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Hardware development on an Autonomous formula Car

A Chalmers formula student driverless Project

Bachelor's thesis in Mechanical Engineering

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Cover: The CFSD19 car on April 9th 2019.

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Abstract

The autonomous driving industry is currently growing rapidly due to the large demand created by our society. Formula student, the largest student engineering contest in the world, assesses the automobile production by developing and competing with formula cars. Formula student driverless is one of the branches of the large competition, Chalmers University of Technology is one of the represented universities with two attending teams. The role of this bachelor's group is to be a part of the 2019 Chalmers formula student driverless team and maintain and develop the hardware of the car.

The thesis is separated into three different sections, where each section describes a problem solving process. The sections are: the aerodynamic package, the steering actuation and the computer case.

The aerodynamic package was designed for a formula car driven manually at a different speed than the current autonomous system. Therefore, an analysis of the current aerodynamic package was performed. The results were generated through simulation methodologies and it was decided that the aerodynamic package was sufficiently valuable to the car's performance.

To analyse the steering actuation, tests were made comparing sent steering requests to readings of potentiometers mounted on the linear actuator and on the steering rack. The conclusion was that the steering system had drawbacks such as play and complexity, but it was kept since it is robust and the time needed to rebuild the system could not be justified.

The computer case's function is to protect the computer from water and dust while also enabling cooling of the components. The case created in 2018 was deemed inadequate for the competition. Therefore a new case where developed to replace the old one. Different concepts were generated and condensed into a final prototype which was manufactured. The final product fulfilled the requirements to confine the computer in a water and dust proof casing.

By implementing a quantitative and qualitative analysis of the three projects, a conclusion was drawn deciding that the aerodynamic package was the most valuable project to score points in the formula student driverless competition. All things considered, the entire result generated an advantageous score to the competition.

Contents

1 Introduction

The engineers of today are constantly trying to construct new solutions for autonomous transportation. Cars are breaking paradigms with steering assistance and smart driving. The business of autonomous cars is a highly coveted industry and in terms of sustainability and modern technology a profitable resource.

1.1 Background

This project is a part of the developing team at Chalmers driverless (CFSD). The goal of CFSD is to develop software and hardware designs for an electric formula car to compete with. The same car that was built by the 2017 Chalmers formula student (CFS) team and used during the previous year's CFSD18 team is to be repaired and modified by the CFSD19 team. Upgrades are necessary to support the developed software and to enhance the performance. The development of new parts is however strictly limited by the competition rules given by formula student Germany [1]. CFS describes the competition according to the quote below [2].

> Formula student is the largest engineering competition in the world with the aim of creating better engineers by giving the students hands-on experience. Every competing team designs, manufactures and tests a vehicle with which they then compete against other teams in several different events – all of this takes place during less than one year. There are both dynamic events such as endurance and acceleration, and static events where the cost of manufacturing and the business idea of the project are presented to the judges. Overall, the car and the competitions are the means used to develop our engineering skills.
>
> The winner has to prove that they have the best concept of a formula style racing car. To be able to reach that goal, several phases have to be well performed; the pre-study, design, implementation and operation processes.

The formula student competition is constructed in two separate disciplines, the static and the dynamic. The disciplines are divided into minor events that each contributes to points to the total scoring system. The static events are thought of as preparations presented at the competition, while the dynamic events are the actual competition performance of the car. This results in that the design choices in the car are to be categorized by the disciplines. The partition is seen in Fig. 1.1. The nature of the static disciplines are of argumentative stance, meaning that design choice generates points if they are well defended and substantiated. The objective is therefore not only to gather points by performing as well as possible in the dynamic events, but also by defending the engineering process behind the choice.

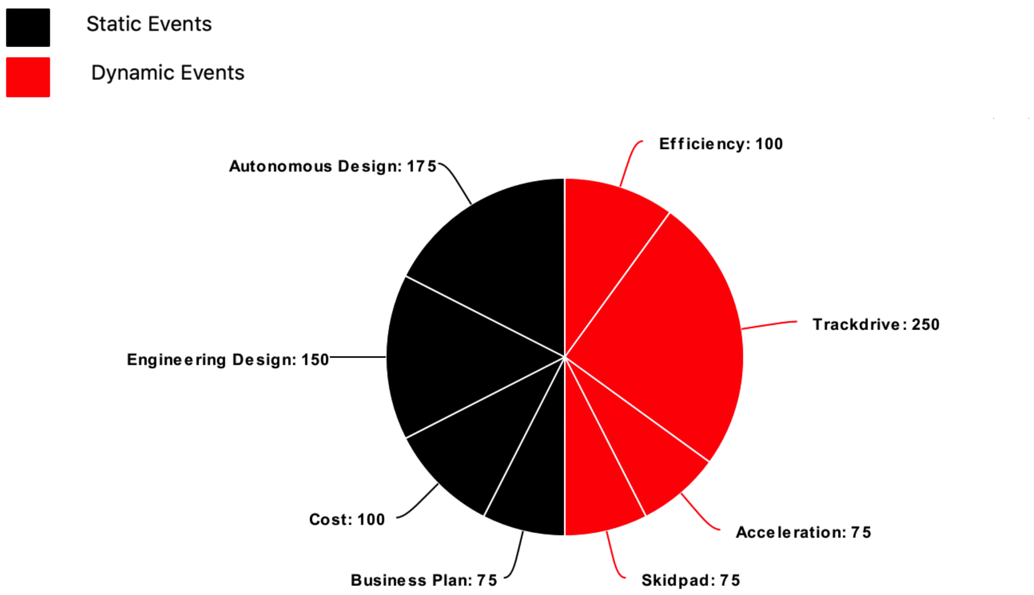


Fig. 1.1. Distribution of points from each event during a formula student driverless competition.

1.2 Purpose

The role of this bachelor's group is to be a part of the CFSD19 team and review the car's hardware, utilizing earlier knowledge gained from the team members various academic backgrounds. It is also expected to develop knowledge by working with sources such as actors from the industry (e.g. Volvo Penta, SKF, ÅF, Pöyri), other formula teams and new academic sources.

The purpose of the project is to refine and modify the CFS17 car, and to score as many points as possible in the competitions partaken in.

1.3 Problem and task

Modifications are planned to substantiate the goals through practical work on the car. These modifications are based on an analysis of the current car compared to the competition rules, as well as other models from different years and teams. The work is divided into enhancements, modifications due to rule changes, and maintenance issues that has to be solved.

- Enhancements
    - Aerodynamic package

- Autonomous steering system
- Container for computer components

- Modifications caused by rule changes
  - Adding a tractive system activation button on the rear of the car
  - Moving the emergency break system release lever
  - Re-attaching the accumulator container lid
  - Replace belts with new classification marked ones
  - Front nose re-formation
- General maintenance
  - Gearbox leakage
  - Breakline leakage
  - Car wrapping

1.4 Limitations

The report mainly focuses on the analysis and development part of the car's hardware. The maintenance and part of the rule-change modifications are standard procedure work that gives us personal experience, although it will not contribute any academic value to the report and will not be of much interest for the reader. Therefore these parts has not been included further in the thesis.

Other tasks that the group have participated in is qualification quizzes and preparing documents for the competitions. These include specific descriptions of the car's structure and layout and must be sent to the organisers prior to the competitions. Presentations and scrutineering during the competition will be done by other members of the team as well. Since these documents heavily rely on earlier work done by previous CFSD teams, they are not included in this thesis.

The time frame for this thesis is from January to May 2019, which limits the documentation of results since the work will continue until the end of August. This requires a disposition of content carefully chosen to fit in the thesis time frame and not the actual project time frame. This would ultimately lead us to our three main projects.

1.4.1 Aerodynamic package

As mentioned earlier in section 1.1 the existing car was built for a non-driverless competition. Cornering speeds at the time were estimated to be approximately 40 km/h [3]. This speed is expected to be lower using the driverless system. Therefore the aerodynamic package, shown in Fig. 1.2, needs to be reevaluated and potentially modified to be more in accordance to the team's existing goals.

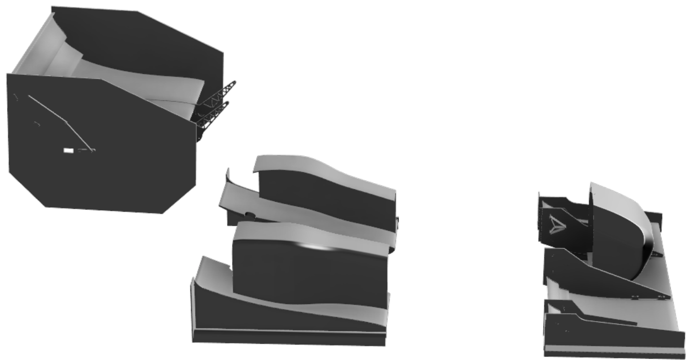


Fig. 1.2. The current aerodynamic package on the CFSD19 car.

A proposed solution is to completely remove the back wing of the car since the added downforce would not be justified compared to the additional drag and overall complexity and cost of the car. This solution is heavily dependent on the expected speed of the car which is determined by both hardware and software related limitations and will naturally change during the development process.

1.4.2 Autonomous steering system

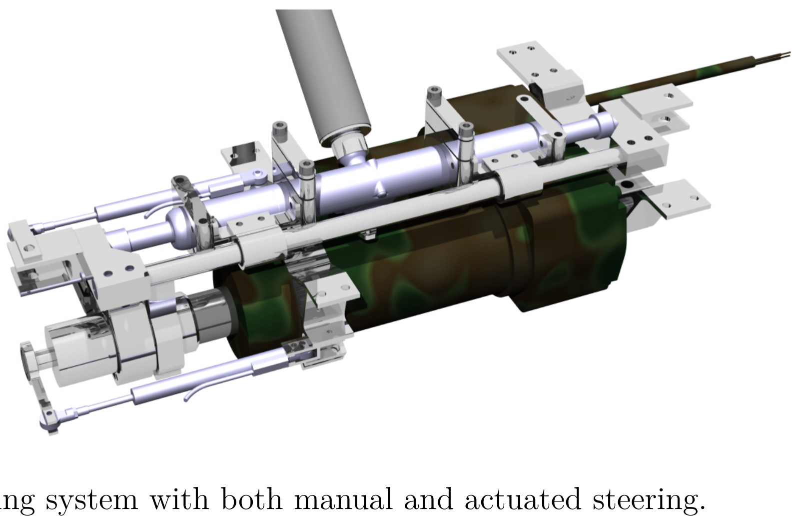


Fig. 1.3. Steering system with both manual and actuated steering.

