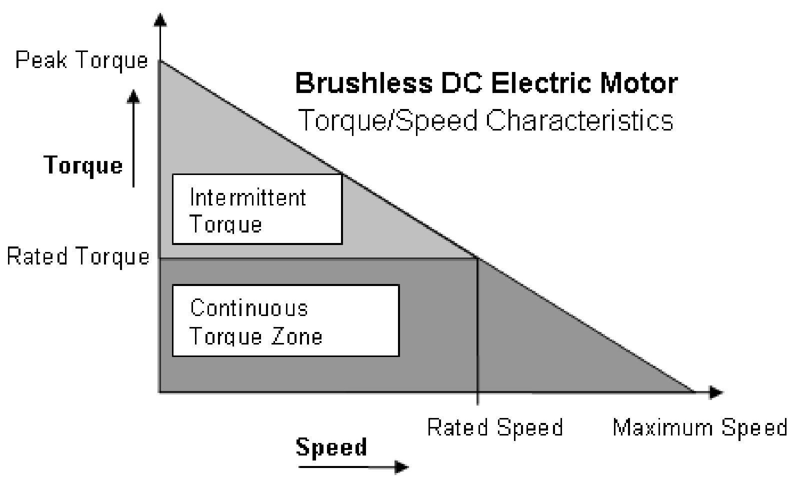



*Figure 32 : Speed-torque characteristics of a brushless DC motor*

**Electromechanical rotary actuator –** This type of rotary actuator is predominantly a brushless DC motor, or a stepper motor which gives a rotary output. This motor is used to directly drive an accessory which has to be moved angularly. The various design parameters governing the right choice of the actuator are the motor supply voltage, power consumption, motor inertia, motor size, rated speed and torque and maximum speed and torque of the motor. Depending on the application and the load, the actuator may require a speed reduction/torque multiplication. This is achieved by means of a gearbox coupled to the output shaft of the motor. If we require a right-angled output, we can use a worm gearbox, but it has the practical disadvantage of non-reversibility of motion i.e., the drive from the motor actuates the worm gearbox shaft at 90-

degree orientation but the other way is not possible. For coaxial speed reduction/torque multiplication, a planetary gearbox could be used which employs a planetary gear train which takes input from the motor shaft, reduces the speed at multiple stages and gives an increased torque output. The magnitude of speed reduction/torque multiplication depends on the reduction ratio of the gearbox.

**Electromechanical linear actuator –** This type of linear actuator is predominantly a brushless DC motor, or a stepper motor whose rotor shaft is coupled with a screw shaft. A nut is engaged with the screw shaft and when the motor rotates, it drives the nut linearly according to the screw mechanism thus converting rotary motion into linear motion. The accessory which has to be moved linearly is coupled with the nut and depending on the rotation direction of the motor and the type of screw, the nut moves towards or away from the motor linearly. The various design parameters governing the right choice of the actuator are the motor supply voltage, power consumption, motor inertia, motor size, rated speed and torque and maximum speed and torque, diameter of the screw shaft, type of screw (lead screw, ball screw or roller screw), profile of the screw (trapezoidal or V-shaped, square thread), lead and pitch of the screw, number of starts of the thread and linear speed of the nut with load. A linear actuator is predominantly used to move a mass about a linear axis with a certain linear velocity and these requirements becomes the design criteria for choosing the right actuator by appropriately changing the design parameters mentioned.

*Figure 33 : Electromechanical linear actuator – lead screw (left) and ball screw (right)*

## 3.4 Performance requirements of the chosen actuator

As far as a rotary actuator is concerned, the motor must have a rated torque of 10 Nm at a rated speed of 34 rpm. This torque is calculated based on the vehicle's specifications and suspension and steering hardpoints. The calculation for determining the static steering torque is as follows:

**Steering force and torque calculation**

Kerb weight of the vehicle = 190 kg (with the additional AS components and without driver as per regulation DV2.2.6 of FS Regulations 2020 [2])

Weight distribution in the car = 45:55

Front axle weight = 190 * 0.45 = 85.5 kg

Quarter car mass of the front axle, $m_{quarter}$= 85.5/2 = 42.75 kg

***The torque required to turn the wheel > resisting torque of the wheel due to friction***

The wheel can turn only if the above condition is satisfied.

Coefficient of static friction, $\mu_y$ = 0.9 (under normal driving conditions on a dry asphalt)

Lateral force of friction on one wheel ($F_y$)= μ * vertical force ($F_z$)= 0.8 * $m_{quarter}$ * acceleration due to gravity (g=9.81 m/s$^2$)

$F_y$ = 0.9 * 42.75 * 9.81 = 378 N

The car steers about the steering axis or the kingpin axis of vehicle (red dotted lines in Figure 34.)

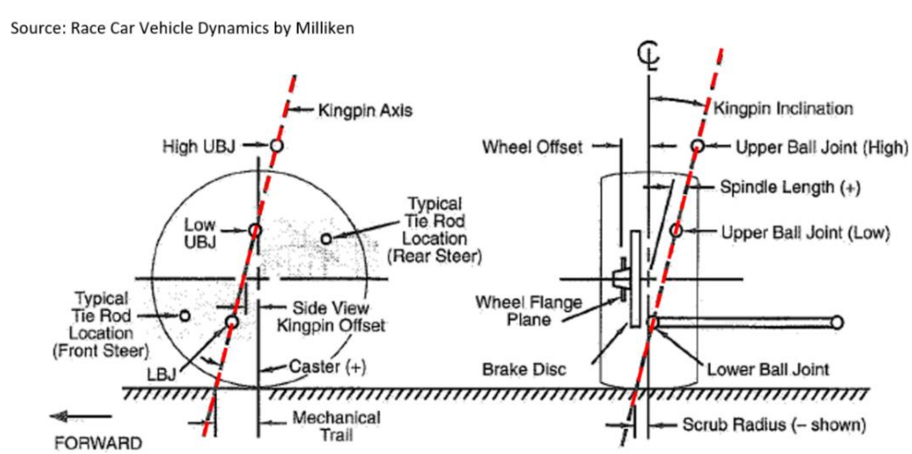



*Figure 34 : Kingpin geometry of a quarter car*

Input torque from the ground (on one wheel) = force of friction on one wheel ($F_y$) * scrub radius ($r_s$)

Scrub radius is the distance, in front view, between the kingpin axis and the centre of the contact patch of the wheel at the plane where both would theoretically touch the road surface (Refer Figure 34)

Scrub radius of the quarter car at zero-wheel travel = 16.3 mm

Input torque from the ground (on one wheel) = 378 * 16.3e-3 = 6.17 Nm

This torque will be equal to the lateral push from the tie rod on the steering knuckle of the wheel.

The torque due to lateral push form the tie rod = force on the tie rod (F) * tie-rod offset from the wheel centre in the X axis (51.3 mm)

6.17 Nm = F * 51.3 mm

Force on the tie rod (F) = 6.17/51.3e-3 = 120.27 N

As one tie rod pushes from one side, the other tie rod pulls from another side and both these tie rods are rigidly linked.

Therefore, total force on the rack = 2 * 120.27 = 241 N

Radius of the pinion, $R_p$ = 27.5 mm

Torque on the pinion, T = force on the rack (F) * radius of the pinion ($R_p$)

T = 241* 27.5e-3 = 6.62 Nm.

This is the static steering torque which is the maximum working torque in an FS vehicle due to the high static coefficient of friction when the vehicle is at standstill and comprises of inertial friction torque of the steering system, gravity aligning torque generated by the vertical force on the front wheels (self-aligning torque) and the tire patch sliding torque. This value of static steering torque reduces to almost 50% of its value while the vehicle is in dynamic condition. Also, the static torque on the wheel is measured objectively by the rudimentary method of using a weighing scale to determine the force acting on the steering wheel tangentially and multiplying it with the radius of the steering wheel. Though this method is not accurate, it enables to get a semi-objective value of the static steering torque and the result is found to lie in the range of the calculated value.

A safety factor of 1.5 is considered and the torque required to steer the vehicle in static condition

**$T_{final}$ = 6.62 * 1.5 = 9.9 Nm**

**Force required at the rack to turn the wheels = 241 * 1.5 = 362 N**

Considering a worst-case dynamic situation such as a high-speed cornering, the Pirelli tyres of SC19 have a lateral dynamic coefficient of friction as high as 1.65. Therefore, at these dynamic conditions, the steering torque and rack force requirement increases linearly.

**$T_{final}$ @ $\mu_y$=1.65 will be 18.15 Nm**

**Force required at the rack to turn the wheels @ $\mu_y$=1.65 will be 664 N.**

These values are considered while choosing the actuator for ASS.

**Actuation time calculation**

The actuation time of the steering decides how close or wide a car can turn in a corner while still maintaining within the critical speed to avoid becoming unstable. The parameter which defines this is called the steering rate which is the angle the steering wheel turns per unit time. As mentioned earlier, the driver could turn the steering wheel in SC19 from -90 degrees to +90 degrees (180 degrees in total) at about 1 second based on the data collected by Squadra Corse team while performing tests. This gives us a target actuation time of 180 degrees per second which gets converted to 30 rpm. Likewise, the rack linear actuation is also required from left lock to right lock in 1 second. The rack travel is +/-25 mm on both sides from the centre.

This gives us the target requirements of a linear actuator to have an actuation force of 664 N while being able to translate at 45 mm/sec while a rotary actuator must have 18.15 Nm torque at 30 rpm which must be inside its continuous range of operation of the BLDC motor.

## 3.5 Evolution of the various design solutions for SC19 ASS

As mentioned earlier in the introduction of this thesis, the project of developing an ASS was started for SC18 Desy since during that period, SC19 Lucia was under development. The steering system are very much different in both cars considering the design of the steering rack and its mountings, integration of the steering assembly into the cockpit and linkages between the components such as the steering wheel and the steering column.

A good amount of time was spent on understanding the car and its architecture, brainstorming with the Squadra Corse team and the professors and above all, understanding the 130-page long regulations of FSD 2019. It was of prime importance to make a compliant car apart from a working prototype as the development not only involves time but also a huge amount of money from the sponsors and the university. So, our team was determined to make it 'First Time Right' to make a compliant and functioning prototype of a FSDV.

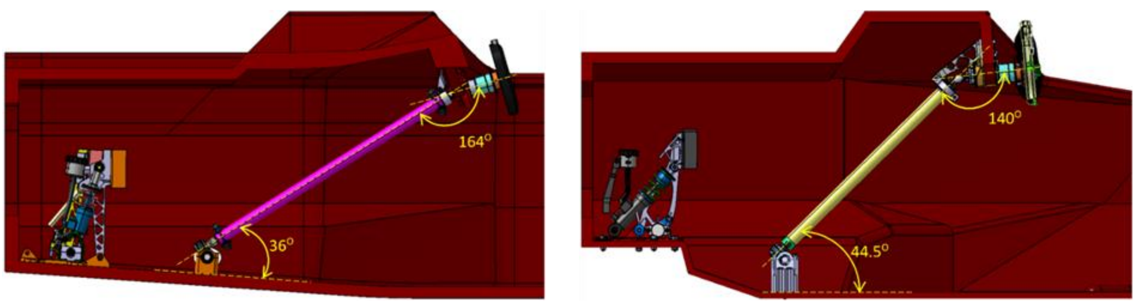



*Figure 35 : Steering column inclination in SC18 (left) and SC19 (right)*

During the course of time, there emerged several design ideas and each idea had its pros and cons which had to be balanced between practicality, performance, compliance, complexity and cost. The design ideas will be chronologically explained here along with the reason why it could not be adopted for FSDV ASS. The choice of adopting or abandoning any solution depends upon a compromise between several parameters such as

- Design complexity
- Redesigning of existing components
- Manufacturing complexity
- Manufacturing cost
- Assembly complexity
- Manufacturing lead time
- Number of new additional components

The decision on choosing a particular actuator solution among several other equally performing ones is decided upon the compromises on the above-mentioned parameters willing to be taken.

## Solution 1: NEMA stepper motor with worm gearbox

During the initial stage of study, it was natural that our level of knowledge and understanding pertaining to the project is minimal and learning is a continuous process. This solution was conceptualised during one such time. The system comprises of a stepper motor coupled with a worm gearbox from output as shown in Figure 36 which has a speed reduction ratio/torque multiplication ratio. The actuator acts as a coaxial drive to the steering column and actuates the steering system. The actuator assembly is from Nanotec Electronic GmbH & Co, Germany.

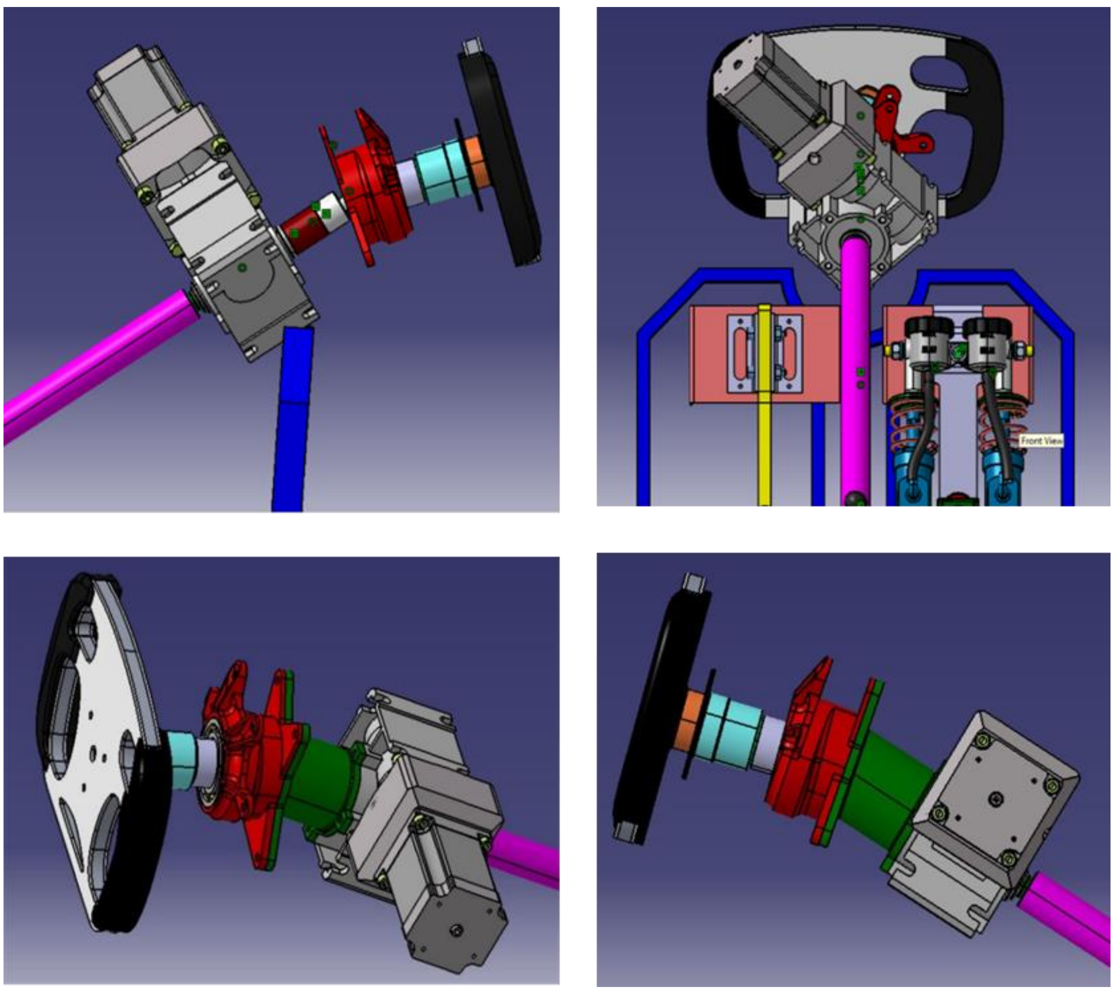



*Figure 36 : Solution 1 - Stepper motor with worm gearbox in SC18*

The gearbox has a double output shaft and one side is linked rigidly to the cardan joint through a metal coupling (Bicchierino) on the steering wheel side and the other output of the gearbox is linked to the steering column both through a key shaft linkage. Few existing parts had to be modified such as the steering column and the support bracket which supports the steering column and the steering wheel on the monocoque. The actuator was oriented in a way so that it does not violate T4.2 of the FS 2020 regulations of a cockpit template being able to fit inside a monocoque as shown in and Figure 40 (component in blue).

