UNIVERSITY OF TWENTE.

Internship

Master Mechanical Engineering

e-Traction®
revolution in motion

Developing of a new subframe for TheWheel

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This internship report is written within the context of the second year of the Master Mechanical Engineering at the University of Twente and is meant for the internship coordinators and UT supervisor.

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Abstract

During this internship I worked on two main assignments at e-Traction, Apeldoorn. e-Traction builds and develops electric in-wheel motors called TheWheel. The current TheWheel V0 will be replaced by a new generation. This new motor is more powerful and will be more efficient. As the design of this motor is different a new subframe needs to be developed. The connection to the subframe will be closer to the middle leaving less space available for the subframe. The first main assignment was to develop a new subframe for the testbus, a Volvo 7700. The goal of this subframe is to test the new motor on the road. It must connect the suspension arms, reaction rods, stator shaft and brake caliper. As there is limited time available for this subframe there is chosen for a quick design approach, which made it very challenging. Mostly there will be looked at proven thicknesses and threat depths of previous designs. Where high stresses are expected overdimension of parts will be used. There is chosen to convert a V0 VDL subframe in stock to fit with the new motor as this would be more beneficial. From the final testbus subframe design a FEA was done from which no high stresses in the subframe are expected. After that the technical drawings and an assembly guideline of the subframe and the new motor were made. The parts arrived and the subframe was being built in-house during the last weeks of my internship.

The second main assignment was to design concepts for a production subframe. To do so there was looked at the geometric boundaries, load cases and service demands. After that 3 conceptual designs were made. The first concept is based on the current V0.3 ZA subframe. This subframe is proven to be reliable and strong over its life time but has relative high production costs. Therefore the second concept is optimised for production efficient parts. This means where possible straight plates and symmetric parts are preferred. This leads to a cheaper and lightweight subframe. The third concept will use a casting part. With the use of a casting part less parts are needed as previous used parts are integrated. Due to its shape it is heavier than the other concepts. FEA were done for a comparison between the concepts. From these FEA the casting parts show room for improvements and less stress compared to the other concepts. After evaluating all concepts the third concept with the use of a casting part shows the most potential and need to be further investigated.

Preface

This internship report is written within the context of the second year of the Master Mechanical Engineering at the University of Twente. During a period of 14 weeks I worked at e−Traction, from 16 January till 21 April. Using my engineering knowledge and experiences obtained during my Bachelor and Master and with the help of my coordinators and colleagues I worked on the design of a new subframe for TheWheel. This subframe allows TheWheel to be fitted under a low floor city bus. First this was done for the testbus, a Volvo 7700, located in Apeldoorn. After that conceptual designs for series production in China were made.

I want to thank all the people that helped me during this internship. ing. A. Jonker ing. L. Potze and for being my internship coordinators and all other colleagues I worked with. Furthermore I want to thank Sabri Murad from HAN Automotive for his internship assignment. It provided a starting point for my work as Sabri did a benchmark study and already pointed out some boundary conditions.

May 8, 2017, Apeldoorn

Michel Hendriks

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Introduction

e–Traction

e–Traction was founded in 1981 in Apeldoorn [1]. TheWheel, as the in-wheel motor driving device is called, is invented and developed in the late nineties. Throughout the years this invention, its applications and its infrastructure have been highly acclaimed and awarded with many prizes. This all for the current development in the automotive industry: diminishing the use of natural resources and the reduction of global warming and carbon footprint. The future is in electric driving. As the mission of e–Traction describes:

> " *It's our purpose to create the most efficient electric drive train solutions that will minimize the impact on our environment and natural resources, improve quality of life in urban areas and become an economically attractive alternative at the same time [1].*"

The overall increasing wealth threatens the quality of life in urban areas. Air pollution in highly populated Chinees cities would benefit from electric transportation. The main focus for e–Traction is on public transportation. Till now this heavy duty solutions are the most promising. Future developments could be the farming and mining industry or even the car industry.

TheMotion describes the whole product and services e–Traction provides to its customers. It is divided in TheWheel, TheDrive, TheControl and TheConnect, as seen in figure 1. TheWheel describes the in-wheel motor driving device, it converts electric energy into torque. Integrated fluid cooling is needed for the heat development by the power electronics. TheDrive product line contains both power train and auxiliary motor drive solutions. TheControl consist of a power train control module (PCM) and vehicle energy manager (VEM). They both are easy to integrate within an existing vehicle. TheConnect provides connection, distribution, fuse and switch functionalities to high voltage electric power train DC-link systems.

Figure 1: TheMotion, from left to right: TheWheel, TheDrive, TheControl and TheConnect

The Chinese market is ready to be conquered by e–Traction as it has recently been acquired by the Tanhas Group. In association with the Tanhas Group a new series production factory will be opened. The current TheWheel system is capable of producing 6000 Nm of torque with a maximal power output of 182 kW and is called the V0 [2]. The maximal achievable efficiency is 91.4 %. This system is however expensive, has a high weight and only a super single tyre can be mounted. It is also only suitable for 12 meter busses. The new V1 has a different design which increases the lifetime and performance. A twin tyre can also be mounted as this is common in the bus market (2x 275/70 R 22.5). The V1.1, as is developed now, is expected to produce 11000 Nm of torque and weights around 85 kg less than its predecessor. The total weight is around 400 kg. This means the system is also suitable for 18 meter busses. Due to clever design solutions the diameter is reduced and the active motor length increased compared to the total length. This causes the torque density to increase with around 120 % and a maximum efficiency of 93 % is expected. The new design is robust with a life time expectancy of >1.000.000 km [3].

There are different competitors of e-Traction. Every competitor has a different design approach, some use a hybrid system and others a geared wheel hub. Two examples together with TheMotion V0 are given in table 1. The main advantage of TheMotion is visible here as there are no additional heat and friction losses because no gearing or drive shaft is present in the system. This reduces the energy consumption and also keeps the weight relatively low. With the new V1.1 design even the ZF could be beaten on weight. Most low floor city busses use the same standard mounting points, to be competitive a subframe for these mounting points will be designed. This allows most busses to be converted to TheMotion from e-Traction. Before this a subframe for the Whisper testbus will be designed. This testbus is a Volvo V7700 with different mounting points compared to the standard mounting points. This subframe will then allow the TheWheel V1.1 to be tested on the road in Apeldoorn. This means that for the testbus a quick, cheap and reliable design must be made. It is an one off production for testing the new V1.1.

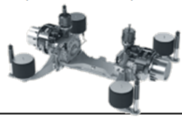
	Central e-motor	**Geared, wheel hub e-motor**	**Direct drive, in-wheel e-motor**
Main suppliers (Heavy-duty segment)	> Siemens (ELFA II) > BAE systems (Hybridrive) 	> ZF (AVE 130) > BYD (BYDTYC90A) 	e-Traction (TheMotion) 
System characteristics	> Energy consumption ~1.06 kWh/km > TCO ~ 11% more than direct-drive > Weight of BAE~ 1865 kg	> Energy consumption ~1.04 kWh/km > TCO ~ 11% more than direct-drive > Weight ~1618 kg	> Energy consumption ~0.91 kWh/km > Weight ~ 1788 kg
Schematic	MOTOR → DRIVESHAFT → GEARING → WHEEL	MOTOR DRIVESHAFT GEARING, WITH IN-HUB MOTOR → WHEEL	MOTOR DRIVESHAFT GEARING WHEEL, WITH IN-WHEEL MOTOR

Table 1: Example competititors [4]

As explained above a new design for the subframe is needed. An overview of all components which need to be connected to this subframe is seen in figure 2. The development of this subframe will simultaneously be done with a Chinese axle manufacturer. The stator shaft needs fixed DOF's at the cylindrical end for the rotor to rotate on. This subframe need to connect the suspension arms, the reaction rods, stator shaft and the brake caliper.

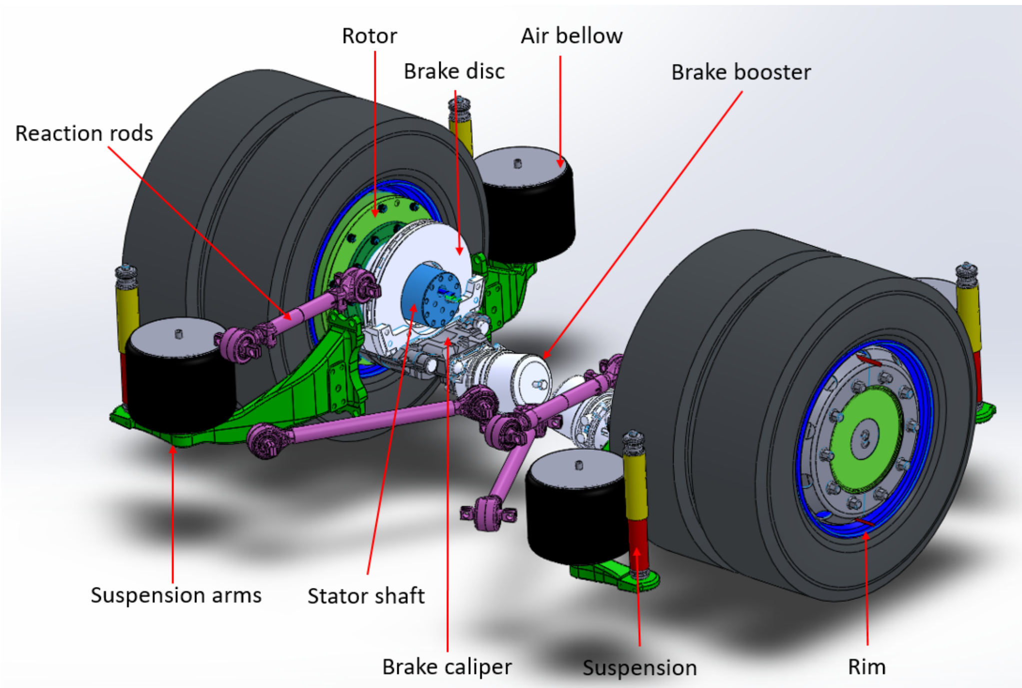


Figure 2: Overview of components

The connection of TheWheels stator shaft with the subframe is different compared to the old V0. In figure 3 the connection distance is shown with a red line. It is closer to the center of the bus leaving less space available for the subframe. The width of TheWheel itself also increased 19 mm and the brakes for the new design are also bigger, leaving even less space. This reduced space need to be taken into account for mounting and service proceedings.

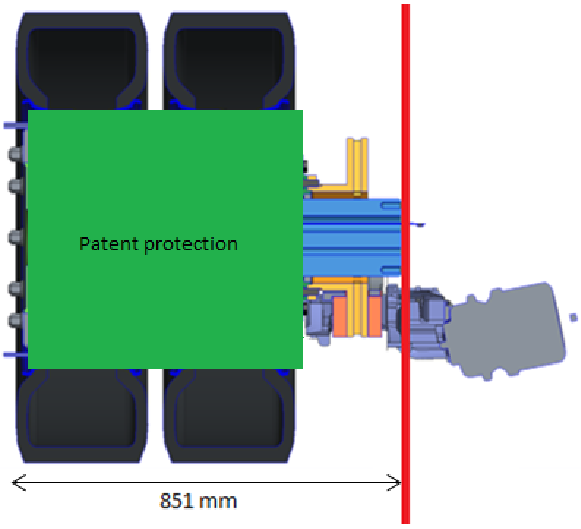


Figure 3: Connection to subframe V1.1 (left) and V0 (right) [2]

In the first chapter the problem will be defined. There will be looked at the geometric boundary conditions, load cases and requirements. There is also looked at possible production methods and materials. The second chapter covers the design steps taken for the subframe design of the testbus. The second chapter also covers the assembly and montage of the subframe and ends with some pictures of the assembly of the subframe. In the third chapter concepts are made for the production subframe. At the end of this chapter a concept choice is made. The report ends with the conclusion and recommendations.

1. Problem Definition

As explained in the introduction a new subframe for the connection of TheWheel V1.1 must be designed. This chapter will cover the problem by stating the boundary conditions and demands of the subframe for TheWheel. First the geometric boundaries will be investigated. Second the different load cases the subframe is subjected to are determined. Then there are some service demands the subframe must satisfy. After that there is looked at the possible production methods which is strictly related to the material choice which is explained finally.

1.1 Geometric boundaries

As explained before several components need to be connected to the subframe. These connection points are fixed and explained in this section. There will be looked at two different cases, one with the new V1.1 mounting points and one for the Volvo 7700 testbus. The x-, y- and z-axis are defined as shown in figure 1.1. The center of these axis will depend on the case looked at. The x-axis is positive in direction to the back of the bus.

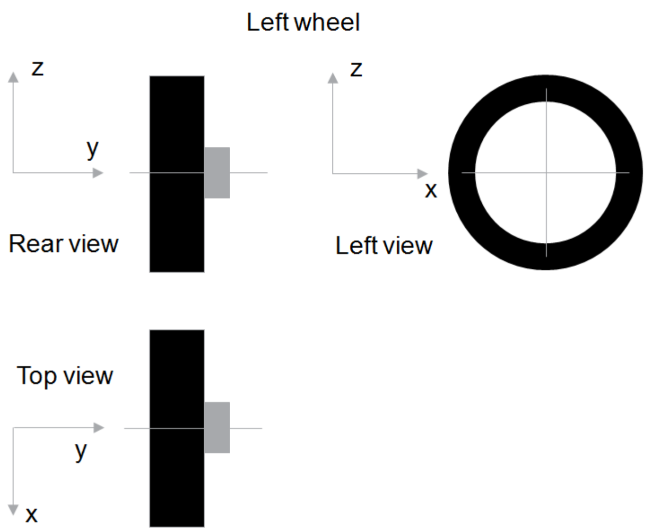


Figure 1.1: The x-, y- and z-axis as seen from the left wheel [5]

1.1.1 TheWheel V1.1 Mounting points

General dimensions

Before looking at the connections there will first be looked at the overall dimensions. Figure 1.2 shows the most important ones: the ground clearance, the outer bus width, the track width and middle path between the two stator shafts. In general there is aimed to be inside the in yellow highlighted ZF dimensions for competitive reasons. The maximum allowable bus width is 2550 mm, as a clearance of 5 mm is used on both sides the bolt to bolt distance is set to 2540 mm. Table 1.1 shows the ground clearance of different bus manufacturers. The aimed ground clearance for the new subframe is the highest from ZF, 177 mm. The clearance between the top of the wheels and the wheel arch will be defined by the location of the suspension arms and the bus design. Between TheWheel and the subframe a clearance of 20 mm is needed.

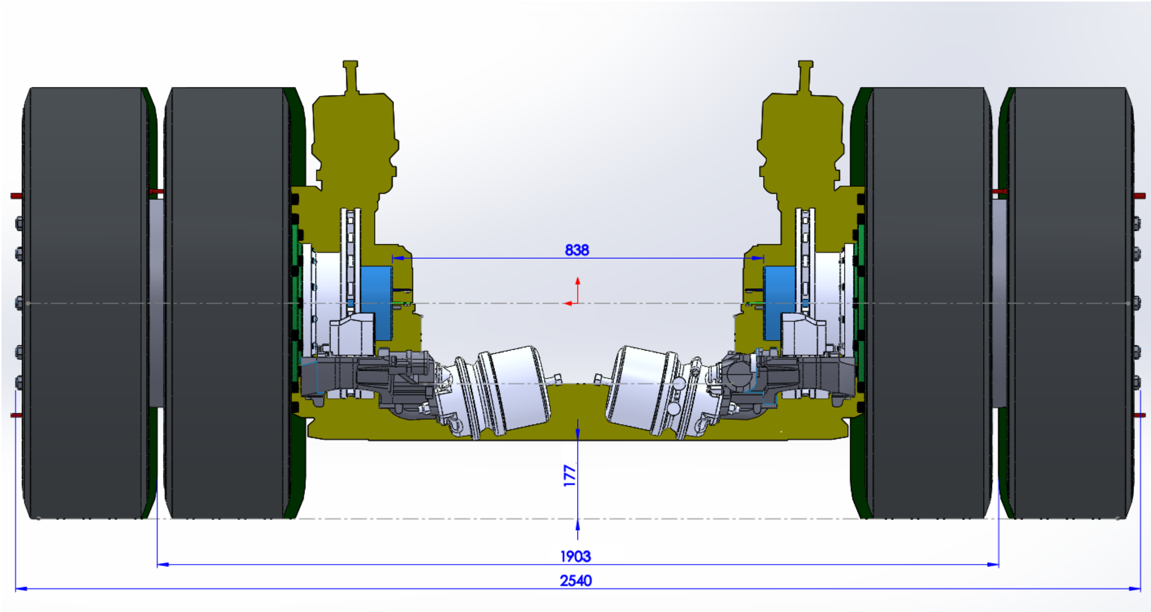


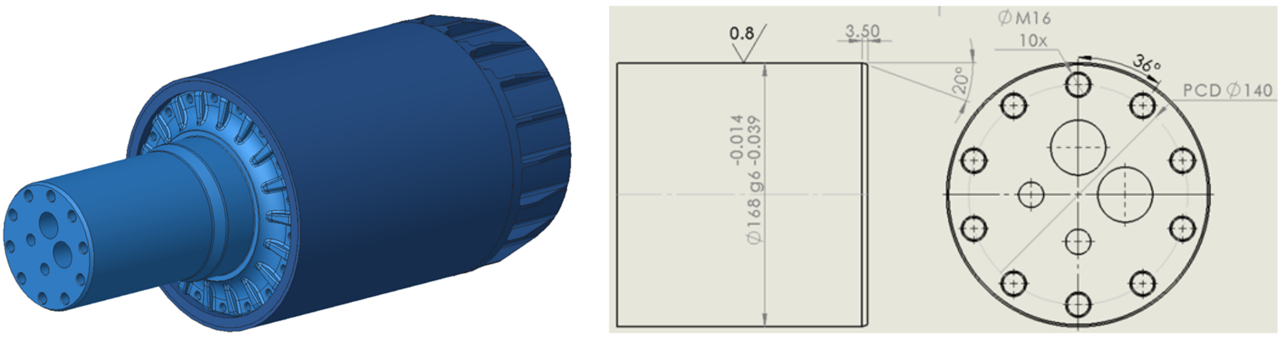
Figure 1.2: General dimensions TheWheel V1.1 and ZF dimensions highlighted in yellow

Table 1.1: Ground clearance for different bus manufacturers [6]

Manufacturer	Van Hool	Solbus	Iveco	ZF
Ground clearance [mm]	130	153	150	177

Stator shaft

The stator shaft is shown together with the cooling jacket in figure 1.3 a. The subframe will be connected using 10xM16 bolts. These bolts are located in a circle around the center with a radius of 70 mm as shown in figure 1.3 b. The strength of this connection is calculated for all load cases which are defined in section 1.2 by Ricardo[1]. The stator shaft is made of 42CrMo4 + QT, which is a well used material for heavy duty shafts. For a rigid connection the use of a flange at the end is expected.