The car's current steering system, shown in Fig. 1.3, is not ideal. The actuator has a duty cycle of 20 % and therefore risks overheating if driven intensively. One way to minimise this risk is replacing the actuator by a new one with a higher duty cycle; another option is to redesign the system. The clamping system shown in Fig. 1.3 is also a risk, it is used to unclamp when the car is to be steered manually, enabling steering through the steering wheel. But while clamped it might have a certain play that would delay the actual steering.

Replacing the actuator would be the easier and faster solution, but redesigning it might have a higher potential for improvement. A rack and pinion design would reduce the amount of parts since it will have substantially lower resistance when not powered, therefore no mechanical release is needed.

1.4.3 Computer case

The housing of the computer on the car is currently inadequate. The case is due to regulations and weather conditions supposed to withstand rain and dust, but at the same time be able to cool the internal computer components with a good air circulation. The current design is completely 3D-printed with one air intake that is protected with a thin air filter. This is a poor protection from water, and because there is only one intake and no outtake of air, the cooling of the computer is insufficient. The plastic used for the case is not graded for higher temperatures and in combination with the bad cooling it causes the case to lose structural integrity and gradually melt due to heat from the computer.

Additionally, there have been some changes to the computer hardware. The graphics card have been updated to a bigger one which makes the current case too small. Replacing the computer case is a high priority in order to make the car rules-compliant and able to withstand rain.

2 Aerodynamic package

This section will deal with the evaluation of the aerodynamic package presented in Fig. 1.2. It will also be covering the theory necessary to achieve results and draw conclusions. The aerodynamic package is a large component in the car (concerning weight, size and cost) and would mean that defending its state is an important part for the competition. This motivates the analysis of the package's existence to result in progression of the main goal, scoring as high points as possible.

2.1 Theory

This section will explain the basic theories behind fluid mechanics and also a brief explanation of the CFD-software and how the simulations are set up.

2.1.1 Governing equations

The two differential equations of interest when solving a problem of fluid motion such as this are the following [4]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0, \tag{2.1}$$

$$\rho \frac{d\mathbf{V}}{dt} = \rho g - \nabla p + \nabla \cdot \tau_{\mathbf{ij}}. \tag{2.2}$$

Eq. 2.1 is referred to as the equation of continuity where ρ is the density and V the velocity vector of an infinitesimal control volume in the fluid. The equation states that no mass is created nor destroyed in the flow.

The second Eq. 2.2 is commonly called the Navier-Stokes equation and is essentially the differential equation for the momentum of a small fluid element. It relates the pressure gradient ∇p, gravitation g and the viscous stresses τ_{ij} with the acceleration $\frac{d\mathbf{V}}{dt}$ of the fluid element.

Using these equations with appropriate boundary conditions one is able to derive the pressure and velocity fields in the fluid, which in turn describes the flow.

2.1.2 Reynolds-Averaged Navier-Stokes

In applications such as this, the flow is often turbulent in certain regions which is characterised by its chaotic and disorderly nature. So far, no analytical solution exists for turbulent flows.

In order to compensate for the chaotic nature of turbulence, each solution variable in the Navier-Stokes equations are divided into a mean value $\overline{V}$ and fluctuating value V' [4].

$$V' = V - \overline{V}$$

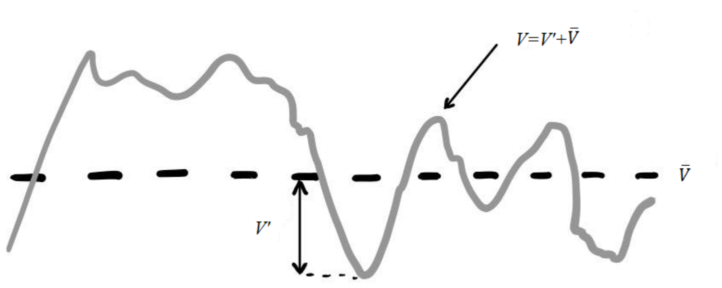


Fig. 2.1. Depiction of mean and fluctuating values in turbulent flow

2.1.3 Lift and drag coefficient

When designing a formula student car, aerodynamic modules are used in order to create more traction without increasing the mass substantially. This is done by changing the direction of the approaching air flow, which in turn creates downforce on the vehicle. To evaluate the performance of the parts one also needs to study the increase in drag that these modules cause.

An important concept in these applications are the dimensionless lift and drag coefficients (C_L and C_D) [4] [5]:

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A},$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A}.$$

It is important to be certain of these definitions since they differ for different applications [4]. In our case, we define the area A as the frontal area of the car. F_L and F_D are the downforce and drag respectively. Observe that the force F_L is defined as positive towards the ground which will give a positive C_L when the air is pushing the car down. V and ρ are the velocity and density of the incoming air. The ratio C_L/C_D is a good estimate of the aerodynamic performance of the car [5].

2.1.4 y^+ Wall treatment

Since walls cause vorticity in flows, to get precise results from simulations in fluid dynamics one must accurately predict the flow across the wall boundary layer. The boundary layer's innermost region can be divided into three sublayers which all have different flow characteristics. These are [4]:

- Viscous sublayer: This is the layer which is in contact with the wall. Because of this the flow is near laminar and therefore dominated by viscous effects.

- Buffer layer: The buffer layer is where the viscous sublayer transitions to the turbulent log-law layer.
- Log-law layer: In this layer viscous and turbulent effects of the flow are equal.

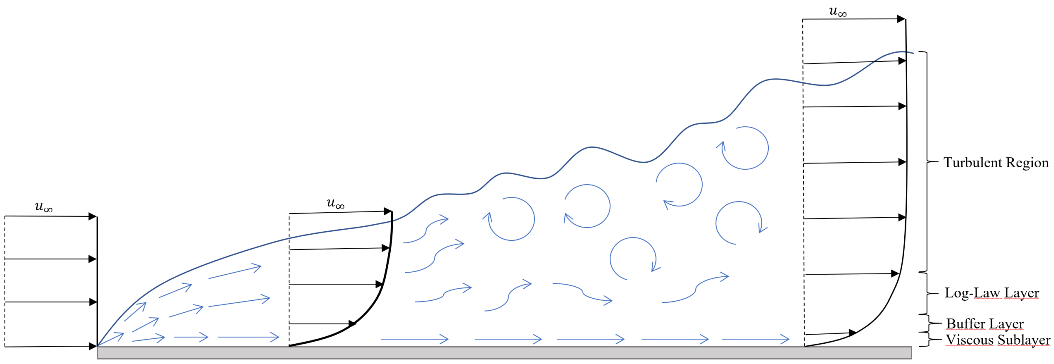


Fig. 2.2. Velocity boundary development.

To see if the mesh is fine enough to accurately depict the flow of the boundary layer a non-dimensional wall distance, y^+, is used.

$$y^+ = \frac{y}{v}\sqrt{\frac{\tau_w}{\rho}} \tag{2.3}$$

2.1.5 Constant density

The density of a gas is highly variable and increases nearly proportionally to the pressure. Therefore it might seem strange to assume a constant density for the air surrounding the car. To determine if the assumption of incompressible gas is valid, the ratio between the velocity of the gas and the speed of sound is first examined. This ratio is called the Mach number,

$$\mathrm{Ma} = \frac{V}{a},$$

where V is the flow velocity and a is the speed of sound of the gas or fluid. If Ma<0.3 the density effects are negligible and the flow can be considered incompressible. [4]

2.1.6 K-Omega turbulence

The K-omega turbulence model solves transport equations for the turbulent kinetic energy and the dissipation rate using a model consisting of two partial differential equations. [6]

$$\partial(\rho * k)/\partial(t) + \nabla * (\rho * k * \overline{v}) = \nabla * [(\mu + \sigma_k * \mu_t) * \nabla * k] + P_t - \rho * \beta^* * f_\beta^* * (\omega * k - \omega_0 * k_0) + S_k \tag{2.4}$$

$$\partial(\rho * \omega)/\partial(t) + \nabla * (\rho * \omega * \overline{v}) = \nabla * [(\mu + \sigma_\omega * \mu_t) * \nabla * \omega] + P_\omega - \rho * \beta * f_\beta * (\omega^2 - \omega_0^2) + S_\omega \tag{2.5}$$

2.2 Mesh

In order to accurately assess the performance of the car in Star-CCM+ a large computational domain was needed. This domain consisted of a large wind tunnel which was 31 m long, 3.6 m high and 16 m wide. Even though a small domain with as few cells as possible would reduce the simulation time and CPU-usage drastically, a large domain was needed to correctly determine the behaviour of the flow, since the car affects the flow even at large distances away from it.