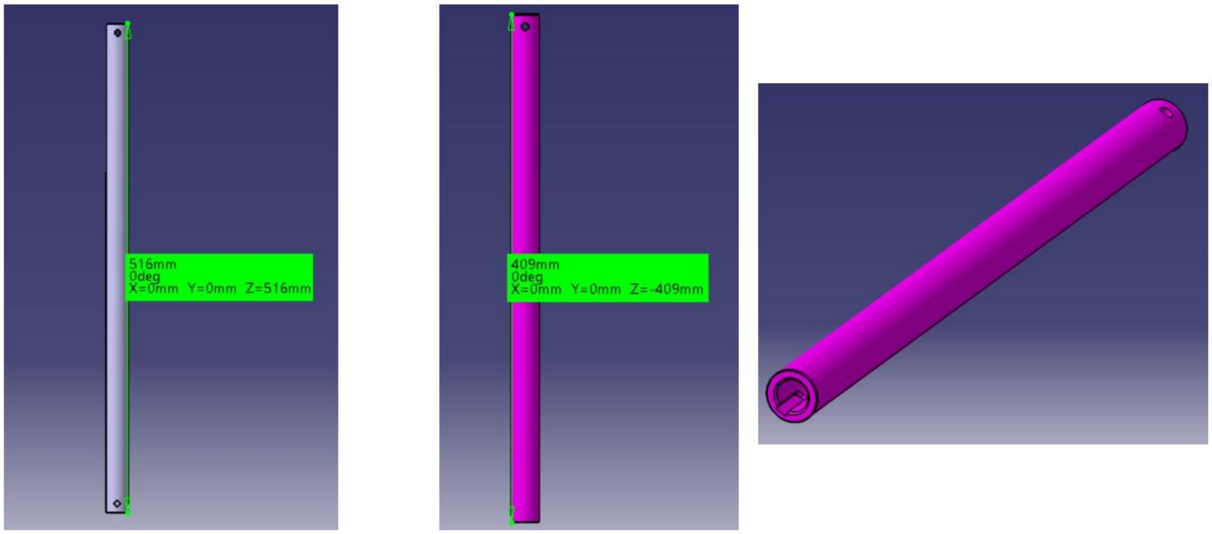



*Figure 37 : SC18 actual (left) & modified steering column (right) – Solution 1*

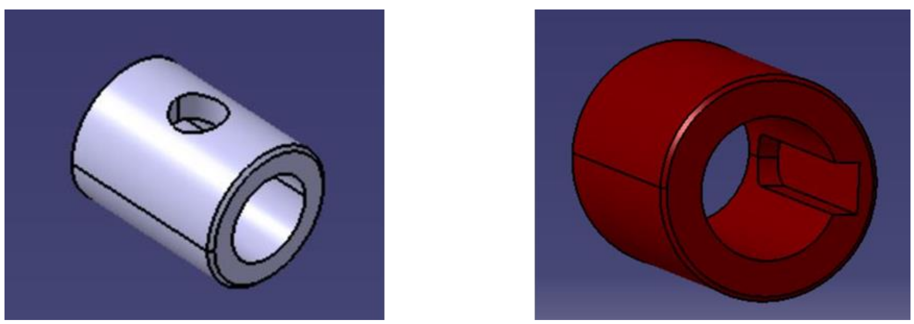


*Figure 38 : SC18 existing (left) and modified (right) bicchierino with keyway - Solution 1*

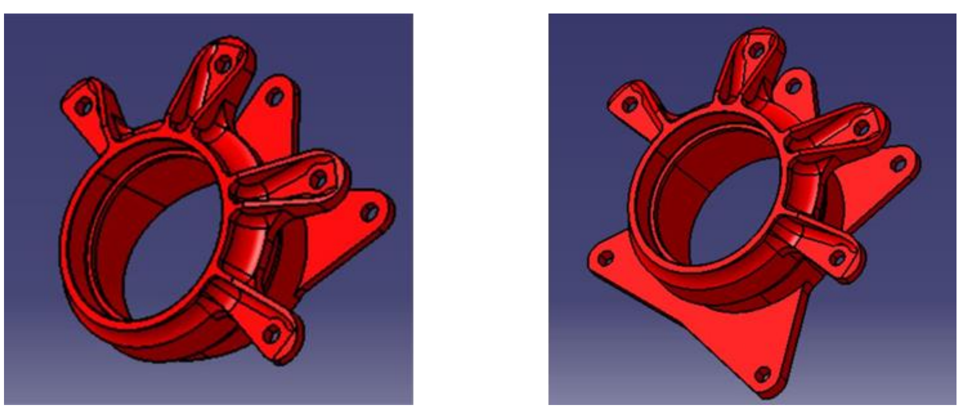


*Figure 39 : SC 18 Steering wheel support - existing (left) and modified (right) - Solution 1*

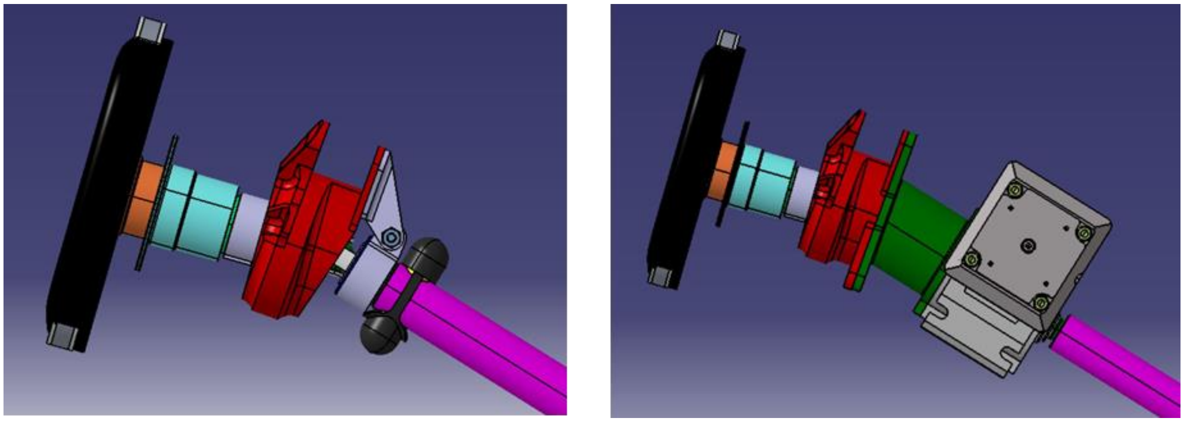


*Figure 40 : SC18 Existing steering (left) and with steering actuator (right) - Solution 1*

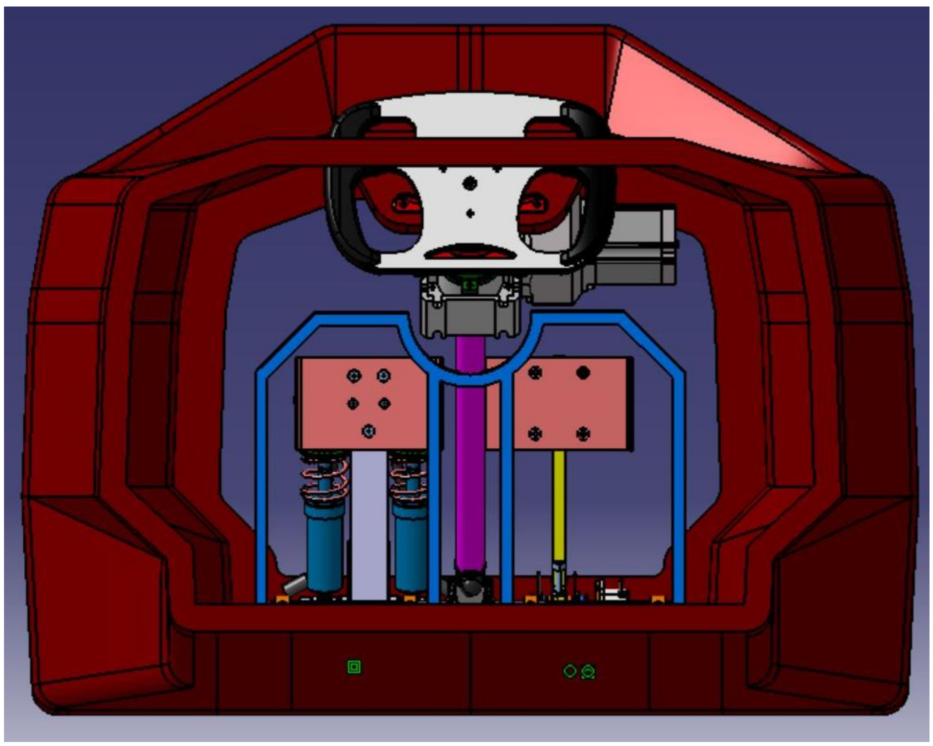


*Figure 41 : Steering actuator orientation with reference to cockpit internal template - Solution 1*

**Why not to adopt Solution 1?**

- The characteristics of a motor is defined by its speed-torque characteristics. As far as a rotary actuator is concerned, the actuator in Solution 1 has a speed-torque characteristic not suitable for our application and it was providing very minimal torque at our required speed.
- The other complication of this configuration if a suitable motor is chosen lies in the mechanical functioning of the worm gear assembly. The worm gear is not a 100% reversible mechanism and the gearboxes' efficiency ranged from $\eta = 0.4$ to 0.82. This means that '1-$\eta$' times the rated torque of the motor-gearbox assembly will remain as a self-inhibiting

torque which gets added to the inertia of the steering assembly when the vehicle is not in autonomous mode. Also, as per DV 2.2 of the FSD 2020 regulations [2], 'When the ASMS is in "Off" position, no steering, braking and propulsion actuation can be performed by request of the AS and it must be possible to operate the vehicle manually as a normal CV or EV when the autonomous mode is disabled.' This will cause the steering to be increasingly hard to be turned by the driver.

- Considering all the above problems have been sorted out, the assembly weighed about 1.7 kg plus the weight of the mounting bracket (green component in Figure 40 right) and its fasteners. In its existing configuration, the steering column's top support was not designed to take the load of mounting an actuator assembly as heavy as this. The next idea was to take the steering actuator to the lower side of the steering column on the side of the rack which had the same problem of the rack mountings and the bearing between the steering column and the pinion shaft not designed to take the additional load of the actuator assembly and its inertia loads.

While working on Solution 1, it was determined that stepper motors were not a viable solution to our application not only because of their incompatible speed-torque characteristics when coupled with a worm gearbox but also their weight. So, it was decided to move to the next best type of motor which is the Brushless DC motor which could also be used in our application and also weighs lesser. With the power unit identified, the next step was to choose the appropriate drive unit for the actuator output which will be driving the steering column. It is necessary to choose a positive drive system as the ASS requires precise position sensing. The following are the options: *chain drive, gear drive and belt drive.* Chain drive was outright ruled out owing to the fact that they are noisy in operation and are not suitable for a relatively compact application as ours. The smaller the chain links' get, they are structurally less capable of power transmission and are prone to fail and break thus jeopardize the entire system.

## Solution 2: BLDC motor + planetary gearbox assembly and synchronous belt drive

Belt drive has the advantages of compact design, economical, easy installation and servicing, less noisy, lubrication-free, has a transmission ratio of up to 95-98% (synchronous belt) and above all, can work even when the input and output shaft axes are askew or misaligned to some extent. The different types of belts are the *round belt, flat belt, V-belt* and *toothed belt or the synchronous belt*. Of these, the toothed belt has the highest efficiency as they are similar to a chain drive in function and thus have the least slippage among the other belt types. The idea is to have a BLDC motor which is coupled with a planetary gearbox so as to achieve the required torque multiplication by speed reduction. Unlike Solution 1, this is not a coaxial drive and the axis of the driver (actuator) and the driven (steering column) are parallel to each other. The motor and gearbox assembly have a key shaft output and engages with a pulley with teeth or pockets similar to a spur gear which acts as the driver or input. Another similar pulley is mounted on the steering column coaxially which acts as the driven or output. A toothed belt runs over both the pulleys and enable power transmission from the driver to the driven.

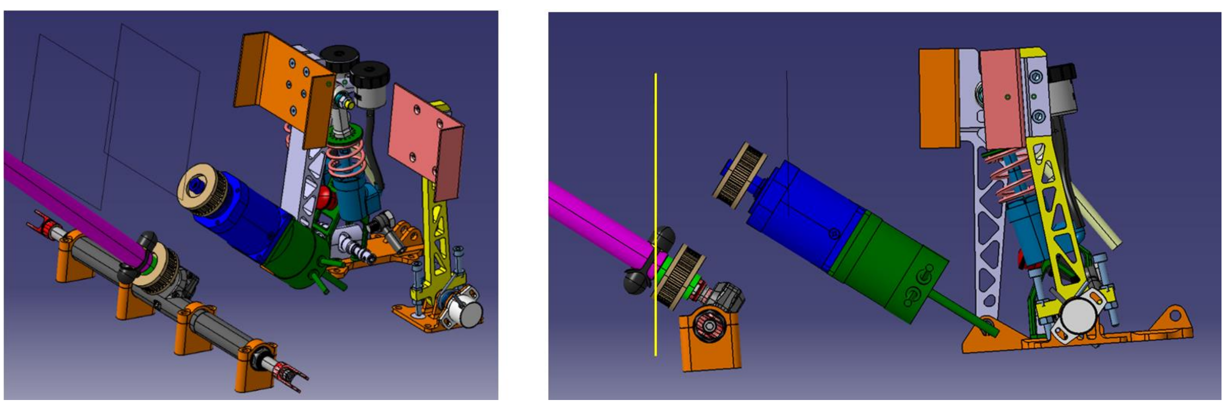


*Figure 42 : Solution 2 - BLDC motor + planetary gearbox & synchronous belt drive in SC18*

The final torque transmitted from the input to the output depends on the size of the input and the output pulleys and in our application, the diameters of both the pulleys are the same to achieve minimum possible centre distances between them both.

The assembly of the pulley drive is similar to how the gears are coupled to the gearbox and the steering column. Since the toothed belt is made of rubber, it is flexible and can accommodate misalignments between the axes of the driver and driven pulleys.

**Why not to adopt Solution 2?**

- Even though synchronous belt drives have negligible slip during operation and can have a transmission efficiency of up to 98%, they are made of rubber which is a compound that can undergo creep. When a belt passes from the slack side to the tight side, a certain portion of the belt extends, and it contracts again when the belt passes from the tight sight to the slack side. Due to these changes in length, there exists a relative motion between the belt and the pulley surfaces. This relative motion is called as creep and it is a parameter that could not be measured accurately. While using a belt drive for the ASS, when the belt is subjected to creep, there exists a nonlinearity between the angular rotation of the pulley and the linear translation of the belt. This leads to differences between the actual and the measured angular displacements of the driven pulley when incorporated into the ASS due to which, the controller will send incorrect signals to the actuator.
- This design has a problem pertaining to its structural aspect. For an efficient power transmission, belt drive requires pretension by increasing the distance between the two pulley centres. This will cause two problems: (i) radial load on the motor/gearbox shaft and (ii) radial load on the steering column which is supported by the rack mounts on the monocoque. The effect of inertia during acceleration and deceleration of the pulley must also be considered and the rack mounts will have to be redesigned accordingly.

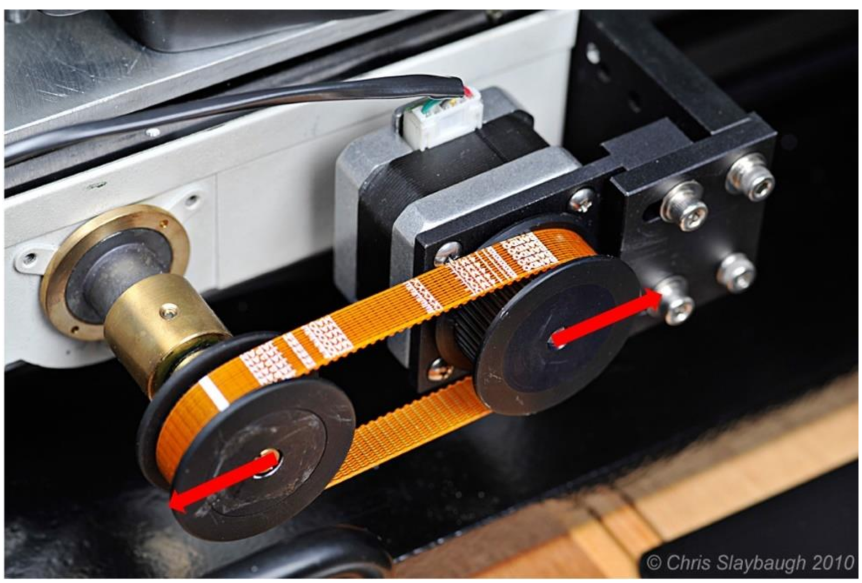



*Figure 43 : Pretension in belt drive*

### Solution 3: BLDC motor + planetary gearbox assembly and gear drive

From this section, ASS solutions conceptualised for SC19 Lucia will be dealt with. Gear drive is a 100% positive drive, has good efficiency and transmission ratio, involves minimal parts and a simple spur gear arrangement could be used which could be lubricated by grease.