(a) Stator shaft with cooling jacket

(b) Technical drawing stator shaft

Figure 1.3

Connection module

The connection module is located at the end of the stator shaft. It is placed on top of the stator shaft in between the bolt circle. The connection module connects systems such as the cooling and the DC cables for TheWheel. Figure 1.4 shows the connection module for the testbus. The connection module is designed to be as small as possible to keep inside the ZF dimensions as stated earlier. The connection module as is used on the testbus is 75 mm wide. The series production connection module is yet to be designed.

[1] © Ricardo plc 2016, Shoreham-by-Sea, England

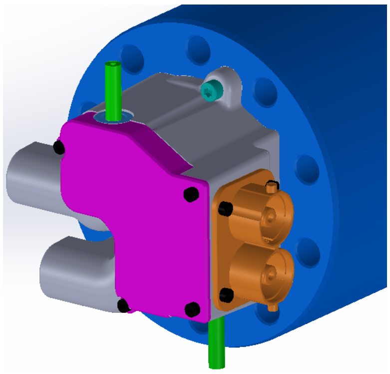
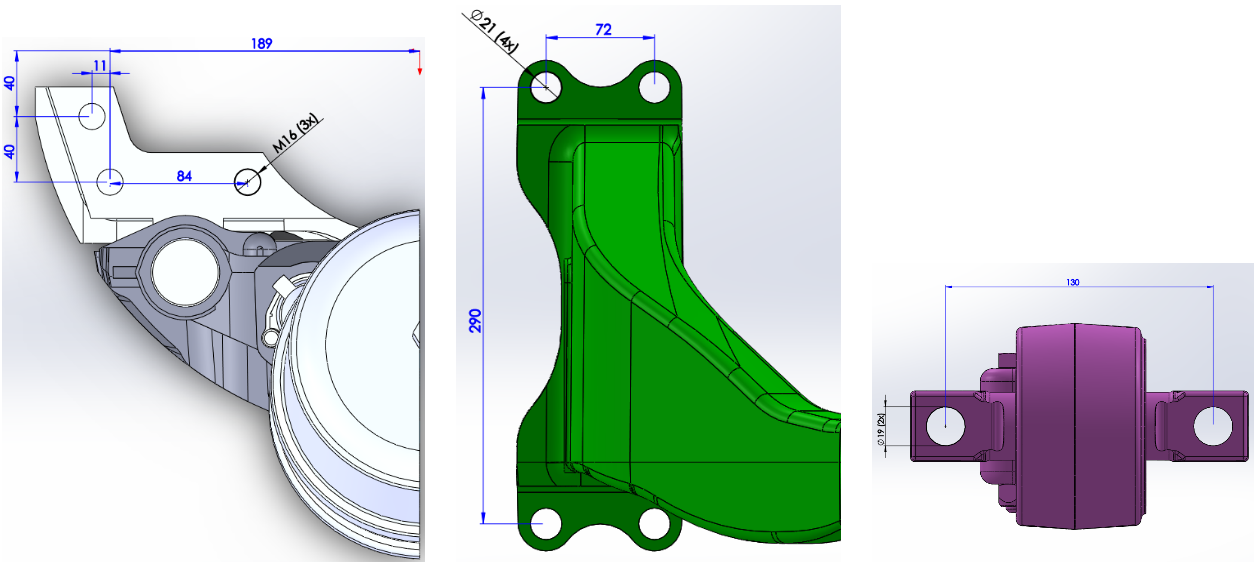


Figure 1.4: Connection module testbus

Brakes
The brake caliper is connected to the subframe using 6xM16 bolts. The dimensions of the brake caliper are shown in figure 1.5 a. Compared to the center of the shaft the outer connection of the brake caliper is located 200 mm away from the x-axis and 40 mm downwards (z-axis). Compared to the end face of the shaft it is located 29.5 mm back (y-axis). Compared to the old V0 the new V1.1 uses bigger brakes, the new diameter of the brake disks is 430 mm. The brake discs are KNORR - II371910061 and the brake caliper and booster are KNORR SN7. Around the brake discs a minimal clearance of 10 mm is needed.

Suspension arm
The suspension arm is connected to the subframe using 4xM20 bolts. The dimensions of the suspension arm ends are shown in figure 1.5 b. The distance between the two faces of the suspension arms is 530 mm. The outer bolts of the suspension arms are 1181 mm apart. The mounting points for the suspension and air bellow on the bus itself are shown in figure 1.6. If the new subframe design requires a renewed suspension arm this is possible but would lead to higher costs.

Reaction rod
The reaction rods are connected to the subframe and bus using 4xM18 bolts as seen in figure 1.5 c. The mounting points of the reaction rods on the bus are fixed as shown in figure 1.6. The length of the reaction rods are however free to determine in the design. The middle reaction rods have an angle of 30° as is the engineering standard. It is preferred that all reaction rods have same length and are horizontal during normal driving. This to minimize difference in parasitic movement of the reaction rods which could lead to a tilted subframe. Although the reaction rods can vary in length the location of every part which needs to be connected is as already shown in figure 2.



(a) Dimensions brake caliper (half)

(b) Dimensions suspension arm

(c) Dimensions reaction rod

Figure 1.5

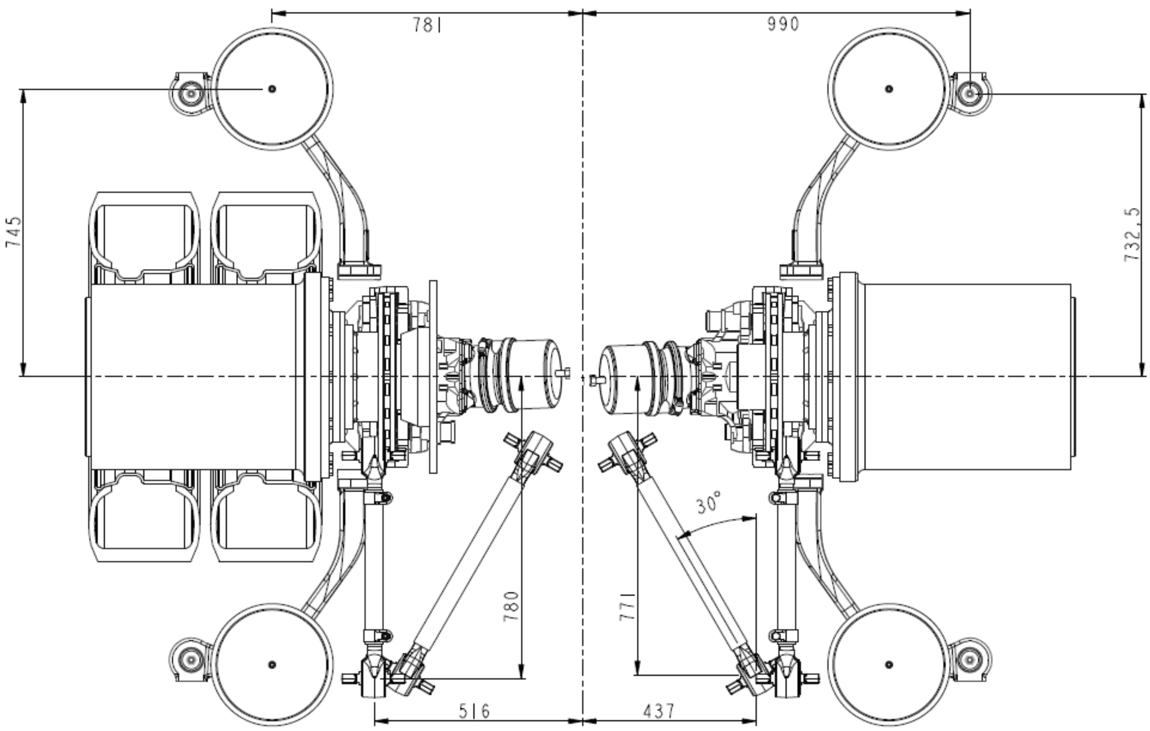


Figure 1.6: Pick up points suspension arms and reaction rods [7]

1.1.2 Volvo 7700 testbus mounting points

For the testbus a slightly different approach is used. A Solidworks 3D model was used as a starting point. From these drawings the mounting points were located as seen in figure 1.7 highlighted in red. These mounting points were then confirmed by measurements underneath the testbus. To do this the testbus was lifted and TheWheel V0 removed. As there are a lot dimensions there is no need in specifying every dimension here. Compared to modern subframes the testbus stabilizer bar is mounted on the subframe itself instead of the suspension arms, as shown in grey.

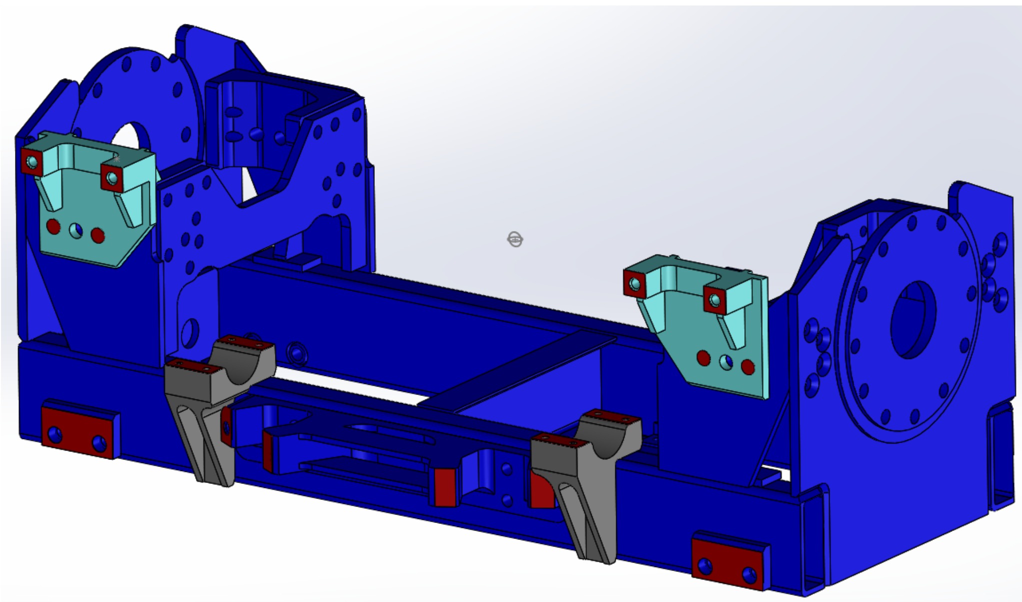


Figure 1.7: Mounting points testbus

1.2 Load cases

The wheels and subframe are subjected to several load cases during their life time. The wheel load generation is already done by Ricardo [5]. The real world loading of the wheel is modelled using static load cases. Appropriate g-factors representing desired dynamic loadings are used to define each load case. Furthermore the load cases are divided into categories according the expected number of cycles as shown in table 1.2. In the cases where it increases the wheel load a load transfer is considered.

Table 1.2: Load cases according to expected number of cycles [5]

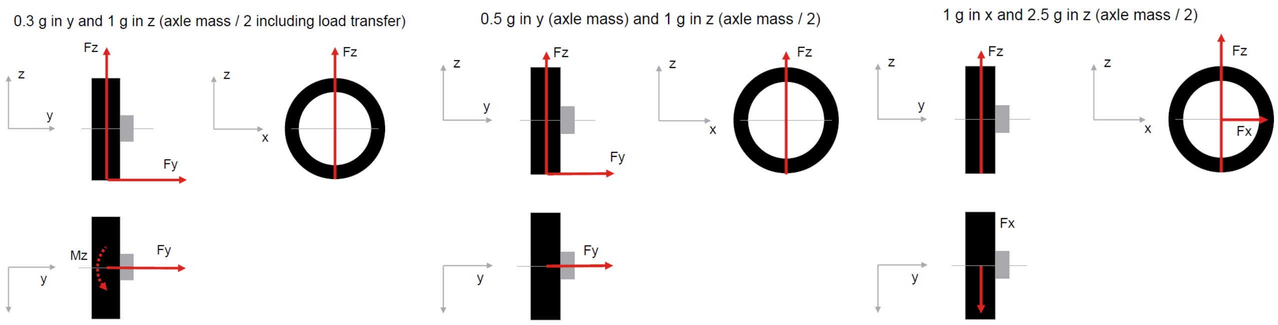
Type	Description
Fatigue	Life assessment of durability load cases, typically sorted in fore-aft, lateral & vertical directions.
Proof	Limit driving events, such as max braking and max cornering. No permanent damage to vehicle, 1000 events over vehicle life.
Extreme	Extreme events that may cause some permanent damage, but not rupture, 100 events over vehicle life.
Abuse	One off events that will damage the vehicle & require repair.

As the calculations from Ricardo are client confidential to e-Traction the whole wheel load generation is not stated here. Only the most important parameters and load cases are stated. The most important parameters of the vehicle model are shown in table 1.3. The mass of 35% on the front axle leads to a rear axle load of 13000 kg.

Table 1.3: Important parameters of vehicle model [5]

Parametre	Value
Vehicle mass	20000 kg
Mass on front axle	35 %
Unsprung mass rear (combined)	900 kg
Wheelbase	6.0 m
Braking to front axle	50 %
Estimated tyre vertical stiffness front	1e6 $\frac{N}{m}$
Estimated tyre vertical stiffness rear	2e6 $\frac{N}{m}$
Estimated pneumatic trail	0.03 m

For the loads a total of 21 cases are investigated by Ricardo consisting of load cases like braking, accelerating, cornering, kerb strikes and pothole braking. From these cases 9 are important to look at. From the fatigue cases these are the Cornering fatigue RH, Lateral kerb strike fatigue outer and the Lateral kerb strike fatigue outer as shown in figure 1.8. The coordinate system of figure 1.1 is again used for each load case. The forces and moments are applied in contact patch although in reality the tire radius changes slightly.



(a) Cornering fatigue RH (b) Lateral kerb strike fatigue (c) Pave 1

Figure 1.8: Left wheel fatigue load cases [5]

From the proof cases the Limit cornering RH, Lateral kerb strike proof outer, Forward kerb strike proof and Max bump are used. Finally from the extreme cases the Pothole braking and Lateral kerp strike extreme outer are used. These load cases are here not further visualized but the corresponding forces are shown in table 1.4. Fx-WC stands for the force in the wheel center in x direction were just the translational effect is considered.

Table 1.4: Important load cases [5]

Load case	Fz [N]	Fy [N]	Mz [Nm]	Fx [N]	Fx-WC [N]
Cornering fatigue RH	86056	25817	775	0	0
Lateral kerb strike fatigue outer	63765	63765	0	0	0
Pave 1	159413	0	0	0	63765
Limit cornering RH	123207	98566	2957	0	0
Lateral kerb strike proof outer	63765	127530	0	0	0
Forward kerb strike proof	159413	0	0	0	127530
Max bump	191295	0	0	0	0
Pothole braking	159413	0	0	39240	127530
Lateral kerb strike extreme outer	127530	255060	0	0	0

The generated loads can be applied to FEA. This will be done using a rigid body, representing TheWheel V1.1 dimensions. This rigid body will transfer the forces to the subframe, more on this in section 2.3.

1.3 Serviceability

To meet the customers requirements for easy installation and servicing the following requirements about the serviceability are set [8]:

1. The brake caliper must be removed without dismounting the motor from the subframe.
2. The dismounting and remounting procedure of the brake caliper must take place within 1 hour and 30 minutes.
3. The connection module must be accessible by tools for dismounting without dismounting the subframe from the bus. This could be obtained by using a flange at the end of the stator shaft.
4. The subframe design may not require any chassis adjustments from the Original Equipment Manufacturer (OEM).
5. Two standardized options for infra routing - with inclusion of all tubes, pipes, cables and connectors - will be designed. One where all cables and tubes go to the front and one where they go to the back of the bus. If the customer wants to design the infra routing himself only the connection module will be delivered which contains standardized plugs.

1.4 Other requirements

Other requirements the subframe must met [8]:

1. The drive axle shall have a design life to operate for not less than 1000000 km on the design operating profile without replacement or major repairs.
2. The Tacho and ABS sensor should be positioned on the subframe and prevented from heat.
3. The subframe must be designed to prevent road obstacles from hitting any critical systems, including brake system components, brake lines, connectors, etcetera.
4. Minimum Angle of Approach and Departure must be $\geq 7°$.
5. The width of the subframe must be modular from the middle. If the customer demands a total width smaller than 2550 mm the subframe width must be reduced by making it more compact in the middle.
6. A grounding point (GND connection) must be present on the subframe by adding a M10 bolt.
7. Comply with GB/T 19260-2003[2] standards which describes structure requirements of low floor city-bus and low entry city-bus.
8. Comply with QC/T 533-1999 and QC/T 534-1999 standards which describes methods and evaluation indexes for automotive drive axle bench tests.
9. Apply coating or surface treatment which withstand 240 hours of a Neutral Salt Spray (NSS) test.

[2]GB/T and QC/T are Chinese national standards [9]

1.5 Production methods

The upcoming designs are related to the production method and also the material choice. This is known as the DPM triangle, were design, production and materials are related to each other. The amount of products that need to be produced also has great influence. A Non-Binding Volume Forecast is shown in table 1.5. In this section possible production methods for the subframe parts are briefly touched. This to give some insight in what is possible for designing the subframe. Two main production methods could be distinguished, machining and casting. Combining different parts will be done using welding and fasteners which is explained last.

Table 1.5: Non-Binding Volume Forecast [8]

Calendar year	Amount of units
2017	≤ 50
2018	7000
2019	15000
2020	20000
2021	26500
2022	35000

1.5.1 Machining

Machining covers different production methods like turning, milling, drilling, laser cutting and water-jet cutting [11]. The principle is the same, a piece of raw material is cut into the desired shape. Depending on the process there is a high material loss. High tolerances of the parts can be achieved. As machining production methods are very common these will not be explained in detail. For the produced sheet metal parts that need to be bended a press brake can be used. The sheet metal part will then be forced between two tools to make the bend. The force required depends on the type of material, the thickness and bend radius [12]. For more complex shapes and multiple bendings a stamping press could also be used [13].

