Sensur av hovedoppgaver

Høgskolen i Sørøst-Norge
Fakultet for teknologi og maritime fag

Prosjektnummer: **2017-04**
For studieåret: **2016/2017**
Emnekode: **SFHO3201**

Prosjektnavn
Norsk: Hjuloppheng for Tunge Kjøretøy med Integrert Elektrisk Drift
English: Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

Utført i samarbeid med: Kongsberg Automotive

Ekstern veileder: Kent Häll

Sammendrag: Vår oppgave er å utvikle et hjuloppheng med elektrisk drift som kan erstatte den tradisjonelle forbrenningsmotoren i tunge kjøretøy på markedet.

Stikkord:
- Hjuloppheng
- Elektrisk drift
- Tunge kjøretøy

Tilgjengelig: JA

Prosjekt deltagere og karakter:

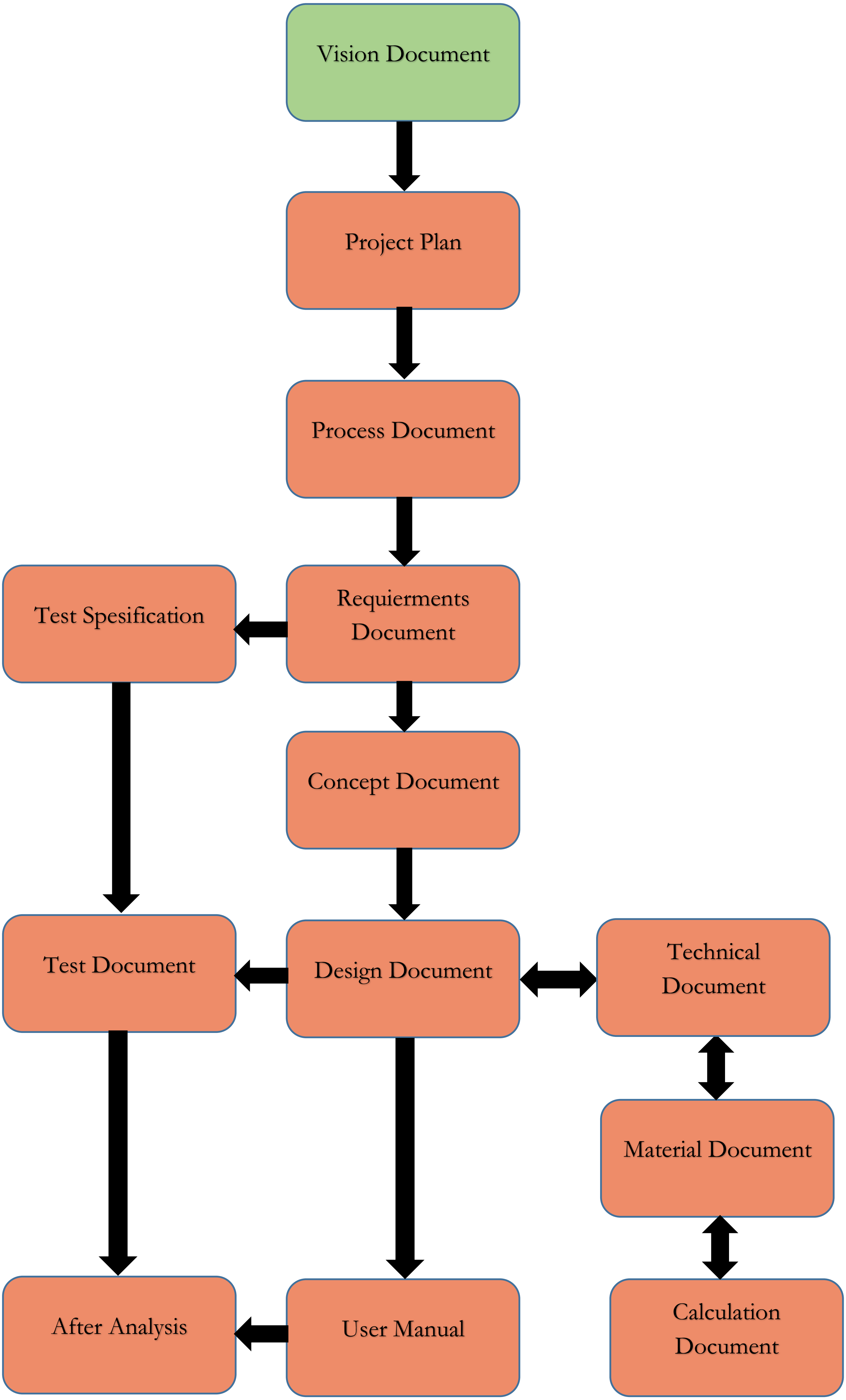
Navn	Karakter
Anis Sadiq	
Abubakar Khan	
Ahat Turgun	
Egide Bampo Rubusa	
Mustafa Moalim	
Pawan Bhatt	

Dato: 9. Juni 2017

__________________	_________________	_________________
Jamal Safi	Karoline Moholth	Simen Skiaker
Intern Veileder	Intern Sensor	Ekstern Sensor

WHEEL SUSPENSION FOR HEAVY-DUTY VEHICLES WITH INTEGRATED ELECTRIC DRIVE

24. mai 2017


Vision Document
Project Plan
Process Document
Test Spesification
Requierments Document
Concept Document
Test Document
Design Document
Technical Document
Material Document
After Analysis
User Manual
Calculation Document

VISION DOCUMENT

Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive

Employer	Kongsberg Automotive			
Group Members	**Name**		**Initials**	
	Abubakar Khan		AK	
	Ahat Turgun		AT	
	Anis Sadiq		AS	
	Egide Rubusa Bampo		ERB	
	Mustafa Moalim		MM	
	Pawan Bhatt		PB	
Document Information	**Version**	**Date**	**Approved**	**Pages**
	4.0	23.05.17	AS	14

21. februar 2017

VISION DOCUMENT

Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive

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REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
11.01.17	0.1	Document created	AS
12.01.17	0.2	Added more information	AS
13.01.17	0.3	Added system summary & minor updates	AK
17.01.17	1.0	Document upgrade	AS
20.01.17	1.1	Information update	AS
24.01.17	1.2	Updated problem- and system statement	AS
02.01.17	1.3	Updated Business opportunity	PB
03.01.17	2.0	Finalized	PB
18.03.17	2.1	Grammar, fonts and design update	AS
18.03.17	3.0	Finalized version	AS
16.05.17	3.1	Grammar and references revised	AS
23.05.17	4.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATION	EXPLANATION
E-Axle	Wheel Suspension with Integrated Electric Drive
OEM's	Original Equipment Manufacturers
KA	Kongsberg Automotive
HSN	University College of South-East Norway
EV	Electric Vehicle

TABLE 2 – DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

The purpose of this vision document is to serve as a preliminary study and give an understanding of our interpretation of our bachelor project. Kongsberg Automotive has given the project to us.

This vision document will ensure a mutual understanding of the given assignment among the various stakeholders. The stakeholders being the group, HSN and Kongsberg Automotive.

1.1. Scope

This vision document applies to the wheel suspension with integrated electric drive, which we will develop.

1.2. Employer

Our employer is Kongsberg Automotive who produces world-class products for the global vehicle industry. They have production facilities worldwide.

1.3. Background

Kongsberg Automotive wants to develop a fully electrical powertrain. This is going to be achieved by developing a wheel suspension with an integrated electric drive to substitute common combustion engines. The new system includes an electric drive consisting of motors, inverters and transmission. The system will be developed to satisfy stakeholders need for environment friendly transportation system.

1.4. Overview

This document presents our understanding of the given assignment. Firstly, the positioning is presented. These are divided into sections where we discuss the "business opportunity", "problem", "product positioning" and "system summary". Secondly the "Stakeholders and User description", which include "primary & secondary stakeholders" and "user summary". Lastly, the "Project Goals" set by the team [1].

2. POSITIONING

2.1. Business Opportunity

At the climate summit in Paris, world nations agreed on a historic climate change. The Paris agreement came in to force 4th of Nov 2016. Every country has committed to cut the greenhouse gas emissions. The Paris Agreement applies to all the countries, but it is expected that the rich countries contribute most. Every country must make a national plan for how they will reduce the emission in their country. This plan will consist of how much emission the country will reduce. This plan must be renewed every 5th year from 2020, and each time the country must be more ambitious about reaching their goal [2].

Therefore, the pressure on the vehicle industry has increased, as they are facing more restrictions and regulations from the government.

EU Emission Standards for Heavy-Duty Diesel Engines: Steady-State Testing

Stage	Date	Test	CO	HC	NOx	PM	PN	Smoke
			g/kWh				1/kWh	1/m
Euro I	1992, ≤ 85 kW	ECE R-49	4.5	1.1	8.0	0.612		
	1992, > 85 kW		4.5	1.1	8.0	0.36		
Euro II	1996.10		4.0	1.1	7.0	0.25		
	1998.10		4.0	1.1	7.0	0.15		
Euro III	*1999.10 EEV only*	ESC & ELR	*1.5*	*0.25*	*2.0*	*0.02*		*0.15*
	2000.10		2.1	0.66	5.0	0.10[a]		0.8
Euro IV	2005.10		1.5	0.46	3.5	0.02		0.5
Euro V	2008.10		1.5	0.46	2.0	0.02		0.5
Euro VI	2013.01	WHSC	1.5	0.13	0.40	0.01	8.0×10^{11}	

a - PM = 0.13 g/kWh for engines < 0.75 dm^3 swept volume per cylinder and a rated power speed > 3000 min^{-1}

FIGURE 1 - EU EMISSION STANDARDS

As shown in the table above, rules and regulations for gas emissions have by time become stricter. As we can observe, there have been a steady decline in the limit of allowed emission over years. This indicates a need of an alternative for the heavy-duty vehicles which primarily run on diesel. Most of these engines run on diesel, since it generates more power and is cost efficient [3].

The lack of zero emission heavy-duty vehicles provides us with a greater market opportunity in this segment. The product will be especially cost efficient in countries with low fees and taxes on zero emission vehicles.

Germany, with the leading automobile market, have issued a plan that suggest banning sale of vehicle with combustion engines after 2030. As the leading automobile market in Europe, the impact will be of great significance. This is an indication that that the world is moving towards zero emission vehicles and that KA needs to adapt to this potential change to stay competitive [4].

Norway have probably the best policy regarding zero emission vehicles. There is no sales tax when buying or leasing an electric vehicle. This is guaranteed by the government up to 2018. This makes the cost of an EV almost the same as a vehicle with a combustion engine.

Other benefits include:

- No toll (small customs fee from 2017)
- Free parking on municipal roads
- Can drive on lanes reserved for buses.

One other benefit that comes with an EV is that company-car tax is reduced by 50 %. In addition, if the car is older than 3 years and is an EV, then the tax is reduced to only 37,5 % of the total. This can be a big benefit for companies who own many transport vehicles. They can reduce their yearly cost quiet a lot in combination with other benefits an EV receives in Norway [5].

To estimate how much, we can reduce the yearly costs around operations of trucks, we must look at what it costs to transport for companies. The table under shows us some of the costs related to the transport of vehicles in Norway.

VEHICLE	COST/HOUR (NOK)	COST/KM(NOK)	CAPACITY (ton)
LGV	409	2.68	2.2
Light Distribution	420	3.17	5.7
Heavy Distribution (Containers)	458	4.86	12
Articulated Semi (Containers)	500	5.94	33

TABLE 3 - COST OF TRUCKING

We can then use these values to calculate how much it can cost us to transport goods from point A to point B. These values do not include other expenses related to transport of goods like toll and cost of loading/unloading.

E.g. if we want to transport goods between Drammen and Oslo, using values from the table above. The time we use to and from is 1 hour and 24 min, and the total distance is 86 km. Toll will be around 150. Using these values, we can calculate that it will cost us about 1361 NOK. Assuming we do this every day for a whole year we can see that only toll will cost us 54.750 NOK. If we assume that all EVs get the same benefits, we can save all this money, and this could lower the prices of transporting goods [6].

Efficiency is a very important factor for people and vehicle industry in general. We know that an EV is two-three times more efficient than a regular gasoline vehicle. The well to wheel efficiency for an electrical car is about 30%, while for a gasoline car it is around 14%. The overall well to wheel efficiency can increase even more in countries where or most of energy is renewable, like Scandinavian countries. If we take this into account this means, we can reduce the overall cost of running an electrical vehicle even further [7].

2.2. Problem Statement

The problem of	existing combustion Powertrain
Affects	the geometric design options
The impact of which is	Less space for desired solutions within the truck frame
A successful solution would be	A design concept that allows as much space as possible for battery units so that the heavy-duty vehicle can be fully electric.

TABLE 4 - PROBLEM STATEMENT

2.3. Product Position Statement

For	Tier one companies; In this case KA.
Who	Wants to sell electric powertrain systems/configurations to OEM's.
The E-Axle	Is a wheel suspension for trucks with integrated electric drive
That	Replaces existing combustion powertrain to an electric power drive.
Unlike	Currently available engines with diesel and gasoline which are a combination of different components which make poor design solutions, pollute and are cost expensive
Our product	Has a more optimal design that can easily replace existing powertrain in heavy-duty vehicles and become cost efficient

TABLE 5 - PRODUCT POSITION STATEMENT

2.4. System Summary

KA wants an electric axle that we can integrate in heavy-duty vehicles. The electric drive consists of motor, inverter and transmission. The wheel suspension should be of torsion beam type, and it should be air suspended with one bellow for each wheel, as well as one shock absorber for each wheel. The system shall:

- Be fully electric
- Replace existing combustion power-drive
- Have independent motors
- Have optimal wheel suspension design

3. STAKEHOLDER AND USER DESCRIPTIONS

Stakeholder is anyone affected by the success or failure of a system. We have primary stakeholders and secondary stakeholders. The primary stakeholders are those directly affected by our product/project, and the secondary are those indirectly affected by our project.

PRIMARY	SECONDARY
KA	Primary End Users
HSN	Secondary End Users
Our Team	

TABLE 6 - STAKEHOLDERS AND USER DESCRIPTION

3.1. Primary

The primary stakeholders for this project: Kongsberg Automotive, University College HSN and the project group. These individuals can be those who are monitoring our project and can directly affect its outcome.

3.2. Secondary

We have defined our secondary stakeholders as those indirectly affected by the product. They are customers of heavy-duty vehicles, which have an integrated electric axle developed by us. E.g. OEMs (original equipment manufacturer) companies. Secondary stakeholders are also the driver of a truck or a bus (heavy duty vehicle). In the lifetime of our product it will need maintenance, thus the maintenance crew is also our secondary stakeholder. Maintenance requirements is therefore considered during the development process.

We have defined the OEM's and drivers as the Primary End users. Maintenance crew as the Secondary End users.

3.3. Stakeholder Summary

NAME	DESCRIPTION	RESPONSIBILTY
Heavy-duty truck drivers	These users are typically transport truck professionals who will drive heavy-duty trucks with an integrated Electric Axle.	To transport goods using trucks with an integrated Electric Axle.
Heavy-duty truck maintainers	These users are professional mechanics who will maintain heavy-duty trucks with an integrated Electric Axle	To repair and maintain heavy-duty trucks, which use our Electric Axle.
Original Equipment Manufacturers	These users are heavy-duty truck manufacturers who will manufacture the trucks with an integrated Electric Axle.	To manufacture, assemble, sell and maintain trucks, which use our Electric Axle.

TABLE 7 - STAKEHOLDER SUMMARY

3.4. User Summary

NAME	DESCRIPTION	RESPONSIBILTY
OEM's	Primary End users	Uses the system to develop heavy-duty vehicles
Drivers	Primary End users	Uses the system for transportation
Maintainers	Secondary End users	Responsible for maintaining the system for the Primary End users

TABLE 8 - USER SUMMARY

4. PROJECT GOALS

For the bachelor thesis to be done properly, we need to define our project goals. These goals will assist us in the process. They will also give us insight in whether we have met them, or not.

4.1. Team Goals

- Increase our theoretical and technical knowledge about engineering.
- Work as a harmonic team all throughout the timespan of the project.
- Get an insight to how engineering projects are from start to finish.
- Deliver a satisfying result that generates a good grade

4.2. Result Goals

1. Clearly define the customer's requirements and formulate different approaches to a satisfying solution.
2. Design an optimal product with CAD drawings that meets the requirements and specification of our customer.
3. Meet the needs and expectations of all the stakeholders of this project.
4. Complete the project and deliver the product to the customer within agreed time.

5. REFERENCES

[1] Team Obiwan, "UTDALLAS," 30 11 2010. [Online]. Available: https://www.utdallas.edu/~chung/RE/Presentations10F/Team-hope/1%20-%20VisionDoc.pdf.

[2] FN, "Webpage for FN sambandet," 23 03 2017. [Online]. Available: http://www.fn.no/Tema/Klima/Klimaforhandlinger/Dette-er-Paris-avtalen.

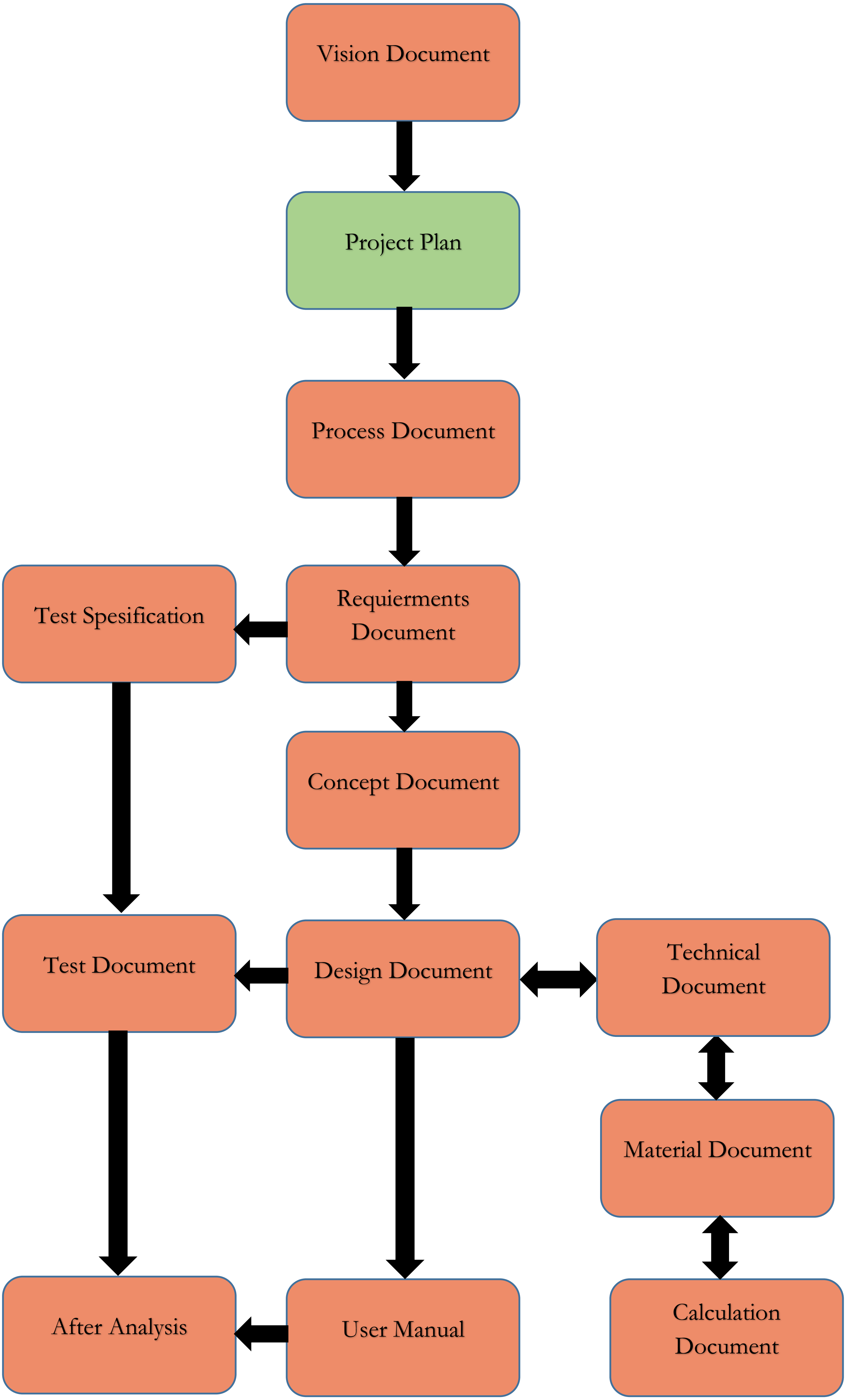
[3] DieselNet, "DieselNet," 01 11 2016. [Online]. Available: https://www.dieselnet.com/standards/eu/hd.php. [Accessed 17 01 2017].

[4] D. Zukowski, "Environmental news site," 10 10 2016. [Online]. Available: http://www.ecowatch.com/germany-bans-combustion-engine-cars-2037788435.html. [Accessed 15 01 2017].

[5] Skatteetaten, "Webpage for skatteetaten," 03 01 2017. [Online]. Available: http://www.skatteetaten.no/no/Tabeller-og-satser/Bilsatser---firmabil/.

[6] S. E. Grønland, "Webpage for national transportplan," 27 11 2011. [Online]. Available: http://www.ntp.dep.no/Transportanalyser/Transportanalyse+godstransport/_attachment/502986/binary/813984?_ts=1400ff020d0.

[7] M. Markowitz, "Energy Matters," 22 02 2013. [Online]. Available: https://matter2energy.wordpress.com/2013/02/22/wells-to-wheels-electric-car-efficiency/.


Vision Document
Project Plan
Process Document
Test Spesification
Requierments Document
Concept Document
Test Document
Design Document
Technical Document
Material Document
After Analysis
User Manual
Calculation Document

PROJECT PLAN

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

Employer	Kongsberg Automotive			
Group Members	**Name**		**Initials**	
	Abubakar Khan		AK	
	Ahat Turgun		AT	
	Anis Sadiq		AS	
	Egide Rubusa Bampo		ERB	
	Mustafa Moalim		MM	
	Pawan Bhatt		PB	
Document Information	**Version**	**Date**	**Approved**	**Pages**
	3.0	23.05.17	AS	33

21. februar 2017

PROJECT PLAN

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

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REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
18.01.17	0.1	Document created	AS & AK
24.01.17	0.2	Added 1. Document 1.3 Introduction 2.1 Team members	AS & AK
25.01.17	0.3	2.2 Areas of responsibility 2.3 Budget	AK
26.01.17	0.4	Meetings description	AK
02.02.17	0.5	Combined content	AS & AK
03.02.17	1.0	Finalized version	AS
18.03.17	1.1	Revised grammar, format & design	AS
19.03.17	2.0	Version update	AS
16.05.17	2.1	Grammar and reference update	AS
22.05.17	2.2	Introduction changes	AS
23.05.17	3.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
E1, E2	Elaboration iteration 1 & iteration 2
A1, A2, A3, A4, A5	Architectural Design iterations 1-5
T1	Transition iteration 1
ATT.	Attachment

TABLE 2 - DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

This document serves as a framework for this project. The meaning of the project plan is to define how we will work towards our product from the start until the end. This plan will explain how work systematically to meet requirements set by Kongsberg Automotive.

Task given by Kongsberg Automotive is to design a wheel suspension with integrated electric drive for heavy-duty vehicles. We must make an optimal design of the wheel suspension and make it as efficient as possible.

Document starts by introducing the team, known as E-Axle. A brief explanation of responsibilities follow. An explanation of project model and work methodology is explained. Time management and activities are also something we will describe.

A description of routines follows. We explain how we solve challenges that might occur. I.e. challenges regarding our design or analytic tests of our design. An elaboration of risk management and necessity of it is included.

1.1. Scope

This document explains how the group approaches the problem statement given by the customer (Kongsberg Automotive). It will contain following information:

- How we plan to reach our goals
- Complete overview of the group structure
- Project model
- Activity plan
- Risk analysis

2. TEAM

2.1. Members

NAME	RESPONSIBILITES
Anis Sadiq 	• Project Leader • Documentation • Group management **E-mail:** Anis.sadiq.83@gmail.com **Phone:** 97732851
Abubakar Khan 	• System Engineering • Tools implementation **Email:** abo_khan99@hotmail.com **Phone**: 97970132
Mustafa Moalim 	• Force calculations • Materials **Email:** warsan110@hotmail.com **Phone:** 47715232

NAME	RESPONSIBILITES
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Pawan Bhatt 	• Analytics • FEM **Email:** pawanbhatt95@gmail.com **Phone:** 91004971
Ahat Turgun 	• Design • CAD **Email**: ahatturghun@gmail.com **Phone:** 94057319

TABLE 3 - TEAM MEMBERS

2.2. Area of Responsibility

Group members have their own specific areas of responsibility. Every member of the project group works in harmony together as a whole group. However to be more time efficient, areas of responsibilities are necessary. Each member of the group id given a specific task or assignment that they work with throughout the project.