*Figure 44 : Spur gear drive (left) & BLDC motor with planetary gearbox assembly (right)*

The assembly consists of a BLDC motor coupled with a planetary gearbox which has a key shaft. This shaft is coupled with a spur gear thus making the driving unit. Another spur gear of the same profile and pitch is coupled coaxially to the steering column which acts as the driven gear. The speed ratio is defined by the ratio of the diameter of the output gear to the input gear which is also the torque multiplication ratio. A planetary gearbox has multiple levels of speed reduction which reduces the output speed and thereby amplifying the torque output.

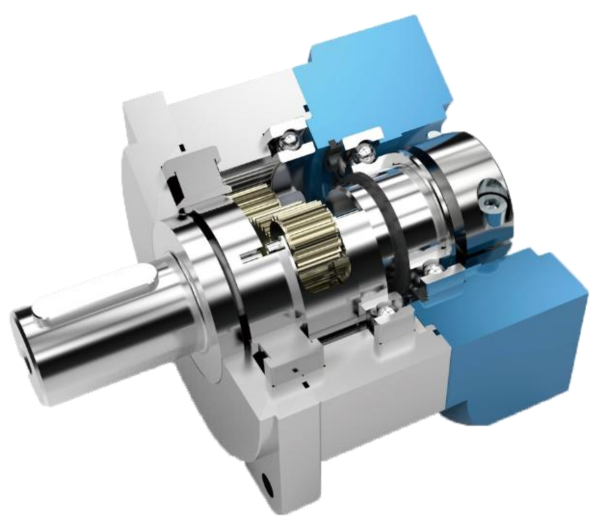


*Figure 45 : Cut-section of a planetary gearbox*

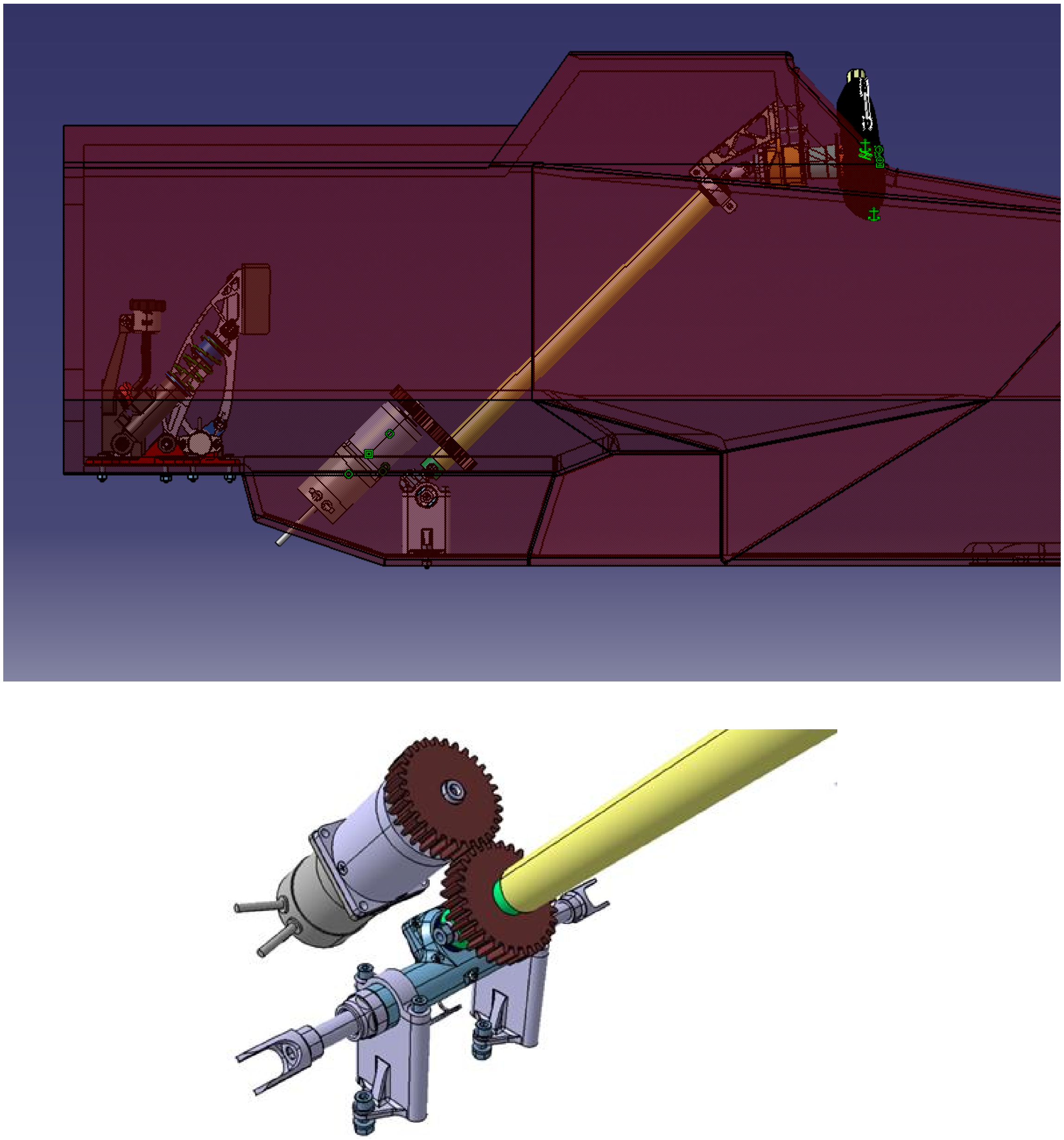


*Figure 46 : Solution 3 - BLDC motor + planetary gearbox assembly and gear drive in SC19*

The actuator could not be mounted on the upper side of the steering column as the steering column support was not rigid enough to take the weight of the actuator also and the monocoque was also inclined to be unable to provide a good support structure for the actuator's mounting. Thus, it was decided to mount the actuator to the lower side of the steering column towards the steering rack as shown in Figure 46. It was required to do few modifications to the steering column of existing system in order to realise this concept. The steering column in SC19 comprises of three parts namely the hollow steering column itself made of carbon fibre and the connections on both sides of the steering column made of aluminium alloy connecting to the side lock pinion input shaft on the rack side and the cardan joint on the steering wheel side. The aluminium connections (green component in Figure 47 & Figure 48) are bonded with the carbon fibre steering column (yellow component in Figure 47 & Figure 48) through industrial adhesive. The aluminium connection on the rack side is linked to the side lock pinion input shaft (grey component in Figure 47 & Figure 48) through a bolt and nut. To avoid mounting the driven gear on the carbon fibre steering column, the length of the aluminium connector is increased as shown in Figure 48 so that the gear could be mounted over it.

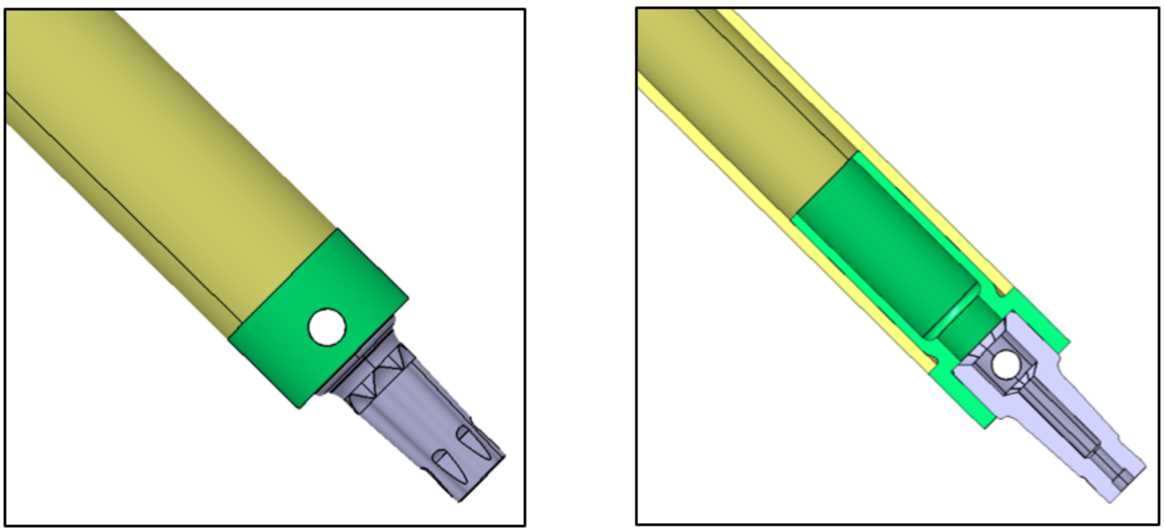


*Figure 47 : SC19 Side (left) and sectional view (right) of existing steering column - Solution 3*

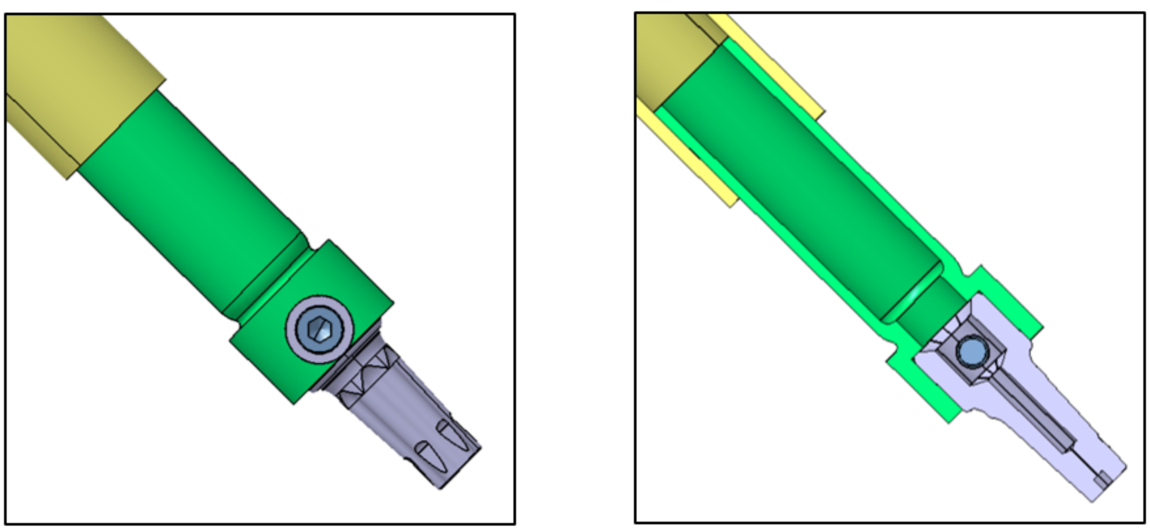


*Figure 48 : SC19 Side (left) and sectional view (right) of modified steering column - Solution 3*

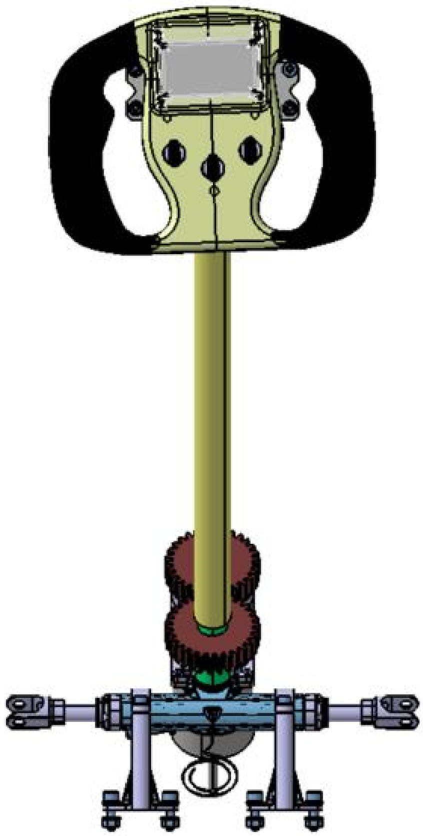


*Figure 49 : Driver's view(left) & front view(right) on SC19 - Solution 3*

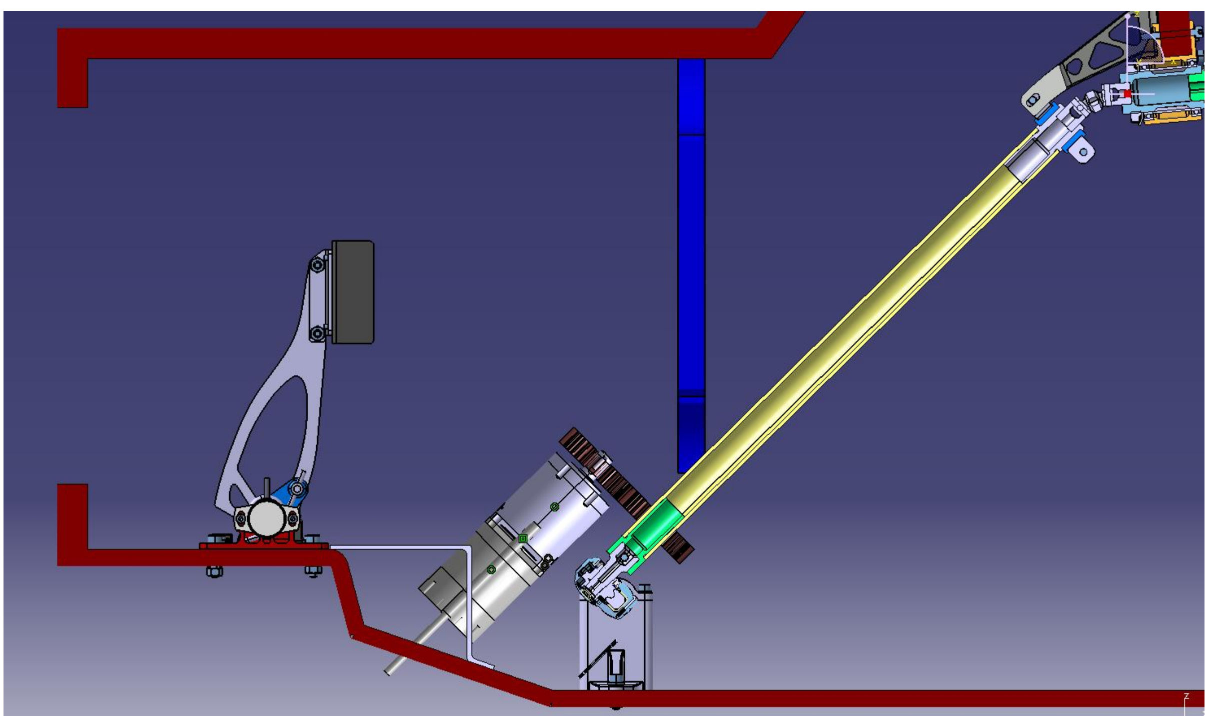


*Figure 50 : Actuator assembly & steering system in SC19 - XZ plane section view - Solution 3*

**Why not to adopt Solution 3?**

In spite of being a realisable design idea, the downsides of using a gear drive are

- Since the ASS in a FSDV is a continually operating system while the car is in motion, the gears are always in constant motion while actuating the steering column. It is important that the axes of both the gears are absolutely parallel with no room for any misalignment. Gear mesh misalignment may result in shifts in the load distribution of a gear pair which may result in increasing contact and bending stresses on the gear tooth thereby moving the peak bending stresses to the edge of the face width and might also increase gear noise. On an extended use, this may even cause breakage of the gear tooth and failure of the ASS.
- Pitch circle of both gears should match tangentially for which the gears may have to be preloaded radially against each other. This induces additional forces on the steering column, so it requires redesigning the pinion radial bearings and also additional bearing support for the steering column. Also, the rack mounting supports must be made stiffer to take the additional loads.