1.5.2 Casting

The proces where molten metal is poured into a mould containing a cavity of the desired shape is called casting. The molten metal cools down inside the mold and solidifies. There are several casting methods. Casting methods can produce one off components or in many thousands [10].

Sand casting uses sand with a bonding agent to create the moulds [11]. Two half moulds are used which are then stacked together, and if needed inserts are placed. Through the gating system the molten metal is poured in. After the metal is cooled down the sand can be removed. The sand could be reused for a new mold. Sand casting could handle high volume production and large parts. The downside would be the accuracy of the dimensions and the high surface roughness without any finishing methods applied. Another method is die casting which uses hardened tool steel as moulds. The molten metal could be poured in under high or low pressure. Compared to sand casting it can produce parts with thinner walls. It is common to use for non-ferrous metals. For ferrous metals like construction steel it is possible but under low pressure. For designing a casting part there are a few things to take into account. It is favourable to have an equal thickness over the part to reduces the internal stresses. Furthermore the parting line and draft angles need to be taken into account.

1.5.3 Welding and fasteners

For the connection between the machined parts a weld or fastener can be used. Welding creates a permanent joint while fasteners could also create a non-permanent joint. During the welding process heat is generated to melt the material of the connecting parts [14]. A filler material is supplied and combines with the parts to create a molten weld pool. After cooling down the weld pool solidifies and thus creating a joint. Compared to casting bigger parts are possible in smaller series. The generated heat causes a so called heat affected zone along the joint. In this zone internal stresses and material changes will take place as the material is heated and cooled down. Heat sinks and cracks could be formed depending on the chosen welding process. MIG/MAG and manual metal arc welding (MMA) are two widely used welding processes. MIG/MAG welding has a less welding penetration depth but is faster than MMA.

Well known and used fasteners are bolts and rivets. Rivets are permanent and take less space compared to bolts. There are a lot standardized parts which have different dimensions and material properties. Compared to welding the use of fasteners is heavier because in most cases there is a overlap. The force transfer of welds is also better between the connecting parts. A downside is, as explained before, welds cannot be unfastened. When there is not much space a wheel stud could also be used.

1.6 Material

The material choice depends on the chosen production method. In this case construction steel and cast iron will be used. Safety needs to be taken into account as if the subframe breaks during driving very dangerous situations could occur. Therefor the material must fulfil the next points:

- The material must have a relatively high stiffness-to-density ratio and sufficiently high yield strength, since it is not desired that it deforms during usage.
- Busses have a life cycle of several decades, because of this it is important that the subframe is fairly resistant to corrosion and has good fatigue properties. Corrosion resistance could also be obtained using surface treatments.
- Of course, the price of the material is also relevant for economic and competitive reasons.

1.6.1 Construction steel

Construction steel will be used in the case of machining. During the production of the subframe it is desired that it is workable. A very hard material will lead to more tooling cost as wear takes place at a higher rate. The price of the steel is also important as most of the time a large amount of material is lost. Weldability is of importance as seen before. Luckily all structural steels are weldable. For welding construction steel the carbon content is very important. Up to 0.45 carbon equivalent (CE) the steel is good weldable, after 0.5 CE it gets poor [15]. The CE is related to cold cracking, as this is the most common weld defect for steel.

1.6.2 Cast iron

Cast iron will be used in the case of casting. There are different cast irons depending on the amount of carbon and other alloying elements. Grey and nodular cast iron are mostly used. Grey cast iron is called that way because its surface appears grey when fractured. Most grey cast irons have a carbon percentage in between 2.5 and 4 and a silicon percentage in between 1 and 3. It has a good wear resistance and a high thermal conductivity. It also has high damping capacity. Nodular or ductile iron is called that way because unbound nodules of graphite are formed. This leads to a increased ductility and a higher modulus of elasticity compared to the graphite flakes of grey cast iron. Both cast irons are good machinable.

Welding of cast iron is difficult but not impossible [17]. It won't create a high strength joint because of the high carbon equivalent. It is wiser to connect the cast iron parts using fasteners. The most common cast iron, grey cast iron, contains around 10 times as much carbon than most steels. When welding flakes of graphite will be formed as a result of the high carbon content. To weld cast iron preheating the part is preferred and afterwards a slow cooling. This will reduce the residual stresses and cracking tendencies.

2. Testbus

As explained in the introduction and problem definition a new subframe for the testbus need to be designed. This chapter will cover the design steps taken.

2.1 Approach

The geometric boundaries from section 1.1 are used as a starting point. There are three main approaches for the design possible, namely:

1. Convert the V0.3 ZA design
2. Convert the V0 design
3. Complete new V1.1 design

The first approach is to convert the latest subframe design to fit the mounting points of the testbus and TheWheel V1.1. This is shown in figure 2.1, where the mounting points of the testbus are again shown in red. As can be seen immediately the mounting points are quite different. Especially the connection of the middle reaction rods and stabilizer bar will be difficult as the V0.3 ZA subframe is narrower in the middle. Converting this subframe will take much time and ingenious mounting solutions need to be found. Therefore there is chosen to leave this approach behind.

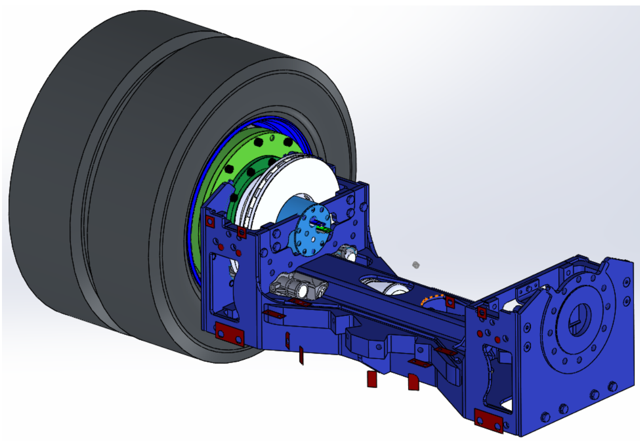
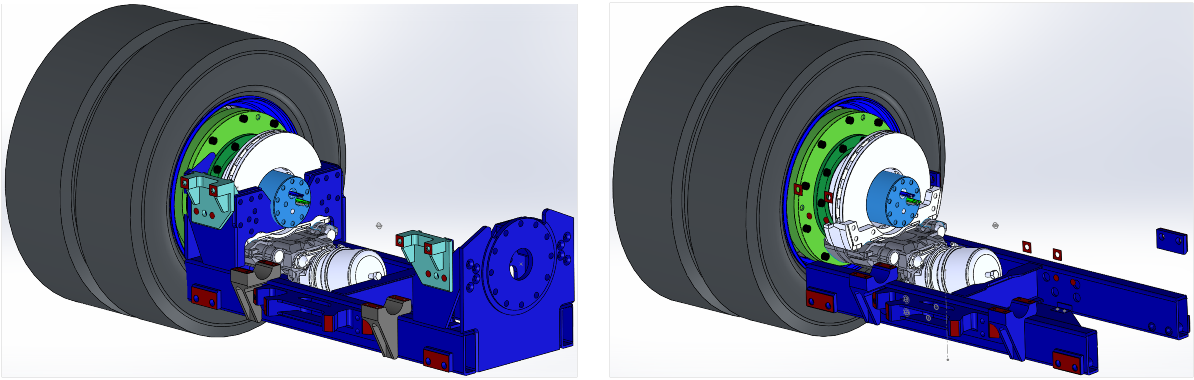


Figure 2.1: V0.3 ZA subframe with TheWheel V1.1 and testbus mounting points

The second approach is to convert the V0 design, as is currently mounted on the testbus with TheWheel V0. This is shown in figure 2.2a. It is a simple design which can be relatively easy converted. It consist of two beams where all other parts are mounted on. Parts that cannot be reused will be grinded off as seen in figure 2.2b. The new connection parts can be welded onto it. The strength of the conversion will be more uncertain as no time for a in depth analysis is available. Overdimension of parts will cover this uncertainty in strength. If the subframe currently mounted is used the consequence will be that TheWheel V0 cannot be mounted anymore afterwards. Luckily there are several unused V0 VDL subframes in stock which have almost the same mounting points as for the Volvo 7700 testbus. If the changes needed for conversion are too much there could also be chosen for a total remake of all parts, the third option. This would then however lead to a much higher production cost and longer development time. The advantage is then that there is more design freedom. The final choice is visualized in table 2.1 where there is looked at cost, time, strength and if there is still a V0 testbus subframe available. From this table and after a discussion meeting with the mechanical engineering department there is chosen to convert the V0 VDL subframe.



(a) V0 testbus subframe with TheWheel V1.1

(b) Reusable parts of the V0 subframe

Figure 2.2

Approach:	V0 testbus subframe available	Cost	Time	Strength
1. V0.3 ZA subframe	✓	€€€	🕒🕒🕒	+++
2a. Testbus subframe	x	€	🕒	++
2b. V0 VDL subframe	✓	€	🕒🕒	++
3. New V1.1 design	✓	€€€€	🕒🕒🕒🕒	++++

Table 2.1: Testbus approach choice

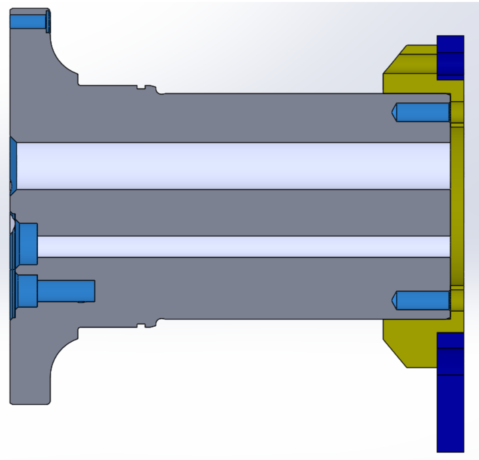
The connection module has a complex shape and is not easily mounted on the stator shaft. As the testbus must be as representative as possible for the serie production of TheWheel V1.1 there is chosen to use the final design of the connection module. Another option would have been the use of a single made connection for the testbus only.

The width of the testbus is 2500 mm. This is 50 mm smaller as the TheWheel V1.1 is originally designed for. Above that TheWheel V1.1 has a 19 mm larger motor length than its predecessor. Using the originally designed width is more representative and leaves more space for tools in the middle. After a discussion with the mechanical engineering department there is chosen for a total width of 2550 mm. As a result of that the wheel arches need to be enlarged as the wheel will stand out the side. If a larger width is needed the only option would be to get a prototype license plate as the maximum width of a bus is 2550 mm.

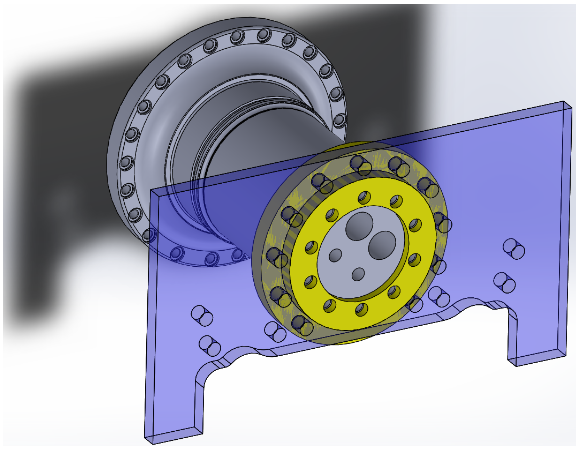
2.2 Design

As there is limited time available for the conversion of the V0 VDL subframe to the testbus and TheWheel V1.1 there is chosen for a quick design approach. Mostly there will be looked at proven thicknesses and threat depth of previous designs. Where high stresses are expected overdimension of parts will be used as the most important job of the testbus subframe is to get the TheWheel V1.1 on the road. The possible extra weight will be of little influence on the testbus dynamics and performance. Furthermore the mountability and serviceability of TheWheel V1.1 must taken into account as the new design takes more space. The first concept designs looked promising, except when there was found out that the brake parts could not be mounted from below as the space between the two beams was to small. The chosen solution was to grind of the beams at the outer sides.

The connection of TheWheel V1.1 will be done through a flange which is then connected to a front plate. There is chosen for a flange connection for a better force distribution. The maximal outer diameter of the flanges is determined for 7 mm clearance with the first interference with the brake parts. The stator shaft design is fixed for the testbus as it is already ordered. To maximize the inner space the front plate is located directly in line with the flange. The cross section of the stator shaft, flange and front plate is shown in figure 2.3 a&b. The brakes are connected with bolts on the top plate. To overcome the space between the brakes and front plate a solid part is placed in between as shown in figure 2.4 a. This part also covers the connection to the side plates as it will be welded in between.



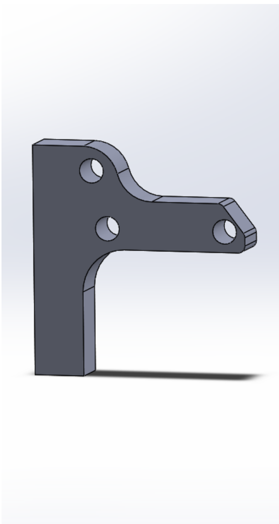
(a)



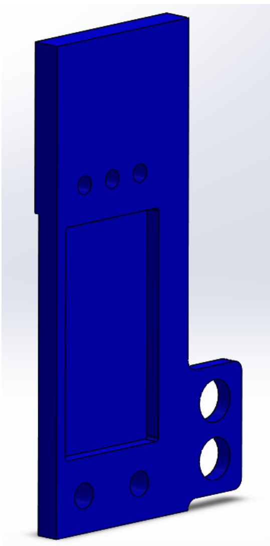
(b)

Figure 2.3: Stator shaft (grey), flange (yellow) and front plate (blue)

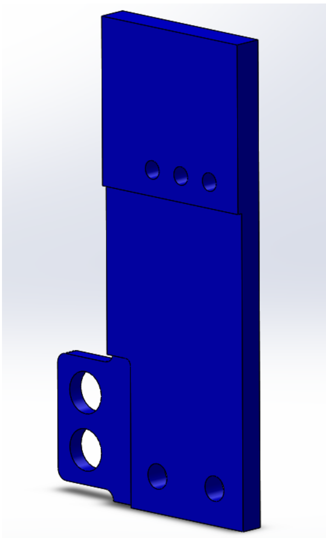
The side plate will be made out of one piece. As the beam is cut away this plate holds the suspension arms alone, therefore the thickness is increased. For this suspension arms a cutout is needed as the middle is thicker. On the inside a cutout is also needed because of the space needed to mount the brake parts, as seen in figure 2.4. A clearance of 8 mm on both sides of the brake is achieved. A better connection to the beams is provided by adding some extra material to the side plates. The inside of two circles of 40 mm are welded around to provide a stronger connection.



(a) Brake connection



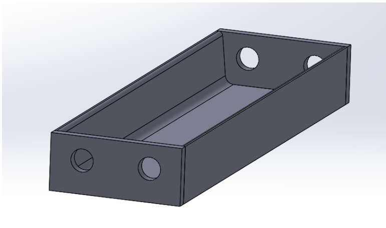
(b) Side plate front



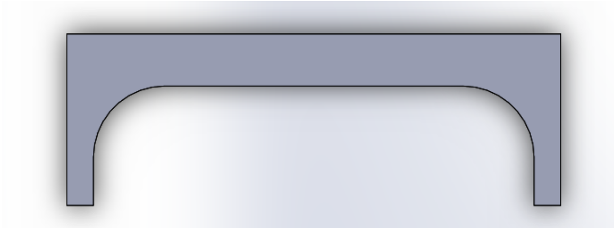
(c) Side plate back

Figure 2.4

For more stiffness a connection is made in between the side plates. This connection is made of a UNP 140 beam with on both sides a plate with a thickness of 10 mm welded. The bolts of the suspension arms go through these holes to fasten this profile. The profile is seen in figure 2.5a. To close the design a top plate is used as seen in figure 2.5b. This plate is welded around all sides.



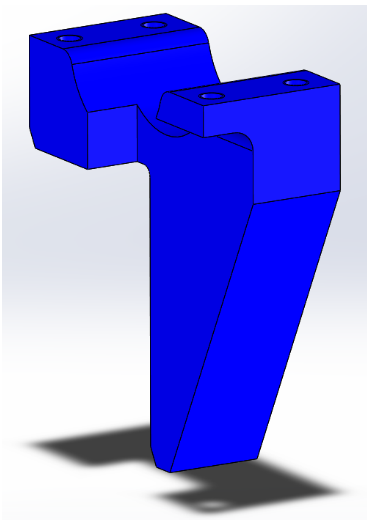
(a) Stiffener profile



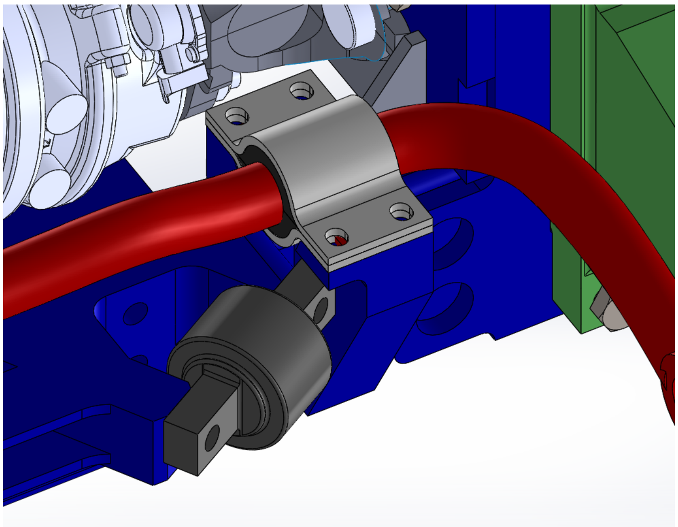
(b) Top plate

Figure 2.5

There is chosen to mount the whole subframe 10 mm lower. This will give a bit more clearance on the top of the subframe where the brake booster is mounted. A consequence is that the ground clearance is a bit lower. The side and front plates also need to be enlarged with 10 mm for the mounting points of the upper reaction rods. For the V0 VDL subframe the mounting points in the middle are placed 40 mm higher. A motion study in SolidWorks is done to investigate the different parasitic motion as a result of the different angles the reaction rods make. When the suspension is going up and down $\pm$ 75 mm a decrease of 17.8 mm is obtained on one side of the subframe as it rotates 1.9 degrees. As the bus is almost always in normal driving height no problems are expected because of this. The mounting points for the stabilizer bar also must be changed because of the higher mounting points in the middle. It will be located 5 mm more to the side, giving a clearance of 5 mm before the bend of the bar begins. Some material need to be cut away to leave space for the tools to fasten the reaction rods as seen in figure 2.6a. A cutout in the front plate is also needed as seen in figure 2.6b. The upper reaction rods are mounted the same as done for the current design.