Our idea and meetings will help everyone to understand the whole problem of the project. Meaning, each member of the group is always up to date on the progression of what members are doing, and help each other where necessary.

2.2.1. Project Leader

- Communicate with our stakeholders
- Lead the project group and divide assignments amongst members
- Organize documentation and keep the motivation up
- Web Page

2.2.2. Systems Engineering

- Implementation system engineering tools
- Utilize systems thinking
- Time management
- Phase supervision
- Documentation

2.2.3. Force Calculations

- Make sure calculations are correct

2.2.4. Materials

- Make sure the materials meet the requirements
- Choose the best options for the design (cost efficient)

2.2.5. Electronic

- Electronic design
- Implementation of electric components in the system

2.2.6. Test

- Supervise testing
- Document the testing
- Select the needed resources

2.2.7. Analytics

- Analyse the design
- Simulation measurements

2.2.8. Design

- CAD modelling
- Optimal design of the product

2.3. Budget

During our project, there will be several expenses. Table 4 shows expenses we have so far, and a rough estimate of the ones we expect to have.

ITEM	COST
Tape	45 NOK
Document binders	91 NOK
CD's for documents	90 NOK
Printing final report	2000 NOK (estimate)
Project poster	400 NOK (estimate)
TOTAL	**2445 NOK**

TABLE 4 - BUDGET

3. PROJECT MODEL

3.1. Unified Process Model

We have chosen the Unified Process Model for our bachelor thesis. We have chosen this model, because it is both iterative and incremental. The model gives detailed guidelines and gives freedom to customize it to fit our project. [1]

3.2. Phases

. The model consists of four phases. (Fig. 1):

- Inception
- Elaboration
- Architectural Design
- Transition

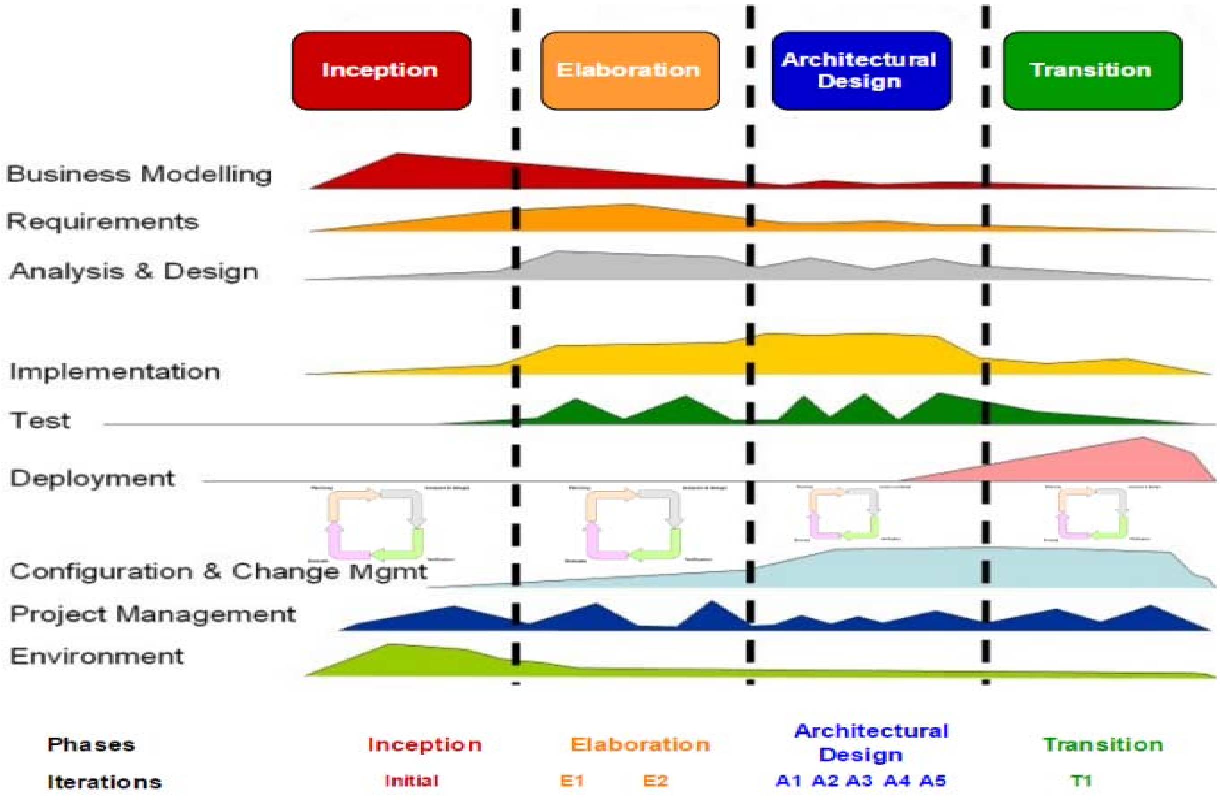


FIGURE 1 - UNIFIED PROCESS MODEL

Every phase has its own purpose, which we explain further.

3.2.1. Inception

During this phase, we do initial planning. This step is not repetitive and here we lay our foundation for the project. Initial planning consists of administrative work, research to understand the system in hand, high-level requirements- and test specifications. Our goals during this phase is to produce:

- Vision document
- Requirements document
- Test document
- Modest design of existing system
- Presentation of our work

3.2.2. Elaboration

This is the second phase in our process. We divide elaboration into two iterations (E1 & E2). Each iteration is of 2-week sprints. The emphasis is on planning the iterations and analysing the problem further. Brainstorm around possible concepts/solutions, and design of these is in focus. We make detailed requirements and evolve the test specification. The goals are to produce:

- At least one or more concepts from each member
- Make architectural decisions and establish a high level architectural foundation
- Supplementary requirements
- Iteration reports

3.2.3. Architectural Design

In this phase of five iterations (A1-A5), we move on to high-level designing. At this point, we have to choose concepts we are going to move bring forward. We make architectural decisions and focus on the sub-components in detail. The goal for this entire phase is to produce:

- Updated schedule and iteration plans
- CAD drawings for 2nd Presentation
- Prepare for 2nd presentation
- Build a prototype
- Add and improve test plans
- Iteration reports

3.2.4. Transition

This is the final phase of the project with one iteration (T1). The system will undergo the final test and verification of high level. We correct possible system errors. The goal for this phase is to produce:

- A system user manual
- Iteration report
- Final report

3.3. Iterations

We divide each of these phases into smaller iterations. Following these core "engineering" workflows:

3.3.1. Planning

This describes the overall goals for the specific iteration. We also explain how we reach these goals.

3.3.2. Analysis & Design

The workflow shows *how* we realize the system during the implementation phase. We draw, model and calculate.

3.3.3. Verification

We test developed components as units and integrate the results into and executable system.

We verify the interaction between objects and test proper integration of all the components. Tests verify that we fulfill all requirements and identification of defects that might occur.

3.3.4. Evaluate

In this phase, we review our work so far. Analysing our work will give us an idea of whether the concepts are good enough or not. Depending on our evaluation, we determine if changes are necessary. These can be either major, or minor.

Each iteration goes through a development loop (fig. 2) to ensure focus on the above-mentioned disciplines. We have chosen to modify the workflow cycle since our project does not have a physical focus. Most of our work emphasises on analysis and design of different concepts. These will work as solutions or ideas for further development. This loop is in each phase in the unified model figure (fig.1).

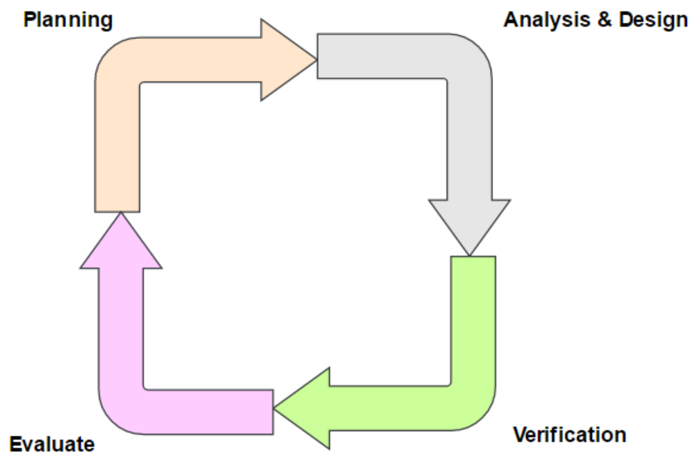


FIGURE 2 - WORKFLOW CYCLE

The reason for choosing an *iterative* model is the benefits of having an executable product after each cycle. This product is a subset of the final product that we are developing. For each iteration, it will grow incrementally to become the desired final system (fig. 2)

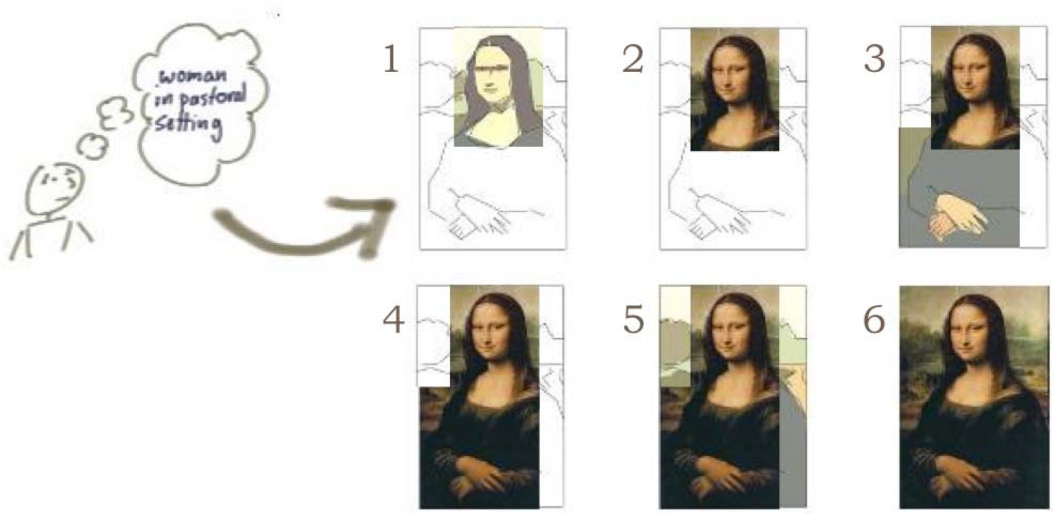


FIGURE 3 - ITERATIVE & INCREMENTAL

By choosing the iterative model, the benefits are:

- Mitigating risks earlier
- Changes that might occur will be more manageable
- The level of reuse is higher

- We can learn along the way
- We can deliver overall better quality [2]

4. TIME MANAGEMENT

4.1. Milestones

We have chosen a various set of milestones in our project. These are the five major milestones, which we must meet for the project to be successful.

MILESTONE	DESCRIPTION	DATE
Initial planning	Start of project	09.01.17
1st Presentation & Documents	Present project plan, requirement- and test spec	07.02.17
2nd Presentation	Present project status	30.03.17
Hand-in	Finalize and hand in all project documents	19.05.17
3rd Presentation	Present finished project	08.06.17

TABLE 5 - MILESTONE

4.2. Timeline

Below follows an illustration of these milestones (fig.4) to give an overview of the entire project. We create a GANTT chart (fig.5) to give a more detailed description of each phase and iteration in the timeline. (Ref: att. A)

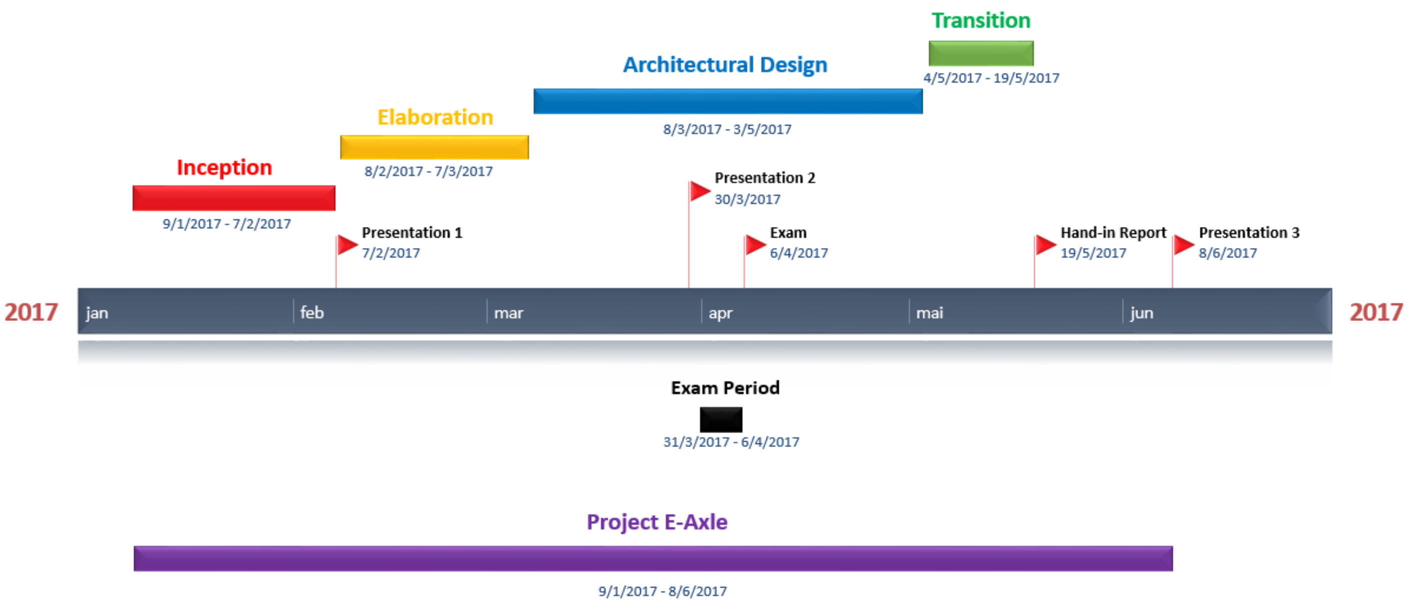
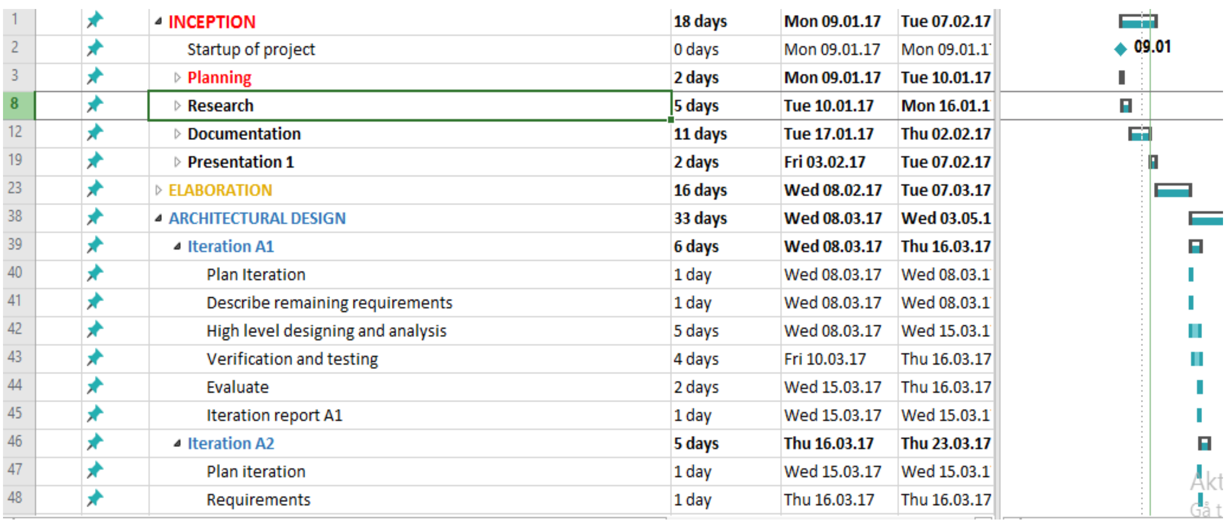


FIGURE 4 - TIMELINE



1	INCEPTION	18 days	Mon 09.01.17	Tue 07.02.17
2	Startup of project	0 days	Mon 09.01.17	Mon 09.01.1
3	Planning	2 days	Mon 09.01.17	Tue 10.01.17
8	Research	5 days	Tue 10.01.17	Mon 16.01.1
12	Documentation	11 days	Tue 17.01.17	Thu 02.02.17
19	Presentation 1	2 days	Fri 03.02.17	Tue 07.02.17
23	ELABORATION	16 days	Wed 08.02.17	Tue 07.03.17
38	ARCHITECTURAL DESIGN	33 days	Wed 08.03.17	Wed 03.05.1
39	Iteration A1	6 days	Wed 08.03.17	Thu 16.03.17
40	Plan Iteration	1 day	Wed 08.03.17	Wed 08.03.1
41	Describe remaining requirements	1 day	Wed 08.03.17	Wed 08.03.1
42	High level designing and analysis	5 days	Wed 08.03.17	Wed 15.03.1
43	Verification and testing	4 days	Fri 10.03.17	Thu 16.03.17
44	Evaluate	2 days	Wed 15.03.17	Thu 16.03.17
45	Iteration report A1	1 day	Wed 15.03.17	Wed 15.03.1
46	Iteration A2	5 days	Thu 16.03.17	Thu 23.03.17
47	Plan iteration	1 day	Wed 15.03.17	Wed 15.03.1
48	Requirements	1 day	Thu 16.03.17	Thu 16.03.17

FIGURE 5 - GANTT CHART

4.3. Schedule

A time schedule is essential for the group project. For the group to reach their goals, time must be taken into consideration. That is why the group is making a schedule of how much time that needed on various set of tasks. This is an estimation of how much time we think we will spend on the different sets of tasks.

Our time schedule is in such a way that we spend 8 hours each day on the project. In these 8 hours, around 1.5 hour is on meetings and lunch breaks. Work days are Tuesday-Friday from week 1-13 (project weeks). From week 13-19 it will increase to Monday-Friday.

As the project develops, inconveniences might occur along the way. We will therefore put more hours in our work every day. This schedule works as a basis for our project planning.

PHASE	START/END PERIOD	ESTIMATED TIME
Inception	Start: 09.01.2017 End: 07.02.2017	822 hours (22%)
Elaboration	Start: 08.02.2017 End: 07.03.17	732 hours (20%)
Construction	Start: 08.03.17 End: 03.05.17	1446 hours (39%)
Transition	Start: 24.04.2017 End: 19.05.2017	714 hours (19%)
TOTAL	**3714 hours (100%)**	

TABLE 6 - TIME SCHEDULE

4.4. Burn Diagram

We extract scheduled time and hours from timesheets and put them into a Burn diagram. This illustrates how much time we estimate, and how much real time hours we have used during the entire project (fig. 6)

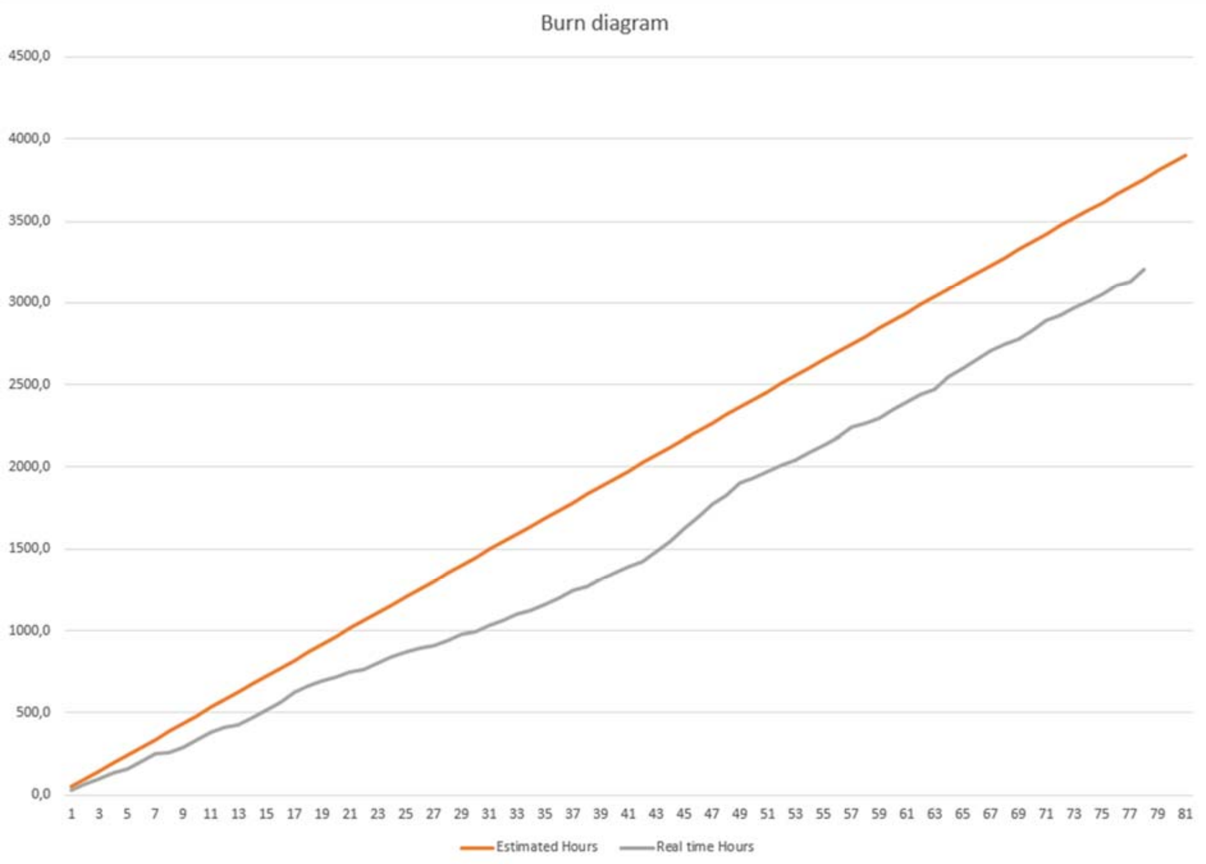


FIGURE 6 - BURN DIAGRAM

4.5. Activity Plan

As part of the project planning, we create an activity list (Table 7). This is primarily to get an overview of planned activities during the lifespan of the project. The activity ID serves as a reference to the GANTT chart and timesheets.

ACTIVITY	ACTIVITY ID	PHASE
Internal Meetings	xx	X
External Meetings	xx	X
Internal Supervisor Meetings	xx	X
Get equipment	xx	P1
Organize & set up room	xx	P1
Vision Document	1	P1
Project Management	2	P1
Initial Research	3	P1
Project Plan Documentation	4	P1
Test Spec Documentation	5	P1
Requirements Spec Documentation	6	P1
Presentation 1 prep	7	P1
Iteration E1	8	P2
Iteration E2	9	P2
Iteration A1	10	P3
Iteration A2	11	P3
Presentation 2	12	P3
Iteration A3	13	P3
Iteration A4	14	P3
Iteration A5	15	P3

ACTIVITY	ACTIVITY ID	PHASE
Iteration T1	16	P4
Final Report	17	P4
Diagrams and charts	18	ALL
Concepts drawings	19	P2 & P3
Documentation control	20	ALL
Presentation 2 prep	21	ALL
Administrative work	22	ALL
Web page	23	P2, P3, P4
Documentation	24	ALL
Prototyping	25	P3
FEM analysis	26	P3
Simulink test	27	P3
Presentations	28	ALL
CAD Design	29	P2,P3,P4
Arduino coding	30	P3

TABLE 7 - ACTIVITY PLAN

5. MEETINGS

Meetings and communication is very important and essential for our project. Meetings with multiple parties involved in our project will increase our knowledge and sets a guideline for how we work efficiently in our project. We have several meetings involving different parties. All of these can directly affect our project. We hold these meetings throughout the whole project.