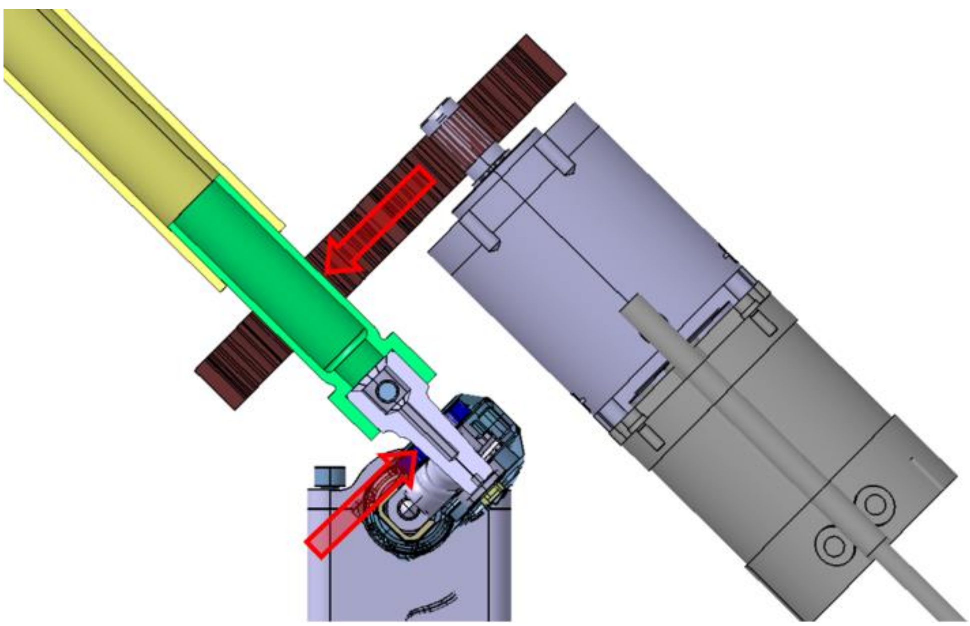


*Figure 51 : : Force from the gear drive loading the pinion bearing – Solution 3*

### Solution 4: BLDC motor + gearbox with a rocker mechanism

From here, the project was dealt with a more practical approach by better understanding the pros and cons right from the beginning. This configuration as represented in Figure 52 involves a BLDC motor coupled to a gearbox (if torque multiplication is required) to keep the motor size smaller, whose output shaft is connected to a rocker arm (purple). An actuator link (green) is mounted below the steering rack supported by the same rack mountings and connected to the clevis joints on both sides. The actuator link has a block (yellow) rigidly attached to it and offset from the rack plane in +X axis. This actuator link slides through a low friction plain bearing in the rack mounting while translating in the Y axis. The rocker arm and the block are connected by a connecting link(red).

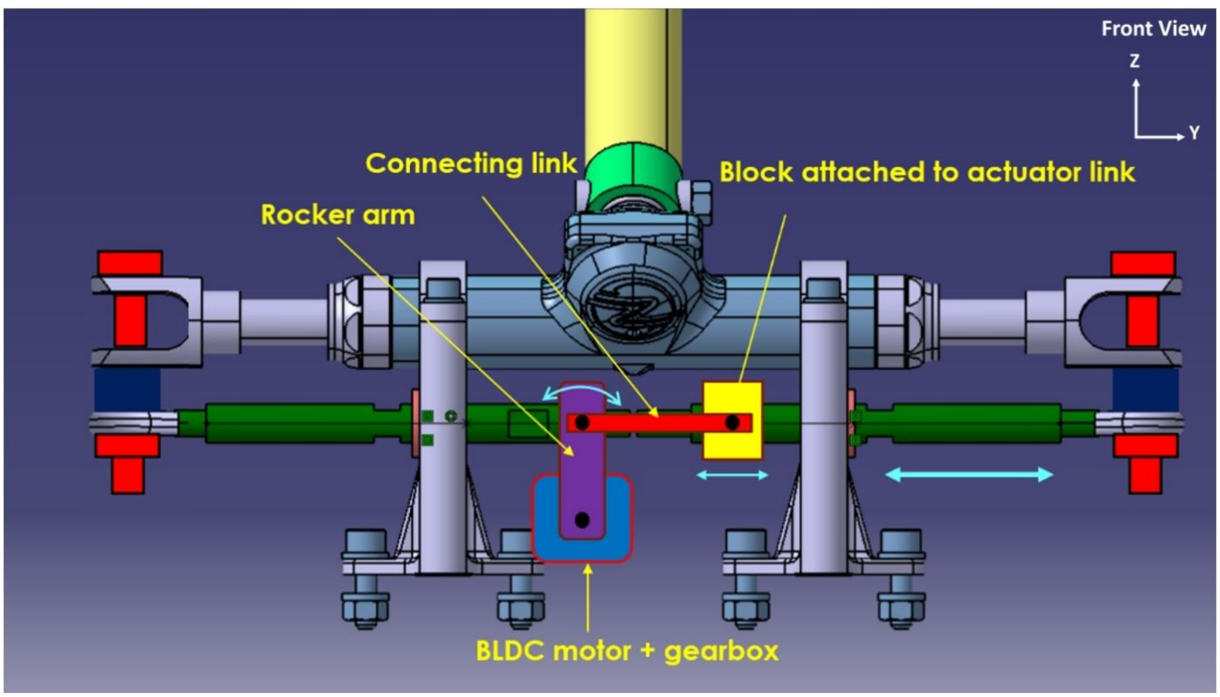



*Figure 52 : Solution 4 - BLDC motor + gearbox with a rocker mechanism*

When the motor shaft rotates, it causes the rocker to have an oscillatory movement about the motor output shaft axis and this pushes/pulls the block through the connecting link. This action causes the actuator link to move in the Y axis and thereby actuate the steering rack to turn the wheels accordingly.

The rocker however has a non-linearity in its linear velocity at its connection to the block. In simple terms, there is no linear relation between the rocker's angular rotation and the block's linear translation. Assume if the rocker oscillates by 10 degrees, the block moves by 10 mm. When the rocker oscillates by 20 degrees, the block moves less than 20 mm. This non-linearity has to be compensated while defining the control logic for the controller design. A look-up table between angular displacement vs linear displacement of the rocker could be made and incorporated in the controller so that the required rack travel could be mapped to the lookup table and the actuator could be controlled to turn accordingly.

**Why not to adopt Solution 4?**

- The mechanism has several additional components such as the rocker, the connecting link, the actuator with block and the mechanical connections between them. The more the number of components and linkages, the closer the tolerances have to be set. Considering all the solutions discussed in this thesis, this solution requires the maximum number of additional components.

## Solution 5: BLDC motor + gearbox actuating a parallel secondary rack

This solution involves incorporating a secondary steering rack below the primary steering rack and they are connected at both ends of their clevises in a way they both move in tandem. The idea is to replicate the driver's steering input on the secondary rack through a BLDC motor and gearbox assembly and thereby achieve an ideal ASS functioning.

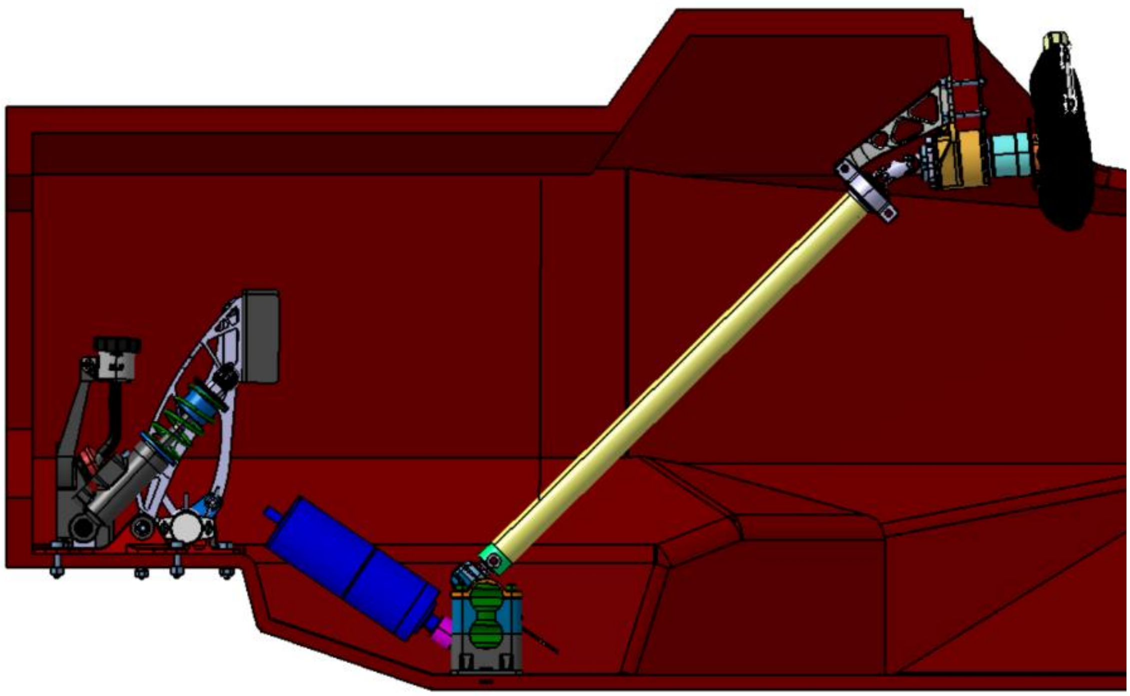


*Figure 53 : Solution 5 - BLDC motor + gearbox actuating a parallel secondary rack*

This idea emerged when thinking about redesigning the existing rack to have two rack tooth profiles and as already one profile is being driven by the steering pinion, another pinion gear driven by a motor-gearbox assembly will engages with the other rack tooth profile. But it was not an easy task since modifying the existing rack is as much tedious as designing a whole new steering rack assembly. An alternate better option is to have a secondary rack and pinion assembly below the primary (existing) steering rack which is connected at both ends through the clevis joints as shown in Figure 54. This configuration is highly practical and with this configuration, while in manual mode, the driver will operate the steering through the wheel while in autonomous mode, the steering actuation will be done through the secondary rack mounted below the primary rack.

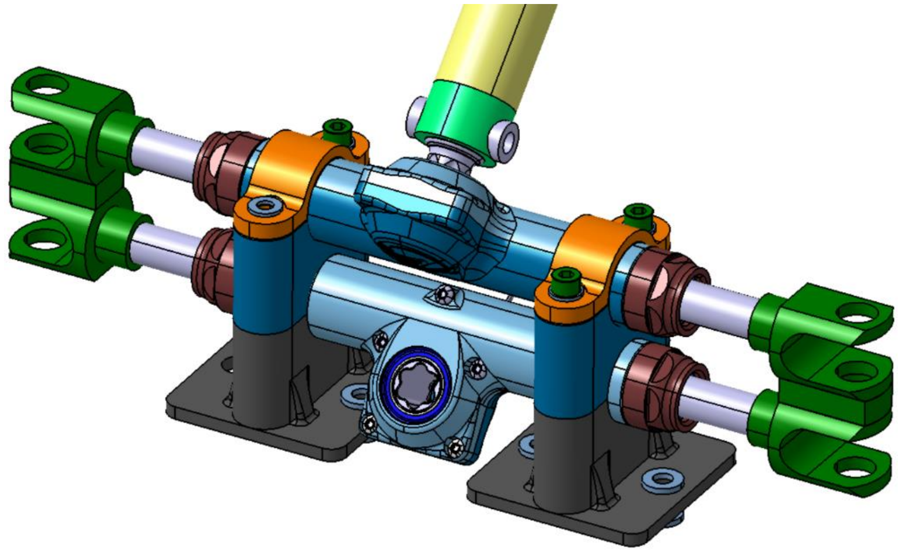


*Figure 54 : Secondary (ASS) rack below primary (existing) rack in SC19 - Solution 5*

This solution requires minimal of additional parts and minimal modifications to the existing components such as the steering rack mounting, the side lock pinion shaft and the rod ends.

- **Steering rack supports** – There exists two supports for the steering rack assembly made of aluminium alloy for supporting the steering rack on the monocoque. As shown in Figure 54, they are made up of a lower part and an upper part between which the primary rack is seated. With this configuration, the secondary rack also has to be seated over the support and thus, it is made into three pieces i.e., the secondary rack sits between the lower and the middle part while the primary rack is seated between the middle and the upper part of the supports. Accordingly, the lower and upper supports are made stiffer by increasing its thickness and additional ribs are added to the flange surface area as shown in Figure 56 and Figure 57.

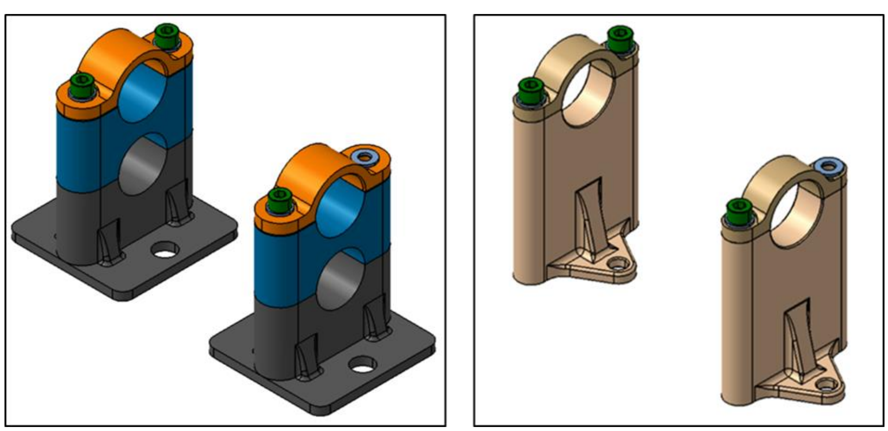


*Figure 55 : Steering rack supports - existing design (left) & modified design (right) - Solution 5*

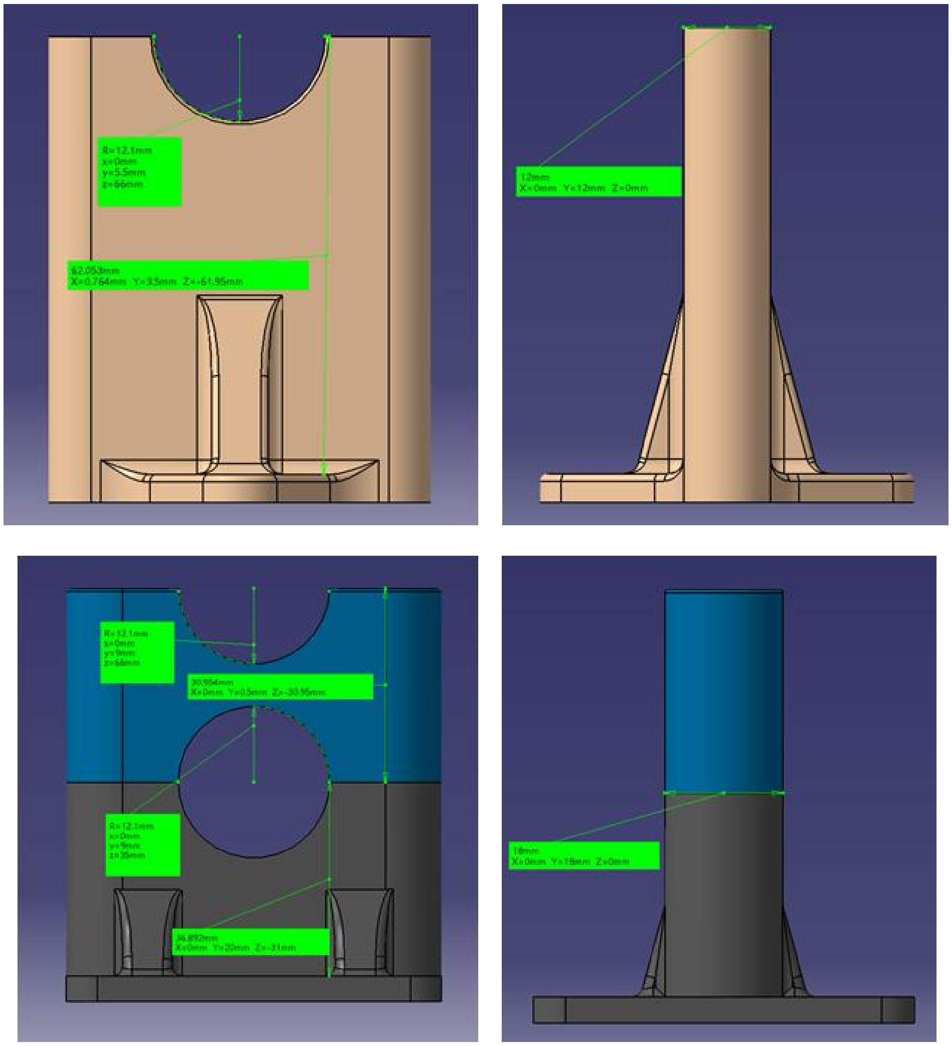


*Figure 56 : Existing (left) and modified (right) steering rack housing lower supports - Solution 5*