(a) Stabilizor bar mounting points



(b) Cutout in the front plate and mounting of the stabilizator bar and middle reaction rods

Figure 2.6

2.3 FEA subframe

A quick and simple static FEA study was done on this design. The suspension arms were added and connected to a fixed bus using a spring. TheWheel V1.1 was approximated by two rigid cylindrical bodies representing the stator shaft and the rim. As an approximation the Pave 1 load case from table 1.4 was added on the rim at the middle of the wheel. A symmetry fixture in the middle reduced the simulation time. For each spring a stiffness of 30000 N/m was used [18]. The pretension of each spring is also set at a approximated 30000 N as a result of the bus own weight. Instead of bolt connections there is chosen to simulate with component contacts due to limited time. The resulting stress and the boundary conditions are shown in figure 2.7. As can be seen the stress never exceeds the yield stress of steel S355 which will be used. Furthermore at the brake connection, top plate and connection to the beams higher stresses are seen.

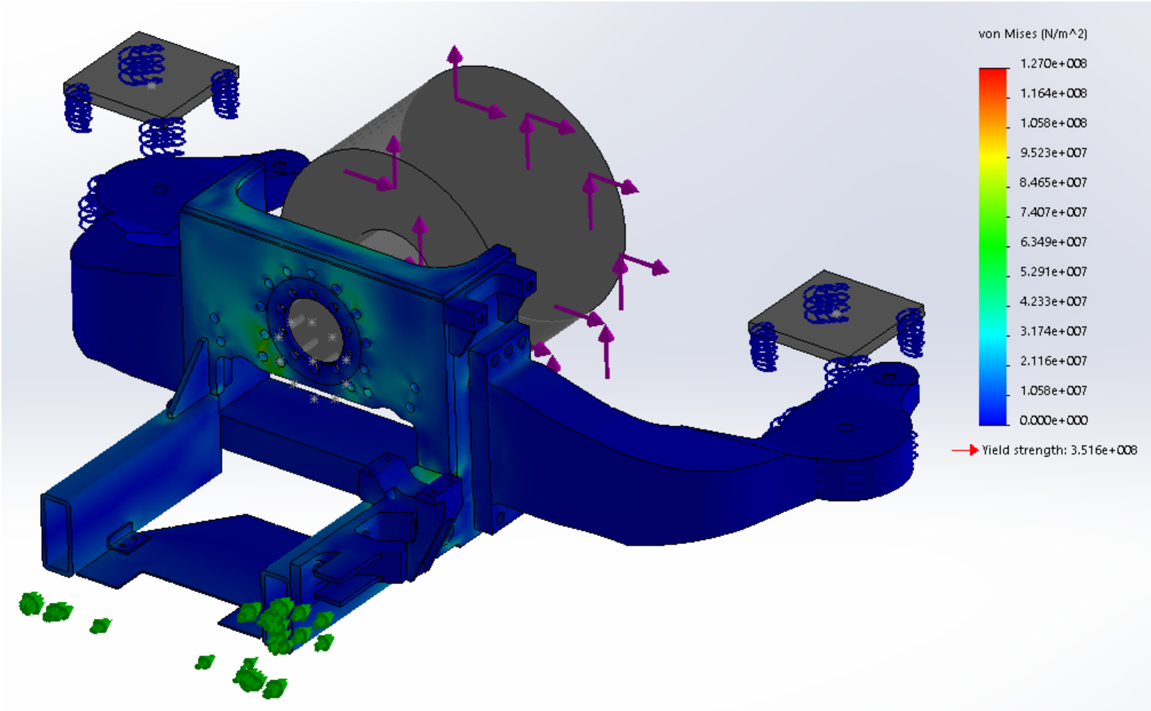


Figure 2.7: Stress distribution subframe

As a validation of the results the old subframe for TheWheel V0 is also analyzed. This subframe broke down once at the connection with TheWheel. For the analysis the same parameters were used. To reduce the computation time even more a quarter part of the subframe was taken. The resulting stress of the analysis is shown in figure 2.8. There can be seen that on the place where the subframe broke down high stresses are seen. They do not exceed the yield strength but are close to it, which would confirm that fatigue was the cause of the failure. As this analysis shows that it is close to reality the FEA analyis of the new design is expected to be close to reality too.

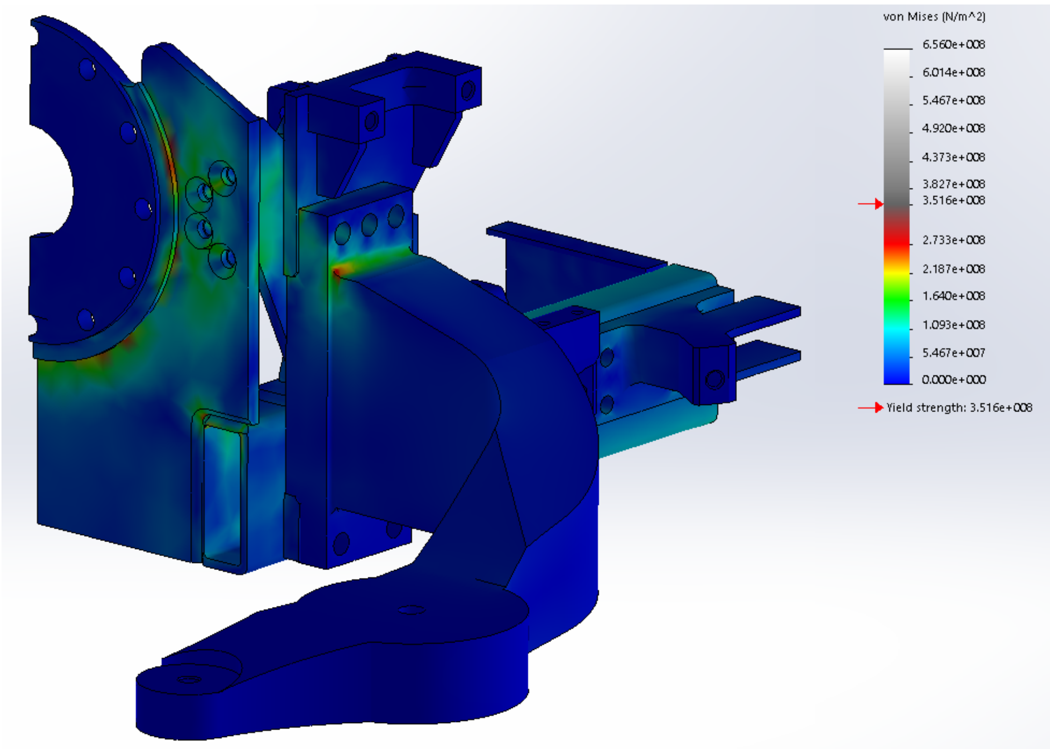


Figure 2.8: Stress distribution old TheWheel V0 subframe

As a result of the FEA some changes are made to make sure the design will not fail. High stresses are seen at the brake connection, which is made slightly bigger. Also the width of the top plate is increased from 10 mm to 15 mm. To have a better connection between the front, top and side plates stiffeners are added. The connection to the beams is increased by adding two extra stiffener ribs between the front plate and stabilizer bar. The final design can be seen in figure 2.9. For the flange the same material as the stator shaft is chosen, 42CrMo4 + QT. This material is mostly used for heavy duty shafts and has a much higher yield strength. The cost and production time will not increase much but a more robust design is obtained. The total weight of the new design is 205 kg, this is even 20 kg less compared to the current subframe of the testbus.

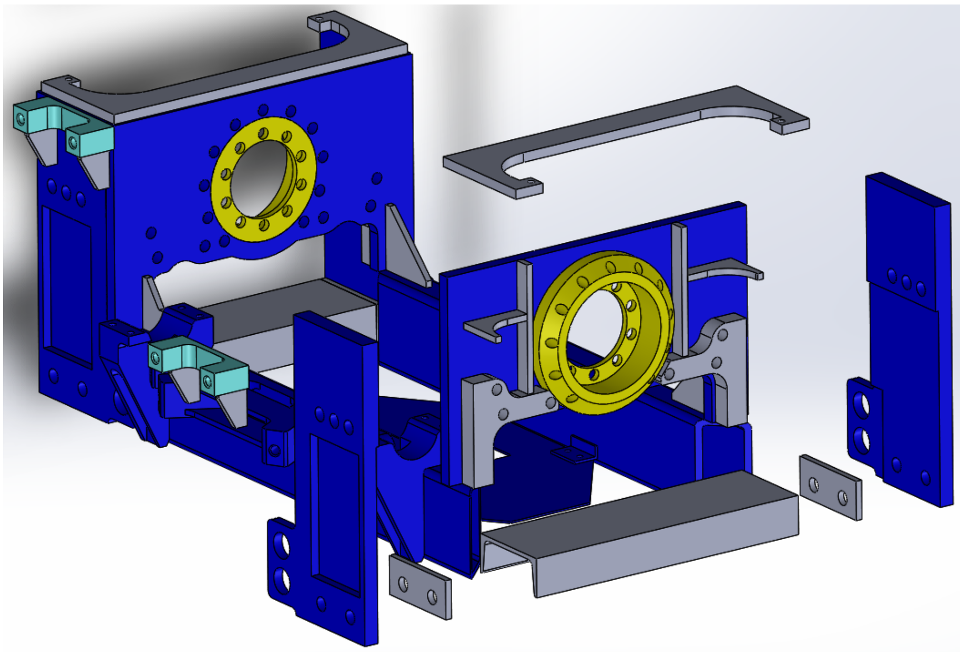
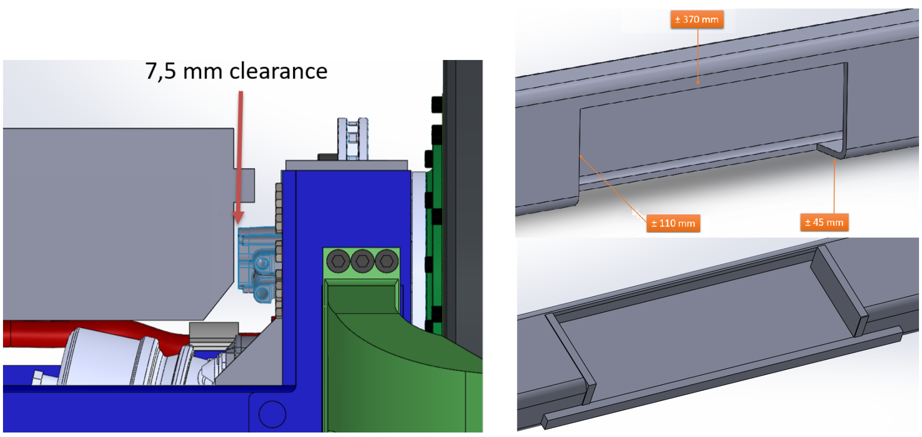


Figure 2.9: Final design subframe for the testbus

Measurements were done on the testbus to determine the clearance between the connection module and the testbus chassis. The dimensions of the chassis were mapped and put into the total assembly. At one side the old Volvo 7700 differential was placed, leaving enough space for the connection module. At the other side however a chassis beam is placed as seen in figure 2.10a. This leaves 7.5 mm of clearance at one side which is not enough. A cutout in the chassis must be made as the whole subframe will move around ± 30 mm to the side when the testbus drives through a sharp corner. This cutout in the chassis is possible as it is only a testbus, no bus services for public transportation will be driven. The determined general dimensions for the cutout are shown in figure 2.10b. A plate of 500x300x10 mm S355 construction steel is used to reinforce the chassis again as shown in 2.10b. A quick FEA showed that with a plate welded at the back, a strip at the bottom and two side plates to close the design the stress would only increase with around 10% compared to the original chassis.



(a) 7.5 mm clearance at one side of the testbus (b) General dimensions cutout chassis

Figure 2.10

2.4 Assembly subframe

In this section the assembly of the subframe is briefly explained. The assembly is done in-house were these steps were the guidelines besides the original drawings. The parts were ordered at an external company.

- First most parts of the V0 VDL subframe needs to be grinded of, leaving only the beams and middle mounting points as seen in figure 2.11.

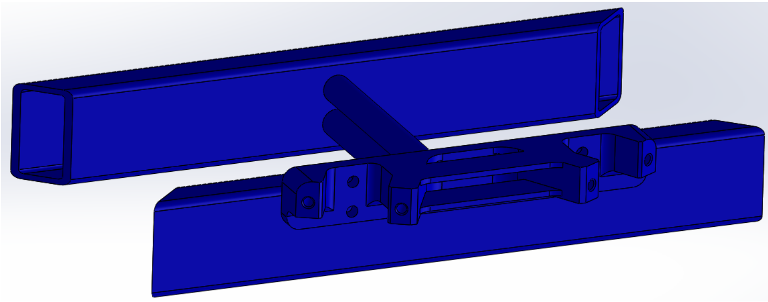
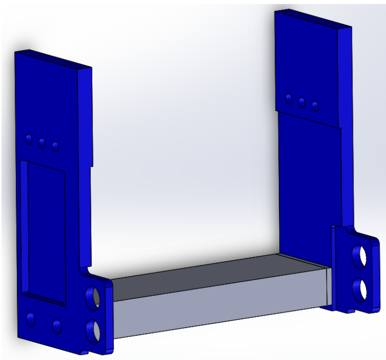
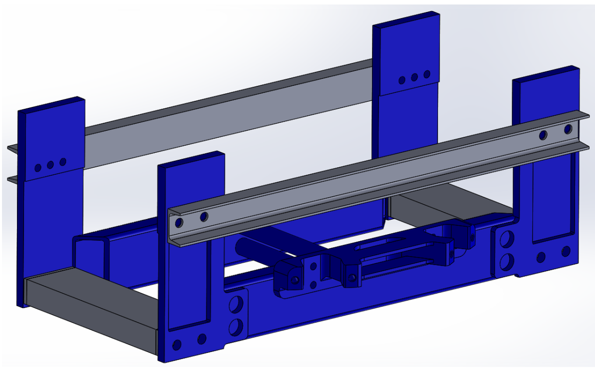


Figure 2.11: Remaining parts V0 VDL subframe

- Next the side plates can be connected together as seen in figure 2.12a. This will be done using 4x2 hex bolts (ISO 4016 M20x90 Grade 10.9) and 4x2 hex nuts (ISO 4034 M20 Grade 10.9).
- Both sides will then be put onto the outer sides of the beams and secured using two helper beams as seen in figure 2.12b. This will be done using 4x2 hex socket head (ISO 4762 M20x65 Grade 10.9). This will assure their correct position during welding and reduce warping of the parts. The holes in the helper beams are not in the middle, the shorter side (38mm) need to be placed upwards.



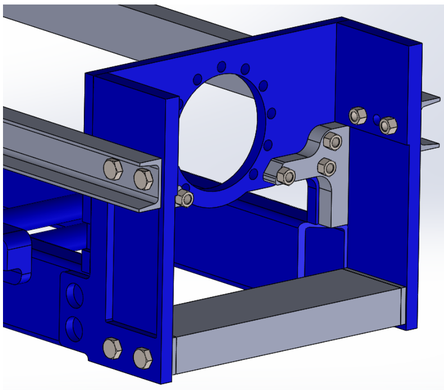
(a) Side plates



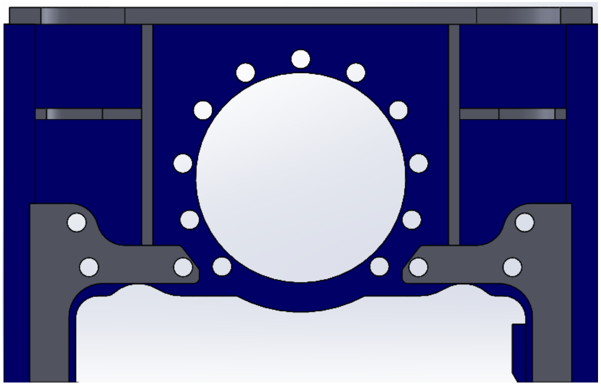
(b) Connection of the parts

Figure 2.12

- Before welding these parts together the brake connections need to be placed in between the side plates and beams, as this would otherwise not be possible anymore. The front plate is also bolted onto these brake connections, as seen in figure 2.13a. This will be done using 4x3 hex bolts (ISO 4017 M16x65 Grade 10.9) and 4x3 hex nuts (ISO 4034 M16 Grade 10.9). Along some lines a small weld could be placed.
- After that the four stiffeners on each side are welded in between as seen in figure 2.13b. To close the design the top plate is welded on top of the front and side plates.



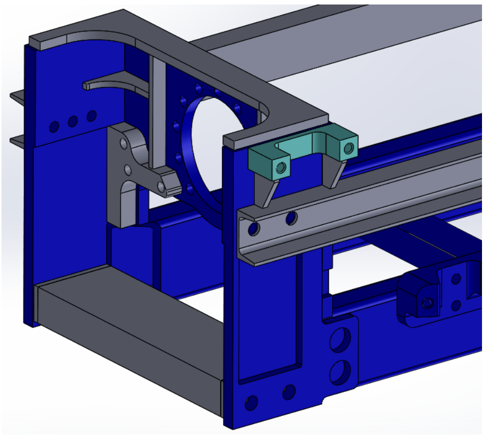
(a) Brake connection and front plate



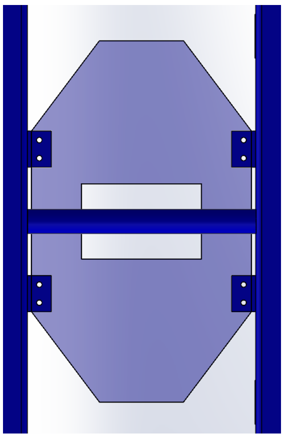
(b) Stiffeners and top plate

Figure 2.13

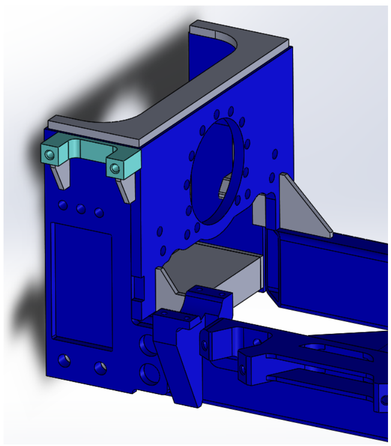
- The top reaction rod mounting points can be placed onto the helper beams and welded onto the side plate as seen in figure 2.14a. Along almost all lines the parts can be welded properly.
- The mounting points for the brake protection plate are welded onto the beams as seen in figure 2.14b. The protection plate could be used to set the right distances and will be fastened using 4x2 hex bolts (ISO 4017 M8x16 Grade 8.8) and 4x2 hex nuts (ISO 4034 M8 Grade 8.8).
- Finally the stabilizer bar mounting points and stiffeners are welded on the beams. The distance for the stabilizer bar mounting points is set by the stiffeners which are placed in between the front plate and the stabilizer mounting points. 2.14c.