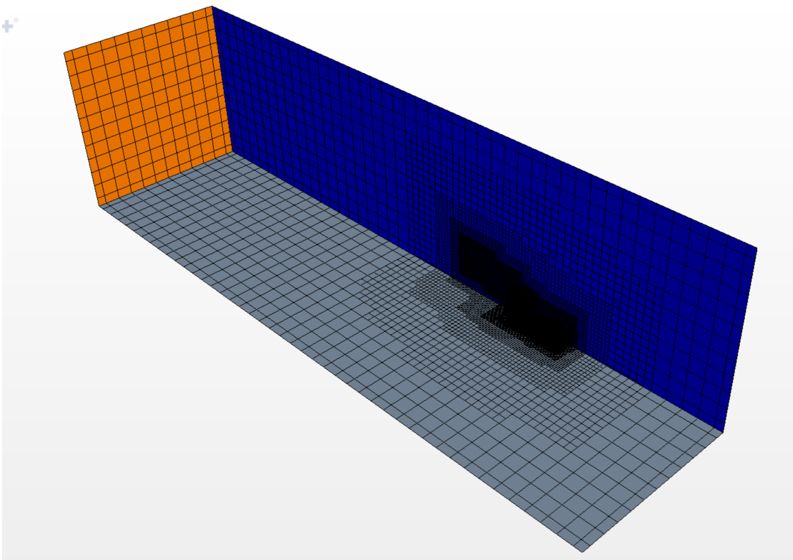


Fig. 2.3. Computational domain

In an effort to save computational power and simulation time the mesh gets coarser further away from the car. As mentioned previously the mesh is studied using the y^+ values in the simulation to determine if it can depict the flow accurately enough.

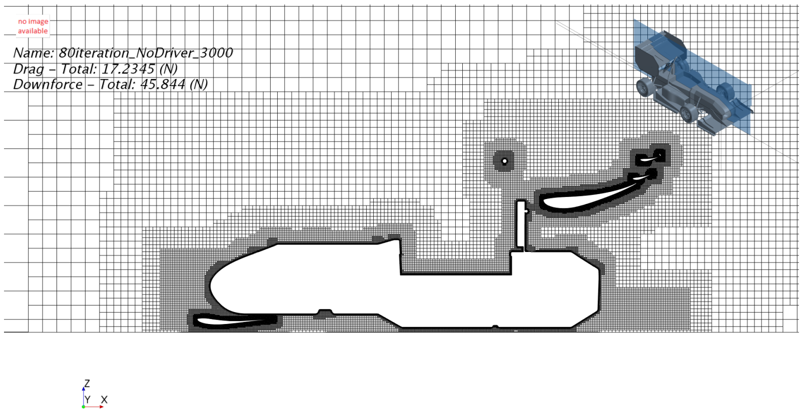


Fig. 2.4. Depiction of the mesh close to the car

To create the mesh a finite volume method with four different meshers have been used. The meshers are:

- Prism layer mesher: The prism layer mesher generates orthogonal prismatic cells next to wall surfaces and boundaries in order to improve the accuracy of the simulation.
- Surface Wrapper: When importing a low quality CAD-file a surface wrapper can be used to ensure a closed, non-intersecting and manifold surface.
- Surface Remesher: Because the surface wrapper is not an optimal mesh, another mesher is introduced. The surface remesher improves the quality of the mesh by retriangulating the surface, and thereby providing a high quality starting surface.
- Trimmer: The trimmer mesher uses a template mesh which is composed of hexahedral cells. It then cuts the core mesh utilizing the starting input surface.

2.3 Method

The process of evaluating the aerodynamic package consisted of running computational fluid dynamics (CFD) simulations. To be able to evaluate the aerodynamic performance without the rear wing, the simulations and values used during 2017 were obtained. To save both time and make the evaluation easier the same simulation file was used as a baseline for the new calculations. The differences between the simulations were the lack of both a driver and a rear wing. The speed is also reduced to better represent the car's current performance.

A thorough review of the existing material regarding the aerodynamic performance was done to determine which new simulations should be used. The speeds of interest were approximately 15–40 km/h. As mentioned in previous studies regarding the aerodynamic performance of a formula student car, it is important to consider all parts of the aerodynamic package when evaluating the performance of the car. Therefore all of the aerodynamic parts were included in the simulations [7].

Setups to test and simulate were the following:

1. The existing aerodynamic package
2. Only the rear wing removed

For each simulation the C_D and C_L as well as values for the downforce and drag were saved after each iteration in a .csv document. These values will later be compared to each other and evaluated in an additional simulation to asses which of the vehicle configurations have the best performance.

2.4 Optimum lap

To identify the effect that the rear wing has on the actual performance during track driving, another simulation software is used called Optimum Lap. Optimum Lap is a simple vehicle dynamic simulation where the vehicle is defined by 10 parameters which all represent different aspects of the car. The car is then put on a track and the performance is measured with a graphing tool which makes the evaluation process of different designs quick and straightforward. Optimum Lap offers a wide variety of tracks, but none that quite suited our simulation. Therefore a new design was needed to better coincide with our goal.

2.4.1 Parameters

The following parameters are needed:

- Weight
- Frontal area
- Motor torque
- Downforce coefficient
- Drag coefficient
- Air density
- Tire radius
- Longitudinal friction

- Lateral friction
- Gear ratio

2.4.2 Track design

Removal of the rear wing will cause a loss of downforce. The part of the competition where this is most crucial is the skidpad dynamic event. In this event the cornering speed of the car is measured. The track is shaped like a figure 8 with a radius of 9.125 m Additionally the track is wet, which results in severe loss of traction.

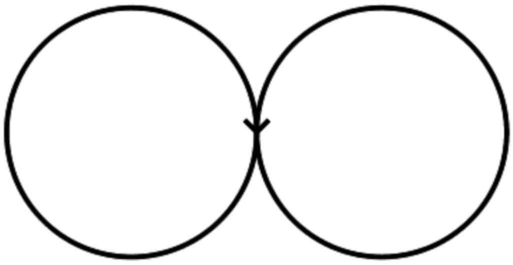


Fig. 2.5. Design of the skidpad track

2.5 Results

The results are compromised of downforce and drag coefficients for both with and without the rear wing.The simulations gave insight in multiple aspects of aerodynamics for the vehicle.

2.5.1 Without rear wing

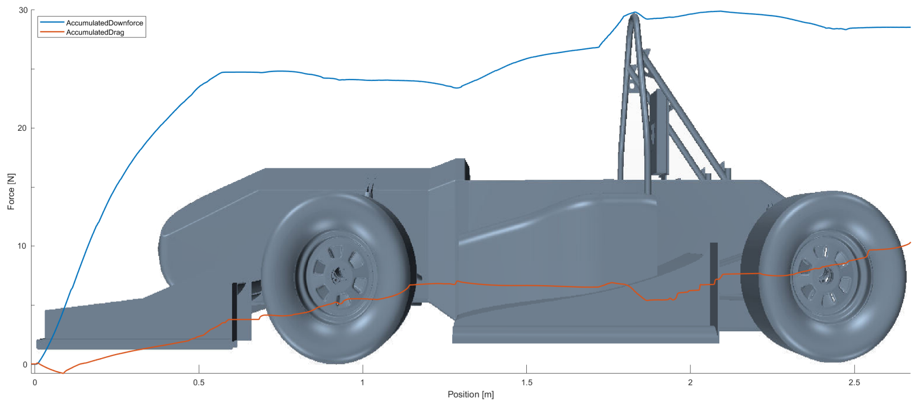


Fig. 2.6. Visualisation of the downforce and drag without a rear wing

As can be seen in Fig. 2.6 the vehicle experiences rapid increase in downforce over the front wing, then a slight decrease over the wheels and a subtle increase as a result of the side wings.

Cd	0.76455
Cl	1.70972
Cl/Cd	2.23624
Total Downforce	27.68631 N
Total Drag	12.38068 N

2.5.2 With rear wing

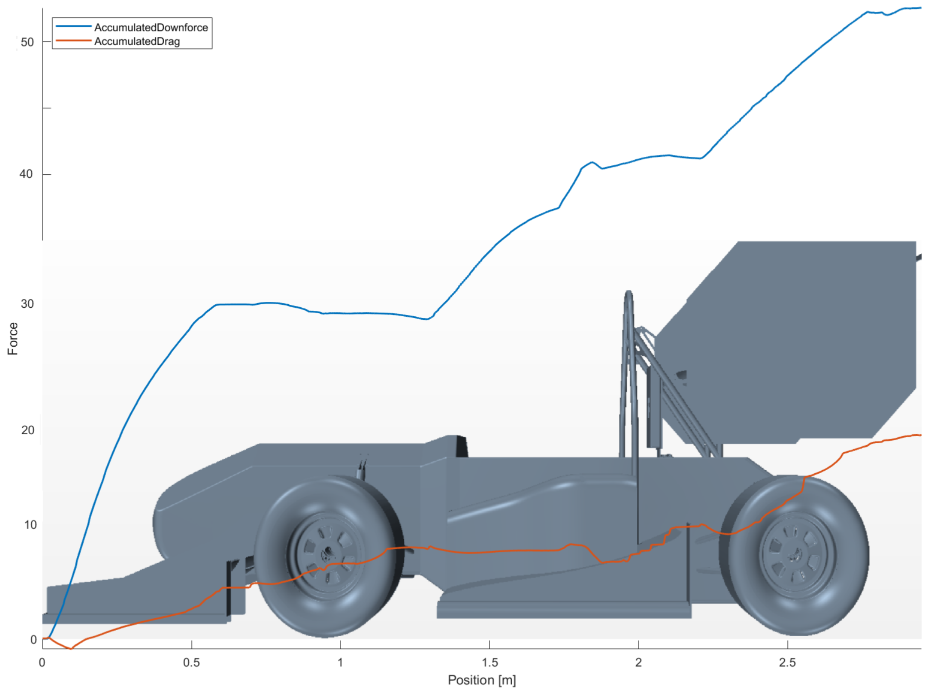


Fig. 2.7. Visualisation of the downforce and drag with a rear wing

As expected both drag and downforce is heavily increased because of the now attached rear wing.

Cd	0.81986
Cl	2.19643
Cl/Cd	2.67903
Total Downforce	45.66614 N
Total Drag	17.04586 N

It can now be established that the rear wing has large impact on the aerodynamic performance of the vehicle. Although the question still remains of how the added downforce and drag affects the actual performance of the car.

2.5.3 Optimum lap

Simulations confirmed that the rear wing configuration, despite adding extra drag, resulted in a slight decrease in lap time in the skidpad event over the configuration without rear wing.