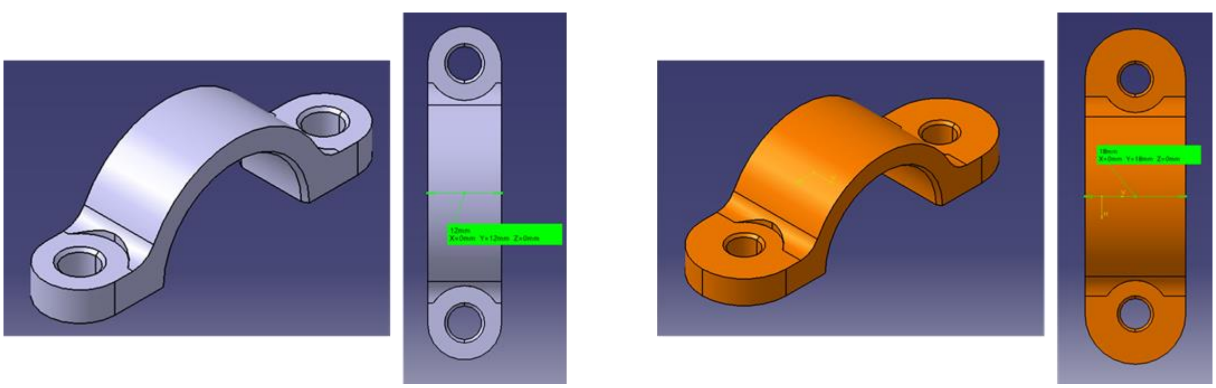


*Figure 57 : Existing (left) and modified (right) steering rack housing upper supports - Solution 5*

- **Side lock pinion input shaft –** this component has a spline on one end which engages with the pinion gear and is connected to the steering column on the other end by a bolt and nut. The primary rack pinion shaft remains unchanged while the secondary rack pinion shaft is modified as shown in Figure 58 to engage with the key shaft of the gearbox. There is also a secondary positive locking between the pinion shaft and the gearbox shaft is provided by a nut and bolt. The steering rack assembly with modifications is shown in Figure 59.

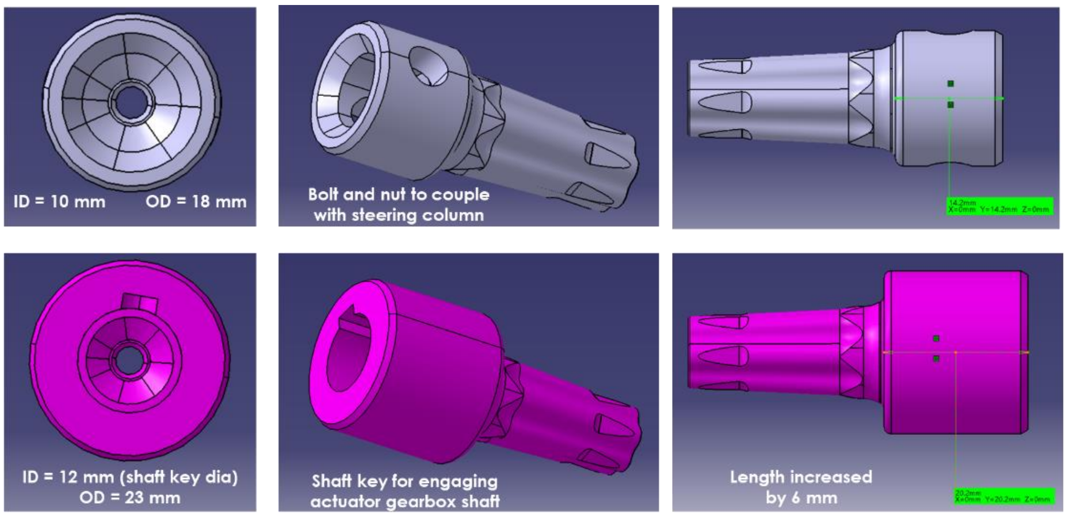



*Figure 58 : Existing (top) and modified (bottom) side lock pinion input shafts - Solution 5*

Upon performing an FEA, the minimum distance that could be had between the axes of both the racks could be determined as the closer the axes are to each other, the minimal the moment they will exert around the rack supports as shown in Figure 60.

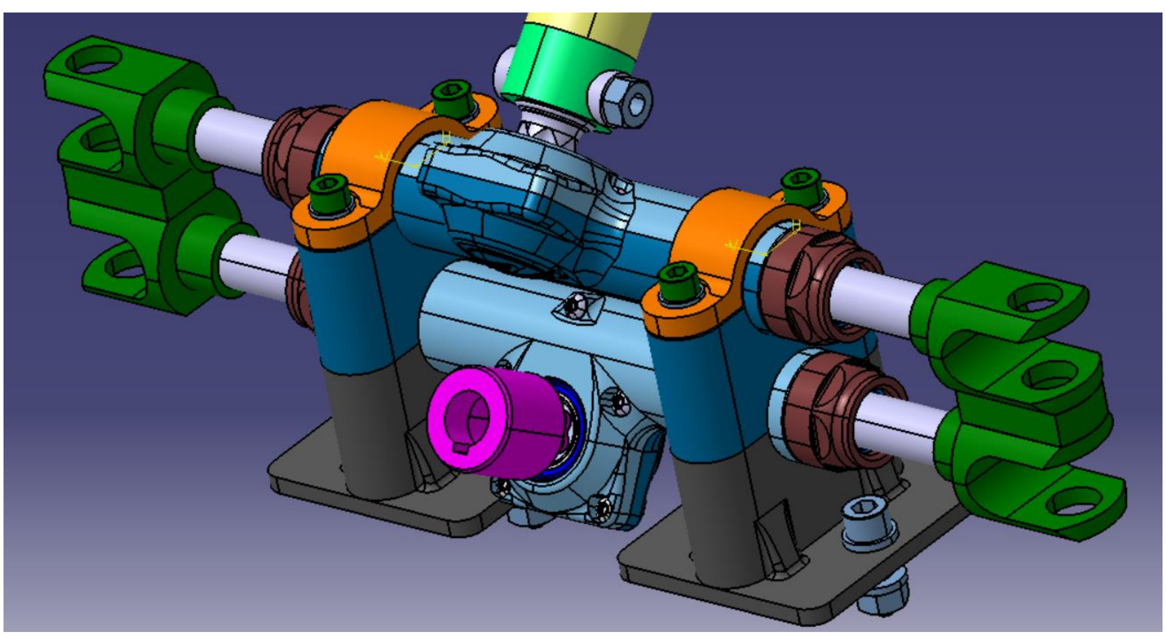


*Figure 59 : Modified steering rack assembly for ASS - Solution 5*

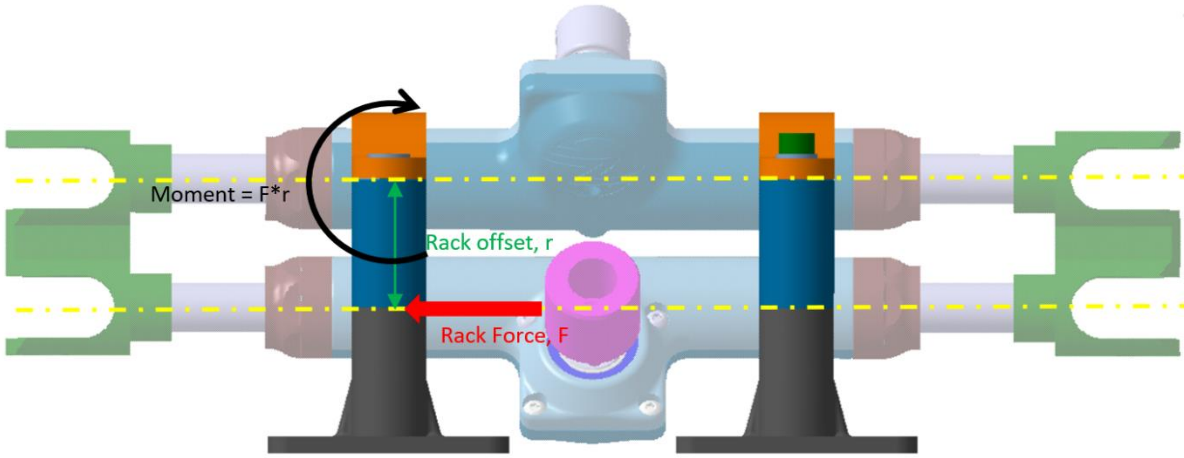



*Figure 60 : Effect of rack-offset in moments acting on rack supports - Solution 5*

Pertaining to the orientation of the actuator, the most ideal is to have it mounted parallel to the monocoque floor in order to be able to make a mounting bracket which is symmetric. However, depending on the length of the motor and gearbox assembly and the interference of the secondary rack's housing with the monocoque floor (refer Figure 61 points A and B), the angle between the actuator axis and the floor will have to be chosen accordingly. Also, as discussed earlier, the axis of the secondary rack could be moved in the +Z axis to avail more clearance from the monocoque after FEA analysis of all cases.

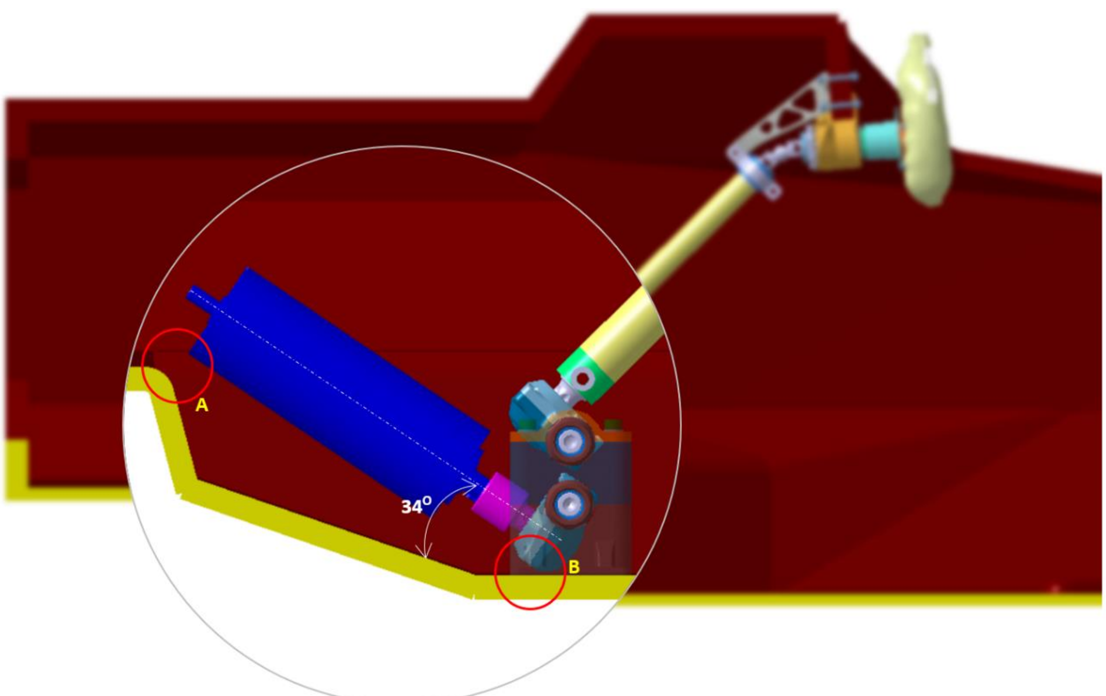



*Figure 61 : Packaging and orientation of the actuator inside the monocoque - Solution 5*

**Why not to adopt Solution 5?**

By far, this solution is the least complex in terms of integration into the existing steering system with minimal modifications to the existing components. However, there still exists plausible reasons to why this solution might be unable to be implemented.

- As simple as it seems to implement a secondary rack similar to the primary, making another rack assembly takes a lead time of almost 2 months to manufacture as well as the cost considering it is a customised part (refer page 23).
- In this regard, possibilities to salvage an old steering column from older Squadra Corse Formula Student cars and buying off-the-shelf steering racks were explored. Since SC19 has a very narrow frontal cross section (refer Figure 29), it was unable to find a compatible short-length steering rack assembly for SC19.

## 3.6 Chosen ASS design solution for implementation in SC19

In contrast to all the previous solutions which actuate the ASS through rotary motion, this solution involves using a linear actuator to steer the FSD car autonomously.

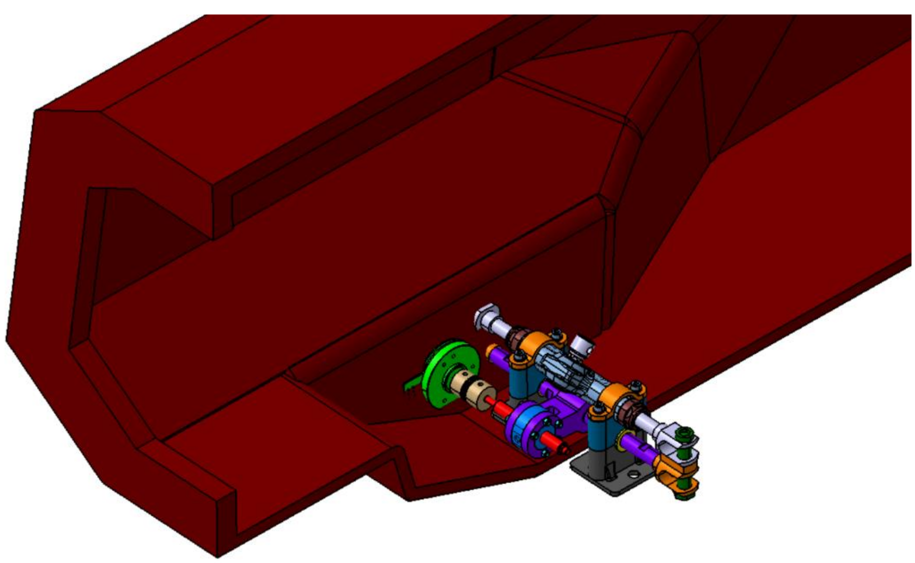


*Figure 62 : Chosen solution - BLDC motor with a ball screw drive and actuating link*

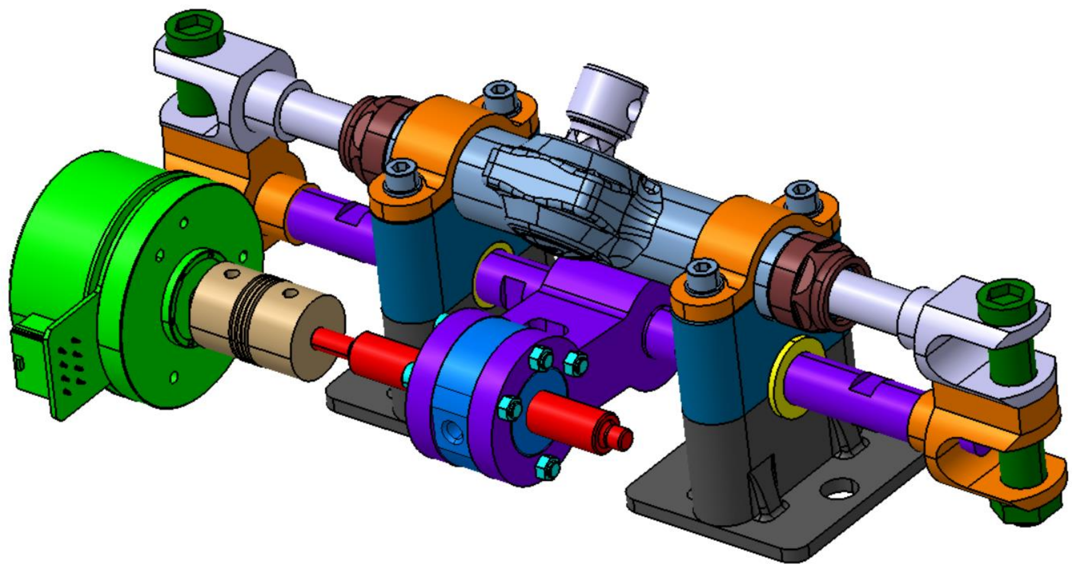


*Figure 63 : Actuator assembly –chosen solution*

As shown in Figure 63, the system comprises of a power unit and a transfer unit. The power unit comprises a BLDC motor (green) from Maxon rigidly coupled by a shaft coupling (beige) to a Bosch Rexroth ball screw shaft (red) over which a ball nut (blue) is engaged. The ball screw and nut mechanism convert the rotary motion from the gearbox to linear motion to the ball nut. The transfer unit comprises of an actuator link with a block (purple) which in turn connects the clevises (orange) on the rack ends of the primary rack as shown in Figure 63. These clevises connect with the steering tie rods on both ends and turn the front wheels. The ball screw drive is a reversible mechanism and thus, the FSDV could be driven in manual driving mode without having to worry about disconnecting the ASS from the mechanical steering system.