These meetings will help us:

- Set a guideline for our project
- Get answers to questions
- Discuss and share knowledge and ideas
- Make sure that everyone is up to date
- Increase team moral

5.1.1. Morning Meetings

Every morning there is going to be a meeting to plan tasks and have a general update. If a member is not done with given task, we contribute with necessary measures to complete the task. If a member is done with a task, we assign and distribute new tasks.

5.1.2. Internal Meetings

After each phase and iteration, we conclude with a meeting. We held these so that we can increase our team efficiency. We reflect on the work so far, challenges and how we need to work further in the process.

5.1.3. Internal Supervisor Meeting

This is a weekly meeting with our internal supervisor. Our internal supervisor is Jamal Safi from HSN. Before we arrange a meeting with our internal supervisor we must send a follow-up document to him 24 hours before the meeting. This will give him the opportunity to understand what we want to discuss in the meeting. The main purpose of this meeting is too:

- Keep him updated on our project at all time
- Ask for guidance
- Receive feedback
- Follow up the feedback and work on it

5.1.4. External Supervisor Meeting

These meetings are not held regularly, but whenever needed. These meeting will be held with our stakeholders Kongsberg Automotive. The reason is to keep them updated and confirm that we are on the same page. We will send a follow up document to our external supervisor too keep him updated on both technical and theoretical aspect of our project. The main reason for these meetings are:

- Ask technical questions regarding our project and product
- Confirm and understand different requirements
- Keep them updated on our progression
- Discuss and share knowledge
- Get feedback
- Follow up on the feedback

6. PRESENTATIONS

During our bachelor thesis, there are three separate presentations. These different presentations have a big impact on deciding our final grade for the bachelor thesis.

These will attended our presentations:

- Internal and external supervisor
- Internal and external examiner
- Anyone else that wants to be present and watch the presentation

6.1. 1ST Presentation

First presentation gives a good insight of how we plan to work and achieve our goals. We give a description of our problem statement given to us by Kongsberg Automotive. It will give a view of how we work systematically and what the status of the project is, and what we plan.

Tasks associated with first presentation:

- Documentation must be delivered two full working days before the presentation
- A 30 minute meeting before the presentation with internal and external supervisor and the examiner
- Presentation with a time limit of 20 minutes
- Possible interrogation
- After-meeting

Documentation submitted needs to consist of:

- Requirements (What are we to make or do?)
- Test (How can we see that we have reached our goals or not?)
- The project plan (Modell/milestones and area of responsibility)

6.2. 2nd Presentation

This presentation is a walkthrough of our project. Meaning the status and the remaining activities. It is like the first presentation; however, we now talk about possible solutions for our problem and the chosen design for our project. If any changes or modification are made to our project plan or too our product design, then this is presented to the viewers. Presentation of how we will keep working towards the final presentation and how we plan to solve our problem. The length of this presentation is 20 minutes.

6.3. 3rd Presentation

The third and final presentation is the most valuable presentation. In this presentation, our project is finished. This is the final stage of our project. Meaning we now present the best possible solution of our project. This presentation is a full overview of our work. The length of the presentation is 1 hour. It divides into three parts:

- 20 minutes of sales review, this gives a review of how and why our product is good compared to the existing products
- 20 minutes of technical review, this contains the technical solution and the development of our product, and how we solve the problem technically
- 20 minutes for questioning of the whole group

7. DOCUMENTATION

Documentation is one of the most important parts of this project. That is why this part will have a major focus throughout the project. Around 50% of the final grade depends on the documentation.

7.1. Guidelines

Here we explain the different set of guidelines we use for the documentation on of the project. The reason we make a guideline for this is to make sure that every member of the group is aware of how to write and present documents. This makes sure that everyone follows standards decided by the group, so that we can avoid any inconveniences along the way.

7.2. Design and Layout

The group has agreed on which standard too use for the documents throughout the project. The reason the group is doing this is to avoid that different documents with different type of format on letters, size, and fonts. We can change the layout if the group feels they can improve it to be more structured.

7.3. Structure

As a book has many chapters, our documentation is going to have many sub chapters. We place information that is common for the subchapters under the main chapter. All the chapters we have also contain a small introduction if we see it fit.

7.4. Document History & Version

It is of utter importance to keep track of the history and document versions. Every document we make has a document history so we can trace it back to when it was made, and check if any changes was made or not.

8. RISK MANAGEMENT

Risk management is a very important part of any project planning. It is a process, which involves identifying, analysing and either accepting those risks or find ways to mitigate it. Early identification of risks that might occur during the development process will save us precious time. We will also be better equipped to handle them.

Risk management determines how we can mitigate these risks. Sometimes we can avoid a risk completely, while sometimes we must accept some risks from a business perspective. Look at the "Mitigation strategy" section for more information on this.

8.1. Risk management process

Risk Management is a systematic process, and involves the same steps, with minor changes per different project.

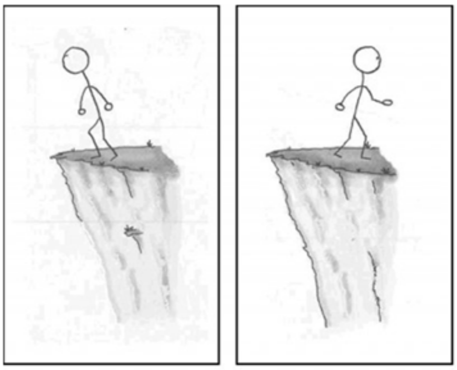
Risk management process consists of following steps:

- **Risk identification** (Identifying possible threats/risk that can occur)
- **Risk analysis** (Determining the consequences and the odds of such risks)
- **Risk evaluation** (Determining the overall impact of the risk and whether to avoid such risks or accept them)
- **Risk mitigation** (Determining how to mitigate the risks completely or avoid it entirely, and the probability of it occurring at all)
- **Risk monitoring** (Monitoring the risks continuously through the development process, and look forward to new risks occurring) [3]

8.2. Mitigation strategy

There are several ways to deal with a potential risk and here we look at some of them. [4]

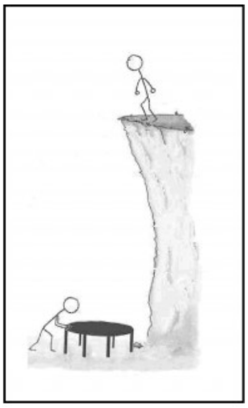
Risk avoidance



Avoiding a risk is one of the most common method we can apply to mitigate the negative effects of a risk. We can change our working strategy to avoid a confrontation with the risk.

FIGURE 7 - RISK AVOIDANCE

Risk reduction



Sometimes we can reduce the overall impact or the probability (or both) of a risk during a development process. This can be done by either reducing the scope of the project or adjusting the working process accommodating the risk.

FIGURE 8 - RISK REDUCTION

Risk transfer

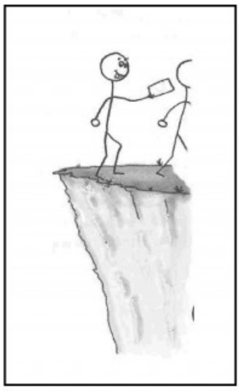


FIGURE 9 - TRANSFER

Risk transfer or sharing is another common strategy when dealing with risks. It means that the consequences are shared among the members working on a project, and sometimes among various stakeholders. This way we can reduce the overall impact it has on the development process.

Risk acceptance

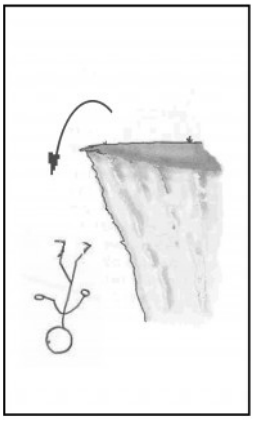


FIGURE 10 - ACCEPT

Sometimes it is not possible to deal with the risk and we must accept it. The reason can be because the profit from the project can be greater than the losses from the potential risk/threat.

8.3. Preliminary Risk Form

We use a preliminary risk form [5] to map out the risk. The risk form covers one category at a time. For each category, we ask Risk Question that we answer in the form. Below is an example of the setup (table 8).

Id	Type	Consequences	Probability	Severity	Score	Strategy	Measures
x	Illness	Excess work	4	4	16	Share	Discussion

TABLE 8 - PRF

A heat map (fig.11) helps us to give a risk score for our different scenarios/risks by multiplying the severity of the risk with the overall likelihood of the risk occurring.

Severity x probability = Risk score

S \ P	1	2	3	4	5
1	1	2	3	4	5
2	2	4	6	8	10
3	3	6	9	12	15
4	4	8	12	16	20
5	5	10	15	20	25

FIGURE 11 - HEAT MAP

Score Indication:

RATE	PROBABILTY (P)	SEVERITY (S)
1	Rare	Negligible – Risk can be ignored as it has no significant impact on the project
2	Unlikely	Low - This risk type may demand some attention, and can have minor negative effect on the project.
3	Moderate	Medium - This risk type will demand a lot more attention and can have significantly affect our project in a negative way.
4	Likely	High - This risk type will demand high attention and monitoring, and can seriously damage our project.
5	Almost certain	Catastrophic - This is the worst-case scenario which can happen, and will require very high resources and attention from whole group to contain, can potentially ruin our whole project.

TABLE 9 - SCORE INDICATION

Risk assessment is available in the appendix for further revision. (Ref: att. B)

9. REFERENCES

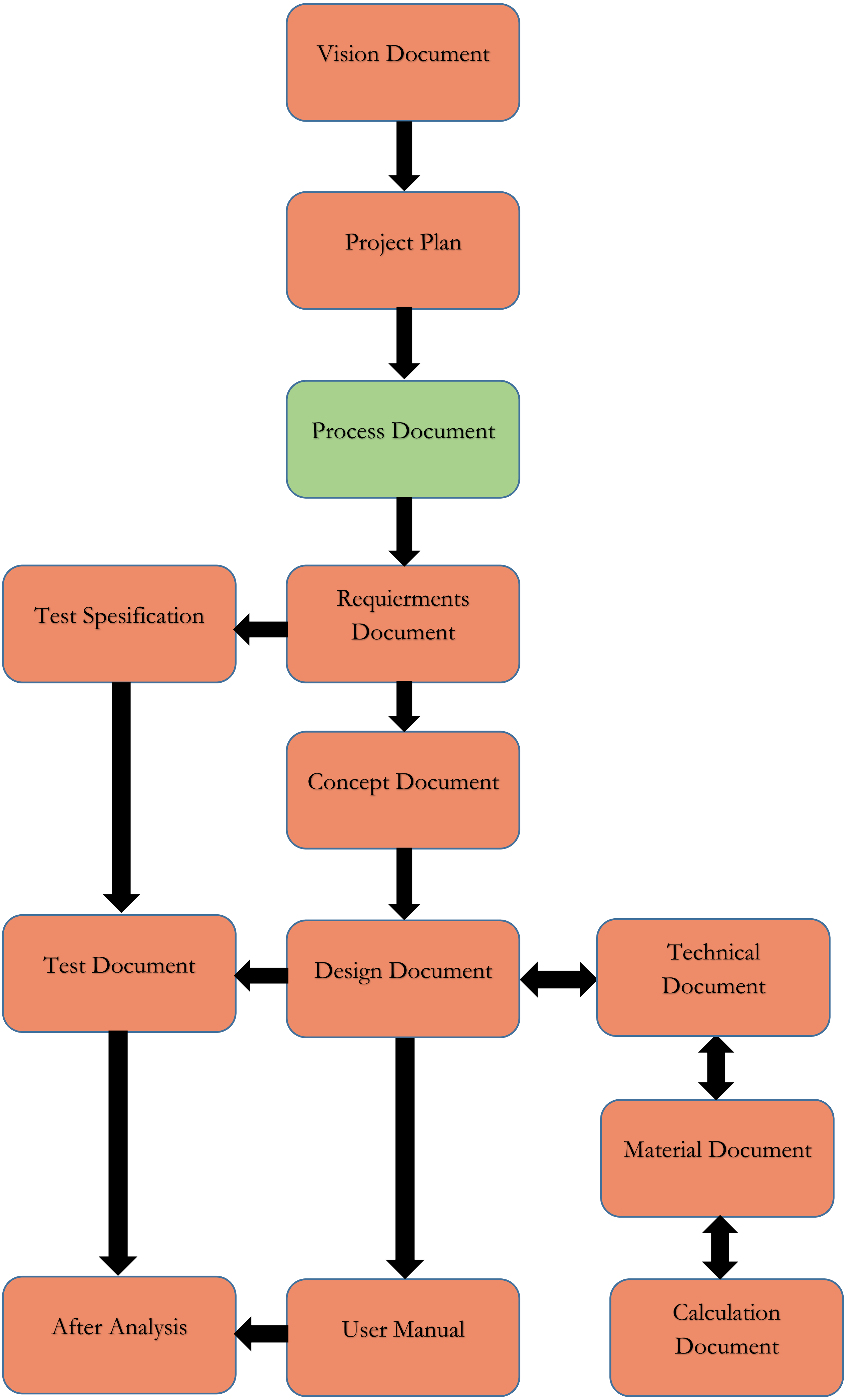
[1] R. Software, "Website for IBM," 01 11 1998. [Online]. Available: https://www.ibm.com/developerworks/rational/library/content/03July/1000/1251/1251_bestpractices_TP026B.pdf. [Accessed 10 02 2017].

[2] S. Thomas, "Itsadeliverything," 3 12 2012. [Online]. Available: http://itsadeliverything.com/revisiting-the-iterative-incremental-mona-lisa.

[3] M. Rouse, "TechTarget," 29 08 2016. [Online]. Available: http://searchcompliance.techtarget.com/definition/risk-management.

[4] A. Watt, "BC Open Textbooks," Creative Commons Attribution, [Online]. Available: https://opentextbc.ca/projectmanagement/chapter/chapter-16-risk-management-planning-project-management/. [Accessed 25 01 2017].

[5] J. Vesper, Director, *Risk assessment methods.* [Film]. USA.2014.


Vision Document
Project Plan
Process Document
Test Spesification
Requierments Document
Concept Document
Test Document
Design Document
Technical Document
Material Document
After Analysis
User Manual
Calculation Document

PROCESS DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

Employer	Kongsberg Automotive			
Group Members	**Name**		**Initials**	
	Abubakar Khan		AK	
	Ahat Turgun		AT	
	Anis Sadiq		AS	
	Egide Rubusa Bampo		ERB	
	Mustafa Moalim		MM	
	Pawan Bhatt		PB	
Document Information	**Version**	**Date**	**Approved**	**Pages**
	2.0	23.05.17	AS	60

8. februar 2017

PROCESS DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
08.02.17	0.1	Document created	AS
21.02.17	0.2	Added elaboration iteration 1	AS
08.03.17	0.3	Added elaboration iteration 2	AS
23.03.17	0.4	Added architectural design 1	AS
23.03.17	1.0	Finalized version	AS
07.04.17	1.1	Added architectural design 2	AS
16.04.17	1.2	Added architectural design 3	AS
22.04.17	1.3	Added architectural design 4	AS
04.05.17	1.4	Added architectural design 5	AS
05.05.17	1.5	Added transition phase	AS
21.05.17	1.6	Grammar correction and updates	AK
23.05.17	2.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
UPM	Unified Process Model
I1	Inception Iteration 1
E1	Elaboration Iteration 1
E2	Elaboration Iteration 2
A1	Architectural Design iteration 1
A2	Architectural Design iteration 2
A3	Architectural Design iteration 3
A4	Architectural Design iteration 4
A5	Architectural Design iteration 5
T1	Transition Iteration 1
KA	Kongsberg Automotive
ABS	Anti-Block System
EPS	Electric Power Steering
MATLAB	Matrix Laboratory
FEM	Finite Element Method
CAD	Computer Aided-Design

TABLE 2 – DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

This document contains iteration reports that gives an overview of how the team has worked during the project. The document is divided into phases accordingly to the UPM [1]. Each phase contains information regarding the iteration; period of the iteration, what we plan to produce, resulting figures, diagrams and/or calculation [2] [3] [4] [5]. The "T" shape method has always been in mind while working with this project. We work on a broad level so that both disciplines can understand each other, but also allow them to dive deeper into their own domain [6]. Diagrams and figures that are created are both general and more specific. This is done so that mechanical and electrical can get a mutual understanding of how the system interacts with each other. To have a constant overview of the entire process, each diagram and figure presented in the document is printed on A3 sheets and put on the project room walls. This is done to stimulate the process and ease of access to relevant information so we are more conscious about challenges and considerations during discussions and evaluations.

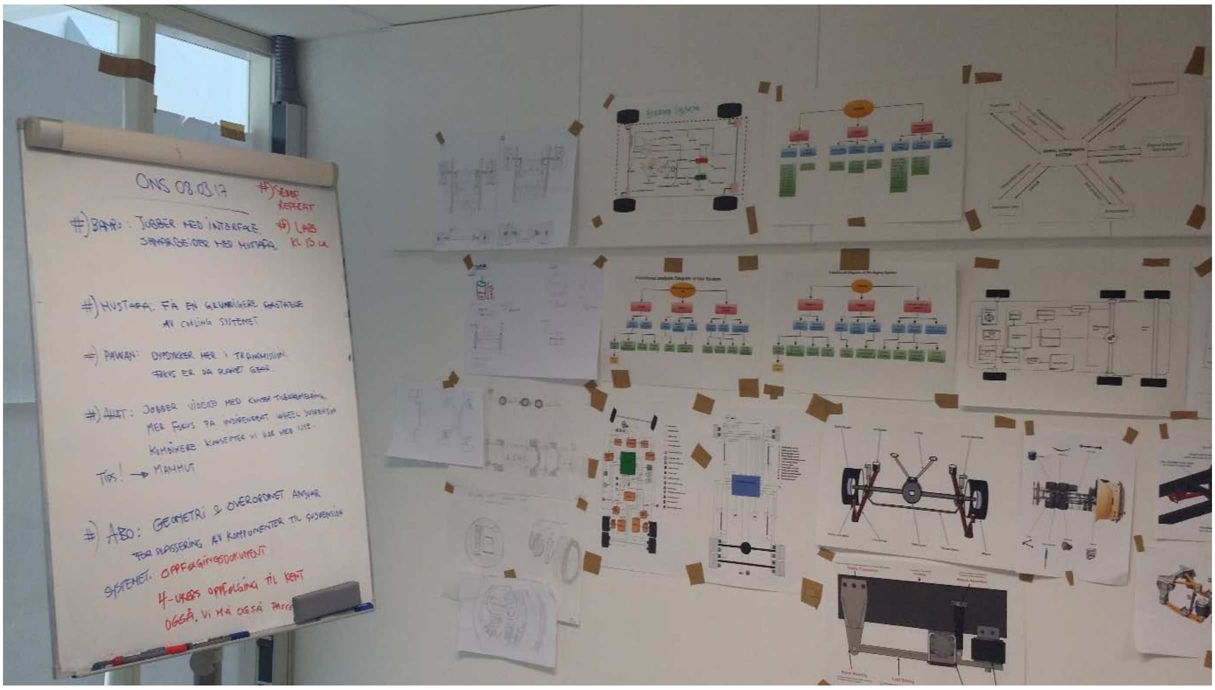


FIGURE 1 - PROJECT ROOM

2. IMPLEMENTATION OF UPM

The first iteration in the Unified Process Model is in the inception phase. This gets the group started with the project. All the administrative work, necessary planning and initial research is done in this iteration.

Elaboration is the second phase where we have 2 iterations. These iterations will build on the information gathered in the inception phase. All the initial research we have done on the existing system will be forwarded to this phase.

The architectural design iterations will build up on what we have elaborated in the previous phase iterations. The design will either extend or build into further detailed design, or be scrapped in expense of new or better ideas.

The last iteration in transition will simply be of finalizing the documents.

3. INCEPTION

This phase consists of one iteration. The period of this iteration is:

- Start: 09.01.17
- End: 07.02.17

3.1. I1

<u>Plan:</u>

- System of interest
- Black box
- Use Case

- Identify stakeholders
- Context diagram
- Control module
- Electric drive sketches
- Vision document
- Project plan
- Test specification
- Requirements specification

Content:

This phase has a clear-cut function of getting the initial planning in place. Administrative work is handled. I.e. group contract, meeting with KA, ordering equipment etc. A system of interest sketch is drawn. As most of the members has little or no experience with existing/legacy truck systems. This needed to be broken down with an easy to understand diagram with the most basic components. A black box diagram is drawn to define the input, output, constraints and controls. A use case diagram is created to give a representation of the user interaction with the system and the different use cases in which the user is involved. Various stakeholders are identified. We drew a context diagram to view the relationship of the existing system with its environment, and the external entities it interacts with. As part of this phase a vision document is created so that all stakeholders will have the mutual understanding of the project. Simultaneously high level requirements are analyzed and clarified with KA. These are then broken down further and put into a requirements document. To get an overview of how the control system interacts in the system, a control module system diagram is created. A project plan is created to organize and structure the whole project. As soon as majority of requirements are finalized a test specification plan is initiated.

Resulting figures & diagrams:

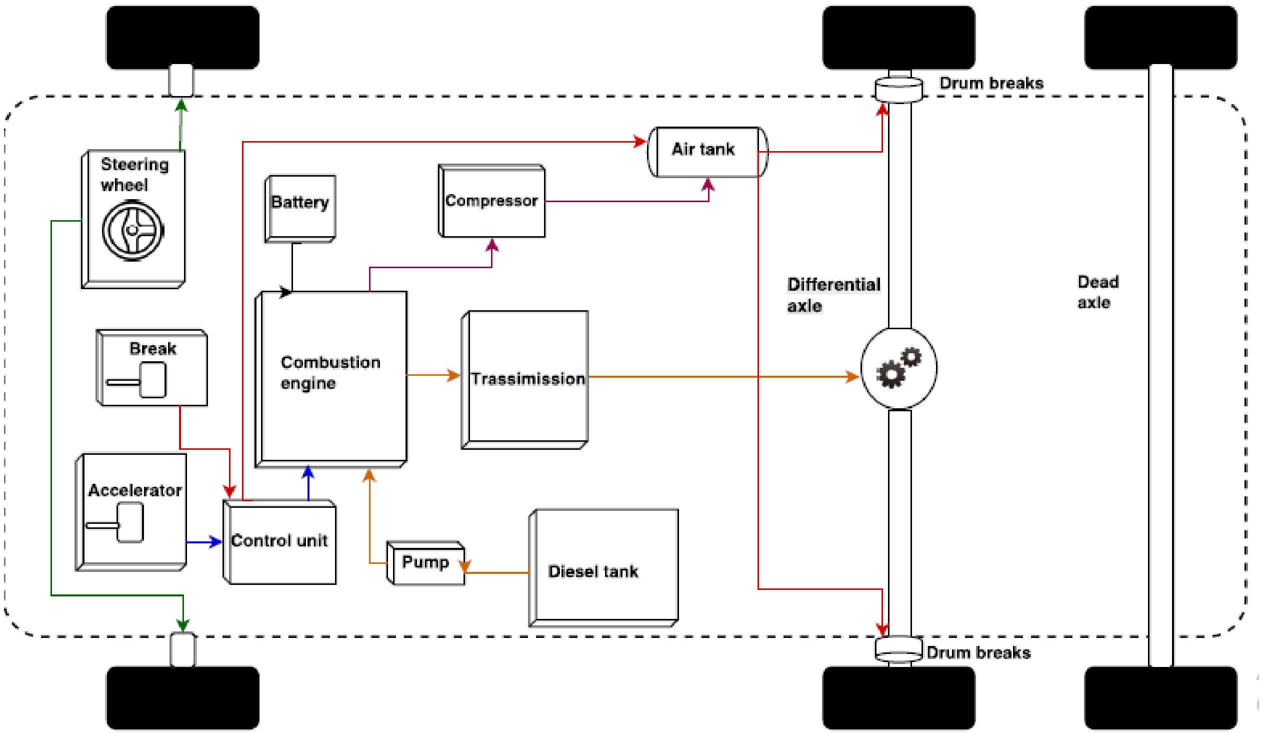


FIGURE 2 – LEGACY SYSTEM OVERVIEW

Block diagram to give a simplified overview of the different components in an existing truck system.