2.6 Analysis and discussion

As previously mentioned the dynamic events in the competition include acceleration and skidpad. The different nature of these events promote different attributes on the final design on the aerodynamic package. In the acceleration event, a fast, agile car with high top-speed is preferred. For the skidpad event, traction is a priority which demands a high downforce. In some ways, these requirements counteract each other as a car with higher downforce generally induces more drag, which in turn reduces the top speed of the car. Here, a prioritization has to be made.

2.6.1 Arguments for keeping the rear wing

The main argument for keeping the rear wing is the added downforce. This is especially important during dynamic events which involves cornering at high speeds. The track layout on the skidpad is very simple, giving the autonomous system a better chance of reaching these speeds, thus potentially making the traction of the car a limiting factor. The best driverless team during formula student Germany last year had a laptime of 5.639 s [8] which means an average speed of approximately 36 km/h. This time even beats some of the teams for the non-driverless competition [8].

Since the aim is to drive at a constant speed around the skidpad (the theoretical speed at which the car starts slipping), the longitudinal acceleration is not crucial as long as the desired speed has been reached. Therefore the drag, acting in this direction, would have less significant impact in the skidpad event compared to e.g. the acceleration event. This reinforces the argument for keeping the wing.

Furthermore, the rear wing includes a drag reduction system that will be engaged during the straights. This system reduces the drag by up to 45 % [9] and is in itself an engineering solution that would be beneficial to include in the static Engineering Design event.

2.6.2 Arguments for removing the rear wing

The trade-off for including the rear wing is as mentioned; the added drag, mass and cost. The added drag will be most noticeable in the acceleration event where high speeds are reached. Here, the added downforce will not be beneficial until the car starts breaking.

If the coefficient of drag is $C_{Dwing} = 0.81986$ with the rear wing compared to $C_{Dnowing} = 0.76455$ without and assumed to be constant for all speeds, the theoretical acceleration would be reduced by:

$$\Delta a = \frac{\frac{1}{2}\rho V^2 (C_{Dnowing}A_{nowing} - C_{Dwing}A_{wing})}{m_{car}} \approx 0.00033V^2 \text{m/s}^2 \qquad (2.6)$$

for the speed V at which the car is moving. The calculation is of course an idealized case but gives some insight in the matter.

2.6.3 Conclusion

Weighing the arguments summarized above, the conclusion to keep the rear wing was drawn. The loss of acceleration is regarded minor compared to the potential scoring

3 Autonomous steering actuation

One of the main features of a autonomous car is the ability to direct the wheels depending on an automatically generated steering request. This section will analyze the current steering system by reviewing a comparison between the sent steering request and readings from potentiometers mounted on the linear actuator and on the steering rack.

3.1 Theory

The sent steering request is a timestamped number between $-25°$ and $25°$ with an accuracy of 10^{-6}. This request is compared to the current direction, given by potentiometers, and the difference between current and requested direction determines the actuation speed. Most actuators work by transferring a rotational momentum into a linear force, pushing the rack sideways.

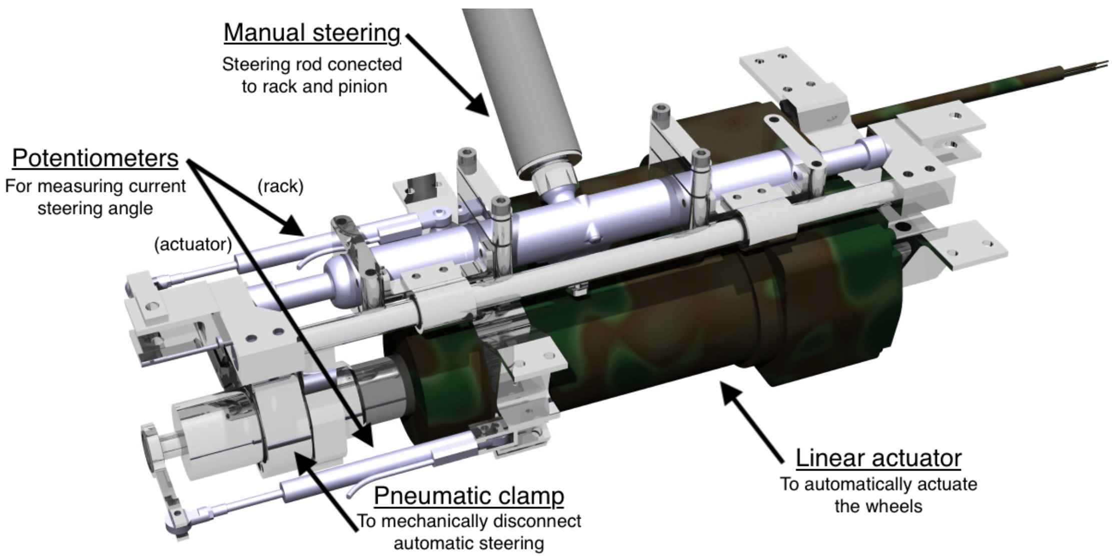
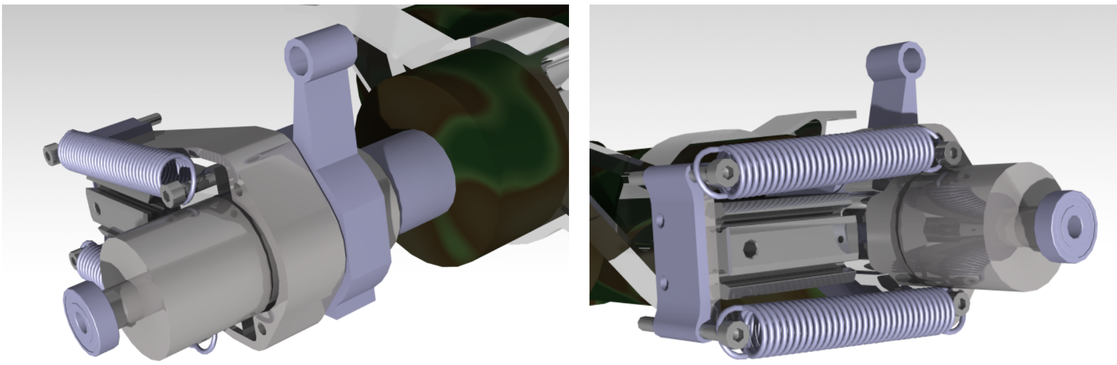


Fig. 3.1. Steering system with both manual and autonomous steering.

Fig. 3.1 shows the current solution where a linear actuator, orthogonal to the steering column, pushes the steering rack and thereby actuates the wheels. A linear actuator has a motor that rotates a screw and thereby results in a linear force. This solution is functional, although it has drawbacks like weight and complexity. The biggest drawback is that it has a high inner resistance and thereby can not be operated backwards, which is required to manually steer the car. In order to be rules compliant, a pneumatic clamp is added to mechanically disconnect the autonomous steering. This enables manual steering but adds to the complexity of the car.



(a) (b)

Fig. 3.2. The pneumatic clamp that connects the actuator to the steering rack, allowing for autonomous steering.

Fig. 3.2 shows the pneumatic clamp mentioned above. The springs pull the clamp open when the automatic steering is disengaged, resulting in a state where the car can be steered manually without resistance or interference from the linear actuator. In order to engage the autonomous steering, the actuator moves to line up with the steering rack and then clamps.

The current linear actuator is from SKF and have the following specifications [10]:

- Operational voltage: 24 V
- Push and pull load: 1500 N
- Linear speed: 50 mm/sec
- Duty cycle: 20%

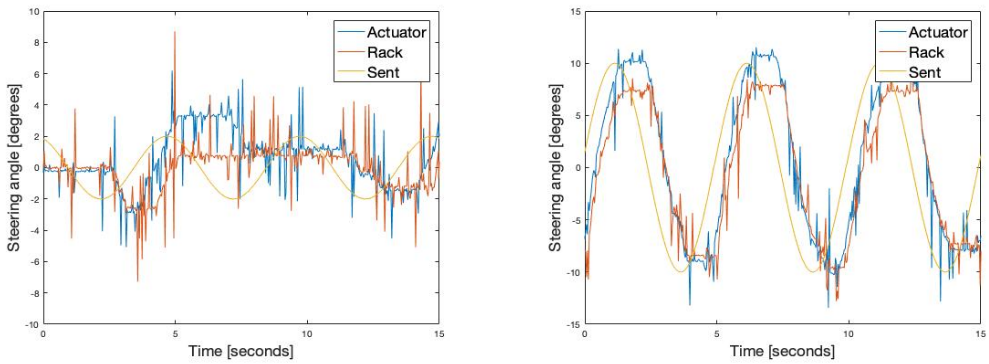
Push and pull load refers to the maximum linear force the actuator can produce, the linear speed is the maximum speed at the maximum load and the duty cycle indicates the relation between work and rest. The current duty cycle of 20% is our main concern since it might be used more during a race.

3.2 Method

In order to evaluate the current autonomous steering system and determine whether it should be redesigned or not, a set of tests were performed. The tests consist of a sent input signal that is compared to readings from the rack and actuator potentiometer, shown in Fig. 3.1. The planned features to investigate is the delay from the sent signal to the actuated wheels, play in the system and noise. Tests were done with different traction conditions, either elevated, with the tires on the slippery workshop floor or out on the rough asphalt. Initially a set of sine waves, varying in amplitude were sent as input signals. Then a set of single steps were sent to further examine the effect of different conditions and to determine the delay.

3.3 Results

The test results are presented in graphs where the input signal are compared to the potentiometer readings at the steering rack and the actuator. Time 0 corresponds to when clamp connection is done, initial errors are solved and the run has reached a steady state.