(a) Top reaction rod mounting points



(b) Protection plate from below



(c) Stabilizor bar mounting points and stiffeners

Figure 2.14

2.5 Montage subframe and TheWheel V1.1

Same as for the assembly of the subframe the montage of the subframe and TheWheel V1.1 is briefly explained. For the torque tightening of the bolts an internal calculation document is used.

- The suspension arms, stabilizer bar and reaction rods are first mounted onto the subframe, see figure 2.15. Note that the lower two bolts of the suspension arms are not connected. The suspension arms will be connected using 4x3 hex socket head (ISO 4762 M20x65 Grade 10.9, 525 Nm). The reaction rods will be connected using 4x2 hex bolt (ISO 4017 M16x65 Grade 10.9, 265 Nm). The stabilizer bar will be connected using 2x3 hex bolt (ISO 4017 M12x35 Grade 10.9, 110 Nm) and 2x1 hex bolt (ISO 4017 M12x25 Grade 10.9, 110 Nm).

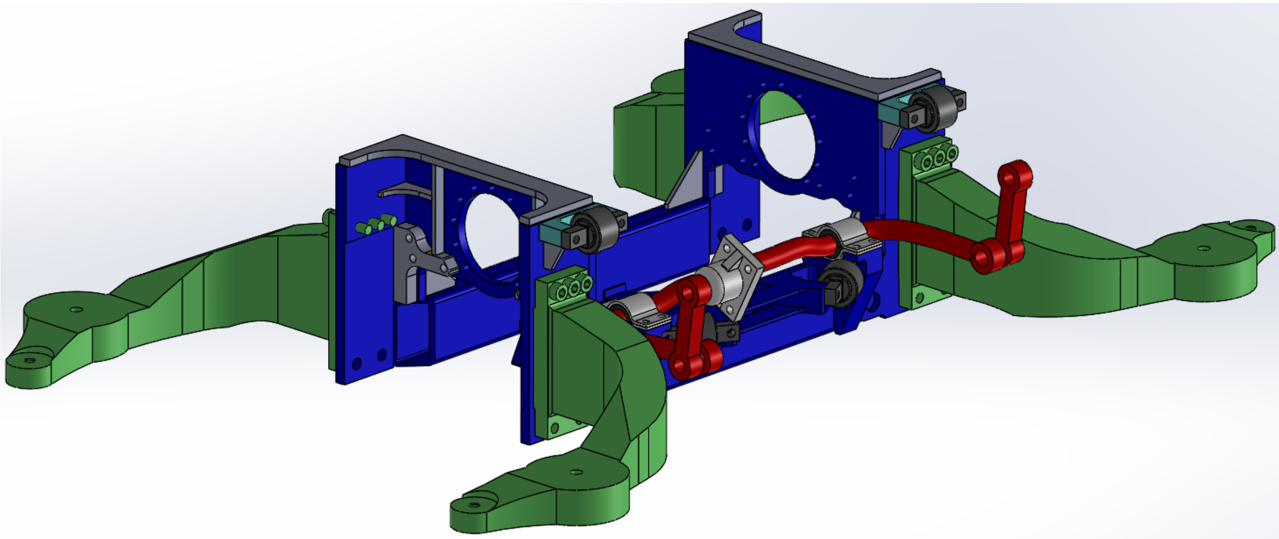
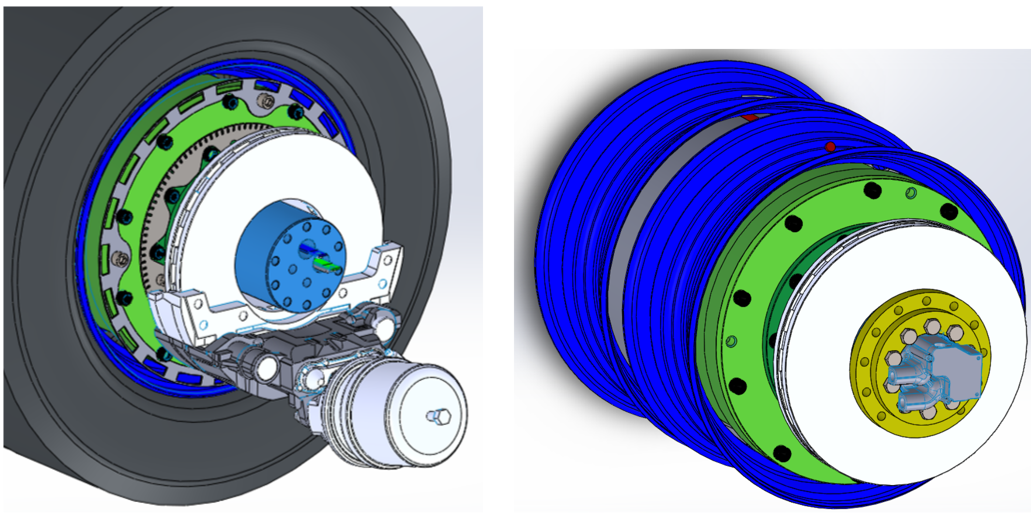


Figure 2.15: Subframe with the suspension arms, stabilizer bar and reaction rods

- Before mounting TheWheel V1.1 the Tacho and ABS pole ring need to be mounted as seen in figure 2.16a. This is done using 2x3 bolt (M16x16) for the Tacho pole ring and 2x3 bolt (M16x16) for the ABS pole ring. Note that the brakes parts, tyre and rim are, as shown in the figure, not yet connected of course.
- The connection module and flange are mounted on TheWheel V1.1 as seen in figure 2.16b. This will be done using 2x10 hex bolts (ISO 4017 M16x40 Grade 10.9, 265 Nm). Note that the rim and tyre are not mounted for more space and a lower weight.

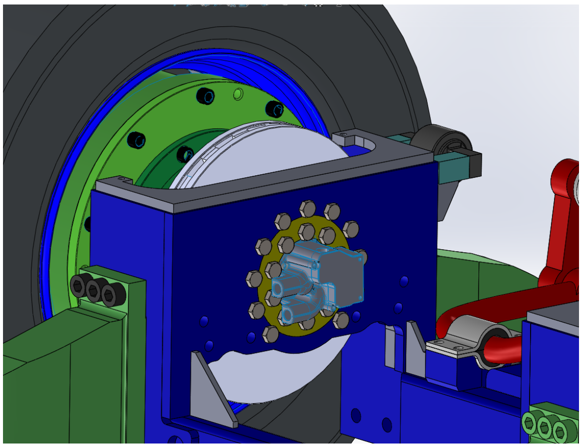


(a) Tacho and ABS pole ring

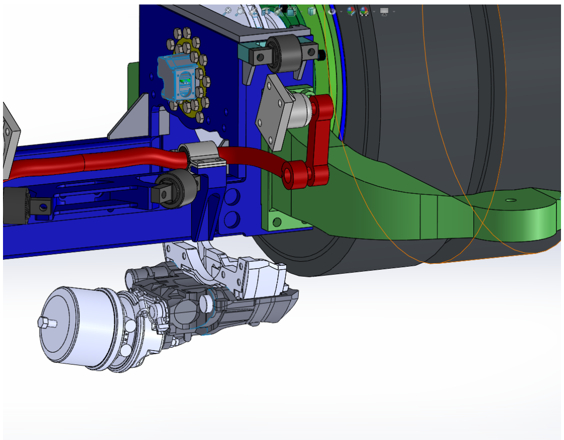
(b) Connection module on TheWheel V1.1

Figure 2.16

- After that TheWheel V1.1 is mounted using2x11 hex bolts (ISO 4017 M16x50 Grade 10.9, 265 Nm) shown in figure 2.17a. This assembly is lifted to be mounted onto the testbus. The rim and tyre could then also be mounted. The rim is mounted with 2x10 wheel nuts (DIN 74361 B M20x1.5, 500 Nm).
- When this connection is secured the brake assembly can be mounted from below, see figure 2.17b, and secured using 2x6 hex bolt (ISO 4016 M16x65 Grade 10.9, 200 Nm) shown in figure 2.18a.



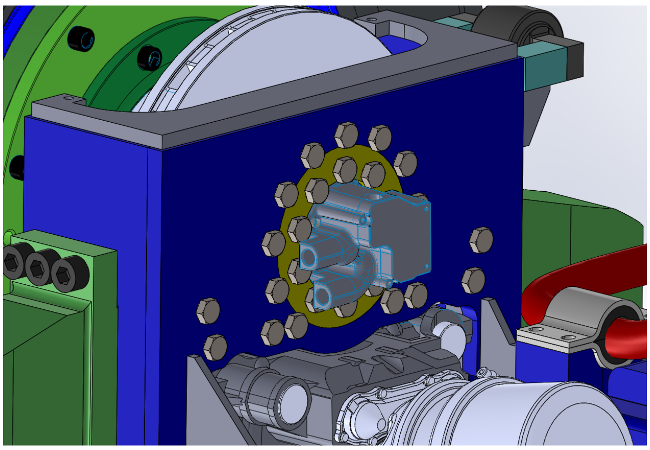
(a) Connection to the subframe



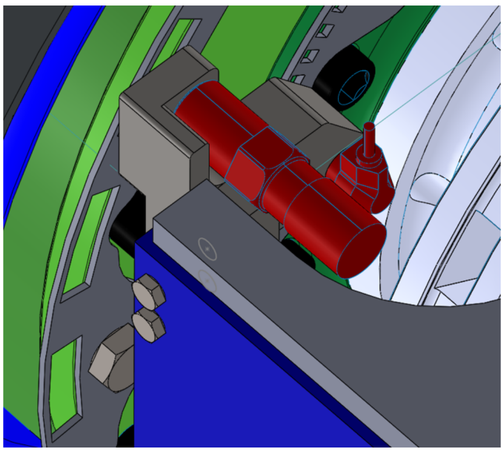
(b) Brake assembly mounted from below

Figure 2.17

- Then the stiffener connection between the two side plates is mounted using the lower two bolts of each suspension arm. This will be done using 4x2 hex bolts (ISO 4016 M20x90 Grade 10.9) and 4x2 hex nuts (ISO 4034 M20 Grade 10.9). The protection plate for the brake parts is also mounted at the bottom. This will be done using 4x2 hex bolts (ISO 4017 M8x16, 30 Nm) and 4x2 hex nuts (ISO 4034 M8, 30 Nm).
- Last the connection of the Tacho and ABS sensor must be bolted onto the side plate as seen in figure 2.18. This is done using 2x2 hex bolts (ISO 4017 M8x50, 30 Nm).



(a) Bolt connections brake assembly

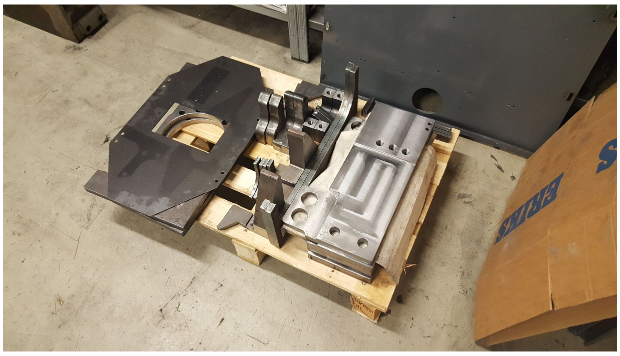


(b) Mounting of Tacho and ABS sensor

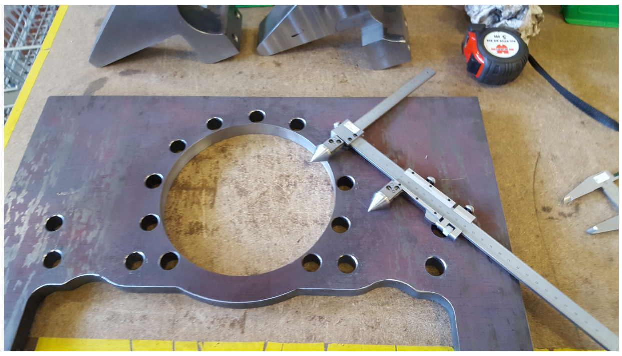
Figure 2.18

2.6 Pictures assembly

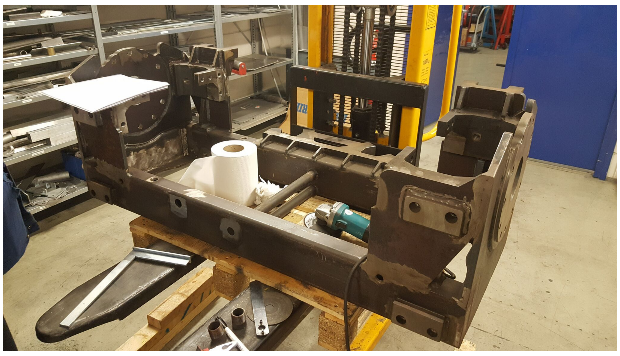
In this section some pictures of the assembly are shown.



(a) Testbus subframe parts



(b) Quality check of the parts



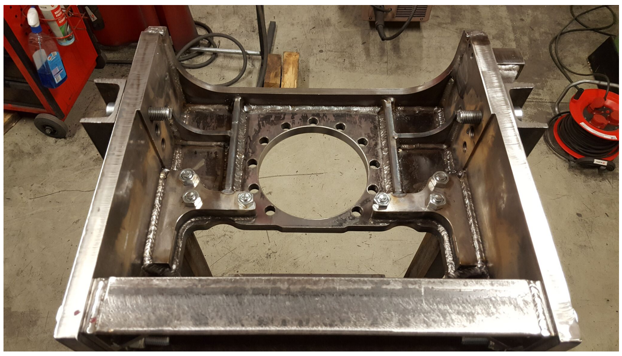
(c) V0.3 VDL subframe starting point

(d) Unnecessarily parts cut off

(e) Assembly 1

(f) Assembly 2

(g) Assembly 3

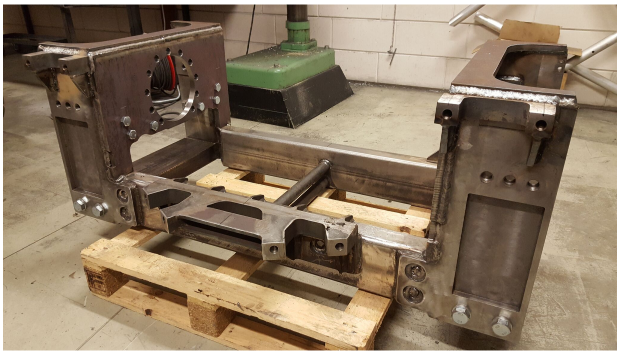


(h) Assembly 4

Figure 2.19: Pictures of the assembly 1

(a) New parts arrived 1

(b) New parts arrived 2

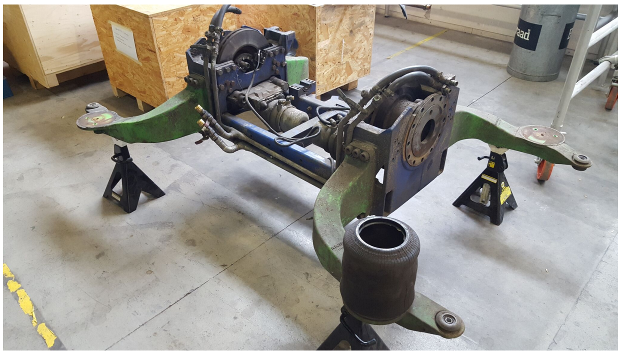


(c) Assembly 5

(d) Ready for powder coating

Figure 2.20: Pictures of the assembly 2

(a) Testbus lifted



(b) Testbus subframe removed

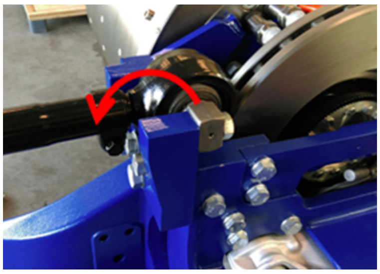
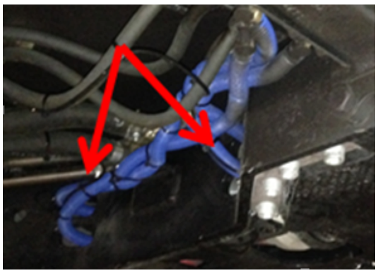
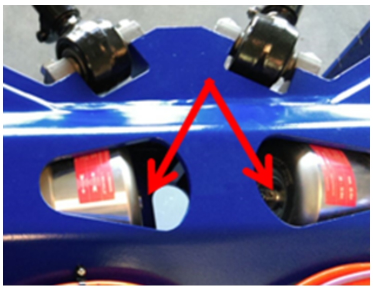
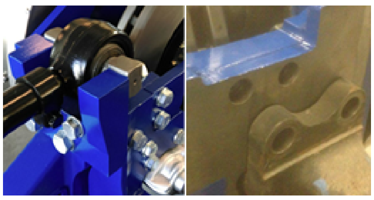
(c) Determining the cutout in the chassis

Figure 2.21: Pictures of chassis modification

3. Concept design

The next step after designing a subframe for the testbus is to start with the subframe for production. To do so there is first looked at lessons learned from the previous subframe. The following service improvements have been identified which are to be adopted in the new subframe design as is summarized in table 3.1. After that there is looked at the current V0.3 ZA subframe. Then 3 concept designs are made which are explained in detail. Every concept will be analyzed on strength using FEA and evaluated on different criteria. From these concepts a concept choice is made.