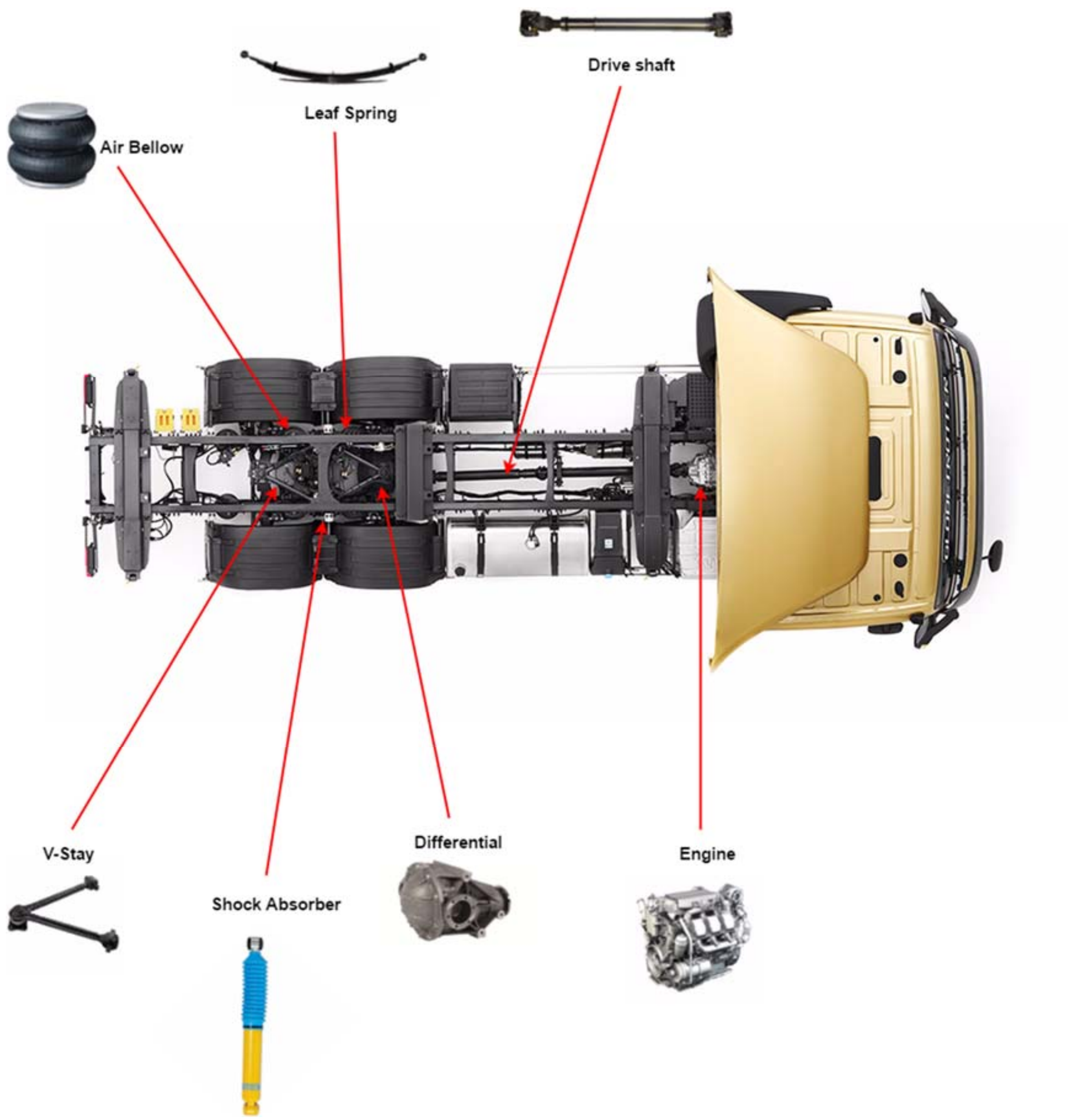


FIGURE 3 – LEGACY SYSTEM OVERVIEW WITH COMPONENTS

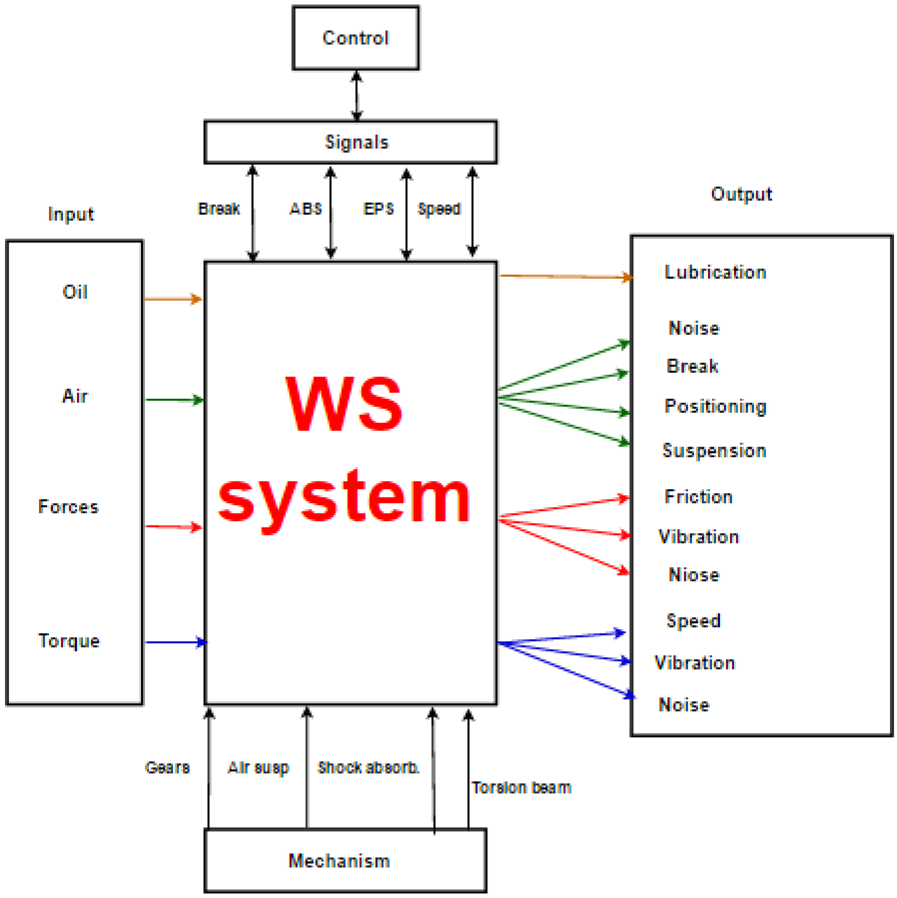


FIGURE 4 - BLACK BOX WHEEL SUSPENSION SYSTEM

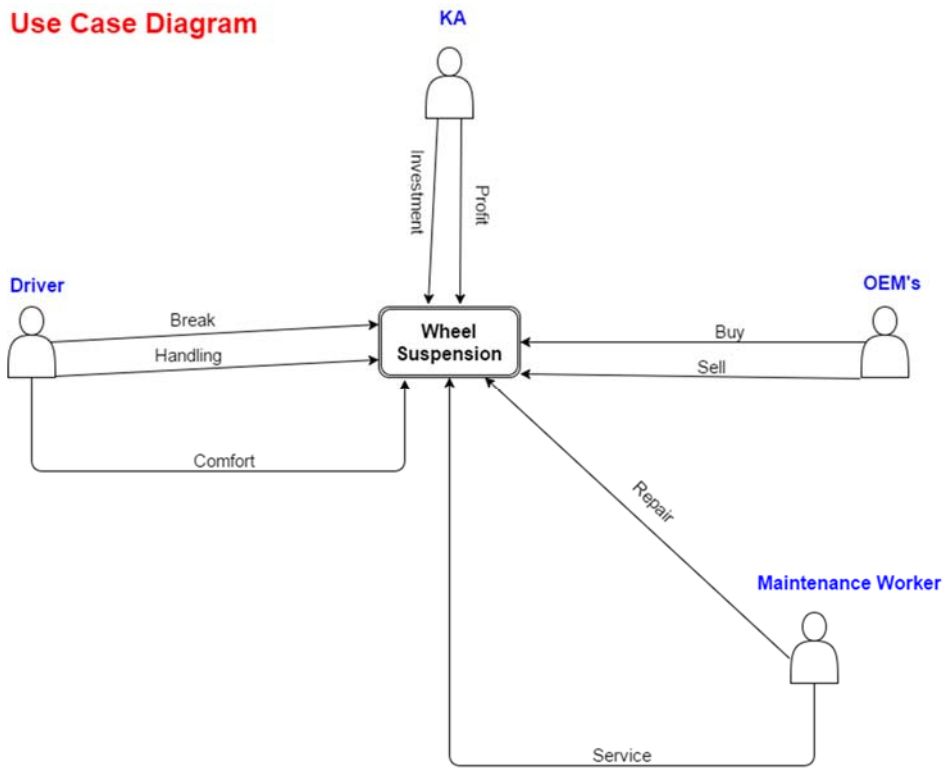


FIGURE 5 - USE CASE

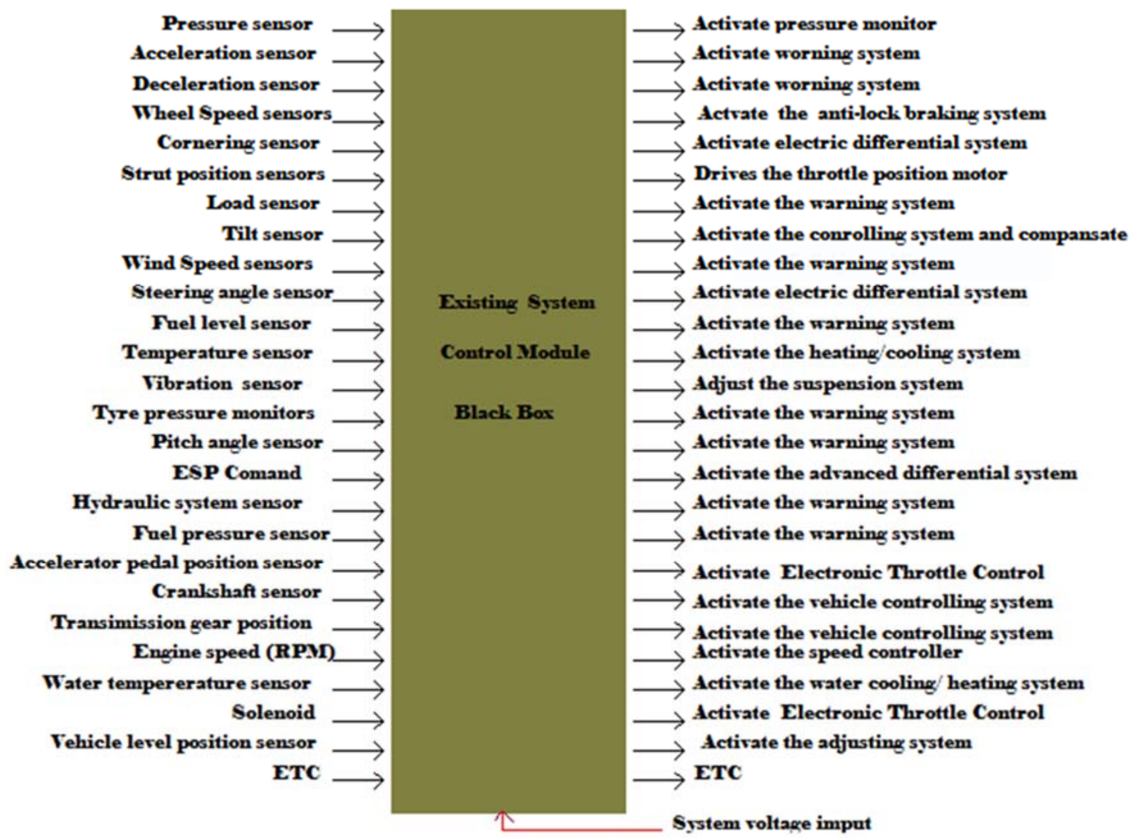


FIGURE 6 - BLACK BOX ELECTRONIC MODULE

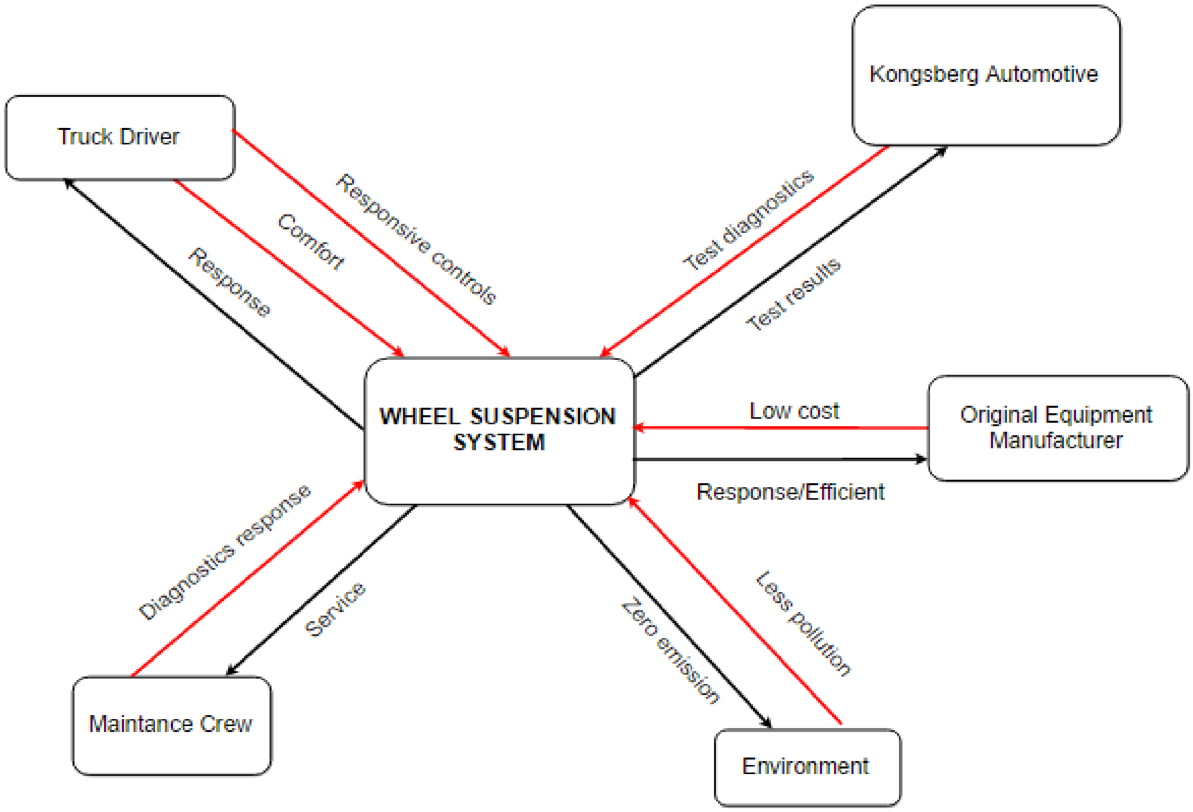


FIGURE 7 - CONTEXT DIAGRAM

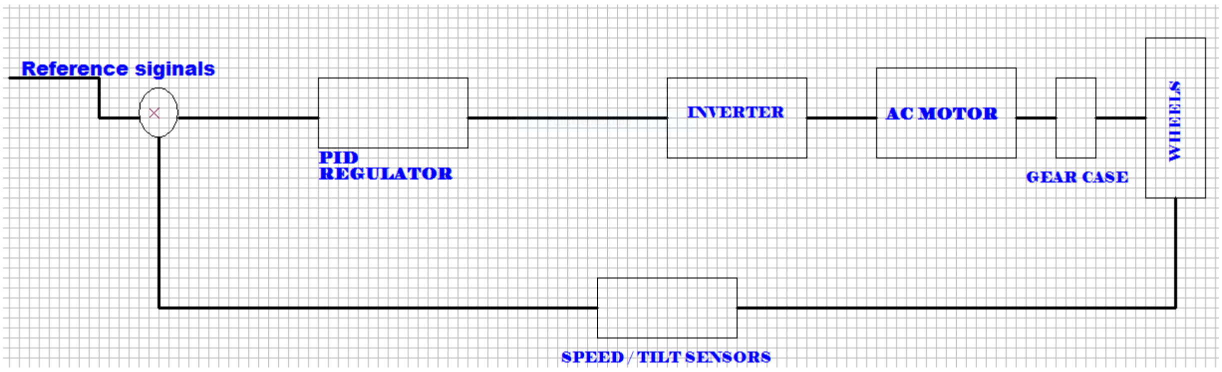


FIGURE 8 - ONE PHASE AC MOTOR

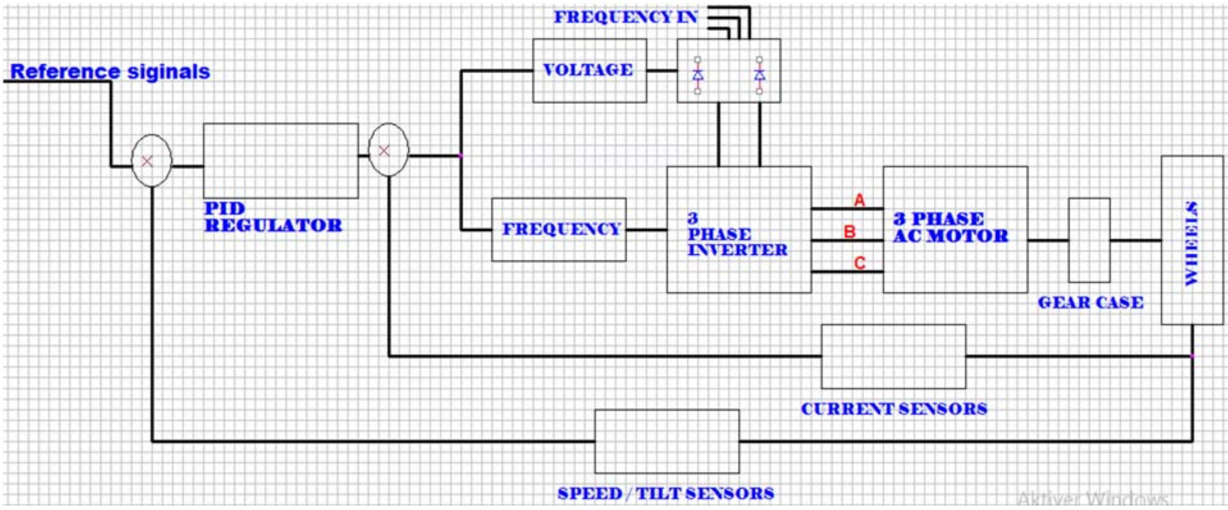


FIGURE 9 - THREE PHASE AC MOTOR SKETCH

Diagrams to explain how the different electrical components will communicate depending on motor type.

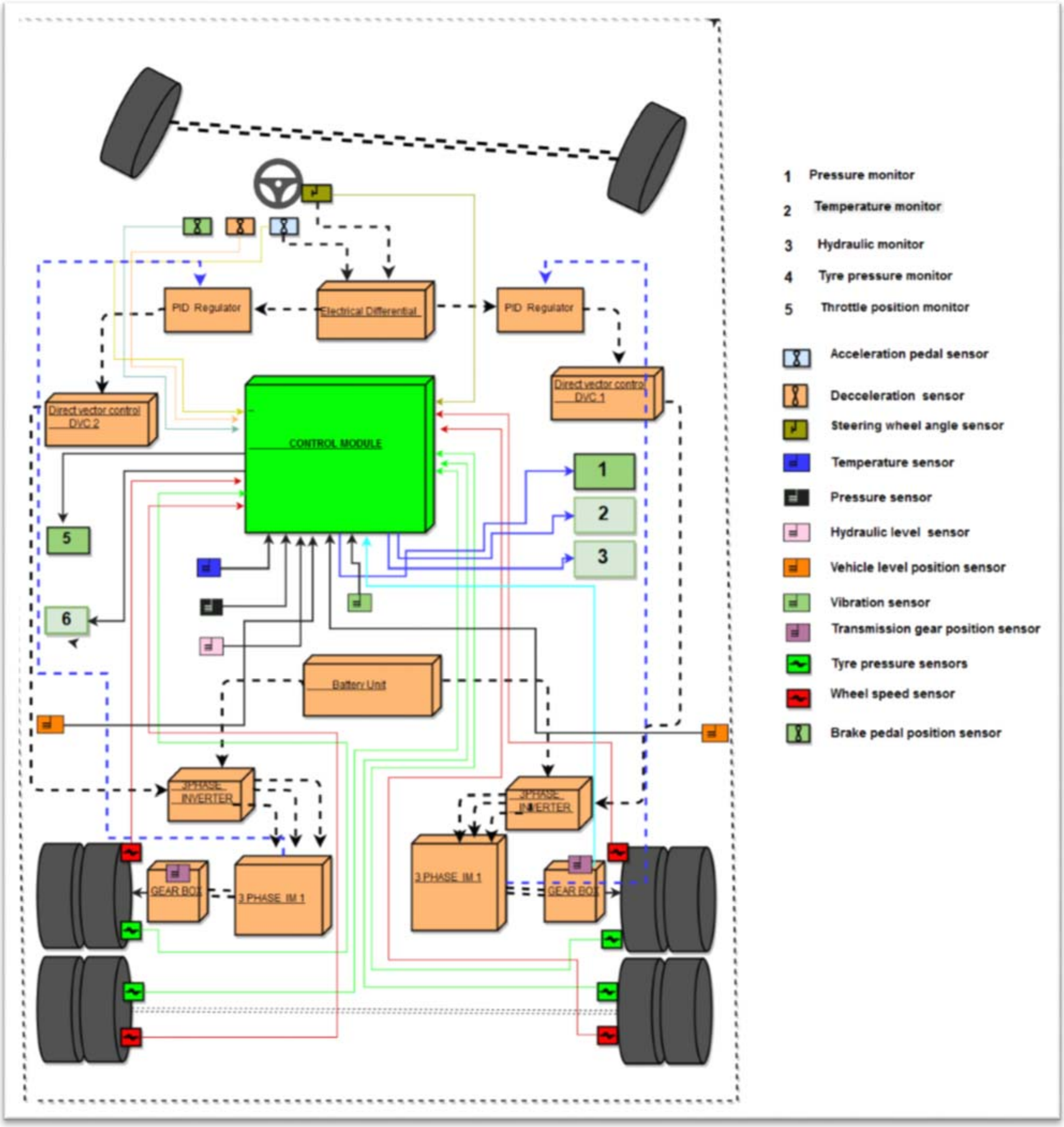


FIGURE 10 - CONTROL MODULE 1

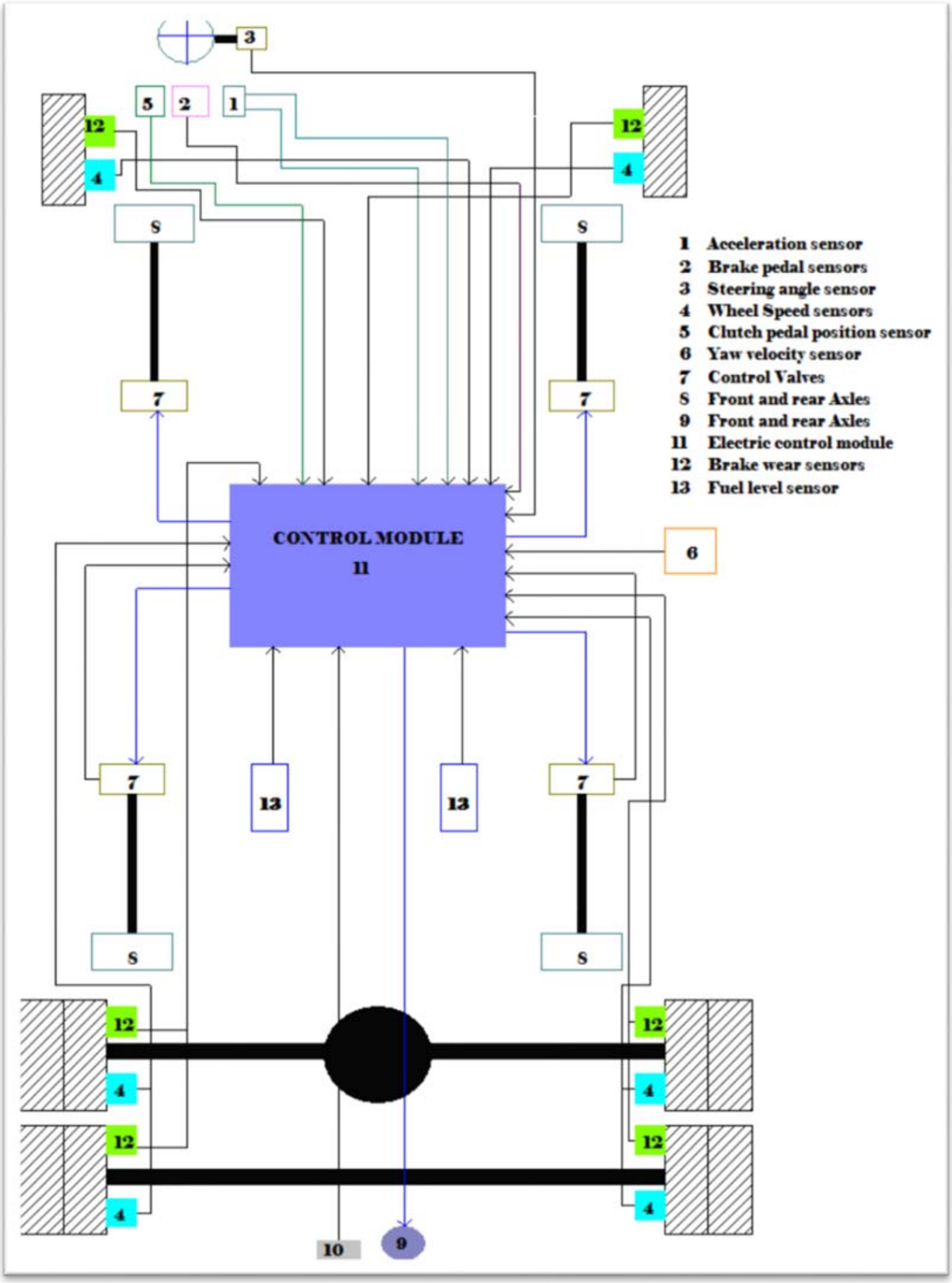


FIGURE 11 - CONTROL MODULE 2

Conclusion:

A foundation of the legacy system is in place. Numerous questions are raised regarding the system. The group needs to dive deeper into the system to get detailed understanding before designing a new system. Mutual understanding of what the stakeholders wants is clarified. The group approves the project plan and decides to carry on with the project to the elaboration phase accordingly.