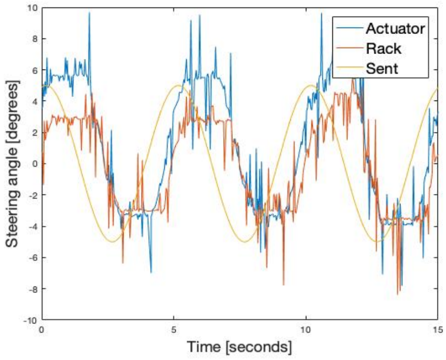


(a) Amplitude: 2°

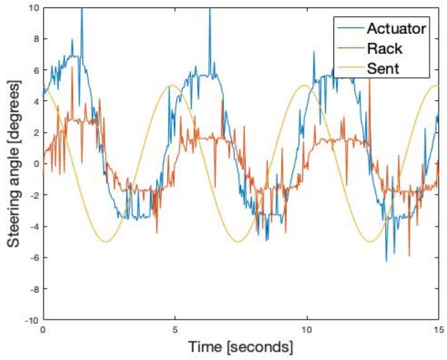
(b) Amplitude: 10°

Fig. 3.3. A test of the steering where the input signal is compared to the readings of potentiometers shown i Fig. 3.1. The input sine waves have different amplitudes between measurements and the tires are elevated off the ground.

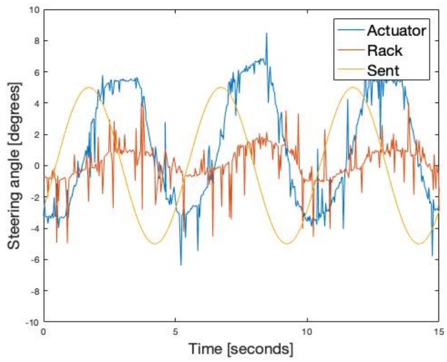
The tests in Fig. 3.3 shows how the readings of the potentiometers: *Actuator* and *Rack* (shown in Fig. 3.1), compares to the input signal: *Sent*. There is a lot of noise, approximately the size of 2–4°, that results in an uncertainty when doing small steering corrections.



(a) Elevated tires



(b) Tires on flat surface

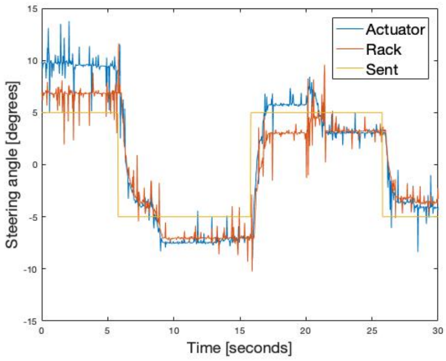


(c) Tires on rough surface

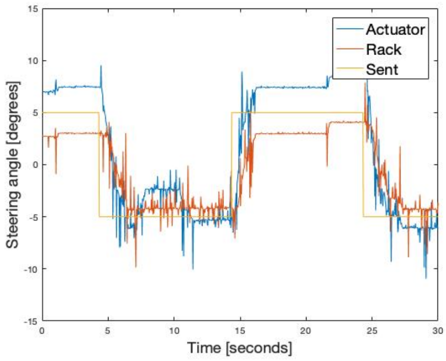
Fig. 3.4. A test of the steering where the input signal is compared to the readings of potentiometers shown i Fig. 3.1. The sine waves have the same amplitude but the traction condition of the tires are different between measurements.

The comparison in Fig. 3.4 shows that the rack moves less than the actuator when the tires are affected by friction from the ground. This can be evidence of play in the pneumatic clamp shown in Fig. 3.2. When elevated, the clamp is strong enough to grip the inner axle, but with higher resistance it slides to the end stops before moving the rack.

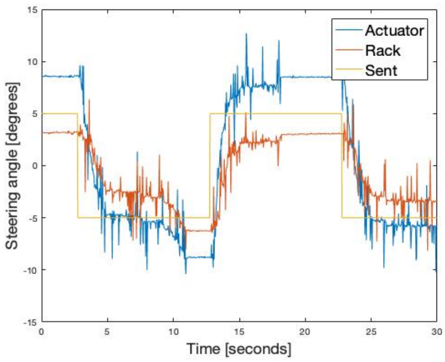
A set of step tests were done to further investigate the impact of play in the clamp, signal delay, actuation time and steering reduction.



(a) Elevated tires



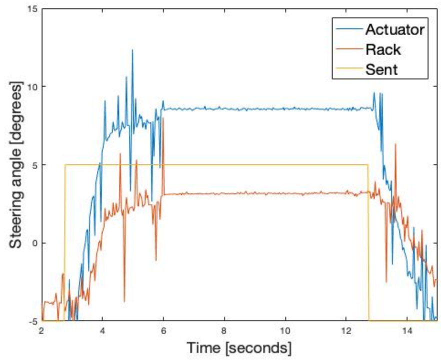
(b) Tires on flat surface



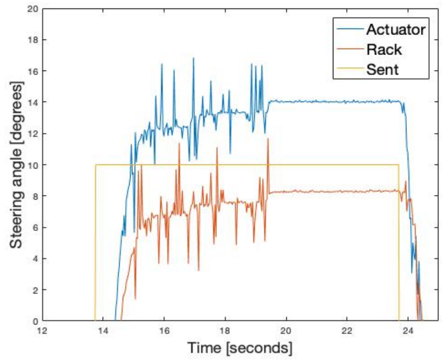
(c) Tires on rough surface

Fig. 3.5. A test of the steering where the input signal is compared to the readings of potentiometers shown in Fig. 3.1. The steps have the same amplitude of 5°, but the traction conditions of the tires are different between measurements.

The test in Fig. 3.5 reinforces the suspicions that there is a play in the clamp that results in steering reduction while on a rougher surface. The difference in maximum and minimum value between the actuator and rack readings are visibly increased the more friction that is applied on the tires.



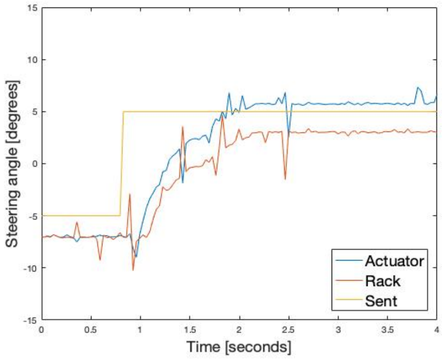
(a) Amplitude: 5°



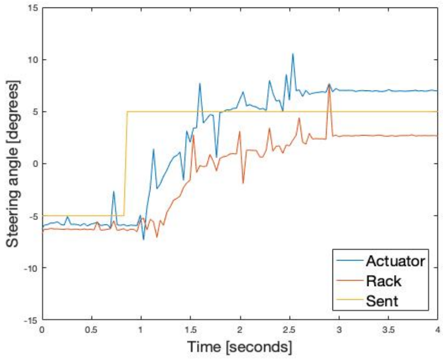
(b) Amplitude: 10°

Fig. 3.6. A test of the steering where the input signal is compared to the readings of potentiometers shown i Fig. 3.1. The steps have different amplitude, but the traction conditions of the tires are constantly on the rough surface. Notice that the y-axis has the same scale.

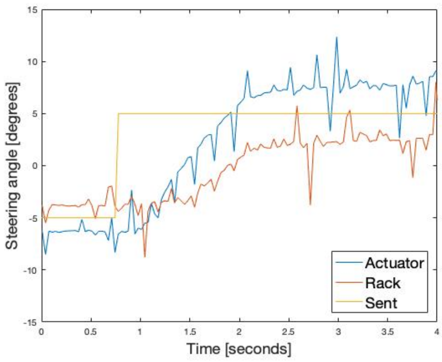
Fig. 3.6 compares the test shown in Fig. 5(c) and another test on the rough surface, with a higher amplitude. The difference in maximum values are approximately 5° in both tests which further upholds the theory that this is caused by play in the clamp.



(a) Elevated tires



(b) Tires on flat surface



(c) Tires on rough surface

Fig. 3.7. Same tests as earlier shown in 3.5 but zoomed in to investigate the signal delay as well as time needed to reach requested actuation.

Fig. 3.7 displays a zoomed in picture of the tests earlier presented in Fig. 3.5. The delay between request sent and actuation are measured to approximately 0.2 seconds. It is noticeable that time needed to full actuation is longer at higher friction, explaining the high difference in actuation and rack reading while sending sine waves in Fig. 3.4.

3.4 Conclusion

The results presented leads to the conclusion that the current autonomous steering system is functional but has mayor drawbacks. The impact of these disadvantages will eventually conclude whether the current system is worth developing, or if it should be redesigned.

The signal delay was expected and mainly depends on software design and signal processing. Since this is outside our main area of responsibility no further investigation or discussion will be made on the subject.

The play in the clamp could, theoretically, be reduced by manufacturing a new sleeve for the linear actuator. However, this would result in a lot of trouble when clamping to engage the autonomous steering, since there are software regulations that prevent the clamp from engaging unless it is perfectly lined up. One solution could be to manufacture a conical slid in the sleeve, allowing the clamp to engage and thereby forcing the rack into position. Such a solution would not be as robust and would probably wear out.

The steering reduction could probably be reduced by adapting the programming with this in mind. Worth mentioning is the theory that the effective friction while driving will be lower compared to that of a car standing still, and thereby the steering reduction might be negligible. After such tests the decision could be made if there is need to replace the actuator with another that has a higher push and pull load or speed.

Another option would be to redesign the steering into a rack and pinion system, more similar to how the manual steering functions. This new system would have a motor with a pinion attached to it, the pinion would push a rack sideways and thereby transferring the angular momentum into a linear force. This system, depending on the motor, can be designed to have a low inner resistance and thereby neither the pneumatic clamp nor the linear actuator would be needed. It would also be able to receive the same input signals and should therefore be fairly easy to implement if all needed components where obtained.

4 Computer case

This section of the report will focus on the process of generating a solution to replace the existing computer case. The method will focus on how different concepts where generated and how they where condensed into a final prototype. The result will describe the new case itself, how the process of manufacturing it went and if it fulfilled the demands that needed to be met. The result will also touch on further development and how it affects the cars ability to score points during competition.