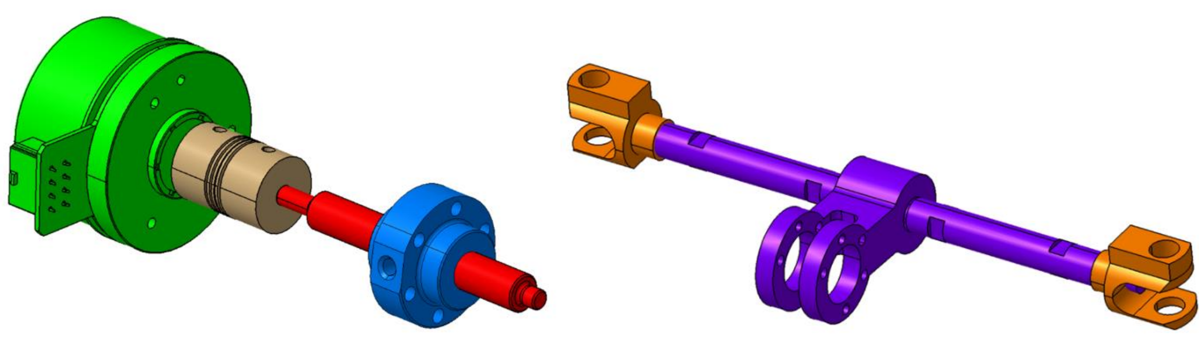


*Figure 64 : Power unit (left) and transfer unit (right) – chosen solution*

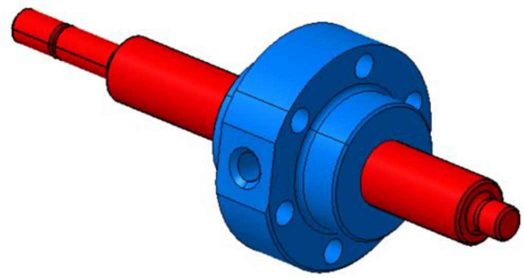


*Figure 65 : Bosch Rexroth ball screw(red) and adjustable-preload single nut (blue)*

The actuator link is supported by the steering rack supports through sleeve bearings (yellow in Figure 63) which ensure there is minimal friction when the actuator link slides over it. Thus, it acts as a member that transmits force as well as a guide spindle to ensure translation axis is never askew with respect to the rack travel axis. This is crucial as an increase in this friction will cause undesired moment on the rack supports. The actuator link could be a single component or made up of multiple sub-components linked rigidly with each other depending on the complexity of the design and corresponding manufacturing processes.

- If the actuator link is made as a single component, the rack mountings have to be split into three parts so that once the base part is mounted, the actuator link is seated over it followed by the middle part of the mounting, then the steering rack and finally the top mounting (refer Figure 66 left image). Long bolts will have to be used to fasten the three parts of the mounting.
- If the actuator link is made up of sub-components which will be coupled rigidly with each other, the supports could be made as just two parts and the cylindrical rods of the actuator link could pass through the secondary holes in the supports and fastened with the central block (refer Figure 66 right image).

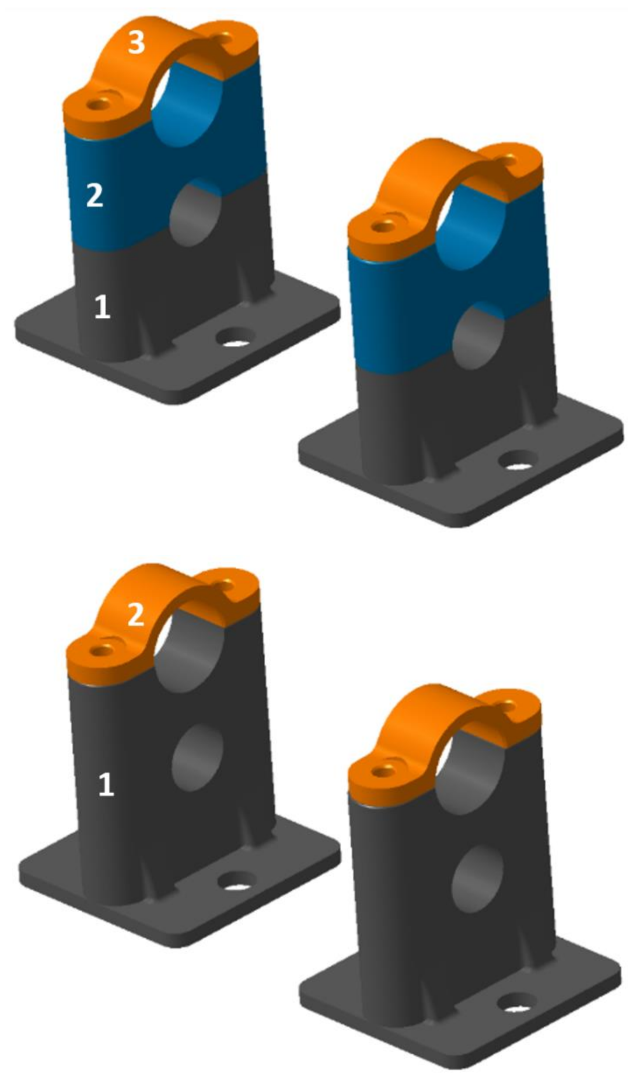
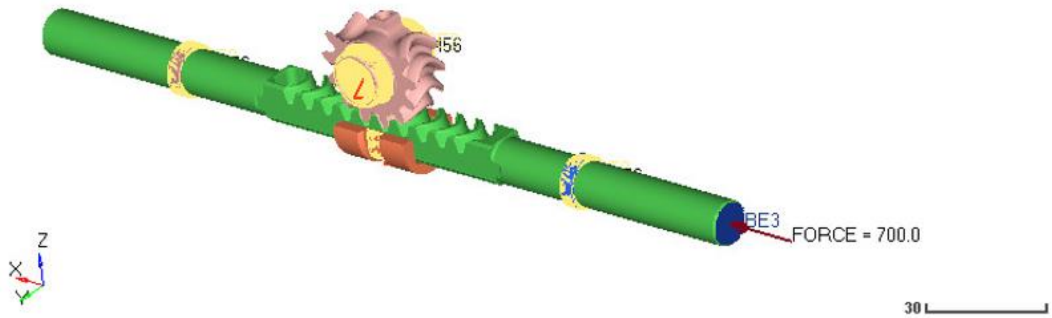



*Figure 66 : Support design for single-piece(above) & multi-piece(below) actuator link – chosen solution*

Here, the parameter to focus on is the force required on the rack to turn the wheels and the vehicle static condition is the worst case as the maximum force is required by the tyre to turn by overcoming the coefficient of static friction. As calculated in section 3.4, the required rack force is 664 N. Our scope is to design a linear actuator comprising of a motor (and a gearbox if required) which drives a ball screw at a linear speed of 45 mm/sec (refer page 49).

As shown in Figure 67, the rack is designed to take an axial load of up to 700 N as per the Finite Element Analysis (FEA) done by Squadra Corse. FEA is required to be performed not only for the new and modified components but also to the existing unchanged components with respect to the new load cases as a result of the addition of ASS to the existing steering system.




| ANALYSIS TYPE: NON LINEAR QUASI STATIC | | | |
|---|---|---|---|
| **LOAD TYPE** | **MAGNITUDE** | **DIRECTION** | **NOTE** |
| FORCE | 700 N | Axial direction | Force evaluated both in push and pull, because on non symmetry of teeth |
| CONST | FIXED | 6 Dof | Applied on pinion |

*Figure 67 : FEA on steering rack - SC19*

**Constraints in implementing this solution**

- The concern with this solution lies in the minimal space available in the Y axis owing to the less wider monocoque of SC19 compared to SC18 (Figure 28 & Figure 29). Due to this, the block of the actuator link has to be centrally placed so as to balance the forces on either side during actuation. The power unit of Solution 6 takes up one side of the monocoque room from the XZ symmetry plane. The lateral space available inside the monocoque is less than the power unit length due to which a hole has to be made in the monocoque to allow space for the motor. This is critical as the mounting points of the multilink suspension is at close vicinity and the structural rigidity of the monocoque has to be re-evaluated. This modification does not violate any rules cited in section T2.1.3 of the FSG 2020 regulations [2].

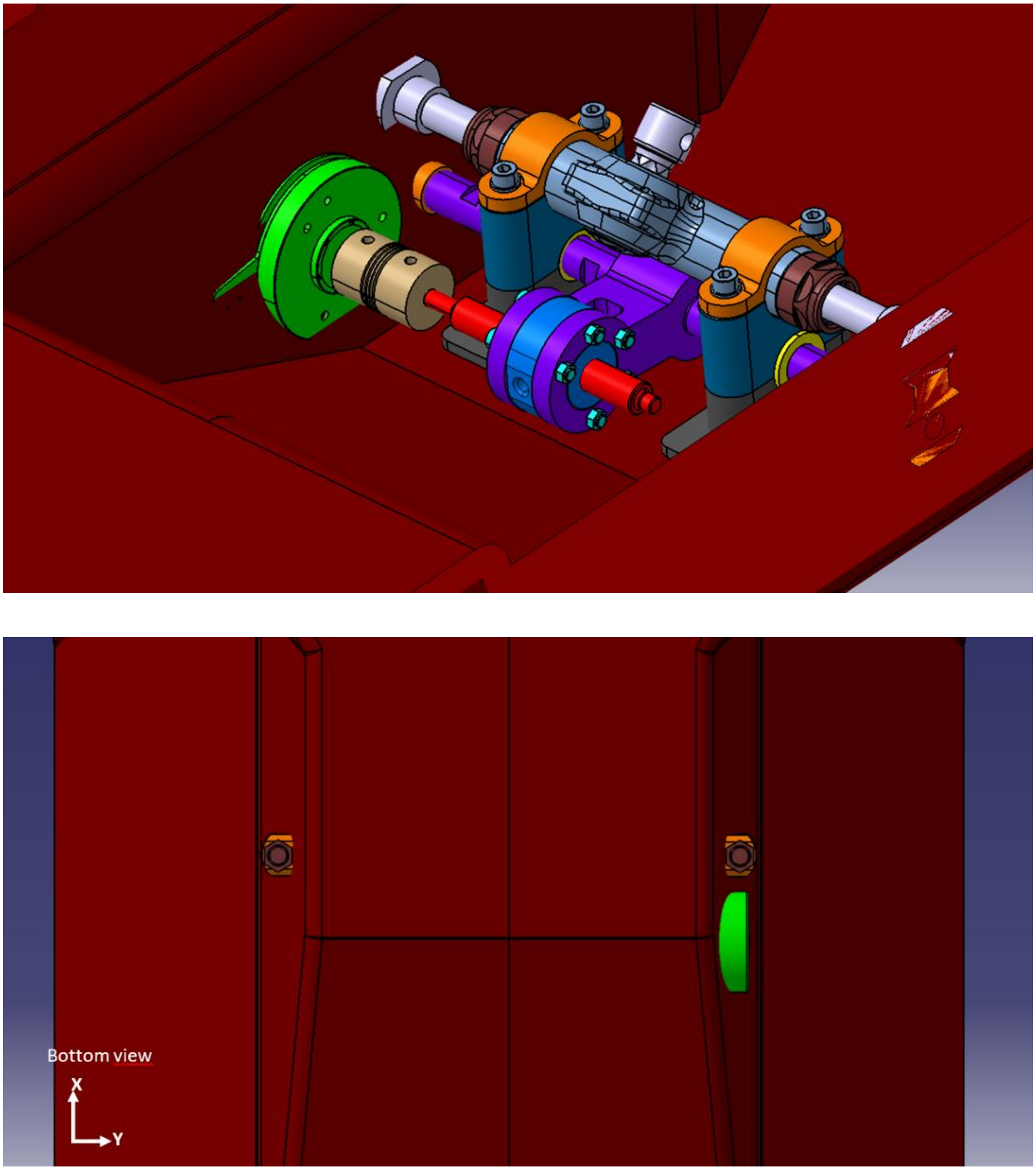



*Figure 68 : Interference of the actuator motor with the monocoque – chosen solution*

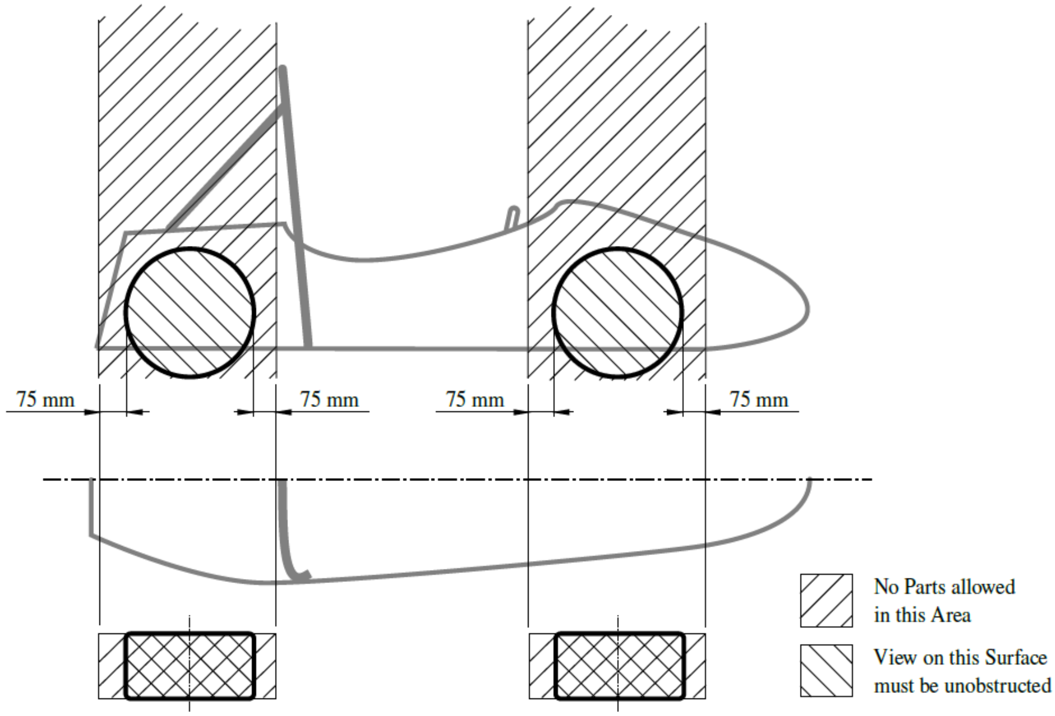



*Figure 69 : Keep-out-zones for the definition of an open-wheeled vehicle - FSG 2020*

- The more the offset of the block from the rack axis, the higher the moment exerted on the supports when the ball screw pushes/pulls the actuator link. Lower the offset, lower the moment but lesser will be the space in +X axis for mounting the actuator components and vice versa. So, it is important to design the system with appropriate trade-offs.