4. ELABORATION

This phase consists of two iterations. Each iteration is of two-week sprints. The period of this phase is:

- Start: 08.02.17
- End: 07.03.17

4.1. E1

Plan:

- Functional analysis of legacy system
- Functional analysis of new system
- Brake system
- Air suspension system
- Detailed requirement breakdown
- System drawings
- Ackermann traction model

Content:

Iteration 1 in the elaboration phase is initiated with discussion of possible challenges we can face in the project. A lot of concern regarding what the new system requires, and the challenges that may occur. The team suggests using time to get the remaining understanding of the existing system. This is key for the group to get a solid architectural foundation for the new system. Functional analysis diagrams are created to help us elaborate further. Requirements are broken down and put in to structure to make the process more manageable. An overview of system components is made to create understanding of which ones the new system needs to have, and which can be removed. Hence the system drawings with components.

Tasks are divided among the team members. Parts of the system that is elaborated further: electric control systems, suspension parts and transmission. An Ackermann traction model is created to determine the vehicles traction during cornering on uneven road. This model will be used later for calculations in the architectural design phase. Transmission is the biggest challenge, mainly because the need of one transmission *per wheel*. The issue of how these will communicate with each other, where they should be placed and what type should be chosen. After extensive research, three types of transmission are considered as potential candidates; manual, semi-automatic and automatic.

Resulting figures & diagram:

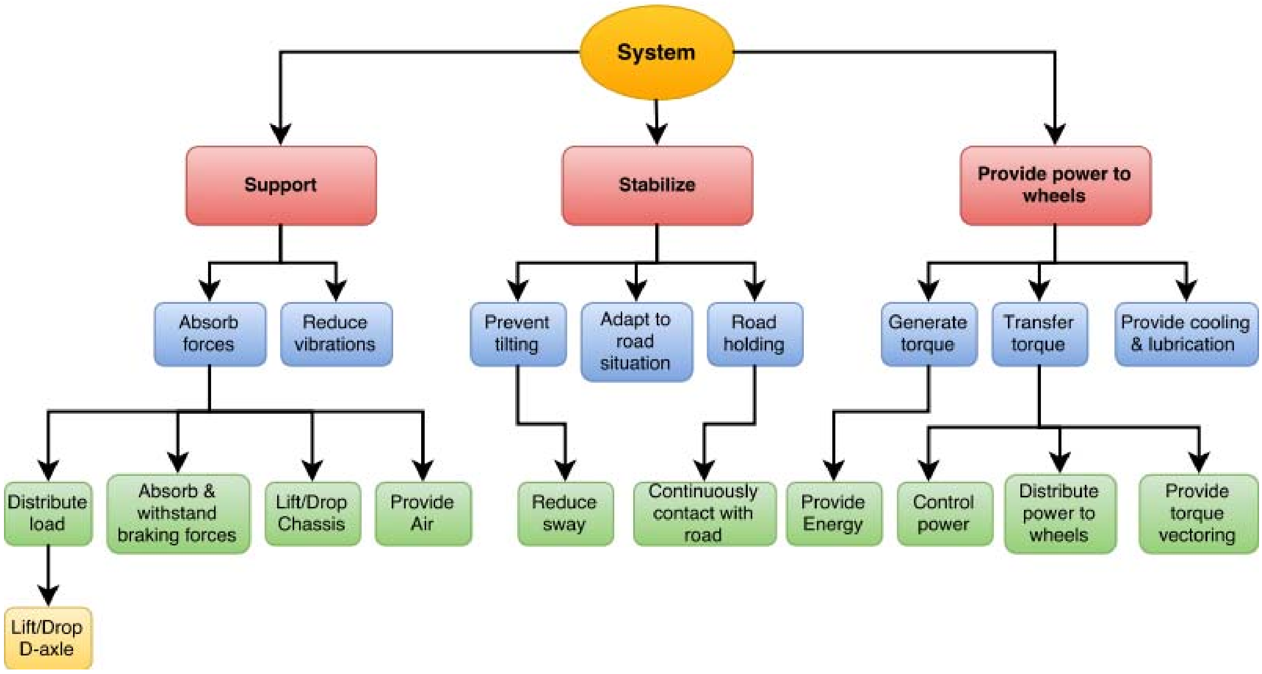


FIGURE 12 - FUNCTIONAL DIAGRAM OF LEGACY SYSTEM

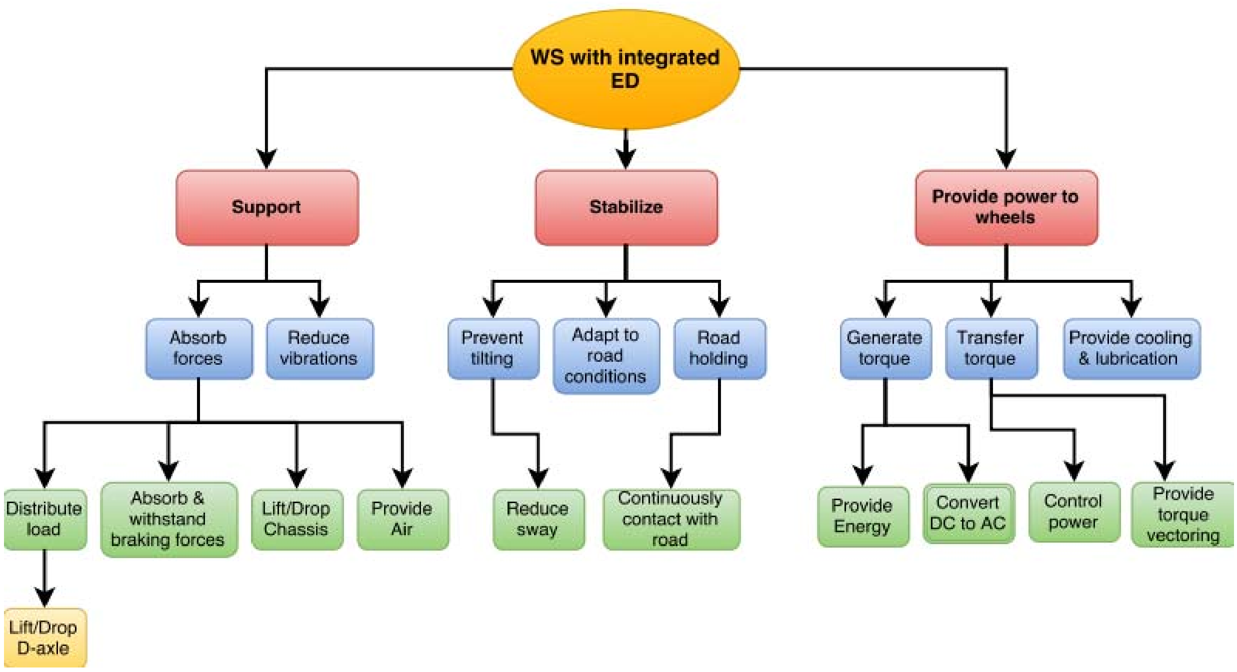


FIGURE 13 - FUNCTIONAL DIAGRAM OF NEW SYSTEM

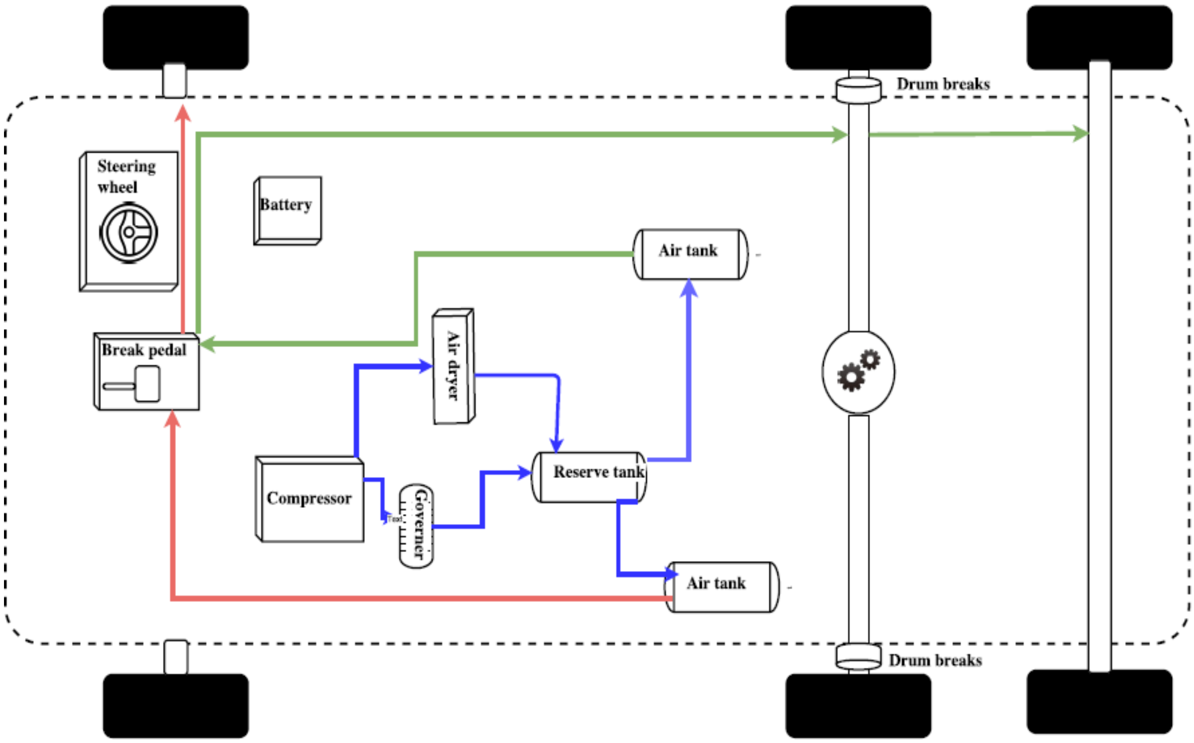


FIGURE 14 - AIR BRAKE SYSTEM

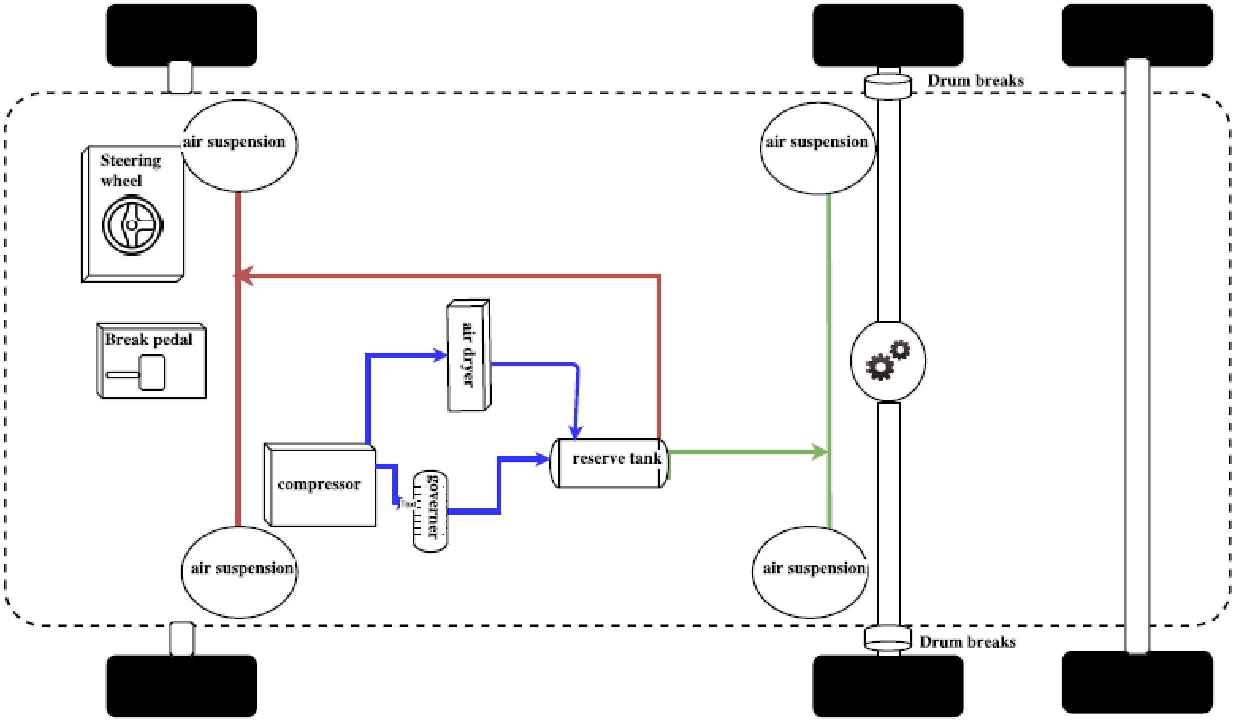


FIGURE 15 - AIR SUSPENSION

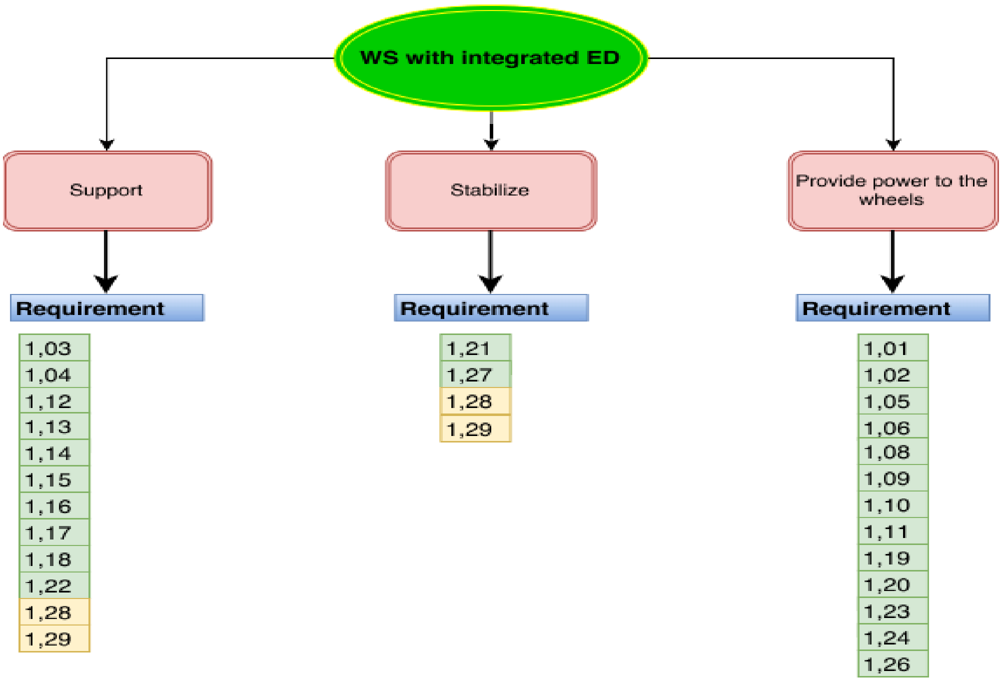


FIGURE 16 - REQUIREMENTS BREAKDOWN STRUCTURE

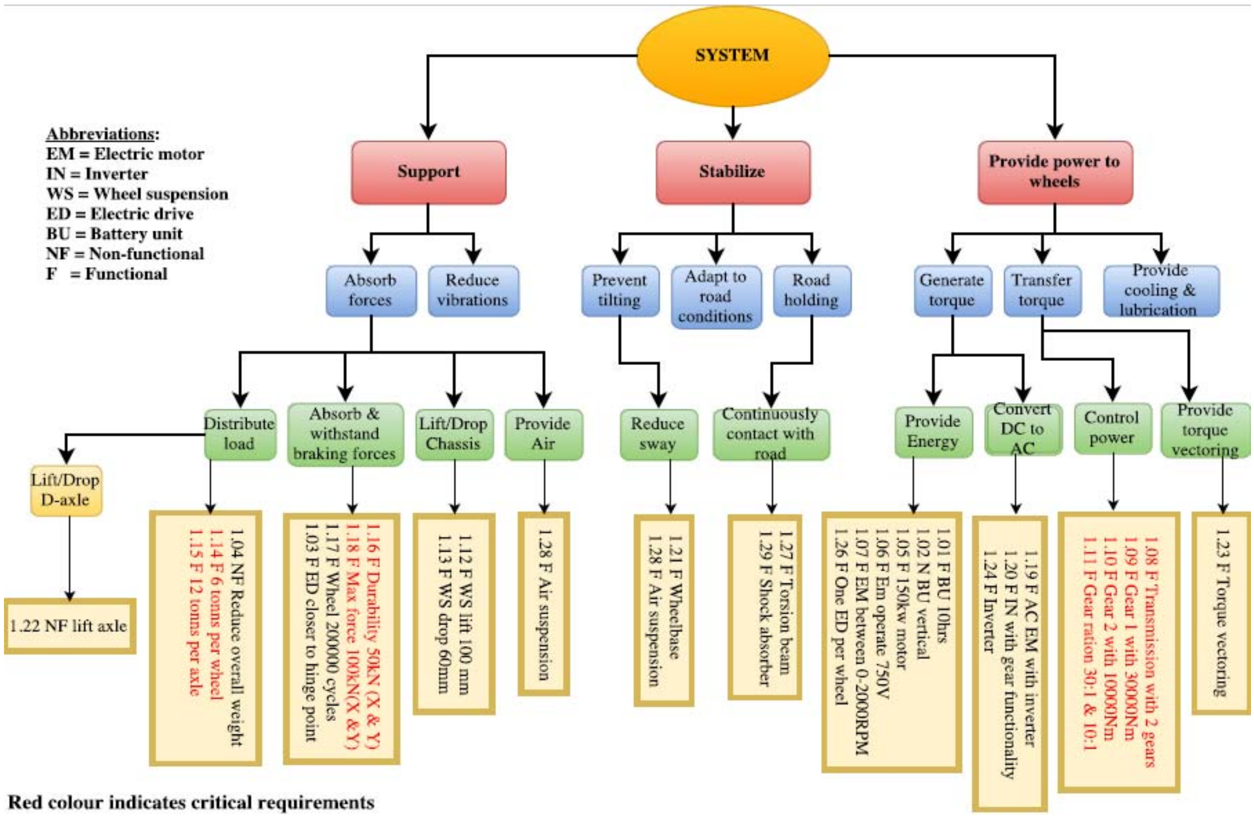


FIGURE 17 - REQUIREMENTS BREAKDOWN

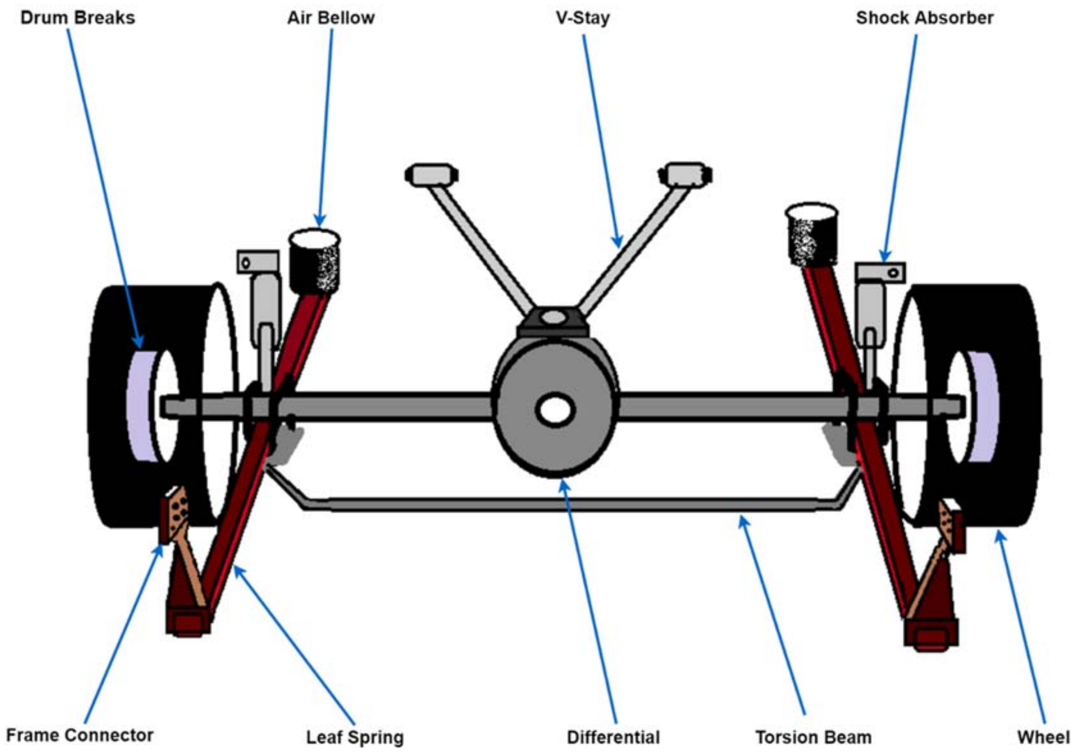


FIGURE 18 - SYSTEM COMPONENTS BACK VIEW

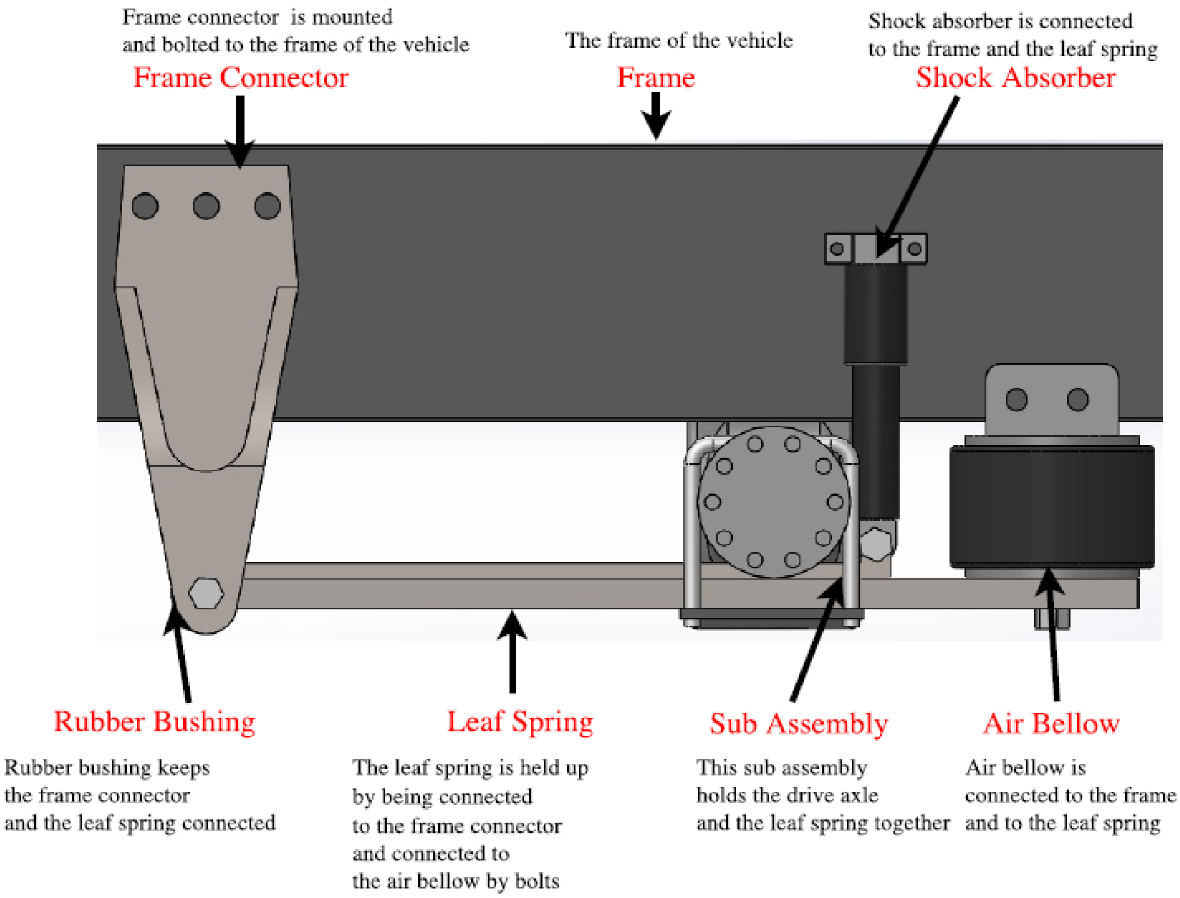


FIGURE 19 - SYSTEM COMPONENTS SIDE VIEW

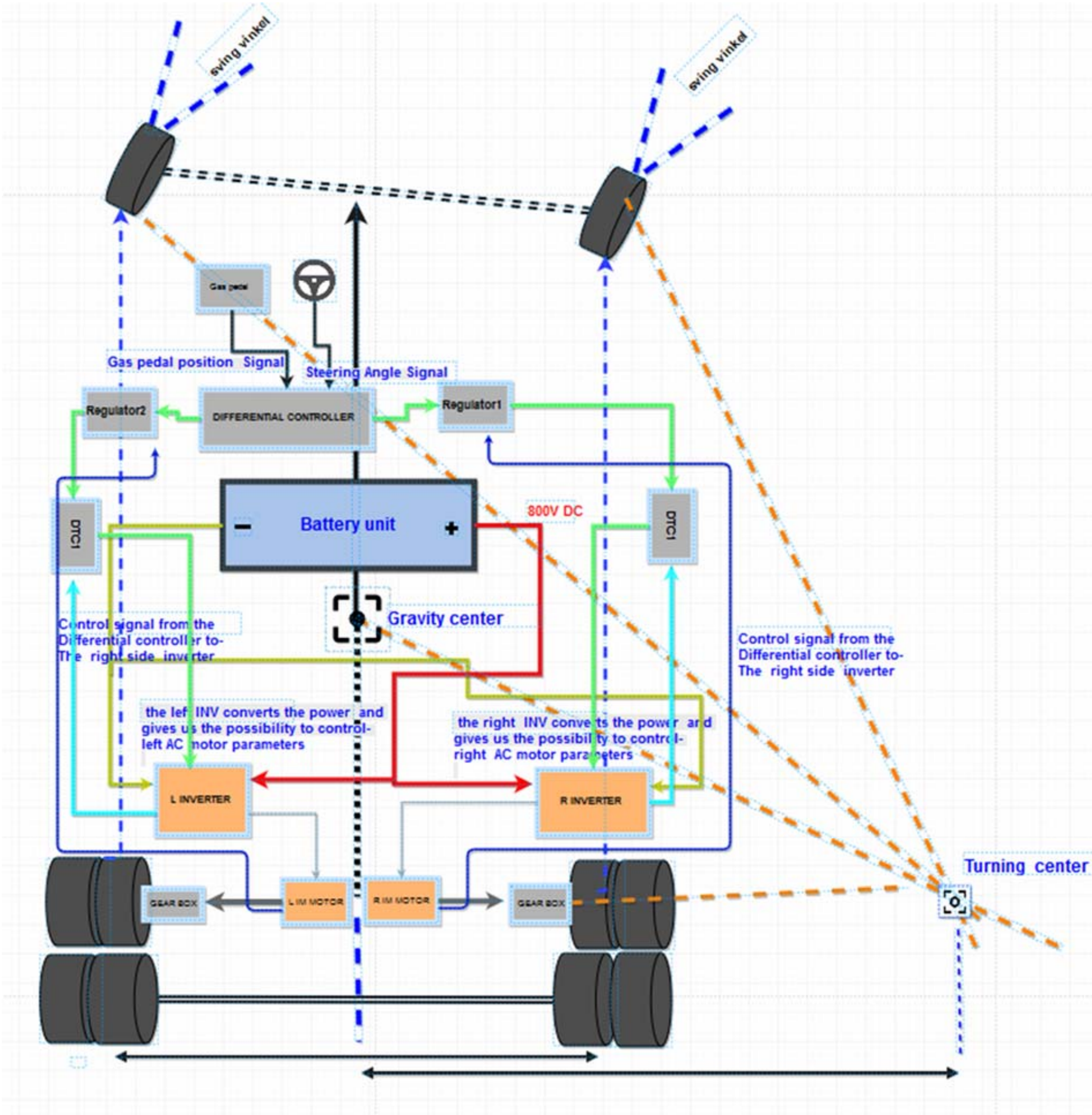


FIGURE 20 - ACKERMANN TRACTION MODEL

Conclusion:

Work so far has been evaluated. At this point each member has got a better understanding of the legacy system. Especially the wheel suspension system. The comprehensiveness of the system requires elaboration of more subsystems before entering the next phase. This is so that everything can be considered before the design phase. Also, as we predicted, the transmission is the most challenging. Main concern is which transmission we can use and still fulfill the criteria for the system to be satisfying. Further research and guidance is necessary to get some sort of progression with this component, since it's a major key for the new system. The information we have gathered in this iteration, will be worked on further in iteration 2.

4.2. E2

Plan:

- Subsystem components breakdown
- Air suspension system breakdown
- Cooling system
- Extended use case
- Sequence diagram
- Calculations
- Wheel suspension concepts
- Electric drive concepts

Content:

The iteration is initiated with status regarding overall progression of the project. Key concerns are discussed. Since this is going to be the last sprint of the elaboration phase, remaining work needs to be finished before progressing.

Remaining subsystems needs to be elaborated. Design concepts must be created. The concepts can be anything from existing to unrealistic ideas. An "out of the box" thinking is applied during the brainstorming. Ideas are hand sketched individually, and brainstormed further with the whole group. Cardboard and clay is used to elaborate the concepts where drawings aren't enough. 14-15 concepts are created during this brainstorming sequence. Calculations of necessary forces must be done for concepts to be as realistic as possible. Transmission issues must be solved. Basic calculations are done to get a better understanding of how this issue will be solved. At the last day of this iteration the team has scheduled a meeting with KA where all the concepts and work will be presented.

Resulting figures, diagrams & calculations:

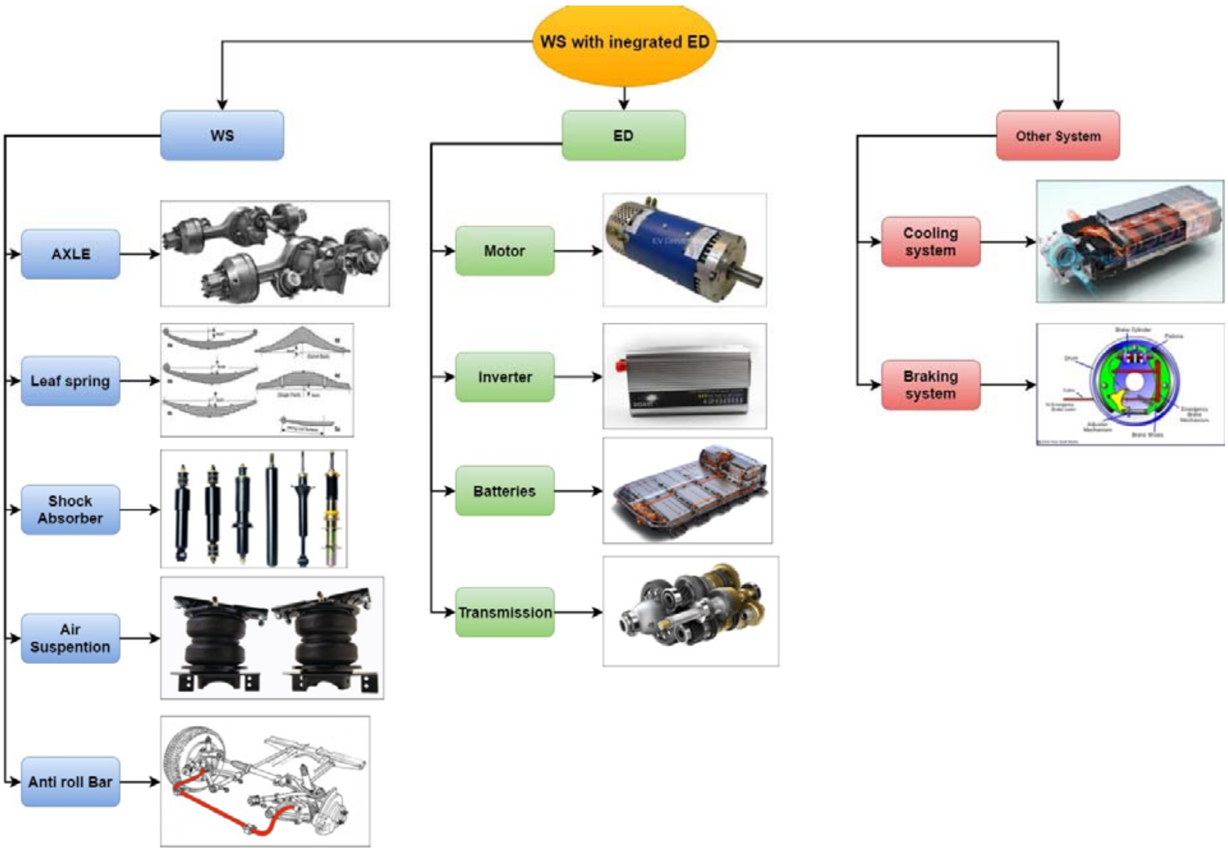


FIGURE 21 - COMPONENT BREAKDOWN

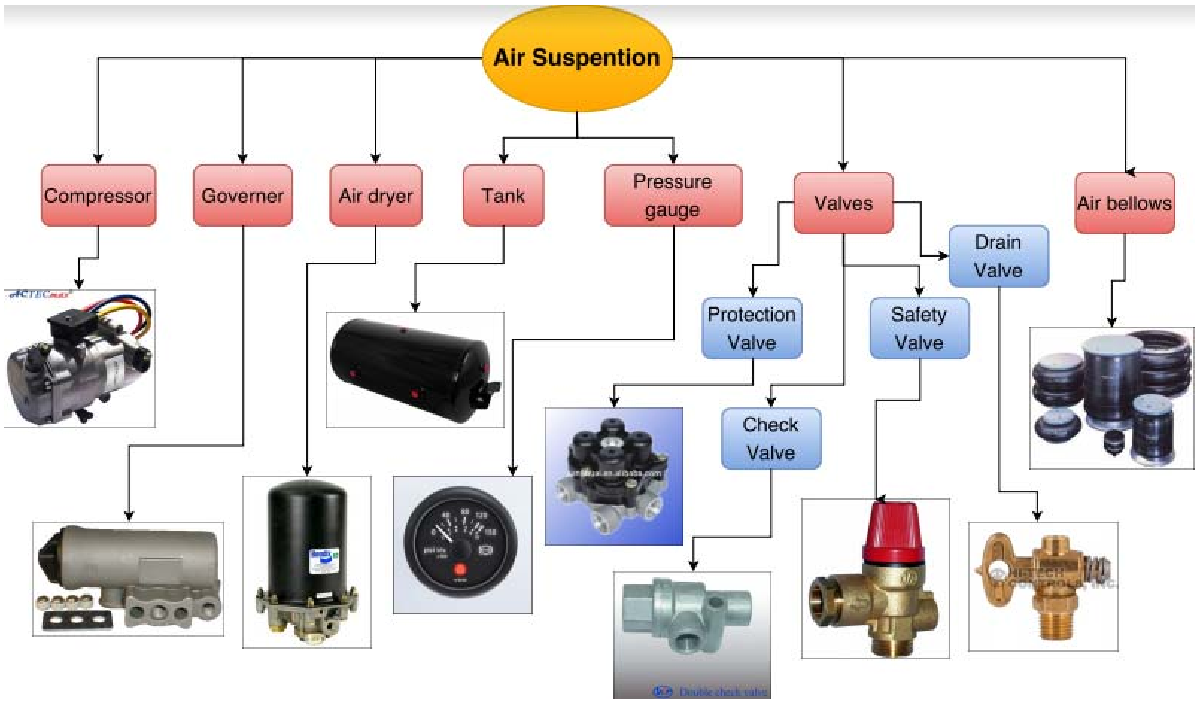


FIGURE 22 - AIR SUSPENSION COMPONENT DIAGRAM

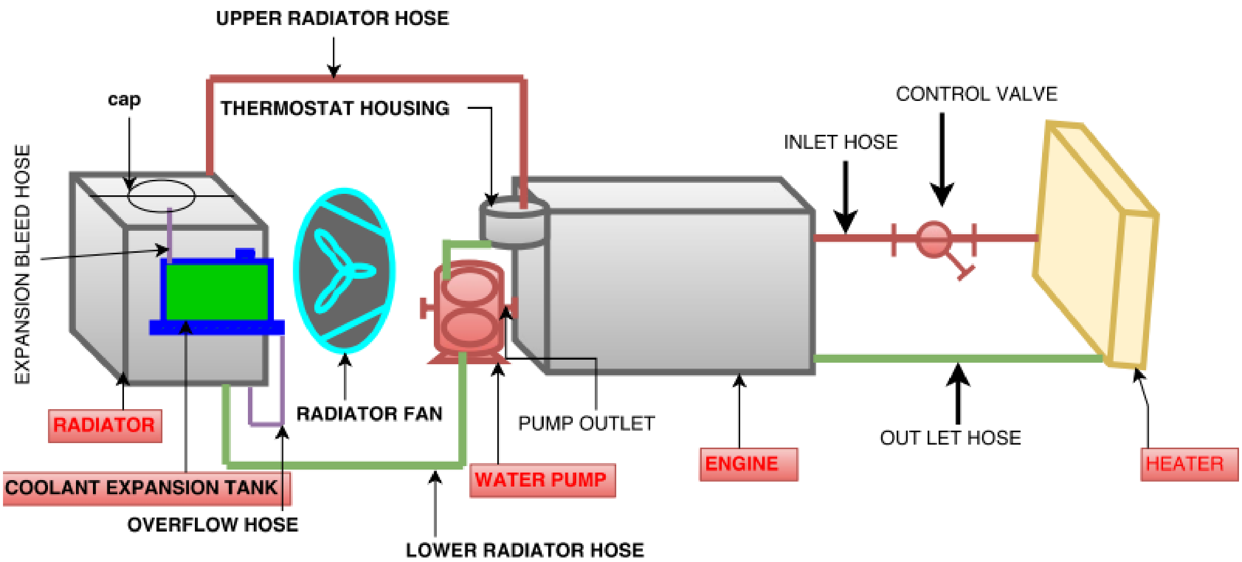


FIGURE 23 - COOLING SYSTEM OF LEGACY SYSTEM

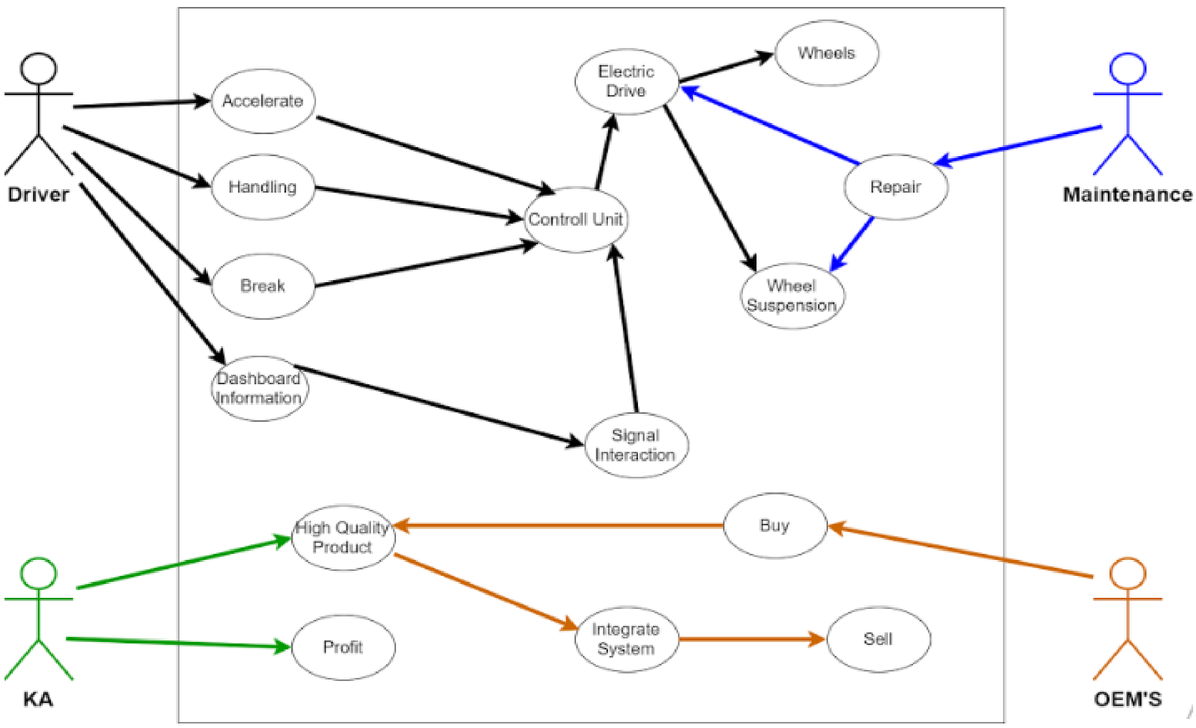


FIGURE 24 - EXTENDED USE CASE DIAGRAM

This diagram explains the interaction of stakeholders in the system.

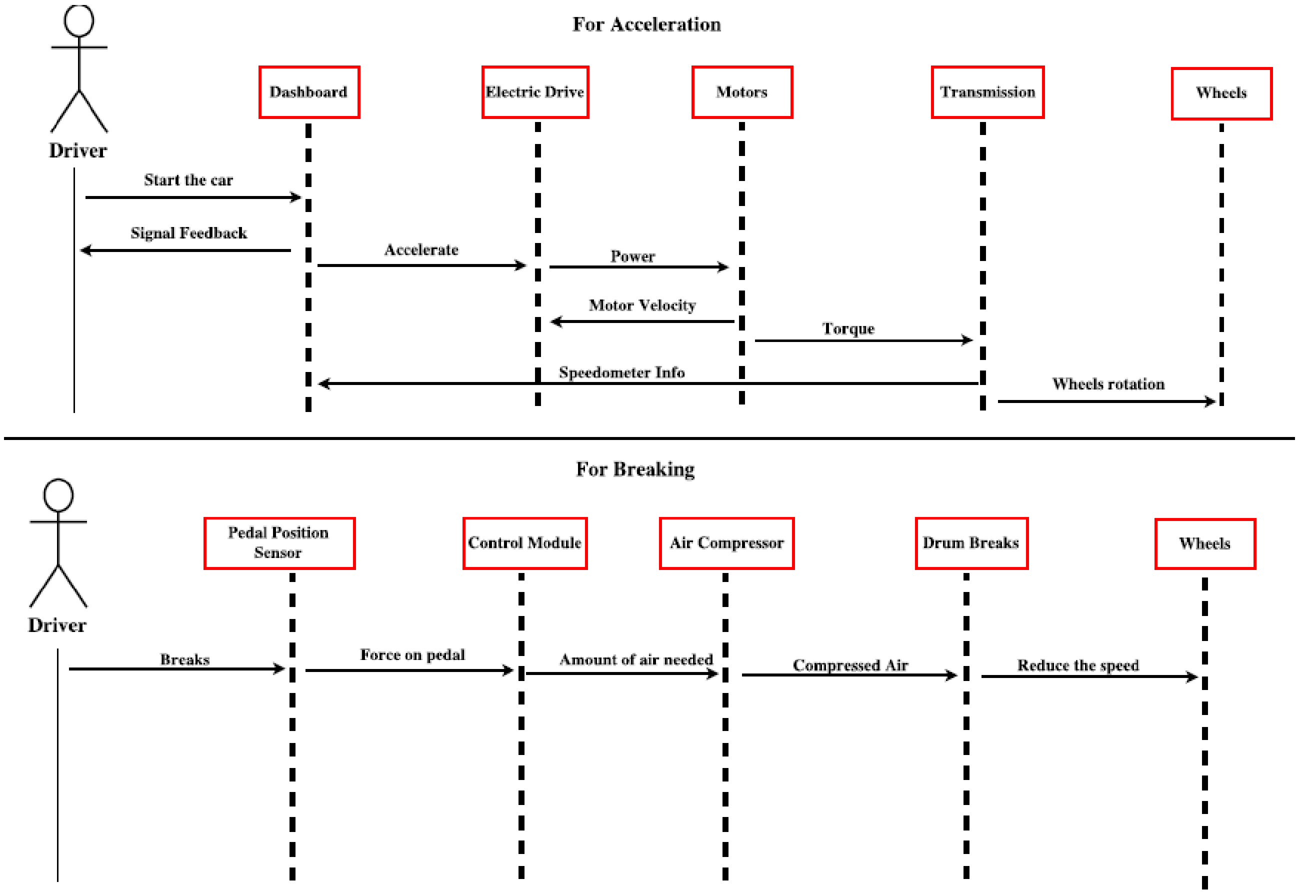


FIGURE 25 - SEQUENCE DIAGRAM

Sequence diagram illustrates how the different objects operate with one and another and in what order.