Table 3.1: Service improvements [8]

Service improvement	Visualised	Possible solution
Reaction rod fixation: The reaction rod fixation is not easily reached for service adjustments.		Consider fixation of the reaction rods to the outer side of the subframe
Brake booster connections: The brake booster connections are not easily accessed in a service environment.		Consider making more space in the subframe.
Brake booster adjusters: The adjustment screws of the brake boosters are hard to reacht.		Consider making them accessable from the bottom side.
Reaction rod mounting support: The mounting support op the reaction rods is a seperate part which is also connected through the bolts of the suspension arms.		Consider making the mounting support integrated to the side plates or lose the connection with the suspension arms.
Countersunk bolts: Countersunk bolts are hard to unscrew over time as dirt accumulates inside.		Consider using other bolt types as several bolts might be unscrewed during maintenance.

3.1 V0.3 ZA Design

3.1.1 Design

The current V0.3 ZA subframe only consist of bended plates and machined parts. This subframe is proven to be reliable and strong over its life time. Figure 3.1 shows the V0.3 ZA subframe. The design consist of two bended outer plates shown in blue. On top a bended plate is welded as shown in light blue. The green parts show the connections and stiffeners between the parts and provide some mounting points. The lower reaction rod mounting points is shown in pink. The grey parts represent the mounting of TheWheel V0.3 and ABS-Tacho sensor. As the mounting of the TheWheel V1.1 is different these grey parts will not be seen in the concept designs. This current ZA design has a mass of 239 kg.

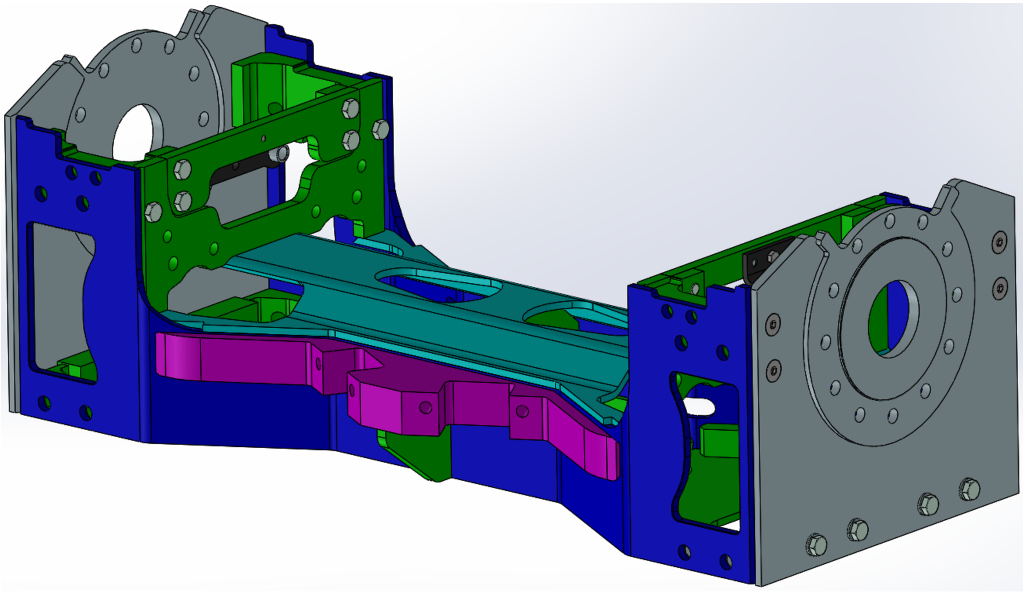


Figure 3.1: Current V0.3 ZA subframe design

3.1.2 Evaluation

For the evaluation of the different concepts the costs and time are quickly estimated for the different parts, due to a limitation in time no quantitative evaluation could be made. The current design is used as a reference as seen in table 3.2. The cost and time are related to the production methods of the parts. A production forecast of 7000 subframes is taken into account (see table 1.5). Note that the milling parts could beforehand be cut by a water-jet cutter for example. As some parts are more complex to produce or need more material some extra distinctions were made.

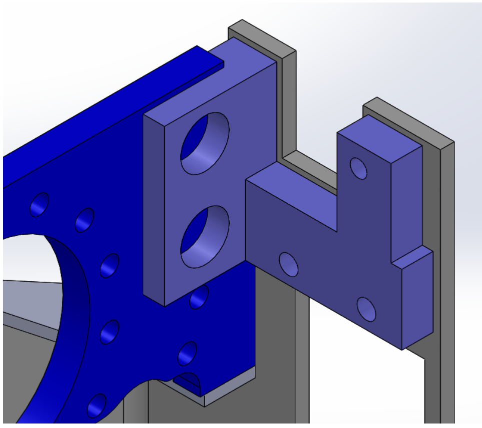
Table 3.2: Evaluation V0.3 ZA subframe

Part	Production method	Nr of parts	Cost	Time
Machined parts:	Milling	6	€	
	Milling complex parts	5	€€	
	CNC	0	€€€	
Bended plates:	Bending	0	€	
	Deep drawing/stamping	3	€€€€	
	Water-jet/laser cutting	18	€	
	Water-jet/plasma cutting >25mm	11	€€	
Casting:	Sandcasting	0	€€€€	
Total:		43	68 · €	59 ·

3.2 Concept 1

3.2.1 Design

As the current V0.3 ZA subframe design is proven to be reliable and strong enough there is chosen to build further upon this design for concept 1. Some parts can be redesigned to fit the new V1.1. As a starting point for this concept this design was placed in between the two TheWheel V1.1 with reaction rods and suspension arms as already shown in figure 2. As learned from previous design the service improvements from table 3.1 will be solved. The upper reaction rod mounting supports will be integrated in the connection block between the side and front plate. This connection block will be higher on one side with tread to fixate the reaction rods as seen in figure 3.2a. This block is completely welded onto the side and front plate as these parts do not need to be removed. For a stronger connection some extra welds are applied inside the circular cutouts as can be seen clearly in figure 3.2b.


(a) Connection block at upper reaction rods

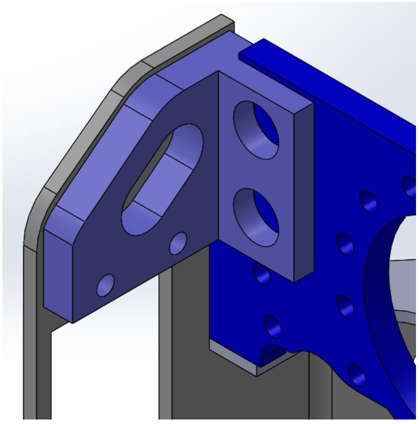
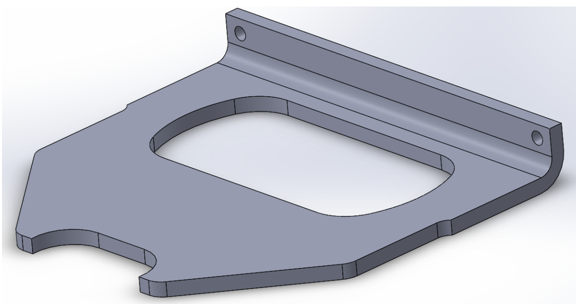

(b) Connection block

Figure 3.2

As the back plates are removed stiffness inside the construction is lost, to cover this a stronger connection between the two side plates at the back is made. This can be done by using a thicker plate, 15 mm instead of the 10 mm currently used. Two options for a connection at the back are possible here as seen in figure 3.3 a&b. On the left the protection plate is bended and bolted onto the two side plates. On the right a plate is welded onto the protection plate which is again bolted onto the two side plates. The plate could be reinforced using some stiffeners. For series production the bended plate shows more potential as only one operation is needed.


(a) Protection plate bended

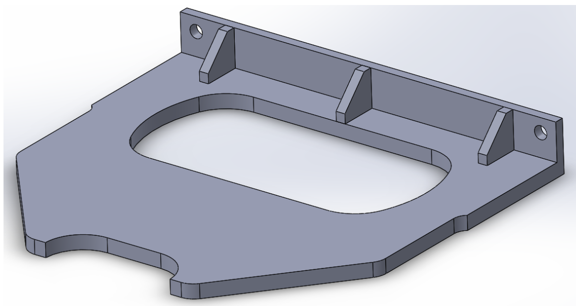
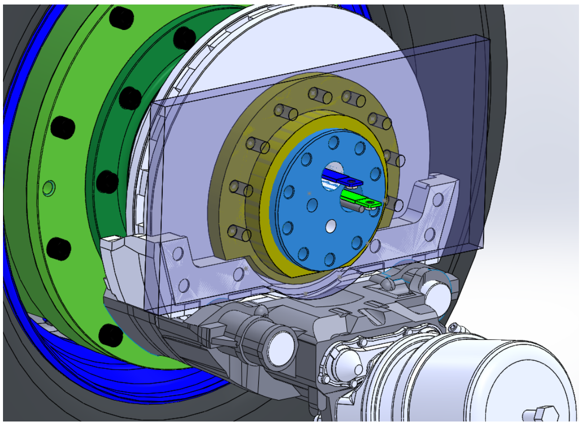
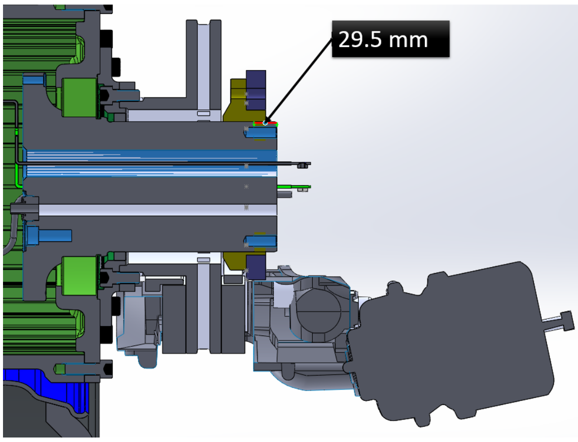

(b) Protection plate welded

Figure 3.3

An optimization is done for the inner path between the two connection modules. Therefore the stator shaft need to be made shorter compared to the ones initially made for the testbus. The front plate can directly be placed onto the brake caliper as seen in figure 3.4a. This is only possible if the flange is adjusted to fit in between the brake caliper. This means that the stator shaft needs to be 29.5 mm shorter. As no stiffeners can be added onto the front plate anymore there is chosen to increase the thickness of the front plate by 5 mm to a total of 25 mm. The flange is also made thicker as it will be narrower because it lays closer to the brake disc as seen in figure 3.4b. The space in between the flange and brake disc is set to 12 mm. Compared to the original design 24.5 mm on both sides is won leading to a shaft to shaft distance of 897 mm. The middle path is 728 mm with the connection module installed. Compared to ZF, as shown in figure 1.2, the design fits exactly in between. As the other parts stay almost the same they are not explained in detail. The final concept 1 design is as shown in figure 3.5.



(a) Front plate placed directly onto brake caliper



(b) Cross section and adjustment of stator shaft

Figure 3.4

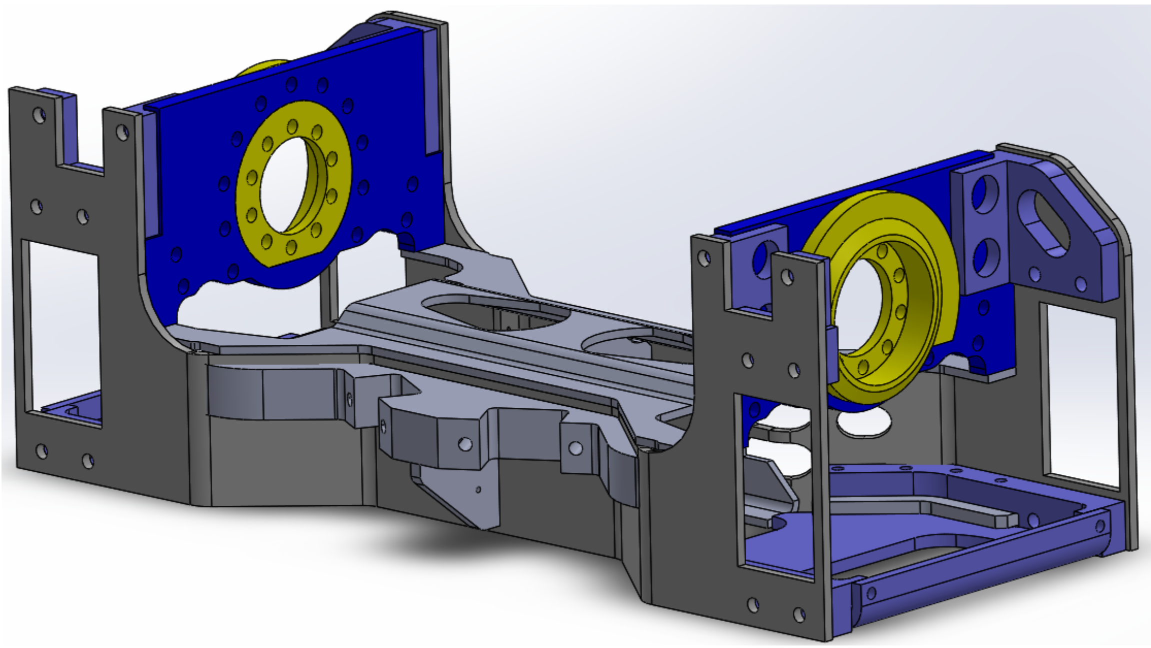


Figure 3.5: Concept 1 final design

3.2.2 FEA

For every concept a quick and simple static FEA will be done. As there is limited time a slightly different approach compared to the testbus (see section 2.3) is applied as the goal is to compare the different concepts. To reduce the computation time of each FEA the suspension arms and attached springs are left out of the analysis. The concepts will all be fixed at the suspension arms and reaction rod mounting points. A symmetric fixture in the middle is also used. At each concept the same mesh is applied. TheWheel V1.1 is again approximated by two rigid cylindrical bodies representing the stator shaft and rim. The material of each part is set at steel S355. For the load case an approximation is done as without the springs the stresses are extremely high. The load case is chosen by trial and error to recreate the same stresses inside the subframe as with springs and suspension arms attached. This is at around $\frac{1}{8}$ of the original Pave 1 load case from table 1.4, resulting in a 18750 N upwards and 7500 N sideways force on the wheel. In the first stress plot, see figure 3.6, these boundary conditions are shown.

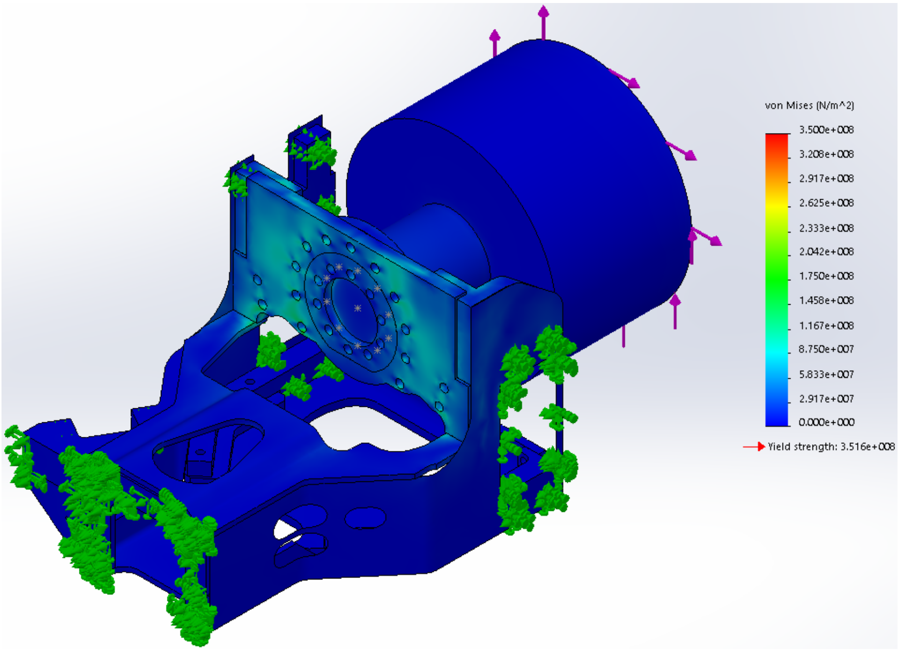


Figure 3.6: Boundary conditions and stress distribution of concept 1

From figure 3.6 & 3.7 there can be seen that the front plate and connection blocks are subjected to stresses of around 100 MPa, with peaks at the holes inside the front plate. The maximum calculated element stress inside concept 1 is 171 MPa and is located at the transition from flange to front plate as seen in figure 3.7.

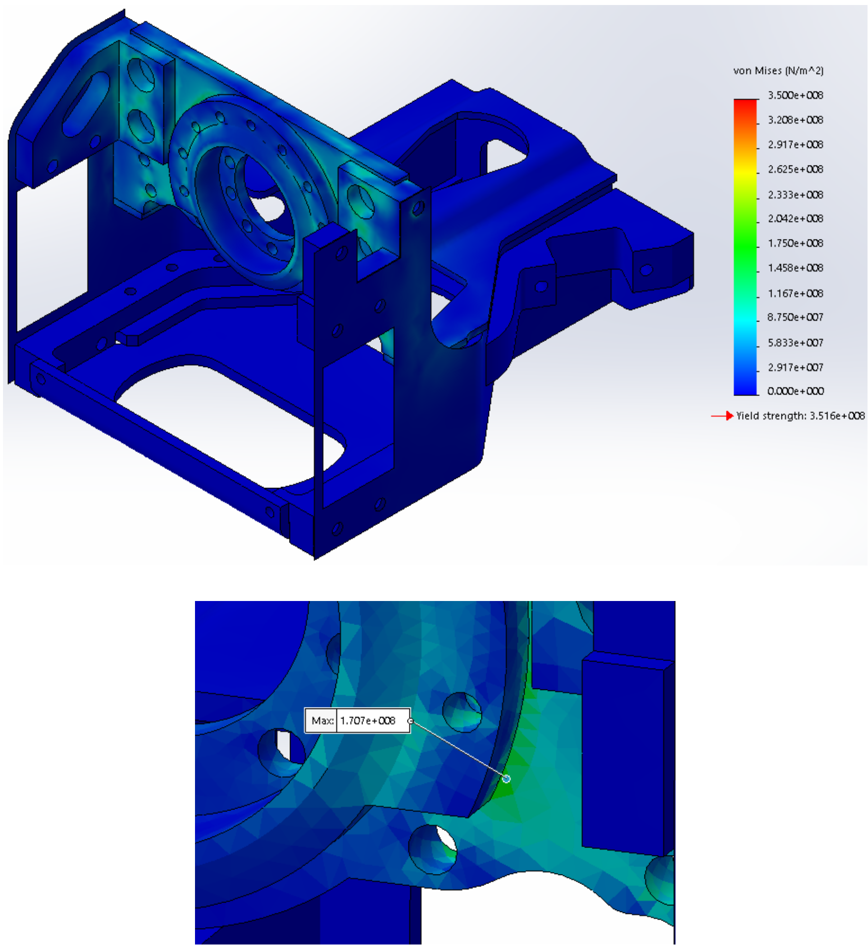


Figure 3.7: Stress distribution of concept 1

3.2.3 Evaluation

The advantages and disadvantages of concept 1 are listed below. Same as for the current design a quick estimation on the cost and time for concept 1 is seen in table 3.3.