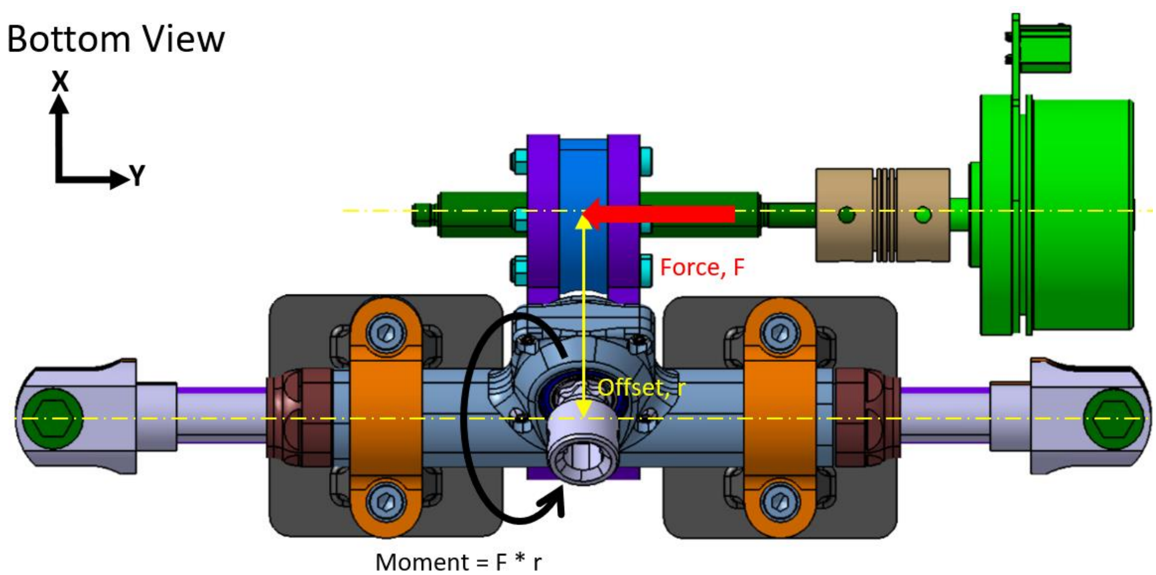



*Figure 70 : Top view of the ASS actuator assembly – chosen solution*

# Chapter 4

# Failure Mode and Effect Analysis (FMEA)

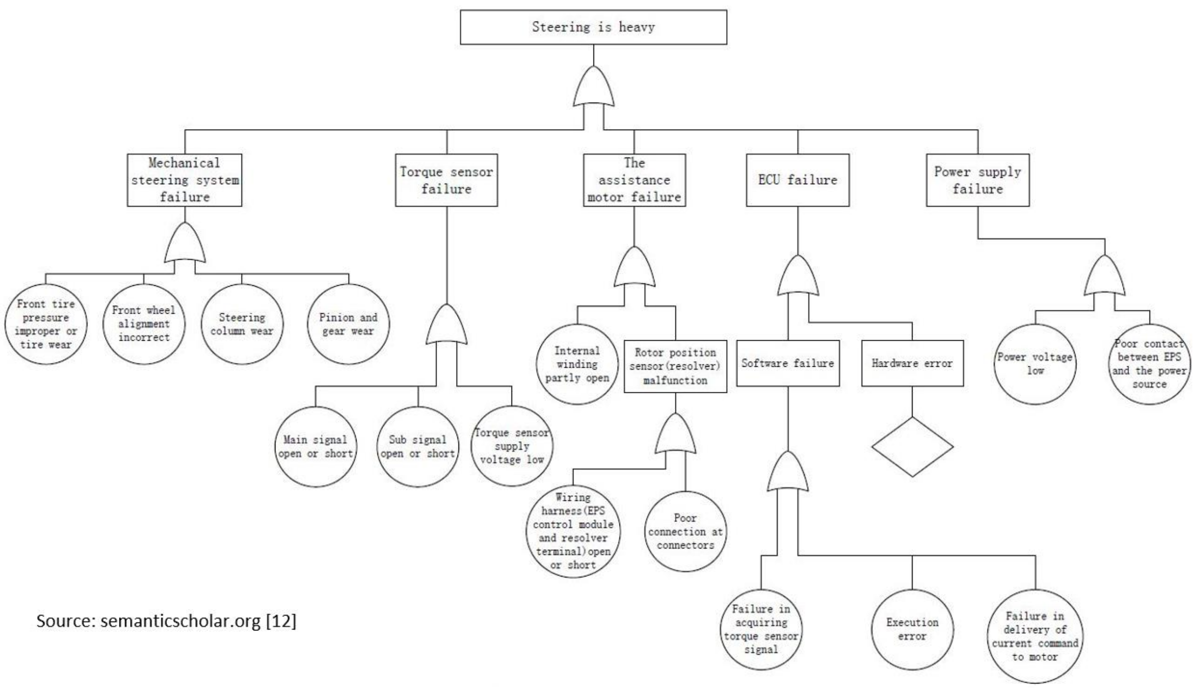
This chapter deals with Failure Mode and Effect Analysis (FMEA) and how it could be applied in determining the possible failure modes of the ASS of our Driverless Vehicle. It is a tool used in a diverse spectrum of industries and this section focuses on its application specific to the automotive industry. Since this is the first time the work on developing ASS is carried out and making a working prototype of the ASS is further away in the FSDV project timeline, this thesis focuses on conceptualising the practical design solution for the ASS and similarly a conceptual FMEA on the chosen solution for the ASS.

## 4.1 What is FMEA and why it must be done

In the news about automotive industry for example, there are numerous instances when certain batches of car models are recalled for a possible failure in any of the components or system in the car. The European Union has a set of regulations pertaining to consumer goods which dictates that, when a product is identified as dangerous, the concerned businesses are obliged to take measures including, if needed, recalling it from the consumers to fix them. In the event that such actions by the concerned businesses prove to be unsatisfactory, the public authorities have to take legal measures to correct them. Though at some instances these recalls are unavoidable, they could be effectively minimised as these recalls cost a lot of money for businesses as they have to do what is necessary to fix the defective component or system.

The main reason to these defective systems in cars causing mass recalls is due to the system not being thoroughly evaluated for failures during any of the following phases of the system's product development cycle – design and manufacturing process. So, the first step in developing a system/component that does not fail is by determining the possible failure modes of the system under usage by the customer. A "failure mode" is anything that can result in a possible defect or a rejection of component or a complete failure of the function of the system/component. There exists several tools and techniques adopted by car manufacturers in reducing the failures of their products during the initial stages of their development and one of the types of classification of these methodologies is the *top-down approach* and the *bottom-up approach*.

Fault Tree Analysis (FTA) is a methodology which adopts a top-down approach in detecting failure modes in a system. It employs analysing an undesired state of a system/subsystem using Boolean logic to combine a series of lower-level events. It is used to evaluate the reliability of a system by understanding how a system can fail and identifying the best ways to reduce risks.




Source: semanticscholar.org [12]

*Figure 71 : Example of a Fault Tree Analysis of an Electric Power Steering system in a car*

Failure Mode and Effect Analysis (FMEA) is one such method classified as a bottom-up approach in detecting failure modes as it relies on brainstorming and systematically identifies the consequence of a single failure in a particular component and works its way up in determining its effects on the higher levels of the system. FMEA is a methodology which is aimed at allowing and enabling car manufacturers to anticipate failures during the design stage by identifying all the possible and probable failures that might occur during the design and the manufacturing process of the vehicle systems. [7] It is a structured approach which helps discover potential failures that may exist and could happen within the design of a product or a process. This method is used to systematically identify the consequences of an individual fault by consistently asking the question "What happens if …?"

Time and money are the most valuable resources for a product manufacturer. Money could be earned back over the period of time, but the lost time could not be recovered or rolled back to make things right. So, the sooner a failure is detected, the lesser it is going to cost the company. The more later a failure in a product/process is discovered, the repercussions are going to increase exponentially and cause devastating impact on the company's image and revenue. FMEA is one of the many tools which helps in discovering a failure early in the Product Development and has the following benefits of:

- Having multiple choices to approach and mitigate the risk
- Higher capability to verify and validate the proposed changes
- An effective collaboration between the design phase and the process phase of the product
- An improved Design for Manufacturing and Assembly which involves making the design in such a way that it is easily manufactured and assembled with minimal labour cost.
- Lower cost solutions as it avoids future recalls
- If done on a continuous manner, it proves to be a vital database of learnings and knowledge which could be taken across multiple products and their developments

FMEA cannot be considered as a direct substitute for good engineering practices. Rather, it enhances good engineering practices by applying the knowledge and the experience of an interdisciplinary team called a Cross Functional Team (CFT) to review the design progress of a product or process and thereby assessing its potential failures and the risks they pose.

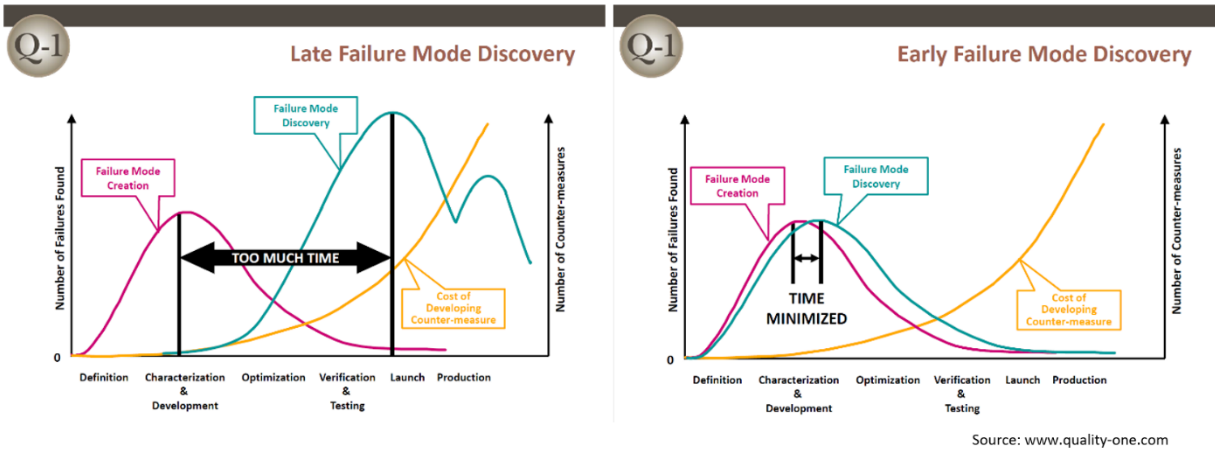



*Figure 72 : Advantage of early discovery of a failure in Product Development*

## 4.2 Classification of Automotive FMEA

Automotive FMEA can be classified into three categories: *System FMEA*, *Design FMEA* and *Process FMEA.* There exists a hierarchical relationship between the three phases in the same order as mentioned here and each phase contributes to making a fault-free product. Considering a conventional steering system, system FMEA will be used for the steering system itself, design FMEA will be used for evaluating the fasteners in the steering system, their material properties, GD&T, interfaces with other components/systems and process FMEA will be used to evaluate the risks due to failure of the fasteners and their effect on the system as a result of process parameters such as human factors, materials and machines used, measurement systems calibration. This example clearly explains the hierarchical relationship between the three automotive FMEA categories and the concept of the bottom-up approach where the effect of a component's failure is evaluated based on its effect on the functioning of the system.

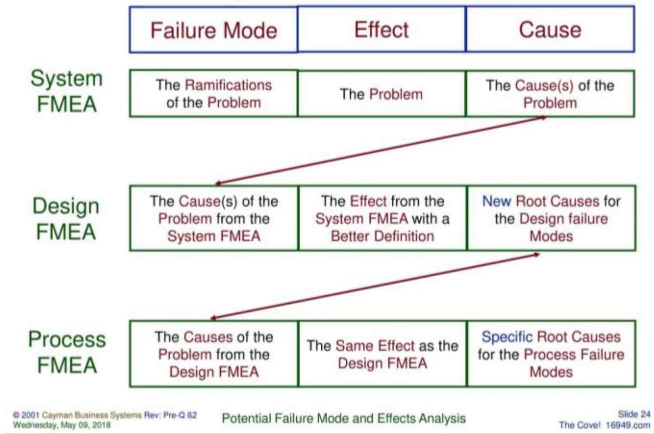



*Figure 73 : Relationship of Automotive FMEAs*

## 4.3 When must FMEA be performed

It makes sense to perform Failure Mode and Effect Analysis several times such as

- When designing a new product, process or service
- When planning on performing an existing process in a different way than currently adopted
- When there is need for a goal in improving quality for a specific process
- When understanding and improving the failures of a process is needed

It is advisable to perform FMEA occasionally throughout the lifetime of a process and quality and reliability must be examined consistently and must be improved to obtain optimal results.

## 4.4 How FMEA must be performed

Standard J1739 by SAE provides guidance on applying the functional FMEA method [8]. The analysis includes the following steps.

1. List each function of the item on an FMEA worksheet.
2. Identify potential failure modes for each item and item function.
3. Describe potential effects of each specific failure mode and assign a severity to each effect.

4. Identify potential failure causes or mechanisms.
5. Assign a likelihood of occurrence to each failure cause or mechanism.
6. Identify current design controls that detect or prevent the cause, mechanism, or mode of the failure.
7. Assign a likelihood of failure detection to the design control.

This study applies the first four steps listed above for the functional FMEA to identify failure modes at the function level that could lead to the vehicle-level hazards. Since this study is implemented at the concept phase and is not based on a specific design, there is no data to support Steps 5 through 7. The completed functional FMEA worksheet is intended to be a living document that would be continually updated throughout the development process.

Another well-known practice in creating automotive FMEA is the "*5-step method*" and it is also introduced in the Verb and der Automobilindustrie (VDA) which is the German Association of the Automotive Industry. In this method, hierarchical groups of system element networks are created, then functions are connected to each system element, the effects of failure operations are defined, risks are evaluated, and finally the risks are ranked and mitigated. This method, though being well-known, involves a high resource capacity because of the high number of reviews for the newly developed product. Therefore, internal know-hows and "best practices" have been used at many car manufacturing companies to quick start the process by using a standard template and one such template is represented in Table 2.

| Item/function | | | Potential Failure Mode | Potential effect(s) of failure | | Severity | Potential cause(s)/ mechanism(s) of failure | Detail cause(s)/mechanism(s) of failure | Occurrence | Detection | RPN | Recommended action(s) | Action results | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subsystem | Assembly | Component | | Local Effect | Final Effect | | | | | | | | Actions taken | Severity | Occurrence | Detection | RPN |
| Steering rack | Steering | Pinion gear | Unable to steer the vehicle as desired | Increased backlash | Drive not transmitted from steering wheel to the tires | 7 | Pinion gear and rack tooth breakage | -Misalignment of the pinion axis with the rack<br>-improper material selection | 6 | 5 | 210 | Ensure a second-level quality check before sign-off | Setup of a precision tool to align the pinin gear with the rack | 2 | 1 | 3 | 6 |

*Table 2 : An example of FMEA worksheet template*

To make it simpler for application on a university project level, the procedure for developing an FMEA could be as represented in the Figure 74.

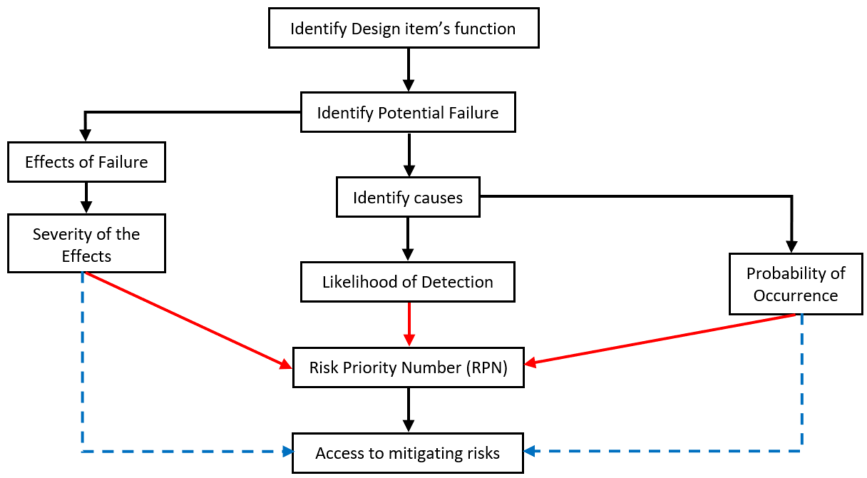



*Figure 74 : DFMEA Process*

- First, the function of the system/component must be identified.
- Based on past experiences and our knowledge, possible ways in which the system/component could fail must be identified. The effects of these failures are studied, and their severity is evaluated based on the table in Figure 75.
- The causes of these failures are identified and understood how it affects the other system functionalities. Another important parameter to evaluate is the probability of occurrence of the failure. If the failure is occurring on a regular basis, it may have to be over-designed accordingly to minimise the occurrences. The probability of occurrence of a failure is evaluated using the Occurrence rating scale in Figure 76Figure 75.
- The next step is evaluating how likely are the chances of detecting such a failure mode if it may happen. A failure mode undetected may lead to the complete downtime of the system and everything associated with it. The likelihood of detecting the failure modes are evaluates using the Detection rating scale in Figure 77Figure 75.
- Each of these three rating scales have values from 1 to 10 and higher the number, higher will be its ramification effect on the system's performance. This final effect is evaluated using a parameter called Risk Prevention Number (RPN) which is a product of the severity rating, occurrence rating and the detection rating. This number could have a maximum value of 1000 and the idea is to have this number as minimal as possible.