Reference motor dimensions [7]

Cylindrical:

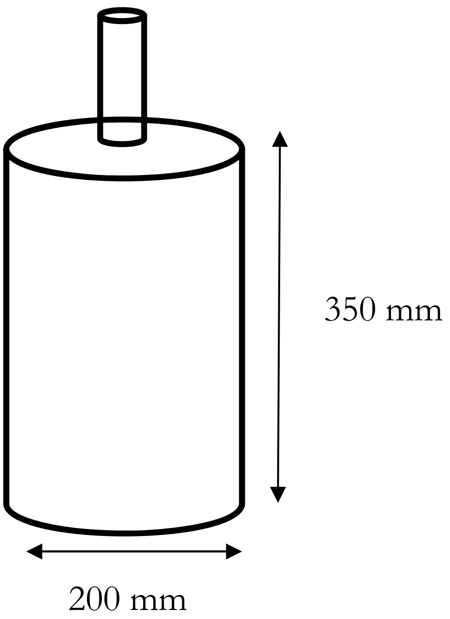


FIGURE 26 - CYLINDER MOTOR

Volume = $\pi\ x\ 100\ x\ 350$ = <u>110 000 mm²</u>

Area = $\pi\ r^2$ = <u>3146 mm²</u>

Pancake:

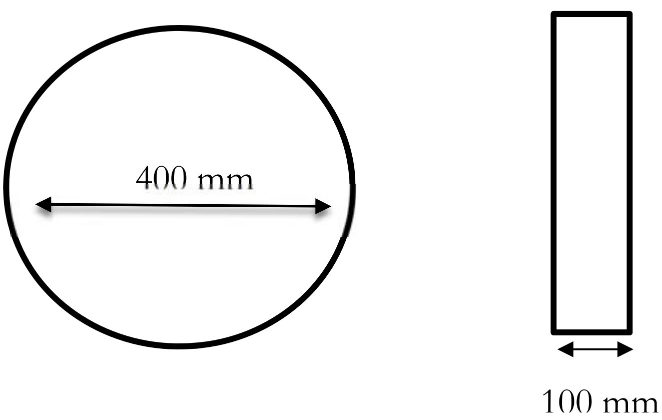


FIGURE 27 - PANCAKE MOTOR

Volume = $\pi r h$ = 62 832 mm^3

Area = πr^2 = 125 664 mm^2

Forces on axle & wheels [2]

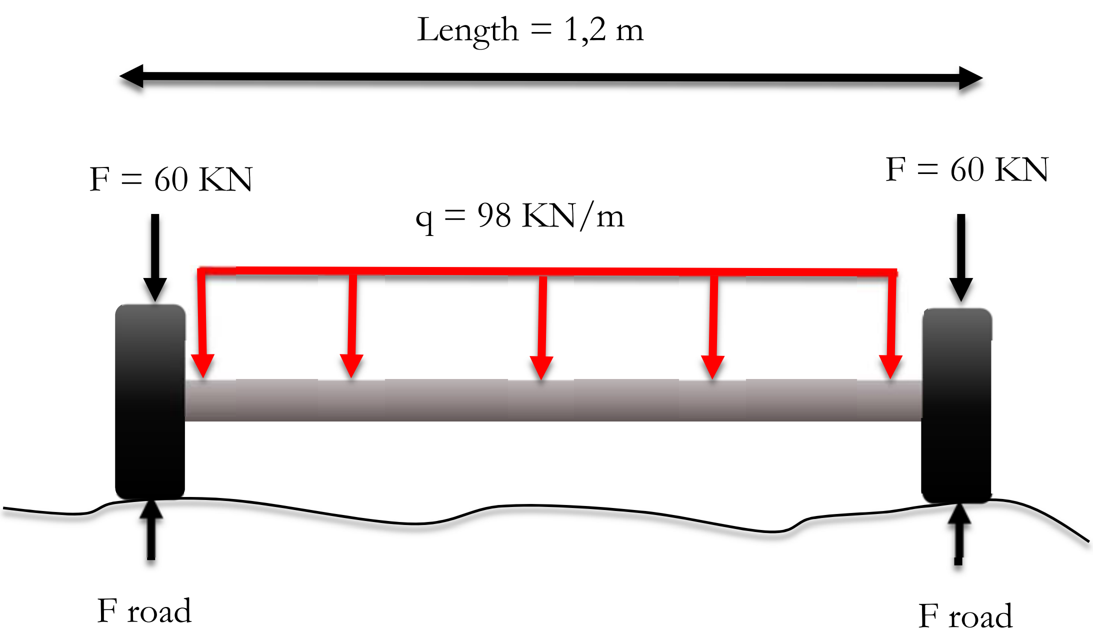


FIGURE 28 - FORCES ON AXLE

Forces acting on wheels. F = 60 KN is the force of each wheel. F road is a force acting on the wheels from the road. q = 98 KN/m is even distributed load acting on the axle. The length of the axle is 1,2 meters.

Applying this to Newtons second law F = mass x gravity, we get:

F = 1200kg x 9,81 m/s^2 = 117,7 KN

Transmission calculations

To comprehend how transmissions work, simple calculations are done using a gear ratio formula [2]. This will benefit us in choosing the correct design for our system.

Pd = pitch diameter N_r = *teeth number of ring gear*

N_s = *teeth number Sun gear* N_p = *teeth number of planet gear*

M = module -> m = pitch diameter/number of teeth

Ratio = 10: 1

Sun gear $Pd_s = 32 \times 1 = \underline{32\ mm}$

$R = 1 + N_r / Pd \rightarrow N_r = Pd\ (R-1)$

$Nr = 32\ mm\ (10-1) = 32 \times 9 = \underline{288\ teeth}$

Pitch diameter of Ring gear = $288 \times 1 = 288\ mm = Pd_r$

Pitch diameter of Planet gears = $(N_r - Pd_s)/2 = (288-32)/2 = 128\ mm$

$N_p = Pd_p / 1 = \underline{128\ teeth}$

$R = 1 + N_r / Pd = 1 + 288/32 = 1 + 9 = \underline{10}$

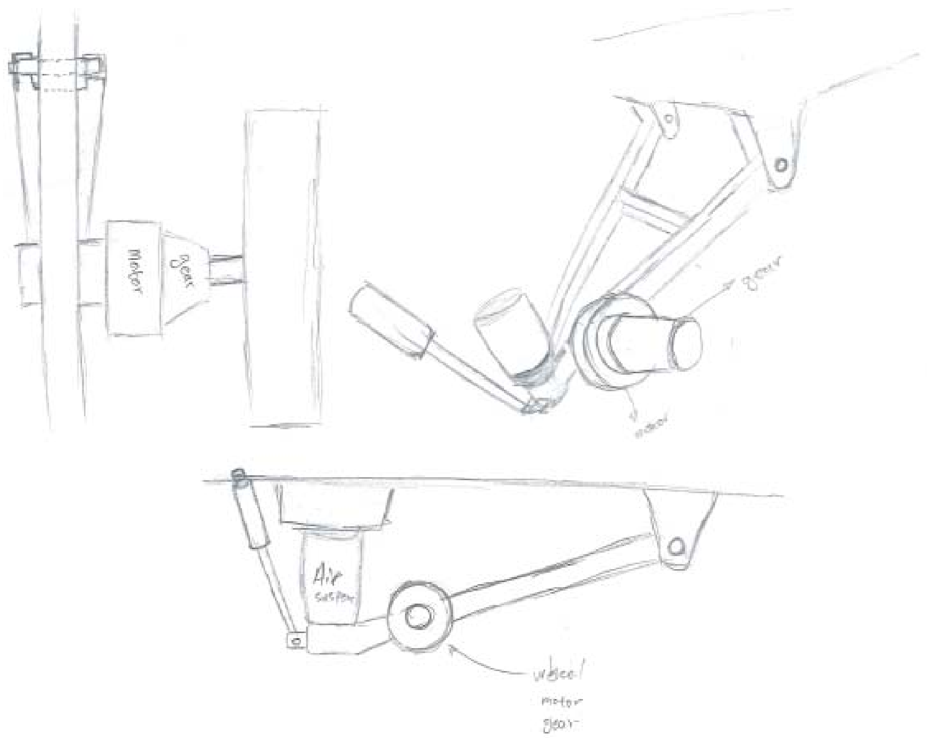


FIGURE 29 - EARLY CONCEPT 1

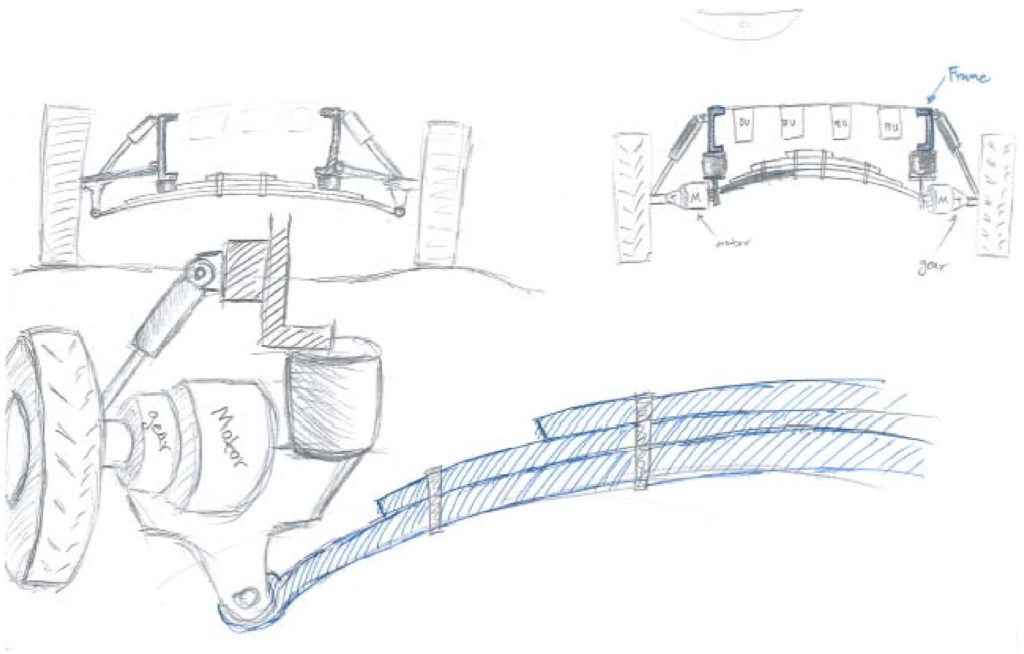


FIGURE 30 - EARLY CONCEPT 2

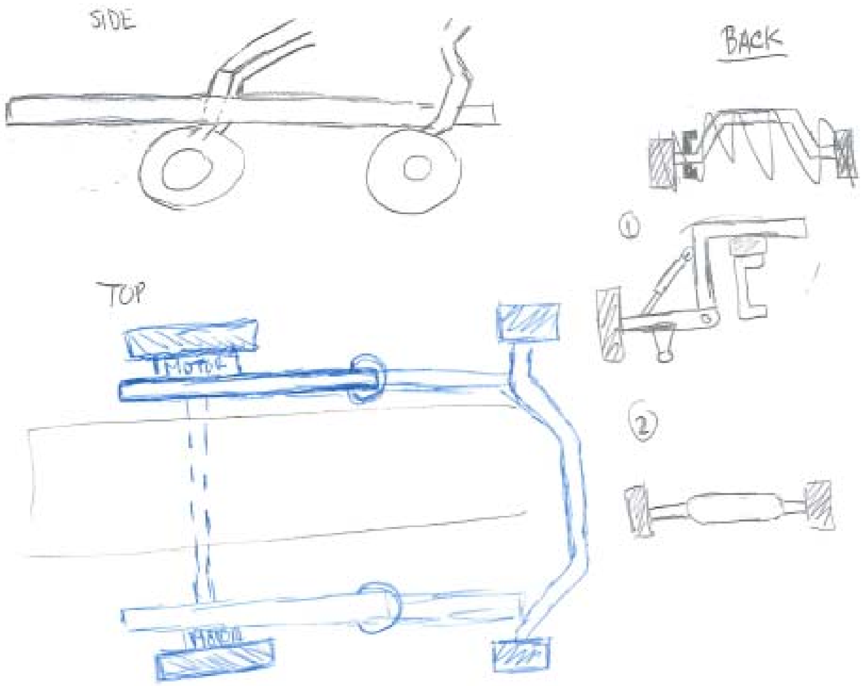


FIGURE 31 - EARLY CONCEPT 3

Some of the suspension concepts created by the team.

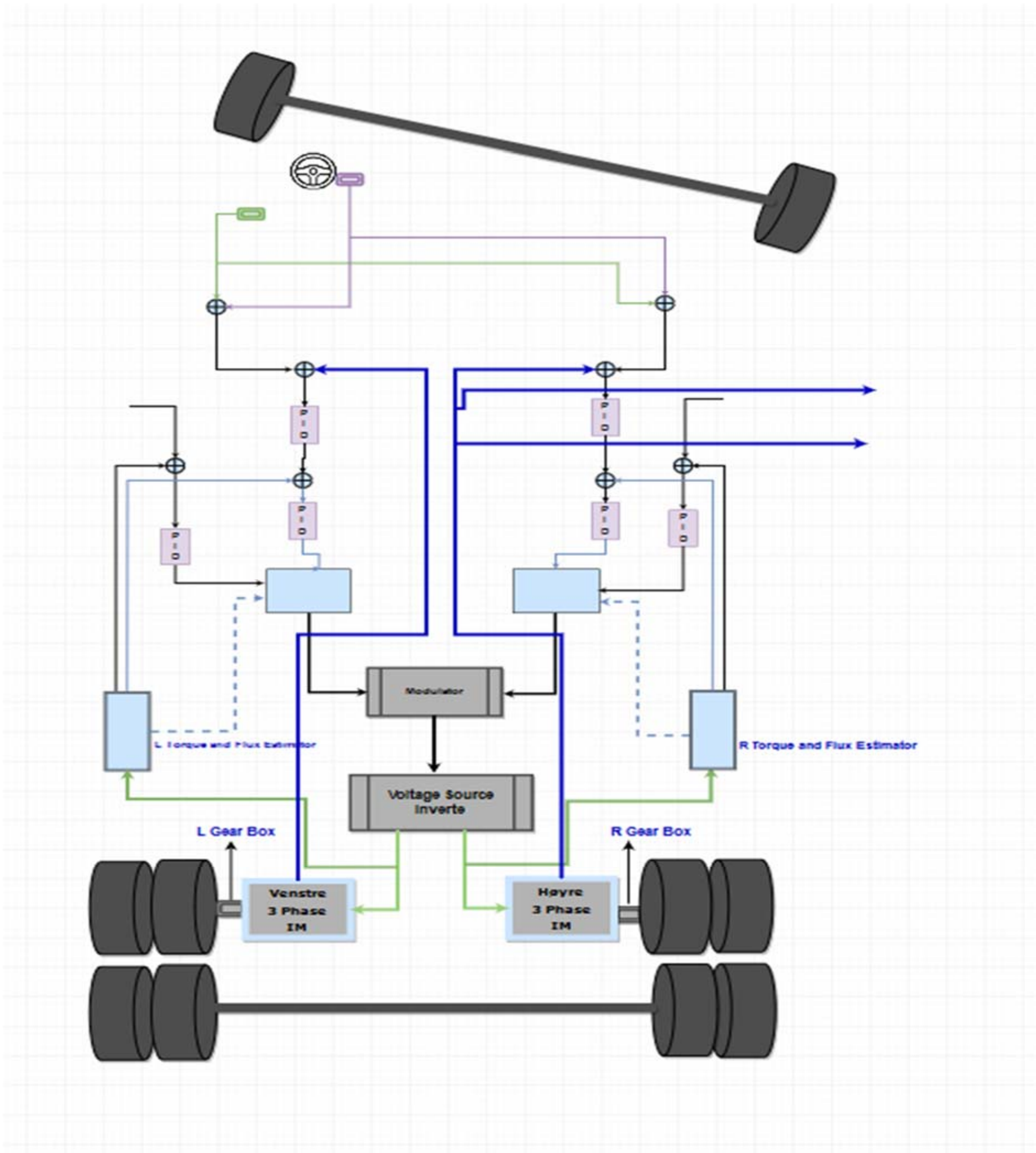


FIGURE 32 - CONCEPT 1

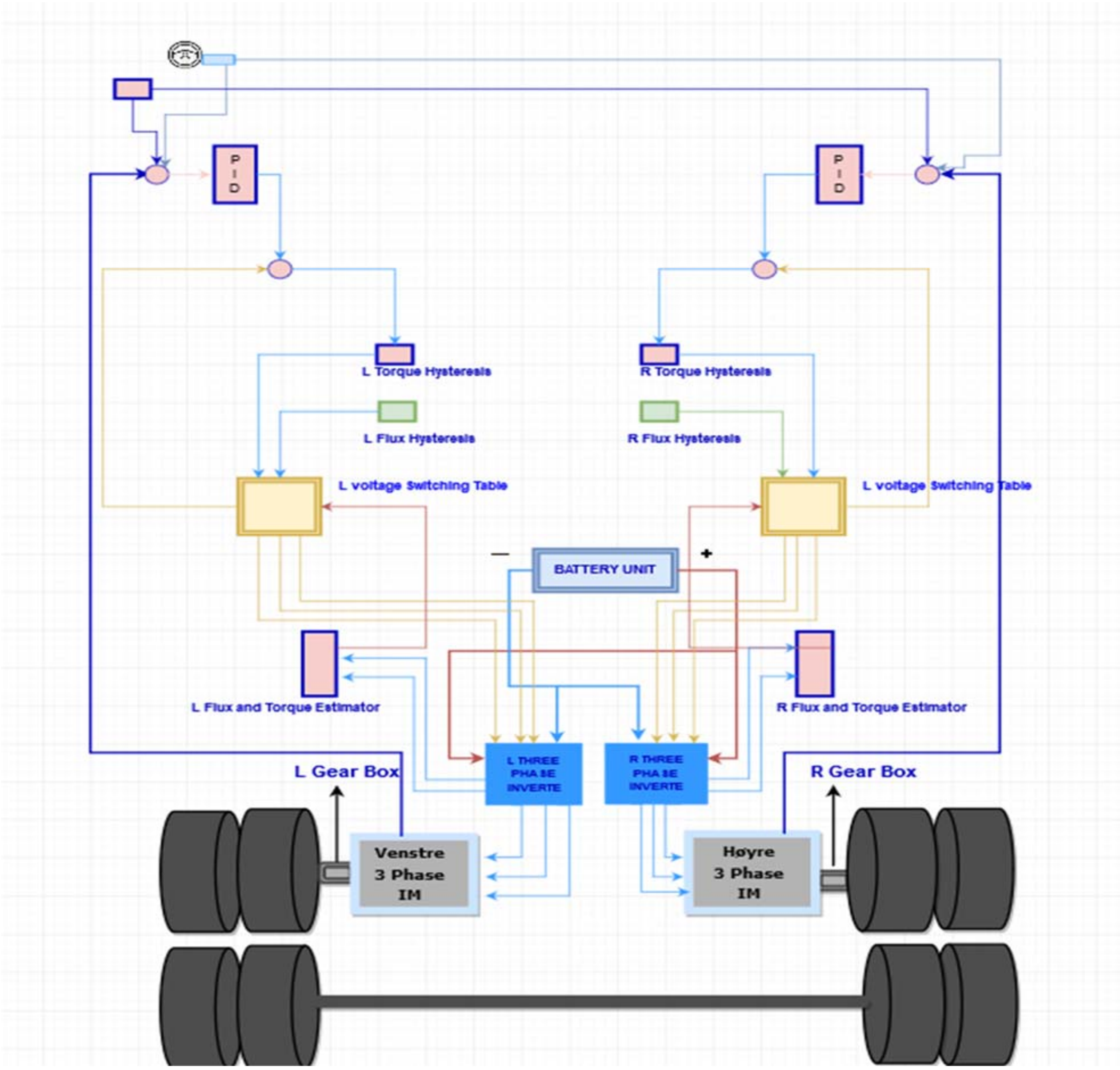


FIGURE 32 - ELECTRIC DRIVE CONCEPT 2

Electric drive concepts created by the team.

<u>Conclusion:</u>

Elaboration phase is now complete. All initial concepts the team has designed have been presented to our primary stakeholder KA. We received positive feedback on the idea process and the amount of work we have put in since the last meeting.

Concepts that we presented were: suspension design, control module concepts and various transmissions we are considering. Transmission was as earlier mentioned our biggest concern. KA sent us in the right direction and wants us to dive further in to planetary gears as the go-to component. We also need to focus more on the concept design in the next phase. Most of our suspension design was of dependent axle types. Now the focus must switch to independent axle types. When this has been done, another round of brainstorming should happen. The idea is to compare and pick the best from each concept. During the concepts designing, we tended to lock our minds to one specific way of thinking. This is something we must have in mind when entering the next phase.

5. ARCHITECTURAL DESIGN

This phase consists of five iterations. In this phase, there is also dedicated exam preparation time for Mechatronics. The period of this phase is:

- Start: 08.03.17
- End: 03.05.17

5.1. A1

Plan

- Produce suspension concepts
- Produce transmission concepts
- Cooling system solution for our system
- Pugh matrixes
- Morphological chart
- Technical document

Content:

This iteration is initiated with discussion regarding the feedback we got from KA. A plan is set for what we want to produce during this iteration. Brainstorming sessions for independent suspension systems are done. Each member produced suspension concepts based on feedback from stakeholder and additional tasks are assigned to develop the entire system. Concepts are organized in different stages from stage 1-3. Different suspensions concepts are combined using a morphological chart. Pugh matrixes are used to compare the newly designed concepts to get an overview of each of the concepts.

Resulting charts & matrixes:

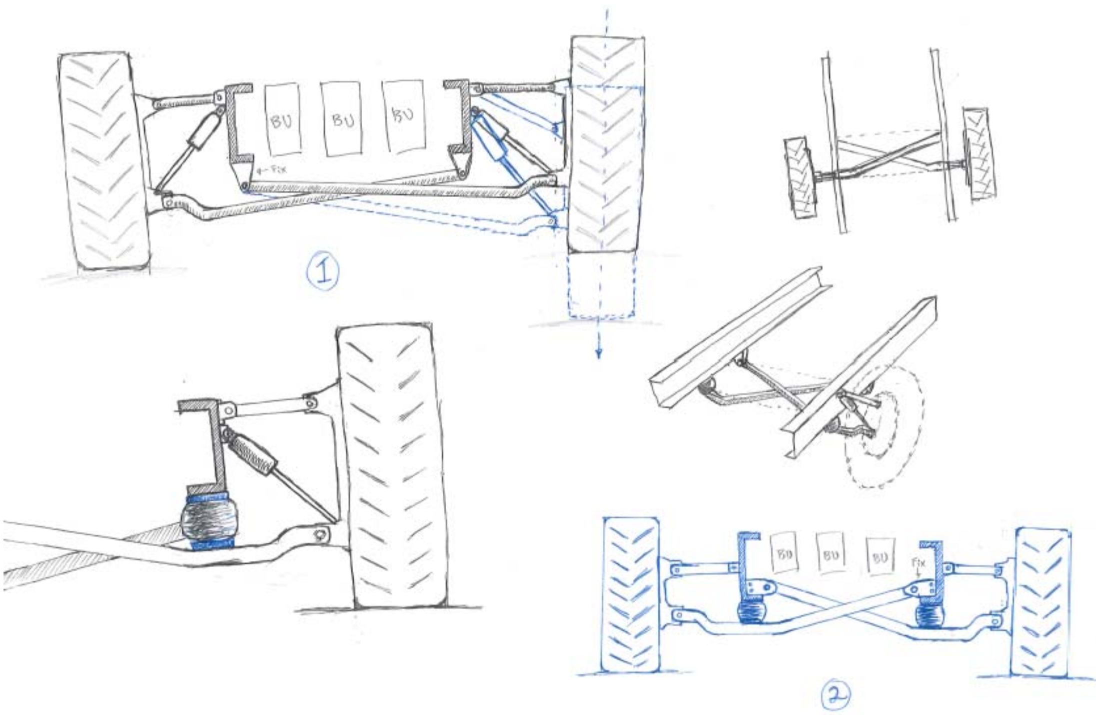


FIGURE 33 - CONCEPT 1 STAGE 3

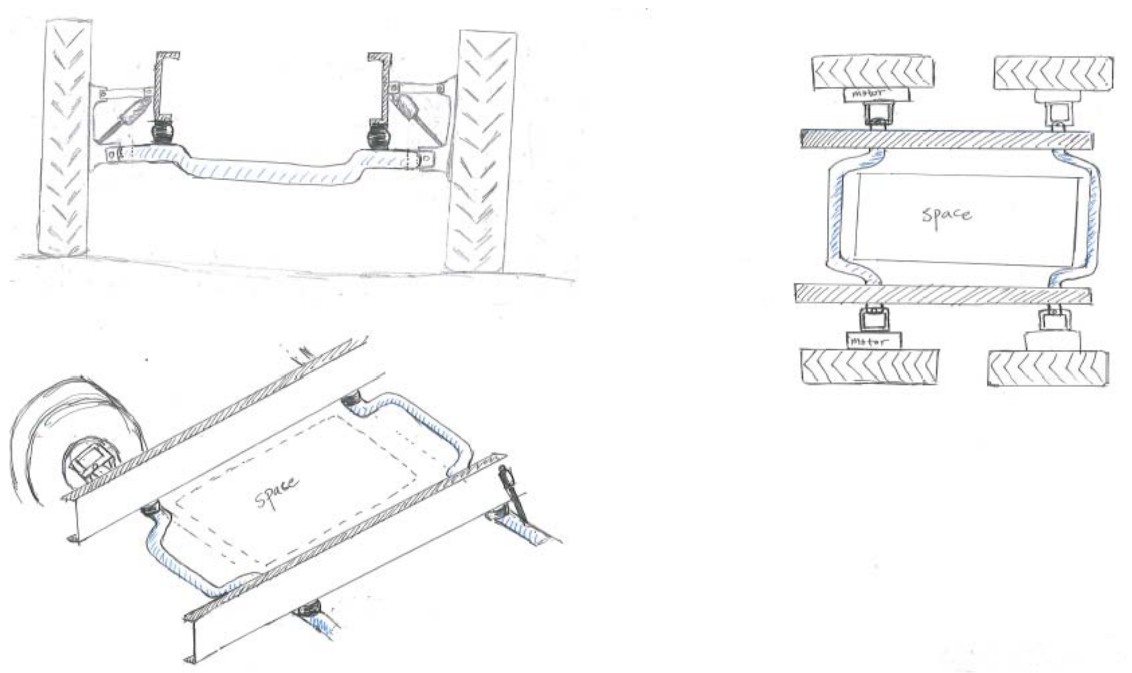


FIGURE 34 - CONCEPT 3 STAGE 3

Example of suspension concepts designed. These are explained in detail in the concepts document [3].