Advantages:

+ Proven to be a reliable design
+ Lightweight design (223 kg) compared to current axle (-16 kg)
+ Service optimalisations according to table 3.1 applied
+ Competitive with ZF axle on middle path length

Disadvantages:

− Production cost and time are relative high (see table 3.3)

Table 3.3: Evaluation concept 1

Part	Production method	Nr of parts	Cost	Time
Machined parts:	Milling	4	€	🕛 🕒
	Milling complex parts	5	€€	🕛 🕒 🕕
	CNC	2	€€€	🕛
Bended plates:	Bending	3	€	🕛 🕒
	Deep drawing/stamping	3	€€€€	🕛
	Water-jet/laser cutting	13	€	🕛
	Water-jet/plasma cutting >25mm	9	€€	🕛
Casting:	Sandcasting	0	€€€€	🕛 🕒 🕕
Total:		39	66 · €	56 · 🕛

3.3 Concept 2

3.3.1 Design

The second concept will also only consist of machined parts and (bended) plates. Compared to concept 1 there is aimed to make more production efficient parts. This means where possible straight plates and symmetric parts are preferred. The main idea for this concept are two plates in the middle which are welded together by the side plates and some stiffeners. These plates ensure the connection with the mounting of TheWheel V1.1. The optimization for the inner path as made for concept 1 is again used. The flange and front plate will thus have similar designs as seen in figure 3.8. The upper reaction rod mounting points will again be integrated in the connection block between the front and side plate. The other side is however lowered to save weight and FEA should confirm if the stresses won't get to high. Again these parts are welded together.

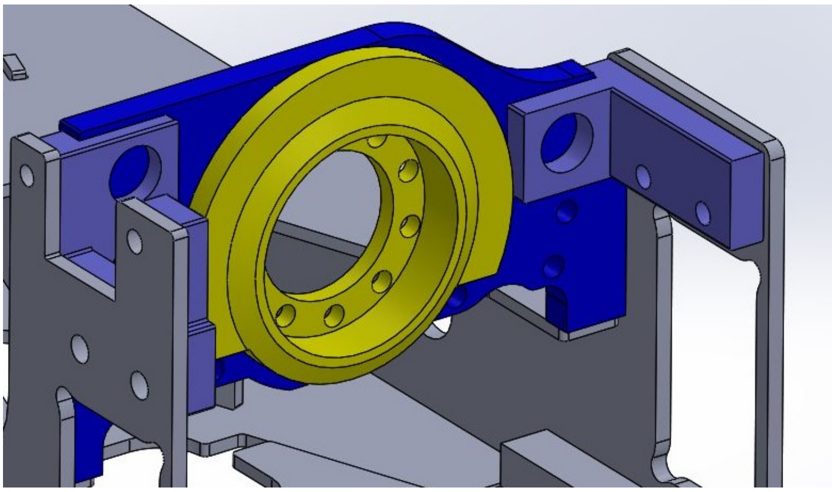
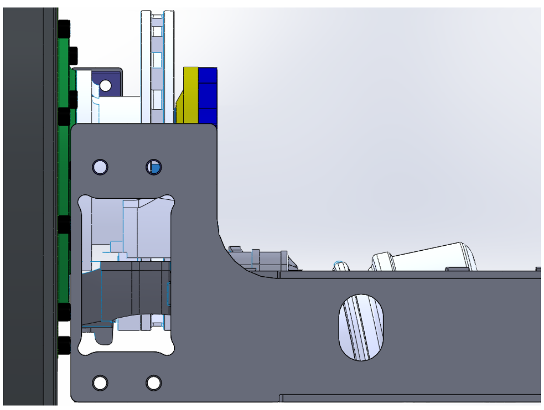
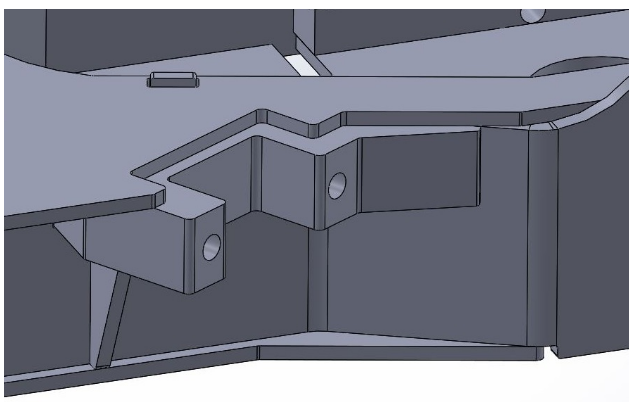


Figure 3.8: Flange, connection block and front plate design

As a whole the front plate is located lower compared to concept 1. This will leave the brake parts more exposed on the top as seen in figure 3.9a. This lower front plate has a downside of creating a narrow middle section of the top plate. FEA must confirm if no high stresses will occur otherwise welding some reinforcements at the top would be an option. The advantage is that the middle reaction rods mounting points can be made lighter and symmetric. The side plate at the front has a similar design as concept 1 but will be bended less. This to make sure the reaction rods are the same length as is preferred for dynamic reasons as explained in section 1.1.1. The side plate at the back is however straight and lower to save production cost and time. Along all edges between the top, bottom and side plates overlaps are created for good weldeability. The connection of the middle reaction rods will rest onto the bended side plate and welded in between the top plate as seen in figure 3.9b. A lot of welding length is achieved by this design creating a strong connection.



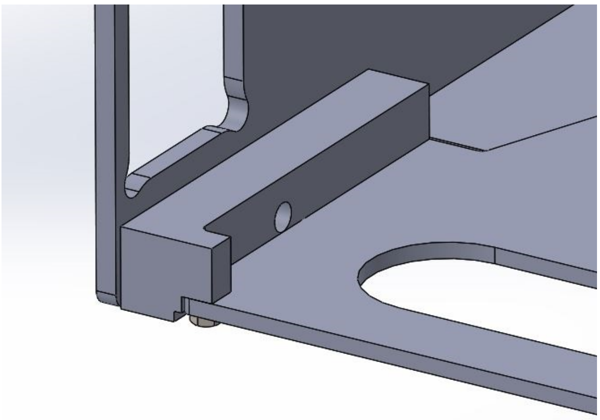
(a) Side view



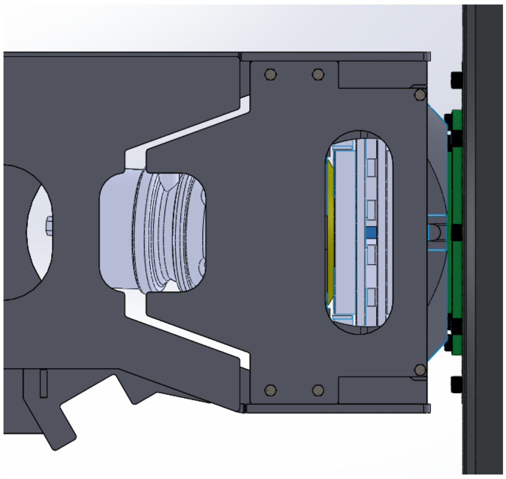
(b) Middle reaction rod mounting point

Figure 3.9

At the bottom the connection block for the suspension arm and protection plate is welded as seen in figure 3.10a. The connection between the two side plates at the back is done using the protection plate. This plate is 10 mm thick and will be connected using 6 x M10 bolts as seen in figure 3.10b.



(a) Bottom connection block



(b) Protection plate

Figure 3.10

As in between the side, top and bottom plates a lot of empty space is present there are multiple stiffeners used to ensure a stiff subframe. Two stiffeners are placed in the middle to close the design, preventing torsion of the subframe. Furthermore stiffeners are placed under a small angle to prevent the subframe from bending. A FEA must prove if the stiffeners as placed in figure 3.11 will be enough.

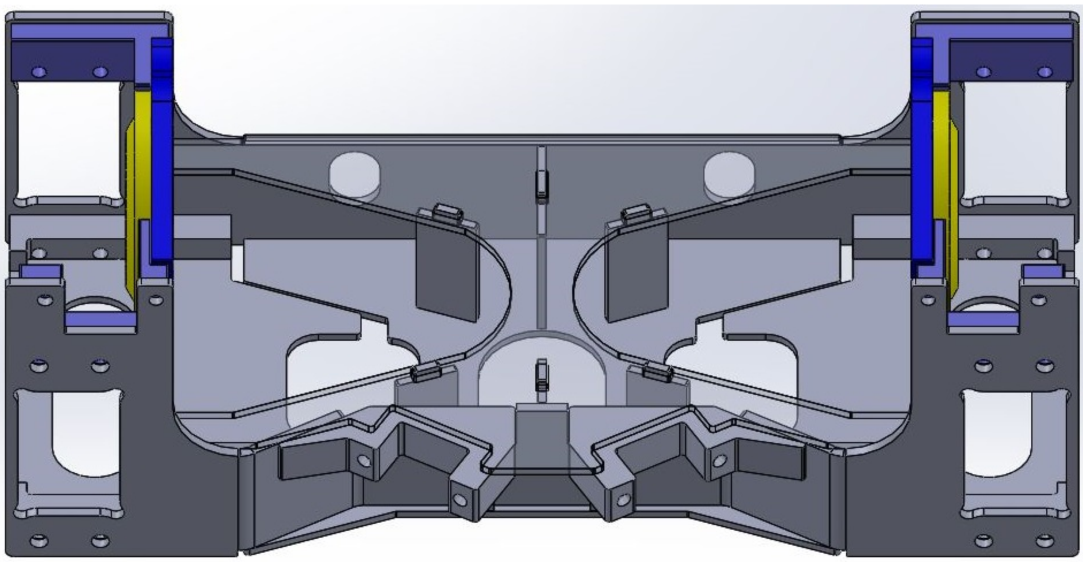


Figure 3.11: Position of stiffeners

3.3.2 FEA

Same as for concept 1 a quick and and simple static FEA of concept 2 is done. The maximum calculated element stress in concept 2 is 199 MPa. As the design of the front plate and flange is almost the same as for concept 1 this maximum is located at the same place. As can be seen from figure 3.12 the stresses in the front plate and connection blocks are around 30 MPa higher. This due to less material used at one side of the front plate. More research has to be done as these higher stresses could cause fatigue failure over a longer period of time. A redesign of the flange, front plate and connection block to decrease the stresses could therefore be made in a further stage.

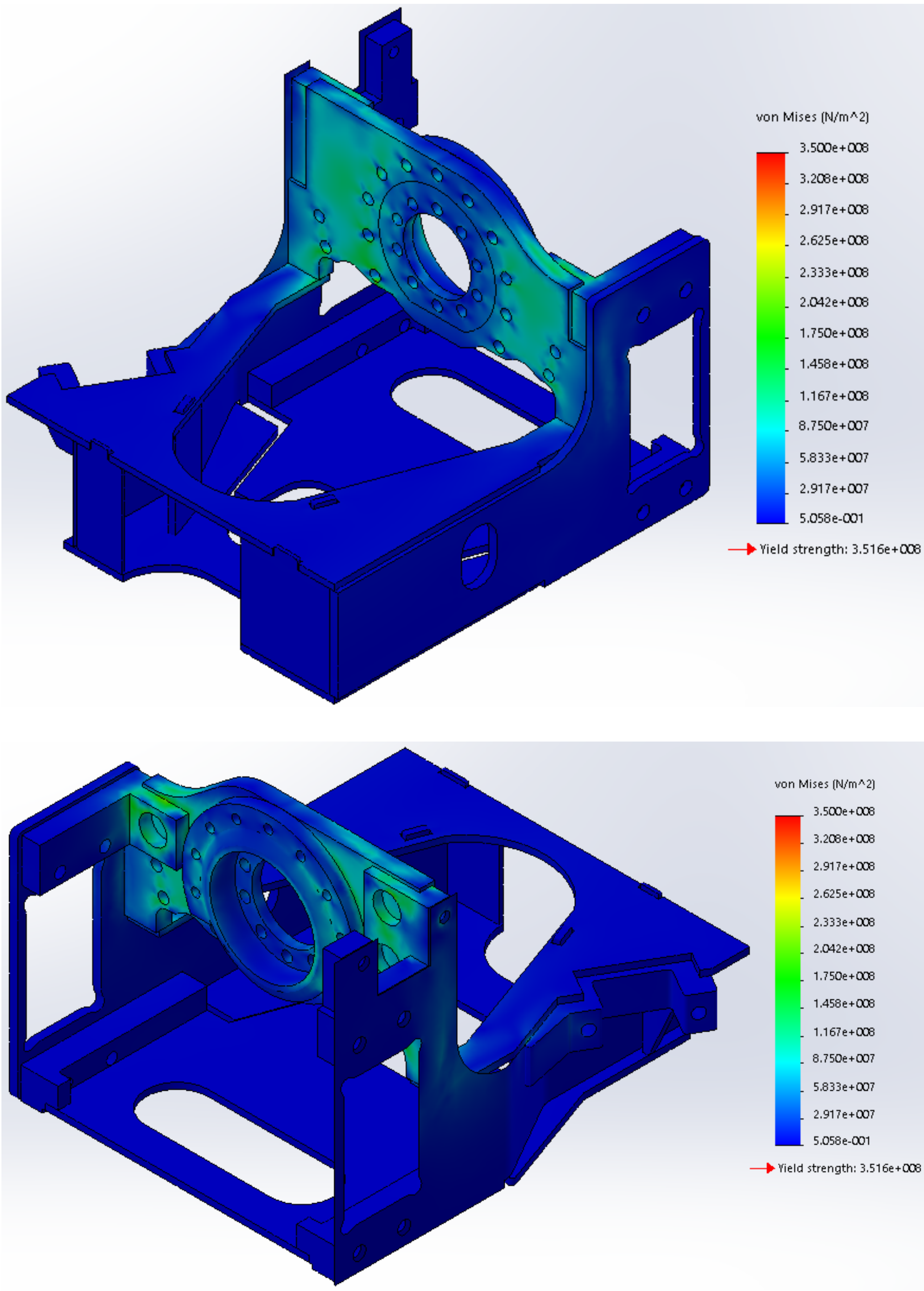


Figure 3.12: Stress distribution of concept 2

3.3.3 Evaluation

The advantages and disadvantages of concept 2 are listed below. Similar to concept 1 a quick evaluation on the cost and time of concept 2 is seen in table 3.4.

Advantages:

+ Production cost and time optimized (see table 3.4)
+ Simple design (symmetric parts & straight plates)
+ Lightweight design (192 kg) compared to current axle (-48 kg)
+ Service optimizations according to table 3.1 applied
+ Competitive with ZF axle on middle path length

Disadvantages:

− Brake parts exposed at the top
− Stresses are relatively high

Table 3.4: Evaluation concept 2

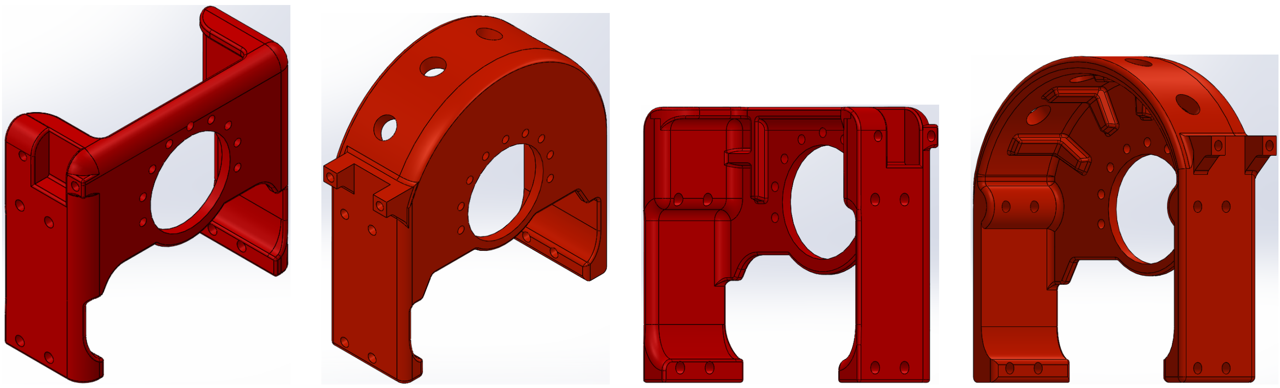
Part	Production method	Nr of parts	Cost	Time
Machined parts:	Milling	8	€	🕛 🕒
	Milling complex parts	2	€€	🕛 🕒 🕕
	CNC	2	€€€	🕛
Bended plates:	Bending	0	€	🕛 🕒
	Deep drawing/stamping	1	€€€€	🕛
	Water-jet/laser cutting	14	€	🕛
	Water-jet/plasma cutting >25mm	6	€€	🕛
Casting:	Sandcasting	0	€€€€	🕛 🕒 🕕
Total:		33	48 · €	45 · 🕛

3.4 Concept 3

3.4.1 Design

The third concept will also have a casting part. This casting part replaces the side and front plate at the mounting point with TheWheel V1.1. The flange cannot be integrated in the casting part. This because its purpose is to let TheWheel V1.1 be removed without removing the connection module. The flange is thus connected with the same bolts as previous concepts. For every casting part the parting line, draft angles and equal thicknesses need to be taken into account. If needed a insert inside the mould could be placed.

Two ideas for a casting part were made. The first one in the shape of an open box (see figure 3.13 a&c) and the second one with an arch going all the way around the brake disc (see figure 3.13 b&d). The first idea looks like previous concepts except it is made out of one part. The mounting of the suspension arms and upper reaction rods will be done through this part, this means extra material needs to be added. This will create unequal thicknesses which could create internal stresses during cooling of the casted part. At the front side a few ribs are added for extra stiffness. Choosing the right partion line for the mould the connection of the upper reaction rods can be integrated with the use of a insert inside the mould. The tread for these connections and other holes will of course be made afterwards.