Having a lower RPN (for example, a severity rating of 10 but an occurrence and detection rating of 1 each will give an RPN of 10) alone is not a good engineering practice as it will lead to far more unanticipated implications on the system performance and quality. So, the best engineering practice is to work on all the three parameters and bring it to as minimum as possible. As mentioned earlier, FMEA is performed occasionally several times during a product life cycle and the target is to minimise the RPN from the previous FMEA performed.

| Effect | Criteria: Severity of Effect on Product (Customer Effect) | Rank |
|---|---|---|
| Failure to Meet Safety and/or Regulatory Requirements | Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning. | 10 |
| | Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning. | 9 |
| Loss or Degradation of Primary Function | Loss of primary function (vehicle inoperable, does not affect safe vehicle operation). | 8 |
| | Degradation of primary function (vehicle operable, but at reduced level of performance). | 7 |
| Loss or Degradation of Secondary Function | Loss of secondary function (vehicle operable, but comfort / convenience functions inoperable). | 6 |
| | Degradation of secondary function (vehicle operable, but comfort / convenience functions at reduced level of performance). | 5 |
| Annoyance | Appearance or Audible Noise, vehicle operable, item does not conform and noticed by most customers (> 75%). | 4 |
| | Appearance or Audible Noise, vehicle operable, item does not conform and noticed by many customers (50%). | 3 |
| | Appearance or Audible Noise, vehicle operable, item does not conform and noticed by discriminating customers (< 25%). | 2 |
| No Effect | No discernible effect. | 1 |

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*Figure 75 : DFMEA scale for Severity*

**Suggested DFMEA Occurrence Evaluation Criteria**

| Likelihood of Failure | Criteria: Occurrence of Cause (Design life/reliability of item/vehicle) | Criteria: Occurrence of Cause (Incidents per items/vehicles) | Rank |
|---|---|---|---|
| Very High | New technology/new design with no history. | ≥ 100 per thousand<br>≥ 1 in 10 | 10 |
| High | Failure is inevitable with new design, new application, or change in duty cycle/operating conditions. | 50 per thousand<br>1 in 20 | 9 |
| | Failure is likely with new design, new application, or change in duty cycle/operating conditions. | 20 per thousand<br>1 in 50 | 8 |
| | Failure is uncertain with new design, new application, or change in duty cycle/operating conditions. | 10 per thousand<br>1 in 100 | 7 |
| Moderate | Frequent failures associated with similar designs or in design simulation and testing. | 2 per thousand<br>1 in 500 | 6 |
| | Occasional failures associated with similar designs or in design simulation and testing. | .5 per thousand<br>1 in 2000 | 5 |
| | Isolated failures associated with similar design or in design simulation and testing. | .1 per thousand<br>1 in 10,000 | 4 |
| Low | Only isolated failures associated with almost identical design or in design simulation and testing. | .01 per thousand<br>1 in 100,000 | 3 |
| | No observed failures associated with almost identical design or in design simulation and testing. | ≤.001 per thousand<br>1 in 1,000,000 | 2 |
| Very Low | Failure is eliminated through preventative control. | Failure is eliminated through preventive control. | 1 |

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*Figure 76 : DFMEA scale for Occurrence*

| Opportunity for Detection | Criteria: Likelihood of Detection by Design Control | Rank | Likelihood of Detection |
|---|---|---|---|
| No detection opportunity | No current design control; Cannot detect or is not analyzed. | 10 | Absolute Uncertainty |
| Not likely to detect at any stage | Design analysis/detection controls have a weak detection capability; Virtual Analysis (e.g., CAE, FEA, etc.) is not correlated to expected actual operating conditions. | 9 | Very Remote |
| Post Design Freeze and prior to launch | Product verification/validation after design freeze and prior to launch with pass/fail testing (Sub-system or system testing with acceptance criteria such as ride & handling, shipping evaluation, etc.) | 8 | Remote |
| | Product verification/validation after design freeze and prior to launch with test to failure testing (Sub-system or system testing until failure occurs, testing of system interactions, etc.) | 7 | Very Low |
| | Product verification/validation after design freeze and prior to launch with degradation testing (Sub-system or system testing after durability test, e.g., function check). | 6 | Low |
| Prior to Design Freeze | Product validation (reliability testing, development or validation tests) prior to design freeze using pass/fail testing (e.g., acceptance criteria for performance, function checks, etc.) | 5 | Moderately |
| | Product validation (reliability testing, development or validation tests) prior to design freeze using test to failure (e.g., until leaks, yields, cracks, etc.). | 4 | Moderately High |
| | Product validation (reliability testing, development or validation tests) prior to design freeze using degradation testing (e.g., data trends, before/after values, etc.) | 3 | High |
| Virtual Analysis - Correlated | Design analysis/detection controls have strong detection capability. Virtual Analysis (e.g., CAE, FEA, etc.) is highly correlated with actual and/or expected operating conditions prior to design freeze. | 2 | Very High |
| Detection Not Applicable; Failure Prevention | Failure cause or failure mode cannot occur because it is fully prevented through design solutions (e.g. proven design standard, best practice or common material, etc.) | 1 | Amost Certain |

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*Figure 77 : DFMEA scale for Detection*

## 4.5 Conceptualised DFMEA on the chosen ASS design solution

As much as it is important to know how a system works, it is more important to know how a system can fail. Thus, it is required to adopt a failure detection methodology and make a database of the failures that has happened/may happen in the system under development. It not only serves to help in the project under development now but also for other similar projects. One such failure methodology adopted in development of the ASS for SC19 is the Failure Mode and Effect Analysis (FMEA). In this regard, a conceptual FMEA worksheet is created as an initiative to record and log all possible failure modes pertaining to the ASS. The following table is a sample template of the conceptual FMEA for the ASS. Out of the three rating scales, severity index is possible to be evaluated for a specific failure mode as the consequences are apparent. The detection of the failure modes could also be known during the initial stage and thus, it is possible to give a score for detection index also. However, the occurrence is an index given based on the number of instances the particular failure mode has occurred. This is an index possible of knowing only after testing the prototype and recording the failures during the course of performance of the FSDV.

This document will have to be updated on a regular basis and all the failures occurring with respect to the ASS and the action plans for rectifying those failures have to be recorded for reference to anyone who wants to know about the history of the system and its failures. This is one such document which is not available currently in the team and since it has been implemented now, it will prove to be a valuable tool and a repository of the ASS failures and action plans taken to rectify them.

| Item/function | Potential Failure Mode | Potential effect(s) of failure | Severity | Potential cause(s)/mechanism(s) of failure | Occurence | Detection | RPN |
|---|---|---|---|---|---|---|---|
| ASS Control module | Failure of the controller | ASS malfunction | 8 | - Hardware fault (sensors, integrated circuits (ics), circuit components, circuit boards...)<br>- Internal connection fault (short or open)<br>- Break incontroller input/output connections<br>- Short in controllerI/O connections to ground or voltage<br>- Short in controller I/O connections to another connection<br>- Signal connector connection failure<br>- Power connector connection failure<br>- Power-assist motor torque command calculation algorithm fault<br>- Firmware crash/failure (software parameters corrupted)<br>- Arbitration logic fault<br>- Programming error or flaw in software logic | | 4 | |
| | Controller to actuator incorrect signal ineffective, missing or delayed | | 8 | - Communication bus error<br>- Hardware open, short, missing, intermittent faulty<br>- Incorrect connection<br>- External control input or information wrong or missing<br>- Power supply faulty (high, low, disturbance) | | 4 | |
| | Sensor to controller signal inadequate, missing, or delayed | Steering output of ASS not same as the target | 7 | - Sensor inadequate operation, change over time<br>- Sensor measurement delay<br>- Sensor measurement inaccurate<br>- Sensor measurement incorrect or missing<br>- Communication bus error<br>- Hardware open, short, missing, intermittent faulty<br>- Incorrect connection<br>- Reference voltage incorrect (e.g., too low, too high) | | 4 | |
| Actuator | Steering actuator malfunction | Actuation delivered incorrectly or inadequately | 7 | - actuation delayed<br>- hardware faulty<br>- incorrect connection<br>- actuator inadequate operation change over time<br>- Incorrectly sized actuator<br>- incorrect power supply to the actuator<br>- high friction in the linkages<br>- overheating due to increased resistance in a subcomponent or internal shorting | | 7 | |
| Mechanisms and Linkages | Failure of the mechanical linkages and connections | No power transmission from the actuator to the steering system | 9 | -incorrect choice of fasteners<br>-incorrect FEA<br>-manufacturing process defects<br>-fouling with adjacent components | | 7 | |

*Figure 78 : Conceptual FMEA for ASS of FSDV*

Chapter 5

# Results and Conclusion

The optimal design solution for SC19 ASS is developed after diligent research and is now ready to be taken to the subsequent developmental stages. This design solution answers the research questions inquired earlier with respect to concept as well as the feasibility in implementing such a system in the FSDV.

Answering to RQ1, being the first team to work on the hardware part of first FSDV project of Squadra Corse was challenging and at the same time daunting. Upon understanding the architecture of SC19 and the regulations for ASS, several design ideas were developed considering the minimal space available inside the cockpit of SC19 and mechanisms and linkages were conceptualised which could perform an autonomous steering actuation. During the course of brainstorming, not only the reasons why those ideas had implementation constraints were known but also the other possible ways in which a similarly working system or mechanism could be conceived were identified. This is the point where things turned to get difficult. At some point in development of each of the design solutions, there emerged a serious problem of compromising on a major design change which would cost dearly in terms of cost, complexity and manufacturing if taken to implementation. The proposed solution has accounted the space availability inside the cockpit, the FSD 2020 regulations [2], manufacturing complexity and cost in the best possible way.

Answering to RQ2, this thesis is focused on the complete understanding of the SC19's steering system, its integration into SC19, constraints which the FSD 2020 regulations [2] dictate and how can an ASS be incorporated into the existing steering system complying to all these parameters. Our FSD car has to compete in certain dynamic events which will prove its efficiency in terms of performance and endurance when compared with the competitors. Thus, it is important to consider all possible driving modes in the FSD competition and design the ASS to be able to perform equally good or better than a human driver. This includes during the increased lateral accelerations while driving around corners at relatively higher speed as the effect of tyre lateral forces will be exerted on the steering system. This is one such driving condition whose data were logged by the Squadra Corse team on a track test. Even though it is initially difficult to conceive a design to perform at extremities owing to the development time and cost, developing a design to perform at relatively ideal situations is of focus here in order to understand the real-time working of the prototype and understand the practical difficulties and failure modes with the ASS in function. Upon understanding and analysing the validation results, the ASS could be made more robust to overcome the failures encountered earlier.

Answering to RQ3, as an FS car, SC19 Lucia is considered the best car yet of Squadra Corse having won the overall 1$^{st}$ place in the Electric Vehicle Formula SAE Italy, a first record for Squadra Corse and Politecnico di Torino. Coincidentally, it was chosen as the car which will be converted into a FSDV for competing in FSD 2020 competition in Germany. However, SC19 was not built to be a DV and this closed doors for several feasible design solutions for incorporating ASS in the car. In spite of those, the solutions discussed in this thesis were formulated based on parameters such as design complexity, redesigning of existing components, manufacturing lead time, cost and complexity, assembly complexity and the number of new additional components. Among the solutions developed, the ideal design solution is the one which has the highest performance, manufacturing and costing scores. In parallel, it is prudent to develop the second-best solution to be tested in the vehicle as it gives opportunities for saving a lot of development time and for improvising two solutions, the best of which could be taken further in the development of the ASS for Squadra Corse's FSDV. In this regard, it is possible that more than one of the ASS solutions are compatible to be incorporated in SC19 upon further design, analysis and testing.

Answering to RQ4, FSD competition also has a score of 100 out of 1000 points for 'Cost and Manufacturing' (Figure 1) and it is vital to design components which are easy to manufacture as the competition is not only about winning but also making the best performing FS driverless car with minimal costs and without compromising on the quality. The cost of developing the proposed solution is not covered in this thesis but however, all the design ideas were made with the thought of manufacturing and assembly feasibility also. Plausible trade-offs have been made in terms of minimising the overall cost of the system. The CAD model of the car does not contain the additional AS components such as the Emergency Brake System (EBS), the controller, GPU and other instruments which will be added additionally.

Answering to RQ5, it is important that the ASS must be designed in such a way that there is no hazard to anyone operating the FSDV or for those in vicinity to the FSDV while in action. In this regard, there has to be a robust hardware and software logic to avoid any consequences due to the malfunctioning of the ASS.

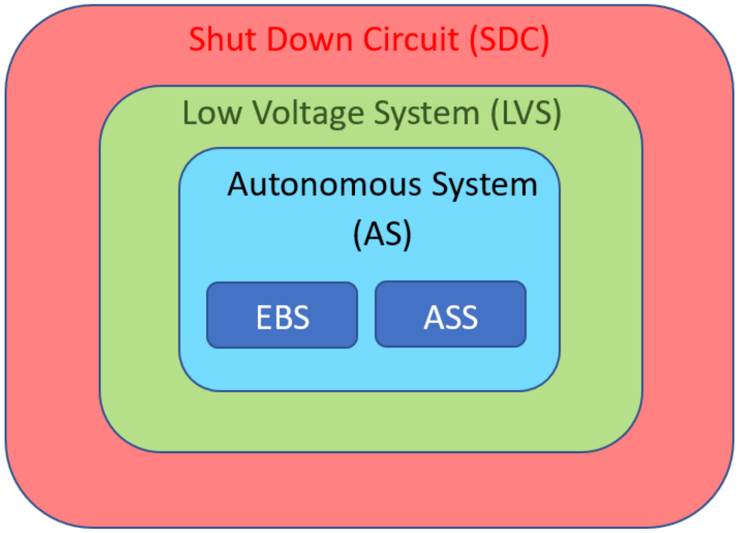


*Figure 79 : Hierarchy of different electrical circuits in FSDV*

As shown in Figure 79, the FDSV must be equipped with a Shut Down Circuit (SDC) which controls the Low Voltage System (LVS) which in turn controls the Autonomous System (AS) controlling the EBS and the ASS. An FSDV must be equipped with a safety system called Remote Emergency System (RES). It has a remote control which controls the module in the vehicle. In case an emergency stop is required, the RES stop button is pressed by the Autonomous System Responsible (ASR) which triggers the Shut Down Circuit (SDC) to open. The AS is a part of the Low Voltage System (LVS) which drives every other electrical and electronic systems in the FSDV such as the GPU, controller, LiDAR, stereo camera, GPS etc., When a system malfunction is detected, the SDC goes to open state shutting down the AS. When any of these have a malfunction, it will trigger the ASMS to OFF due to which, the SDC will open and disengage the AS. By this safety logic, any malfunction of the ASS will lead to an emergency stop since it is a subset of AS, LVS and SDC.

In any project, there is always scope for improvement. One could use this study while designing the next FSDV car of Squadra Corse so as to develop a FSDV from scratch. This way, several design constraints existing in SC19 could be addressed and possibly, one of the several solutions proposed in this thesis could be taken forward towards implementation in the newly developed FSDV. When the design of the car and its sub-systems are developed in tandem, it creates a harmony while building the FSDV and make it better than the previous FSDV converted from an FSAE car.

To start with the way forward, the individual components of the ASS could be 3D printed and checked for interferences inside the actual car. This way, it is possible to get a practical understanding of the available cockpit space for assembling the ASS inside the FSDV. Any such modifications which shall be required can be made in the CAD file and upon verifying the ASS is free of any interferences with the neighbouring systems/components and from the data gathered while testing the FS vehicle on the test track, load cases could be developed for FEM analysis of the ASS components.

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