4.1 Background

When the 2017 CFS car was remodelled to become driverless in 2018 it meant a computer had to be added. Since the competition rules state that the car still has to be maneuverable manually, there was no abundant space where the computer could be fitted inside of the car. The autonomous system has to process large amounts of visual data, as well as computing a trajectory using the software developed by the team. The computational processing is somewhat demanding which resulted in relatively large components being used. The rules state that all components in the car must be able to withstand a rain-test procedure where water is splashed in all directions [1]. To ensure the longevity of the components used in the computer; it also had to be dust proof and somewhat shock absorbent. The case had to fit the following components used by the 2019 team when designing the autonomous system:

- CPU : Ryzen 7 1700 8 cores[11]
- CPU-fan : AMD Wraith Spire (RGB programmable LED)[12]
- RAM: GSKILL FLARE X F4-2400c15D DDR4-2400 1.2V 8G[13] (2 pcs)
- Motherboard : GIGABYTE GA-AB350N-Gaming WIFI[14]
- GPU : GeForce® GTX 1060 Mini ITX OC 6G[15]
- CAN-card : PCAN-M.2 Four Channel[16]
- SSD : Samsung 850 evo 500gb[17]

4.2 Method

To generate a concept without preconceiving the design of the end product; a systematical product development strategy was applied. Concepts where generated in a brainstorming-process and unrealistic and non rules compliant ideas were weeded out initially. Different ideas were cross-tabulated to create various combinations of solutions. To determine the final winning concept; product development matrices were used. The concepts were processed and improved until a satisfying result was achieved through an iterative process. The case had to be designed in approximately 3-4 weeks while not taking up a considerable amount of time from other vital processes such as maintaining critical hardware.

A specification of requirements was generated to ascertain the quality of the case and compliance to the rules of the competition. The requirements were based on the field of application. With the case being mounted on a race car with weather conditions varying greatly and dust being a major concern.

The requirements for the computer case were set by examining what rules and tests the case must endure during the competition. What kind of other attributes it would need to ensure that the computer would function properly; taking into account dust, vibrations etc. After thorough investigation and discussions within the team, a requirement-list was put together as a template for generating concepts. The following is the list of requirements the solution should fulfill:

Requirements for onboard computer case			
Nr	Requirement	Requirement type	Requirement origin
1	Quick and easy to produce	Demand	CFSD-team
2	Lightweight	Good to meet	CFSD-team
3	Rain and splash-proof	Demand	Formula student rules
4	Cooling solution	Demand	CFSD-team
5	Heating conductive material	Good to meet	CFSD-team
6	Easy to access internal components	Good to meet	CFSD-team
7	Vibration robust	Good to meet	CFSD-team
8	Fit in the mounting space of the car	Demand	CFSD-team

4.3 Concept

With the requirements set, the team came up with ten different concepts. After an elimination process and a morphological matrix three different concepts where left. These concepts where mainly focused on how to cool and keep the computer protected from water and dust since this is the most crucial objective of the computer case. Refinements of parts and choices of materials were something that where open to change when the final concept had been chosen.

4.3.1 Concept 1

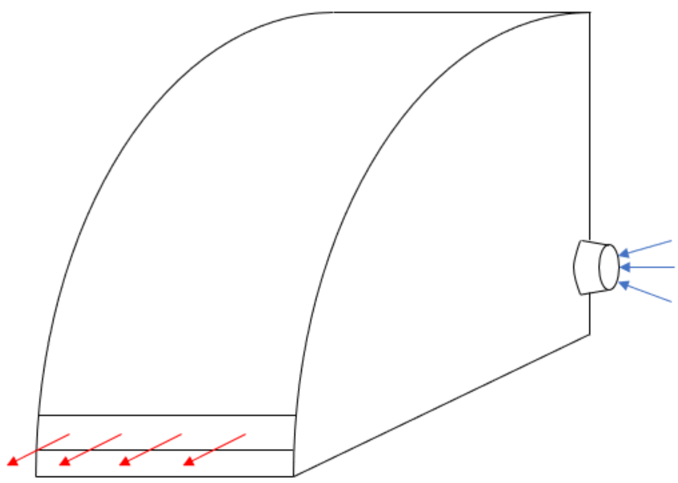


Fig. 4.1. Concept 1

Concept 1 consists of an air-cooled chassis. The case has an air intake with a standard case fan attached. For added waterproofing the fan sucks air through a hydrophobic filter. The air outtake is implemented through a slit in the wall which is protected from water by the geometry of the channel leading into the case. A simple air filter provides the channel with sufficient dust protection. Due to the geometric complexity of the channel (needed to keep water out), 3D-printing was deemed the easiest manufacturing method for the chassis. Metal sides were chosen to add structural integrity to the relatively weak build and to improve the thermal conductivity of the case. The components are mounted with rubber fittings to make it vibration-proof and each removable part of the chassis (e.g. the opening for the connection panel) is caulked with rubber sealants.

4.3.2 Concept 2

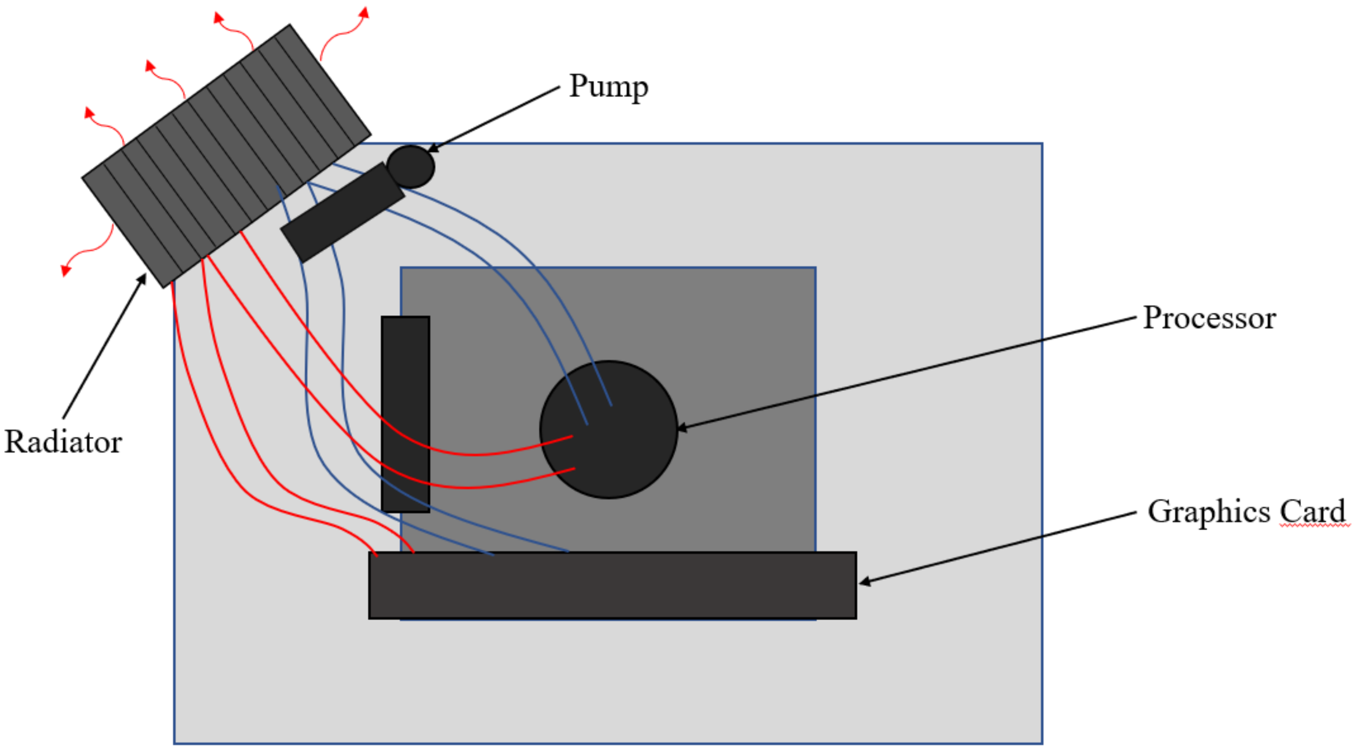


Fig. 4.2. Concept 2

Concept 2 consists of a water-cooled, completely sealed chassis. The water is cooled on the outside of the case by a radiator and then circulated through the system to each heat-generating component using a water pump. All components are mounted with rubber fittings and each removable part of the chassis is caulked with silicone. The case itself is made of metal sheets that are welded together. By using metal, heat transfer to the outside of the case will be improved compared to the usage of plastic. This is good for cooling the rest of the computer components.