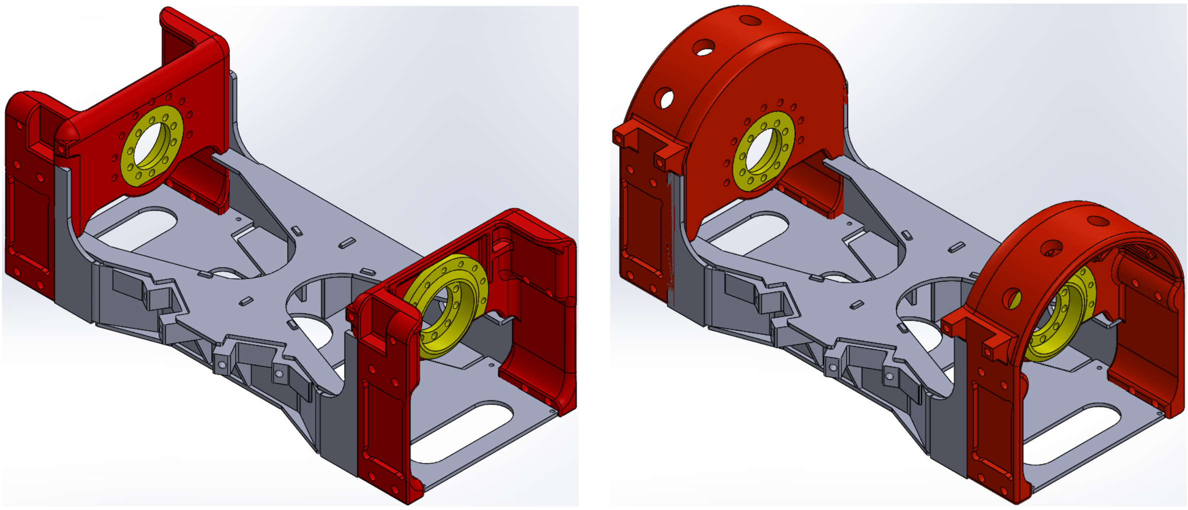


(a) (b) (c) (d)

Figure 3.13: Concept 3 Box (a&c) and Arch (b&d)

As the connection to the upper reaction rods is again integrated it is hard to make the parts symmetric. For the first idea it will be just a matter of were the insert inside the mould is placed. As the connection to the upper reaction rods for the second idea standout the arch this would not be possible. Two moulds must be used in that case leading to a slightly increase in production costs. The arch around the brake disc of the second design is expected to add extra stiffness to the design. The downside would be the increase in weight as a lot of material is added. The arch also makes a closed design. To prevent the brake discs from overheating some holes for cool air were made in the top. These could afterwards be drilled as it is unfavorable to use 4 inserts inside the mould.

For the middle path the same idea of concept 2 is used. The connection to the middle path of the subframe will be done by welding the side and top plate to the casting part. To proper weld the parts together the casting parts can be machined such that the side plate falls in between the casting part. As the casting part already needs to be machined for the connection of the suspension arms this could be done the same time. The final concept ideas are shown in figure 3.14. Another option would be a connection to the middle path without machining the casting parts. This can be done by widen the side plates a bit such that they overlap.

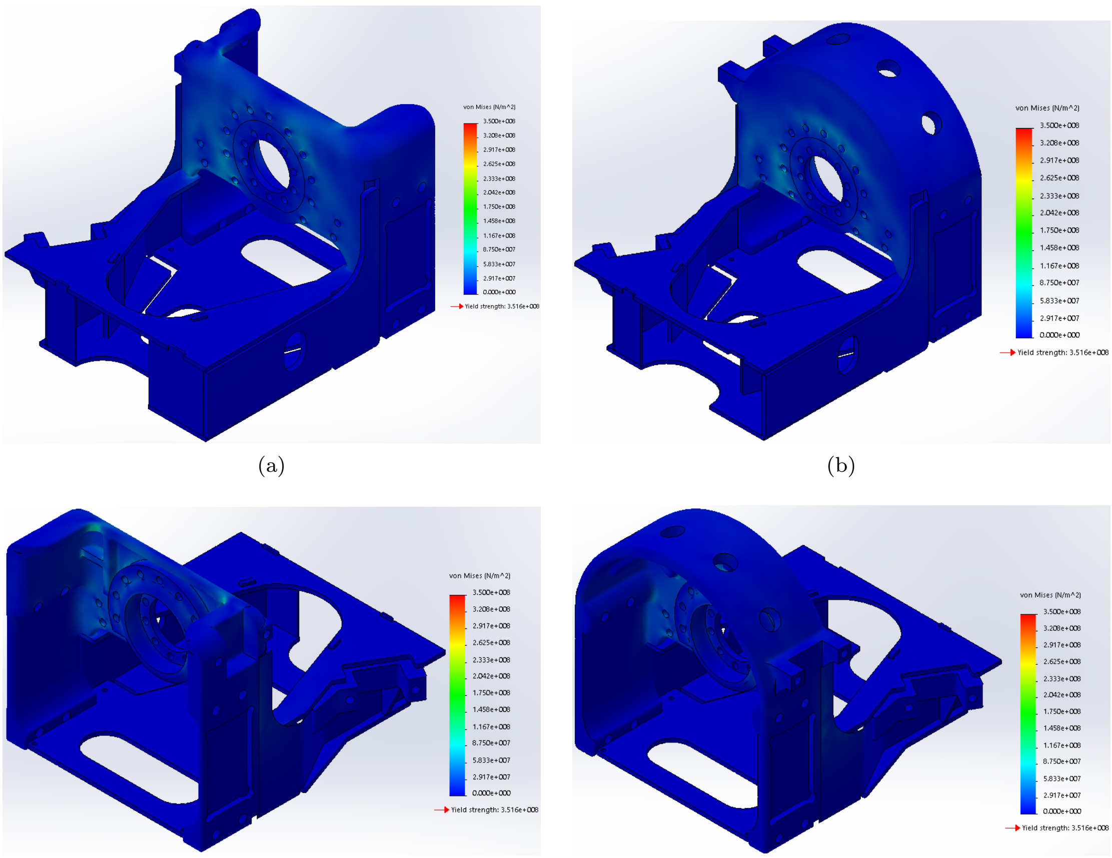


(a) (b)

Figure 3.14: Total assembly of concept 3 Box (a) and Arch (b)

3.4.2 FEA

Same as for concept 1 & 2 a quick and and simple static FEA of both concepts 3 are done. The calculated maximum element stress in concept 3 Arch is 73 MPa and 111 MPa for concept 3 Box. The maximum stresses are located at the holes in the front as seen in figure 3.15. The placement and thicknesses of the ribs could be adjusted for a better stress distribution as the current placements were an initial guess. As can be seen not much stresses are located inside the arch. An optimisation of the thickness of the arch could be done to reduce the weight of this concept.



(a) (b) (c) (d)

Figure 3.15: Stress distribution of concept 3 Box (a&c) and Arch (b&d)

3.4.3 Evaluation

The advantages and disadvantages of concept 3 are listed below. Similar to concept 1 & 2 a quick evaluation on the cost and time of concept 3 is seen in table 3.5.

Advantages:

+ Less parts due to casting (see table 3.5)
+ Lightweight design (217 kg) of concept 3 Box compared to current axle (-22 kg)
+ Service optimisations according to table 3.1 applied
+ Competitive with ZF axle on middle path length

Disadvantages:

− Heavy design (253 kg) of concept 3 Arch compared to current axle (+14 kg)

− Brake parts exposed at the top

Table 3.5: Evaluation concept 3 Arch & Box

Part	Production method	Nr of parts	Cost	Time
Machined parts:	Milling	2	€	🕛 🕒
	Milling casting parts	2	€€€	🕛 🕒 🕕 🕐
	CNC	2	€€€	🕛
Bended plates:	Bending	0	€	🕛 🕒
	Deep drawing/stamping	1	€€€€	🕛
	Water-jet/laser cutting	12	€	🕛
	Water-jet/plasma cutting >25mm	2	€€	🕛
Casting:	Sandcasting	2	€€€€	🕛 🕒 🕕
Total:		23	42 · €	35 · 🕛

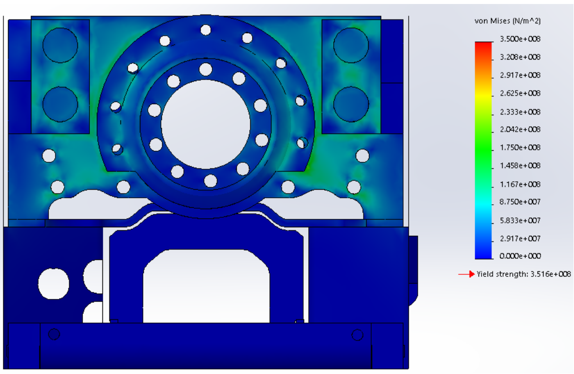
3.5 Concept choice

The concepts will be evaluated on different criteria. First the criteria as already stated during the concept evaluations are summarized in table 3.6. As can be seen the concepts score better on cost and time compared to the current V0.3 ZA subframe. For concept 1 this is only little as this design is based on the current design. The other two concepts have a better score on cost and time. For concept 2 this is due to the optimisation for production and for concept 3 this is due to the lower used parts.

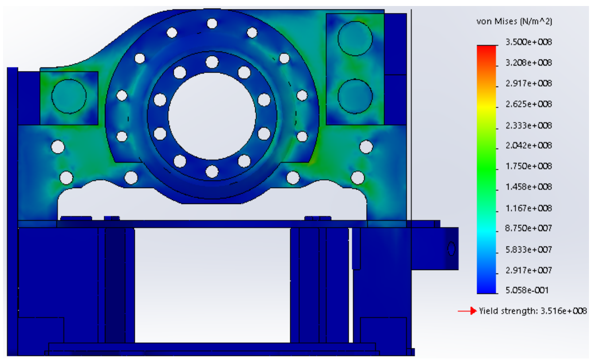
Table 3.6: Concept choice

Concept	Cost	Time	Highest stress [MPa]	Mass [kg]
V0.3 ZA Design	68 · €	59 · 🕐		239
Concept 1	66 · €	56 · 🕐	171	223 (-16)
Concept 2	48 · €	45 · 🕐	199	**192 (-48)**
Concept 3 Arch	42 · €	35 · 🕐	**73**	253 (+14)
Concept 3 Box	42 · €	35 · 🕐	111	217 (-22)

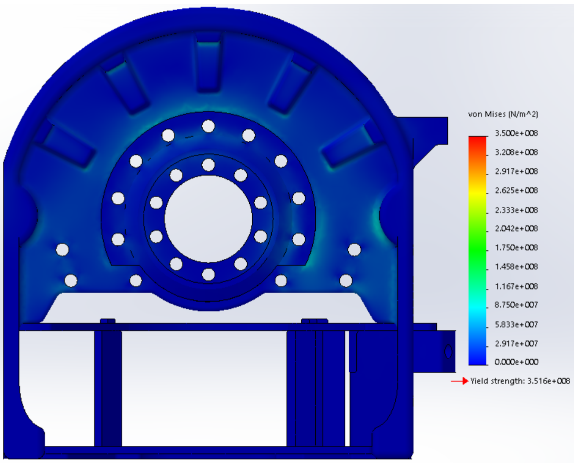
For a good comparison of the stresses of each concept a side view is shown below in figure 3.16. Although concept 1 is based on the already proved V0.3 ZA subframe on strength the stress inside the front plate is relatively high. For concept 2 the stress is even higher as less material is used. As the designs of concept 3 are more closed lower stresses are seen. For concept 3 Arch this is at the cost of an increase in mass, +14 kg compared to the current design. Concept 3 Box is lightweight compared to the current subframe and shows low stresses. The FEA also showed there is room for optimisation of the casting parts shape, this means the stiffeners and thicknesses could be adjusted to achieve less weight. This leads to concept 3 Box as the concept of choice and need to be further investigated as it is a more overall achiever.



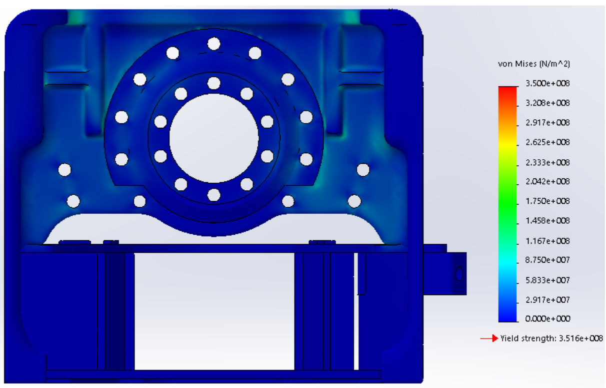
(a) Concept 1



(b) Concept 2



(c) Concept 3 Arch



(d) Concept 3 Box

Figure 3.16: Stress distribution of the concepts

4. Conclusion and recommendations

Conclusion

For the testbus the geometric boundary conditions were obtained from a Solidworks 3D model and measurements underneath the testbus. From the different approaches possible there was chosen to convert a current V0 VDL subframe as this would be most cost and time efficient. TheWheel V1.1 is designed for a 2550 mm wide bus, as the testbus is only 2500 mm wide the wheel arches need to be enlarged as the wheel will stand out the side. From the finished testbus subframe design a FEA was done. This FEA showed no stresses close or over the yield stress of the material in the subframe. As a validation of these results the subframe of the current testbus was also analysed. This subframe broke down once at the connection with the TheWheel. The analysis shows high stresses close to yield at these places, confirming it was due to fatigue. As this analysis shows that it is close to reality the FEA of the new design is expected to be close to reality too. The new subframe for the testbus has a mass of 205 kg which is 20 kg less compared to the current testbus subframe. As on one side of the testbus only 7.5 mm clearance is present between the connection module and the chassis a cutout has to be made. By reinforcing the chassis a quick FEA showed that the stress would only increase with around 10% compared to the original chassis. Finally the assembly and montage of the subframe and TheWheel V1.1 were made as a guideline besides the original drawings.

For the concept design of the production subframe the geometric boundary conditions, load cases and requirements were investigated. Together with the service improvements 3 concept designs were made. These concepts were evaluated on the cost and time to make. As a reference the current V0.3 ZA design was used. An optimization for the middle path length was made, leading to a 29.5 mm shorter stator shaft. This means that the middle path length is now competitive with ZF. For the first concept the current V0.3 ZA design was converted to fit TheWheel V1.1. The production cost and time for this concept are relative high but the current V0.3 ZA subframe is proven to be a reliable design. The second concept is designed to be more production efficient, where possible straight plates and symmetric parts were used. This results in a simple and lightweight design. From FEA there can however be seen that the stresses are relatively high. The third concept has a casting part replacing a part of the side plate, the front plate and the connection blocks that were placed in between. This results in less parts and a cost and time efficient design. Two casting parts were made, concept 3 Arch and concept 3 Box. The first one is due to its shape a lot heavier than the other concepts but shows lower stresses. The second one is lightweight compared to the current design and shows only a slightly increase in stress. Overall concept 3 Box scores best and is therefore the concept of choice to be further investigated.

Recommendations

- Due to limited time no decent FEA of the concepts could be made, now there is just a comparison. For a good concept choice this is crucial as there is now only an expected strength of each concept. To finalize the concept choice every concept must be analyzed under the same conditions for a good comparison. Using all important load cases, as shown in section 1.2, would complete the analysis as the concepts would probably perform different for each load case.
- The time spent on each one of the concepts is around one week, from an idea to a 3D CAD model in SolidWorks and documentation. Some time could be spent to optimize the concept designs a bit more in detail for a better concept choice. This regarding production and serviceability. The use of a flange design could for example be reconsidered. There could be looked at a design were the flange is integrated in the front plate to ease the montage of TheWheel V1.1.

References

[1] e-Traction, Company History, Purpose & Core values.
Retrieved from http://www.e-traction.com/en/company at 18-01-2017

[2] e-Traction Academy, Mechanical V1.1
e-Traction Academy November 2016 V1.1 Mechanical Combined.pptx

[3] e-Traction Academy, Electromagnetic & Thermal V1.1
e-Traction Academy January 2017 V1.1 Electromagnetic & Thermal V2.pptx

[4] e-Traction HR, Corporate presentation
e-Traction Corporate Presentation 2017.pptx

[5] Ricardo plc 2016, Generating loads for FE analysis, Shoreham-by-Sea, England
E-Traction - Wheel Loads Generation v2 CAE Report.pdf

[6] Sabri Murad, Development of rear axle mounting part for TheWheel V1.1,
Internship report HAN-Automotive, 13-01-2017

[7] e-Traction mechanical, Pick up points suspension and reaction rods, 12-05-2016
Suspension pick up points.pdf

[8] TeT, Roel van de Pas, Subframe Assy Design Brief, 02-02-2017
20170202 RFQ D&D Sub Frame and Suspension Assembly.doc

[9] Code of China, Chinese classification
Internal documents, could be bought from http://www.codeofchina.com/

[10] Steel construction info, The free encyclopedia for UK steel construction information, Construction steel
Retrieved from http://www.steelconstruction.info/Steel_construction_products at 20-01-2017

[11] Kals, H. J. (2007). Industriele productie: Het voortbrengen van mechanische producten. Den Haag: Academic Service.

[12] Hydram Engineering, How sheet metal bending works
Retrieved from http://www.hydram.co.uk/technical/how-bending-works/ at 23-01-2017

[13] Gotos, Micron Precision Stamping Manufacturer
Retrieved from http://www.gotos.co.jp/english/introduction/ at 23-01-2017

[14] Steel construction info, The free encyclopedia for UK steel construction information, Welding
Retrieved from http://www.steelconstruction.info/Welding at 23-01-2017

[15] Wikipedia, The free encyclopedia, Equivalent carbon content
Retrieved from https://en.wikipedia.org/wiki/Equivalent_carbon_content at 24-01-2017

[16] Cambridge Engineering Selector. (2016). CES EduPack 2016: Standard edition. Cambridge: Granta Design Limited.

[17] The Lincoln Electric Company, Guidelines for Welding Cast Iron
Retrieved from http://www.lincolnelectric.com/en-us/support/welding-how-to/Pages/welding-cast-iron-detail.aspx at 26-01-2017

[18] CTMS, Control Tutorials for Matlab & Simulink, Suspension: System Modeling
Retrived from http://ctms.engin.umich.edu/CTMS/index.php?example=Suspension&section=SystemModeling at 15-02-2017