4.3.3 Concept 3

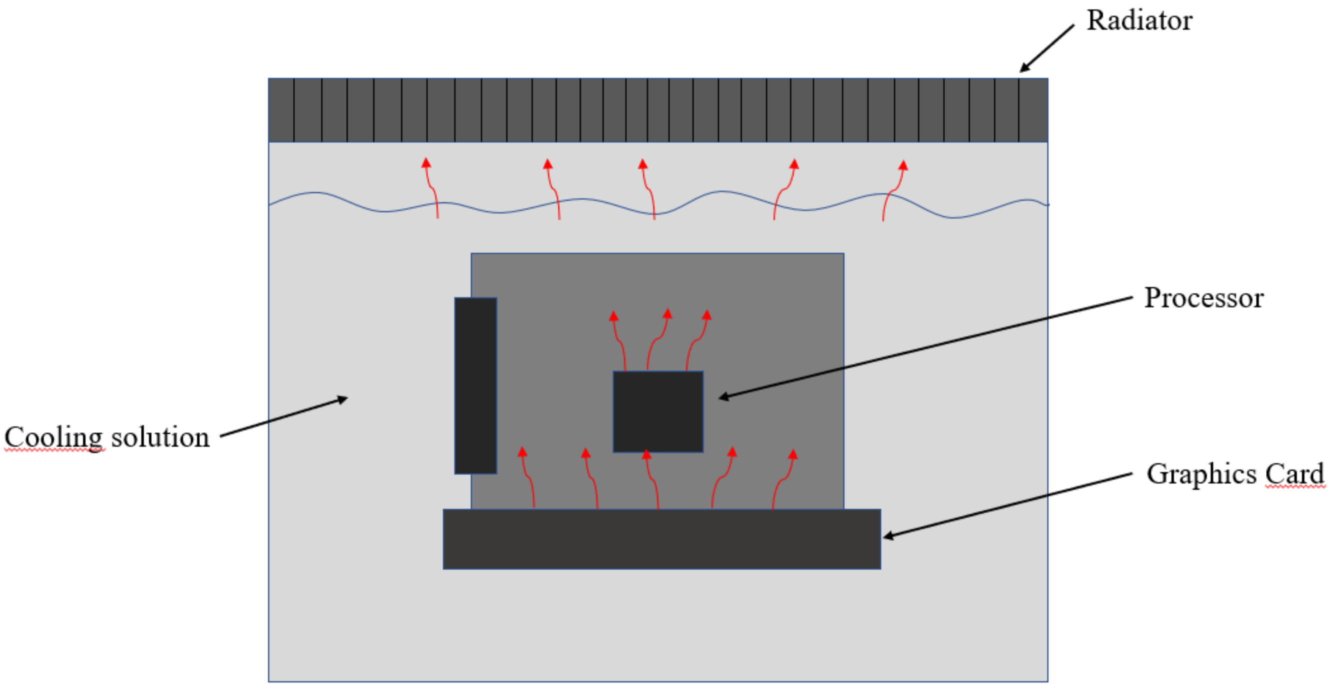


Fig. 4.3. Concept 3

Concept 3 consists of a waterproof, sealed box filled with a dielectric coolant solution. The liquid has such high electrical resistance that the components can be submerged in it without short circuiting. When the coolant solution boils it transports the heat up to the surface of the tank where a radiator condenses it back to liquid. The concept would have excellent cooling abilities and at the same time be completely waterproof. The case is made from a molded plastic container to keep the case waterproof and have a lid containing the radiator that are fastened to the top of the container using silicone.

4.3.4 Solution process

To rank the importance of the different attributes in order to evaluate which concept had the best solution, a Kesselring matrix was made. The relevance of the attributes used in the matrix were as follows:

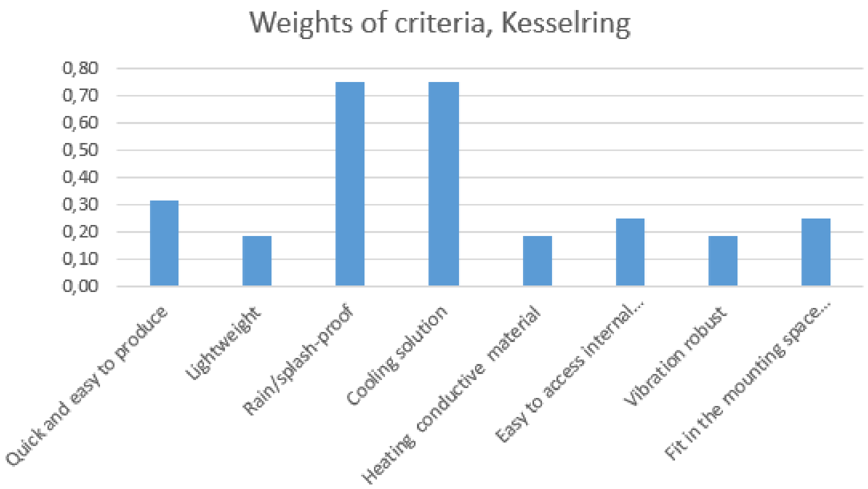


Fig. 4.4. Weight of requirements

Each requirement were weighed against each other scoring either 0, 0.5, or 1. The scored is based on which attributes are deemed most important; where 1 is considered the most important, 0.5 is equally important, and 0 less important. For each attribute a mean weight was calculated, which was then used in the Kesselring matrix to evaluate the total score of the product.

Chalmers		**Kesselring-matrix: Computer case**							
Publisher: CFSD-team		Created: 2019-04-10			Modified: 2019-05-16				
Requirements		**Concept**							
		Ideal		1		2		3	
Attribute	w	v	t	v	t	v	t	v	t
Quick and easy to produce	0,031	10	0,31	8	0,25	4	0,13	1	0,03
Lightweight	0,019	10	0,19	6	0,11	4	0,08	1	0,02
Rain/splash-proof	0,075	10	0,75	8	0,60	10	0,75	10	0,75
Cooling solution	0,075	10	0,75	7	0,53	8	0,60	10	0,75
Heating conductive material	0,019	10	0,19	5	0,09	6	0,11	5	0,09
Easy to access internal components	0,025	10	0,25	7	0,18	5	0,13	1	0,03
Vibration robust	0,019	10	0,19	6	0,11	6	0,11	6	0,11
Fit in the mounting space ofthe car	0,025	10	0,25	9	0,23	5	0,13	2	0,05
T (Total weight value)		80	2,88	56	2,10	48	2,03	36	1,83
T / Tideal		1,00	1,00	0,70	0,73	0,60	0,70	0,45	0,64
Mean		10,00	0,36	7,00	0,26	6,00	0,25	4,50	0,23
Standard deviation		0,00	0,20	1,00	0,15	1,50	0,21	3,25	0,26
Median		10,00	0,25	7,00	0,20	5,50	0,13	3,50	0,07
Number of weak points		0		0		0		4	
Rank				1		2		3	

Tab. 4.1. Kesselring matrix including the three different concepts.

The matrix shows that concept 1 scored the highest total value, however concept 2 was a close alternative. Concept 3 scored to low and could be eliminated from the development process. The concept had too many weak points as well as being overly complicated. The case would have taken too much time to manufacture and would likely weigh far to much to be tenable. The size and accessibility of the internal components would further complicate the build. Concept 2 was eliminated due to a few crucial shortcomings. The water cooled system would not be able to cool all the components in the case (it only cools components locally, which are compatible with the system). All components not connected to the cooling-system, which generates heat, would therefore increase the temperature of the case. The energy dispersion through the walls would likely be insufficient to cool these components, leading to the case overheating. The effects would be even worse if the case was exposed to direct sunlight.

4.4 Results

To easily manufacture the complex geometries (the water resistant air outlet) of the final concept, 3D-printing was selected as manufacturing method for the chassis. Aluminum sides were chosen to increase the robustness of the design, as well as being an excellent thermal conductor. To manufacture the sides with high precision (to match the contour of the chassis) in as little time as possible, water-jet was selected as manufacturing method. The air is blown into the case from a hole in one of the side-plates, through a filter, and lastly through a tube with a fan built into it. The air pressure increases on the inside which forces the hot air out through an open slit in the 3D-printed hull. The conceptual design of the air slit is shown in Fig. 4.5.

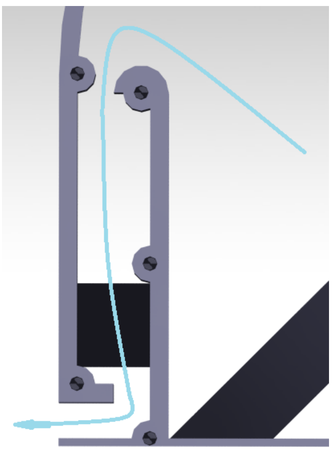


Fig. 4.5. Air-slit in the 3D-printed chassis seen from the side without side-plates. The air-slit makes it possible for air to be sucked into the case and successfully cooling the computer while sealing it from water.

4.4.1 Manufacturing

The manufacturing process went as planned with exception to a few problems during the 3D-printing caused by warping. With minor alternations to the chassis and upgrading to a 3D-printer with a heated chamber, the problems where solved. The sides were manufactured without any complication and the same went for the smaller 3D-printed parts. The bottom of the chassis (in contact with the 3D-printer plate) came out a bit rugged, and had to be reshaped using a plastic filler to create a smooth surface. Inside the chassis, 3D-printed mountings were fitted for holding the motherboard. Rubber bearings were glued on top of the mountings to minimize vibrations. The rest of the components were fastened with Velcro for easy accessibility and increased modularity. Threaded brass inserts were melted into the chassis to make it possible to screw the metal side-plates shut. On the contact area between chassis and aluminum sides, rubber sealants were glued to waterproof the case. A panel for the connections going into the case was 3D-printed with customized slots for every connection, and the slots were then sealed with silicone. The panel was also protected by a small 3D-printed box to avoid water splashing directly at the connections. The product with all components mounted is seen in Fig. 4.6.

Fig. 4.6. The final product with all components mounted (without sides).

4.5 Discussion

The final case 4.7 fulfilled the requirements that was set for the solution. The overall result was satisfying given the limited time frame. The case contributes to value in the car through its protection of the computer. The computer is arguably one of the most crucial components of the entire autonomous system. Thus giving the case an important role and therefore promotes the engineering process that generated the solution. By analysing other solutions and weighing through matrices, security in failure prevention is obtained which is of great importance for the specific task.

Furthermore, the case fulfills a role as score generator in the competitions in the sense that the engineering design rewards well processed engineering solutions, defending the design choice of the construction. Recollecting the main purpose, this would impose goal fulfillment.

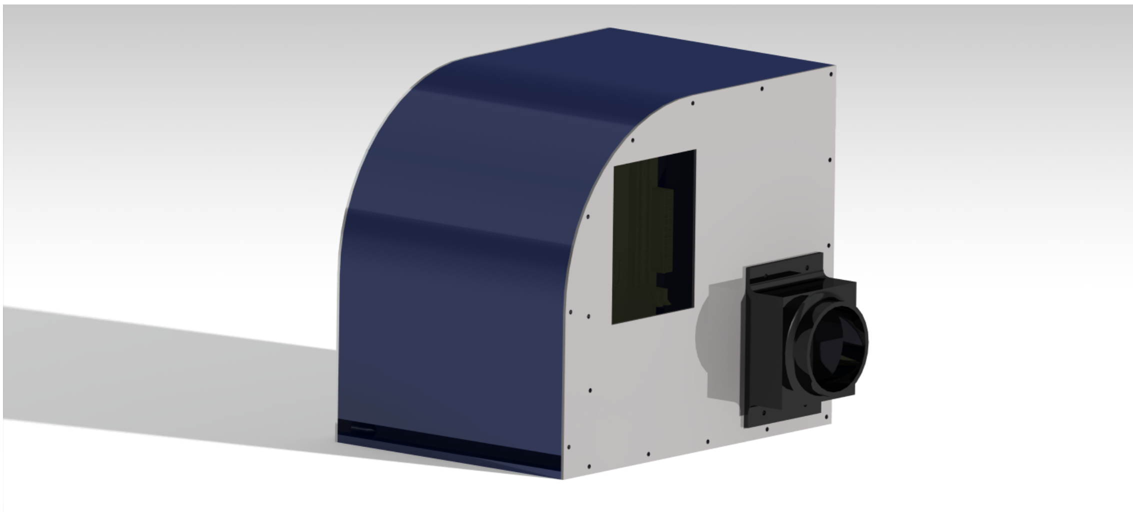


Fig. 4.7. The final concept

4.5.1 Further development

To develop the product further, more tests could be conducted on how hot the components get under high load. CFD simulations could be made to optimize the position of in- and outlets of air. Tests could also be made to ensure the integrity of the design during higher temperatures and under direct sunlight.

Formula student driverless will always be operating the autonomous system through a computer and in which case there will be a need of an enclosure. The integration of the computer into the monocoque is seen in today's autonomous car applications and it is highly possible to mimic these kind of solutions.

5 Social and ethical aspects of autonomous driving

Autonomous driving is in the forefront of developing technology and has a large potential to positively affect the socio-economic state in the near future. The most substantial changes when transitioning to self driving systems are probable to be [18]:

- Superior safety

- Higher efficiency in traffic flow
- Improved fuel economy
- Savings in professional driving
- Time savings
- Cultural changes
- Vehicle maintenance

Traffic accidents are today a big issue containing a large amount of lethal accidents. In a thorough analysis in crash causation done at the institute for research in public safety at Indiana University [19], it was concluded that the human error is more frequently the deciding factor in accidents than either environmental or vehicular factors. A functioning autonomous driving car will therefore have the potential to decrease the amount of injuries and crashes significantly.

Implementing self driving while manually controlled vehicles are still dominating the market will likely be hard at first. Progressession of the of the usage of autonomous vehicles will lead to a substantially less congested traffic. The possibility is that it will result in both time and fuel savings. Autonomous driving is also promising in the strive towards further improving the fuel economy by eliminating ineffective acceleration and braking.

Implementation of self driving will eventually render manual driving in commercial traffic obsolete, resulting in considerable savings in money spent on employees. At the same time this could potentially be life ruining for the employees working in this area, which will have to find and learn new professions.

The possibility for self maintenance, available for autonomous vehicles, will keep the system in good conditions at all times and therefore save both time and repair expenses.

Continually increasing demand for vehicle transportation leads to a plethora of problems, in both environmental aspects but also in decreasing amounts of accessible oil [20]. Fossil fueled vehicles increase fossil carbon intensity and also the amounts of pollutants like nitrogen oxides and sulphur dioxides. Pollutant problems can mostly be solved by the use of filters and catalytic converters, but the greenhouse gas and resource depletion issues would still remain. A change to electric driven vehicles seems therefore like a favourable solution to address these looming environmental predicaments. Electrical systems are not without their drawbacks though. Most systems, including the car which this report is based on, use lithium-ion batteries. The major reason for this is the material's favourable characteristics which leads to high energy and power density. The study contribution of lithium-ion batteries to the environmental impact of electric vehicles [21] uses a detailed life cycle inventory of a lithium-ion battery and a rough life cycle assessment of battery electric vehicles to compare the environmental impact of commonly found combustion engines and lithium-ion based electrical vehicles. The research concluded that despite the drawbacks of using lithium-ion batteries, E-mobility is environmentally beneficial compared to conventional mobility.

While self driving cars could potentially decrease the total amount of crashes, all accidents are impossible to prevent. There is a possibility that autonomous cars might have unintended consequences for public safety just as robots might in the future be forced to make ethical judgments. Agreeing on a universal moral code for these vehicles might be a difficult task since ethical concepts varies among people. To gain public acceptance and trust in the autonomous cars it is important to have a consensus about how these vehicles should behave in inevitable situations.

6 Conclusion

This project has achieved various results concerning the car hardware of the 2019 Chalmers formula student driverless project. From these results, the mission of this bachelor project is completed. As the purpose of the thesis states, the main goal was to modify the existing car to generate competition points in order to rank as high as possible. Therefore to summarize the report it is of value to evaluate the different projects to compare against each other and thus conclude what project is most beneficial.

6.1 Quantitative analysis

The modifications can first of all be categorised in the engineering design section of the competition. The nature of this section is an argumentative stance against the construction of the car which implies that well documented engineering processes are profitable. The engineering design resides in the static disciplines and consists of several subcategories described in Appendix A. The three thesis sections can thus be arranged in the engineering design scoring categories.

- Aerodynamic package
    - Overall vehicle concept
    - Vehicle performance
    - Mechanical/ structural engineering
    - LV-Electrics / electronics / hardware
    - Engineering design report

Engineering design score impact:

$$\frac{85+30+20+40+5}{325} = 55\%$$

- Steering actuation
  - Overall vehicle concept
  - Vehicle performance
  - Mechanical / structural engineering
  - LV-Electrics / electronics / hardware
  - Engineering design report

  Engineering design score impact:

$$\frac{85+30+20+40+5}{325} = 55\%$$

- Computer case
  - Overall vehicle concept
  - LV-Electrics / electronics / hardware
  - Engineering design report

  Engineering design score impact:

$$\frac{85+40+5}{325} = 40\%$$

Regarding the engineering design, both aerodynamic package and steering actuation has a score impact equal to 55 %, whilst the computer case has 40 %. This means that out of the entire event, the percentage is what proportion of the scoring that might be influenced by the project. Comparing the three different parts through event impact is a starting point for the objective ranking.

The above listing is a descriptive overview in what way the three projects can assort and what amount they profit the main goal This enables comparison between different projects with quantifiable measures: competition impact. Therefore the layout principle is suggested to be implemented in the CFSD methodology of scheduling. If every befitting sub-project of the car is analyzed equivalently as the projects of the thesis, a comparable overview of impact and categorisation can be applied. This would branch out the entire car project and eventually cover every part of the car. With this information, scheduling and planning would be beneficial for following years and provide substance for priority decisions.

6.2 Qualitative analysis

Although the proportion impact generated by the different projects is a highly substantial comparing methodology, other aspects needs to be regarded. Since the engineering design event is an argumentative point system as judges evaluate the design, the presented information regarding design choice is important. Therefore, each project can be categorised in what can be described as content satisfaction. Considering the three thesis sections, the argumentative stand point of each design choice differs from simulation techniques and measurements to materials science. Thus a qualitative arrangement is advisable. Comparing each section's capability to strengthen the argument of the design choice, a similar score impact system from which a hierarchic arrangement can be formed.

- Aerodynamic package: The results generated are of simulation genre and theoretically evolved. CFD simulations are a persistent method throughout the automobile industry [22] regarding design choices. Therefore it is considered a reliable source of results. The analysis and results of the aerodynamic project substantiates the defence of the preservation of the package. Furthermore, the aerodynamic project is a part of the car which also has association to the dynamic events in the sense that it actually enhances the car performance, increasing the value of this project even more.

- Steering actuation: The steering actuation section is a straight forward analysis of the steering system's response abilities. The methodology is a reliable result generator considering that measurements are reflecting the reality of the car's actions. The results however, shows a play that is downgrading the cars performance. But through knowing this resources can be focus on other positive attributes of the current steering, such as robustness and reliability since it was deemed to time consuming to change the current system.

- Computer case: The computer case has, from the quantitative arrangement, a lower score impact than the two other sections. Although lower involvement in the different event categories, the defendant stand point from an engineering product development perspective, is highly rated. Minimizing malfunctions in the later stages of the process is not only time efficient but also profitable scoring wise. The proof of a well thought out engineering process, is essential to a competition such as Formula student driverless and the strive to become better engineers. The computer case is crucial to the autonomous department of the entire project.

6.3 Project value

By paring the project results to the purpose and goal, clarity has been given upon what efficiency each project is worth in terms of competition value. The combination of the quantitative and qualitative analysis form a conclusion of total impact in relation to each project generated. The qualitative analysis can be arranged in ranks of project value, and would be the following:

- Aerodynamic package. Rank 1
- Computer case. Rank 2
- Steering actuation. Rank 3

By fusing the analysis, the aerodynamic package becomes the worthiest modification made on the car. Since the character of the qualitative analysis is difficult to measure and fuse to a quantitative analysis, the computer case's project value is difficult to compare to the steering actuation's. The steering actuation has a larger involvement in the quantitative analysis but is valued lower in the qualitative analysis. From a different perspective the steering chapter delivers a lot of information regarding the system control of the car. This is of value but does not defend the original design more than reading values of the current. The results help understand the car and can be utilized to perform better along with the software. This would mean that it has an expected value in the dynamic events since it directly affects the performance. The computer case has different nature in the meaning that it does not directly affect the car in the performance sense, but is essential to the autonomous existence. This leads to a comparing point where the project value is decided subjectively due to dissonant objectives. Conclusively they each have rewarding results and contributes to the main goal. This project has generated sufficient results to achieve a higher score in a flexible and more rewarding way than expected.

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A Competition details

Formula Student Germany
Engineering Design Scoring Categories

Categories	FSC & FSE Scores	FSD Scores
Overall Vehicle Concept	40	85
Vehicle Performance	30	30
Mechanical / Structural Engineering	20	20
Tractive System / Powertrain	30	30
LV-Electrics / Electronics / Hardware	10	40
Driver Interface	15	---
Autonomous Functionality	---	90
Engineering Design Report (EDR)	5	5
Autonomous Design Report (ADR)	---	25
	150	325

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formula student germany

Fig. A.1. Engineering design scoring description