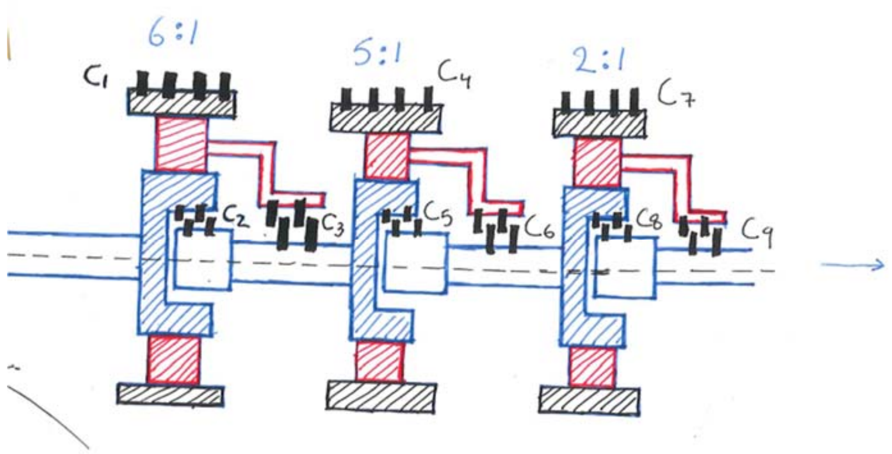


FIGURE 35 - TRANSMISSION CONCEPT 1

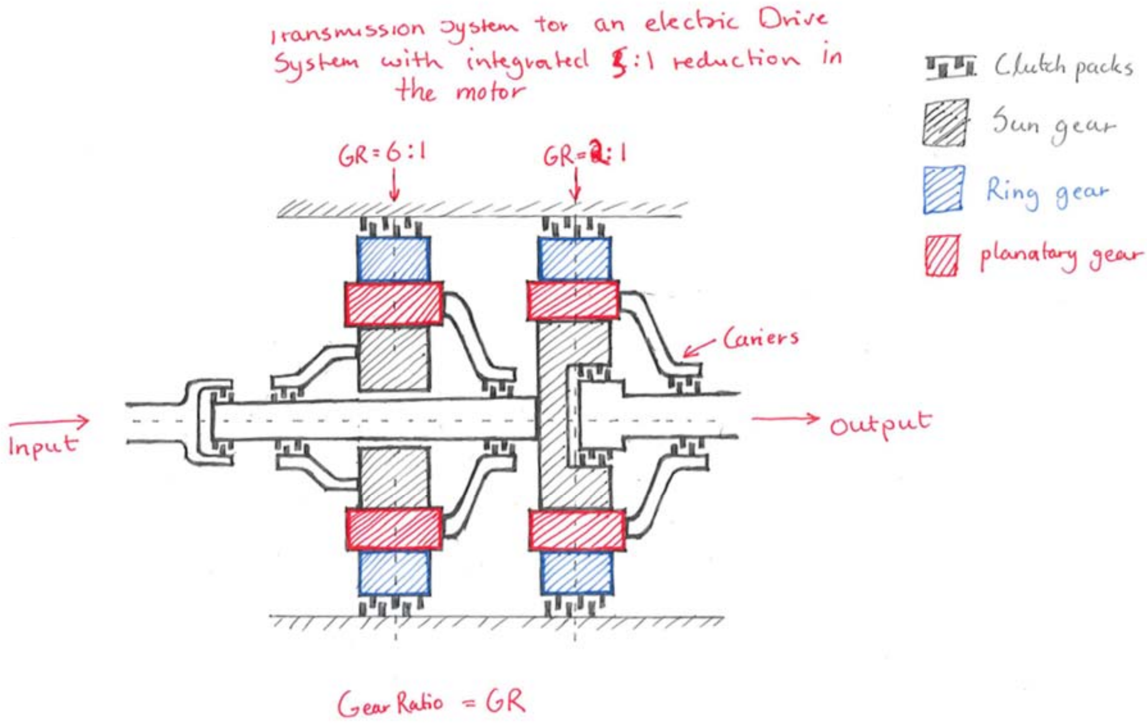


FIGURE 36 - TRANSMISSION CONCEPT 2

Transmission concepts. Explained in detail in the concept document [3].

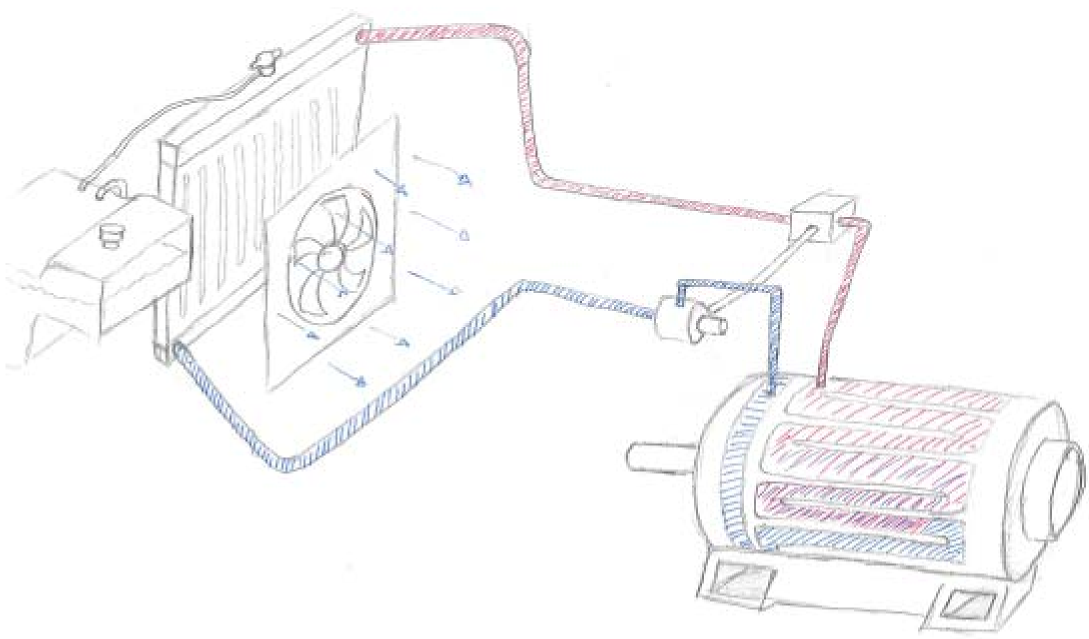


FIGURE 37 - CONCEPT FOR NEW COOLING SYSTEM

Cooling system we are going to use. Explained in the technical document [5].

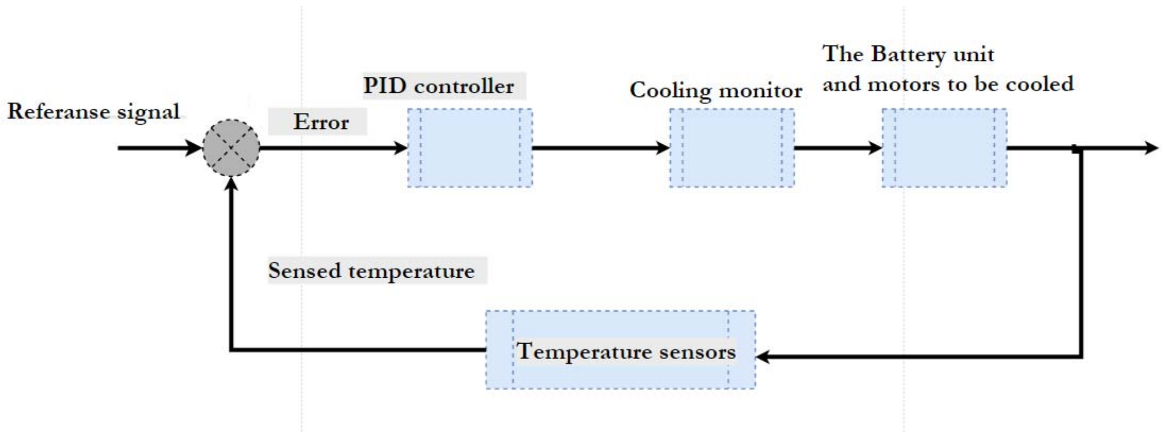


FIGURE 38 - ELECTRONIC REGULATION OF COOLING SYSTEM

This diagram explains how the cooling system will be regulated electronically.

Components	Option 1	Option 2	Option 3
Axle	Independent	Dependent	Semi-independent
Shock Absorber	Twin tube	Monotube	Struts
Electric Drive	Close to hinge point	In Wheel	Outer Wheel
Motor	Pancake	Cylinder	Optional design
Transmission	Planetary	Semi-Automatic	Automatic

TABLE 3 - MORPHOLOGICAL CHART

Morphological chart used to combine the different concepts together.

#	EVALUATION CRITERIA	RATING (1-5)	AXLE TYPE	
			DEPENDENT	INDEPENDENT
1	Durable	**5**	+	-
2	Stabilize	**4**	+	S
3	Forces	**4**	+	S
4	Weight balance	**3**	S	+
5	Space for battery	**2**	-	+
6	Comfort	**1**	S	+
7	Cornering	**3**	S	+
8	Flexibility	**2**	-	+
9	Cost	**2**	+	-
10	Un-sprung mass	**1**	S	+
11	Traction	**1**	S	+
Sum of Positives			4	7
Sum of Negatives			2	2
Sum of Equals			5	2
Weighted Sum of Positives			15	13
Weighted Sum of Negatives			4	7
SCORE SUM			**11**	**6**

TABLE 4 - PUGH MATRIX FOR AXLES

Pugh matrix represents the two different axle types for our concepts. We have to make a comparison on which of these axles will score best and take this in to consideration while moving on to next concepts design stage.

#	EVALUATION CRITERIA	RATING (1-5)	CONCEPT			
			1	2	3	4
1	Complexity	**1**	+	S	-	+
2	Feasibility	**3**	+	S	-	+
3	Weight	**4**	S	+	+	-
4	Durability	**5**	+	S	-	+
5	Placement of motors	**2**	S	+	S	+
6	Placement of transmission	**2**	S	+	S	+
7	Battery space	**4**	+	+	S	+
8	Stability	**5**	+	+	+	+
9	Independence	**5**	S	+	+	-
Sum of Positives		5	6	3	7	
Sum of Negatives		0	0	3	2	
Sum of Equals		4	3	3	0	
Weighted sum of Positive		18	22	14	22	
Weighted sum of Negatives		0	0	9	9	
SCORE SUM		**18**	**22**	**5**	**13**	

TABLE 5 - PUGH MATRIX FOR CONCEPTS

Pugh matrix in table 5 is used after the concept design in stage three is done. Four of the concepts we designed are compared with each other to bring forward to stage four.

Conclusion

Three of the latest designed concepts have been presented to external supervisor at KA. We got feedback on each of them. Some are feasible, others have complexity issues that we have not taken into consideration. We learned that solving a problem in one concept, creates new ones that we aren't aware of. These problems have been brought into the newly designed concepts and made them almost impossible to realize. Two of the concepts are considered feasible. One will be more challenging, while another one is "easier", but will not bring anything new to the table. The group is now going to have a new round of brainstorming on which of the concepts we want to proceed with in the next iteration. Concepts that we do not want to proceed with will be put aside for now, but not scrapped totally.

5.2. A2

Plan:

- Choose wheel suspension concept
- Choose transmission concept
- Choose control module

Content:

In this iteration, the group developed the concept ideas further. The goal here is to decide the final concepts we want to move further with. Concepts that are presented to KA is brought up again. Older concepts that weren't elaborated further is also brought to the table again. The group decides to use most of the resources on a wheel suspension concept from the 1st stage. A fitting transmission concept is also chosen to be designed, as well as a control module.

Resulting drawings:

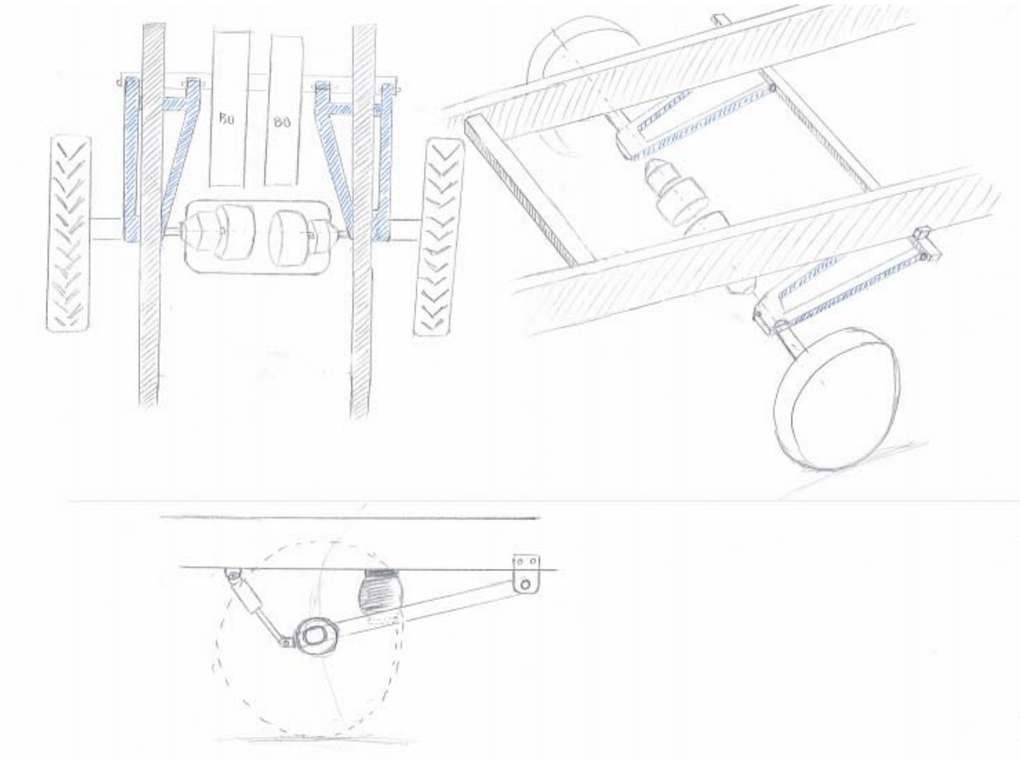


FIGURE 39 - CONCEPT 2 STAGE 4

This concept is a modification of concept 12 from stage 1. Design of the A-arms are modified slightly. Rearrangement of the motor, transmission and air bellow is also done. Motor and transmission are placed in the middle. The air bellow is moved further back on the arm. This preliminary design will be the basis for further development.

Conclusion:

The preliminary design of the wheel suspension is going to need further modifications. Assumptions indicates that the placement of motor and transmission as it is makes the design not feasible. An improved design is necessary to make the A-arms in the suspension to move up and down freely. The team will take this into consideration in next iteration.

5.3. A3

Plan:

- CAD drawings of A-arm and wheel suspension system
- CAD drawings of transmission
- Modelling in Simulink

Content:

This iteration is used to develop the final design of the chosen concept. Modifications must be done to make the design feasible. Motor and transmission are placed closer to hinge point and inside the A-arm. CAD drawings of the chosen wheel suspension and transmission design is created. CAD drawings are used to simulate and evaluate realism of design. In addition, we modelled a closed loop model in Simulink.

Resulting drawings:

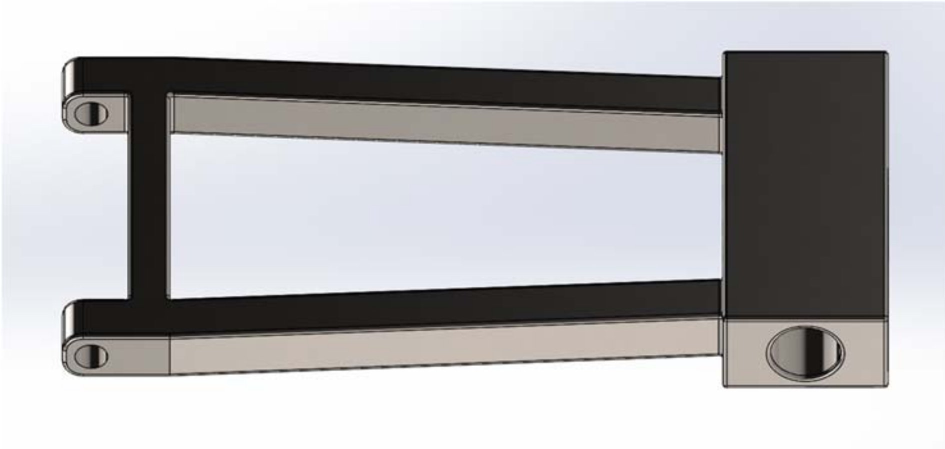


FIGURE 40 - INITIAL A-ARM DESIGN

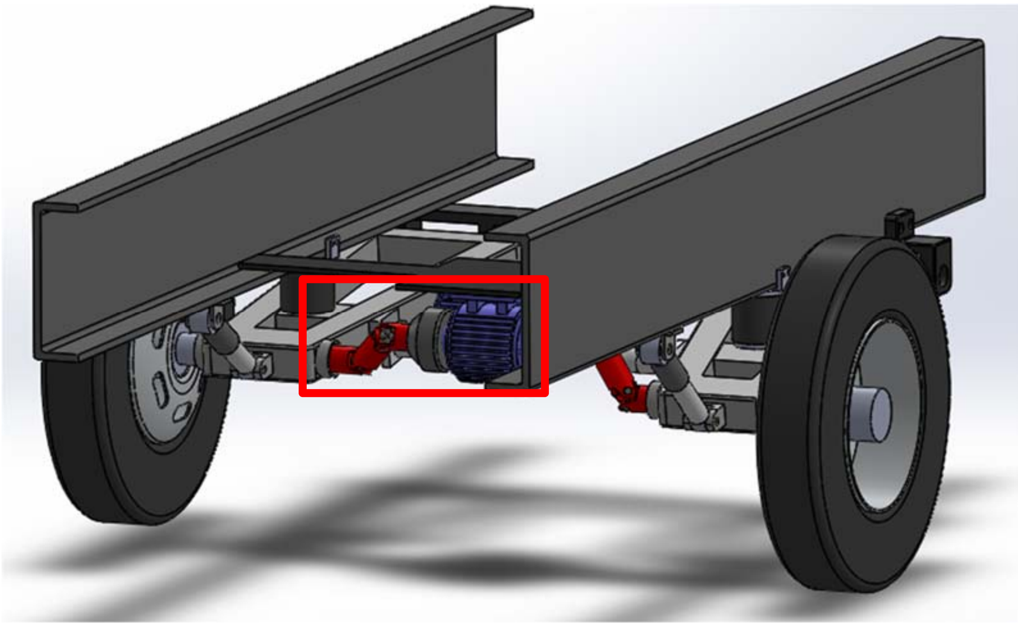


FIGURE 41 - WHEEL SUSPENSION DESIGN 1

After designing the wheel suspension in 3D, we confirmed our assumptions. The placement of the motor and transmission limits the suspension arm from moving up and down. This led to a re-design of the suspension system.

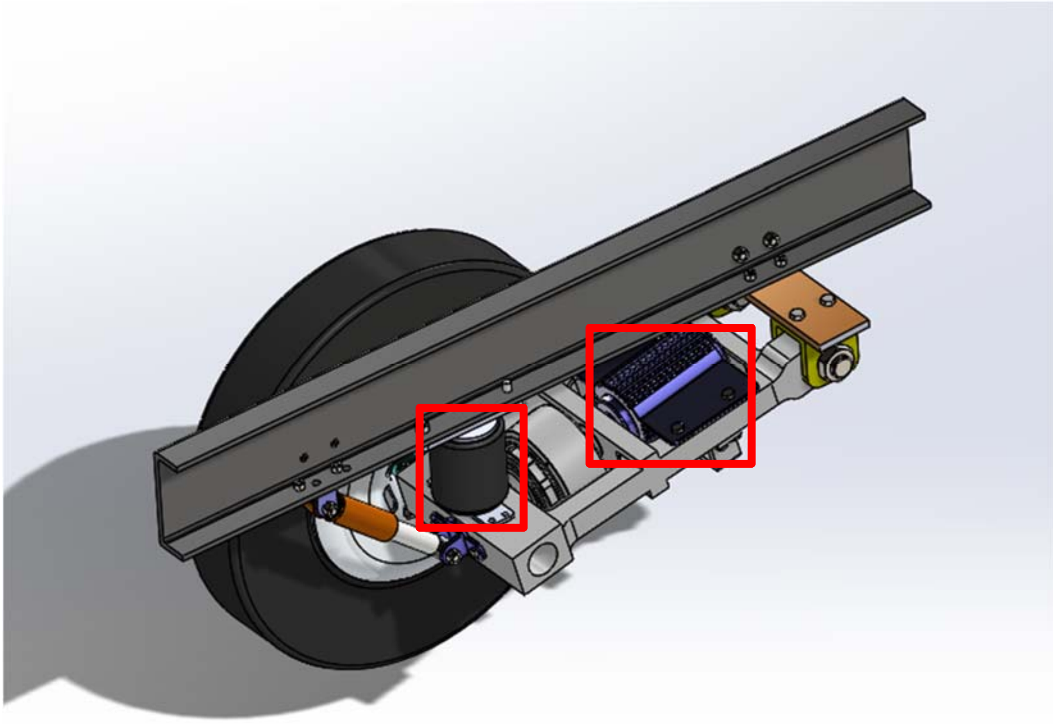


FIGURE 42 - SECTION VIEW OF DESIGN 2

Sectional view of improved design after the motor and transmission has been replaced inside the A-arm. Simulations confirmed free movement of suspension system.

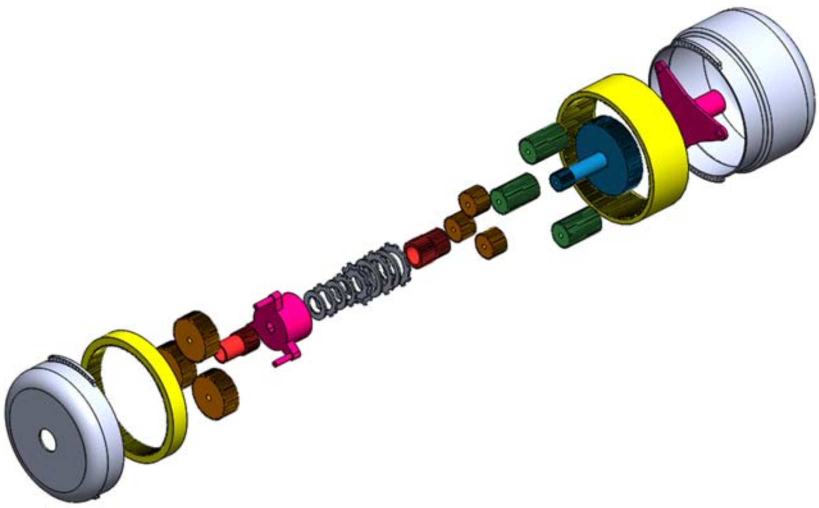


FIGURE 43 - TRANSMISSION DESIGN 1

CAD drawing of the chosen transmission design.

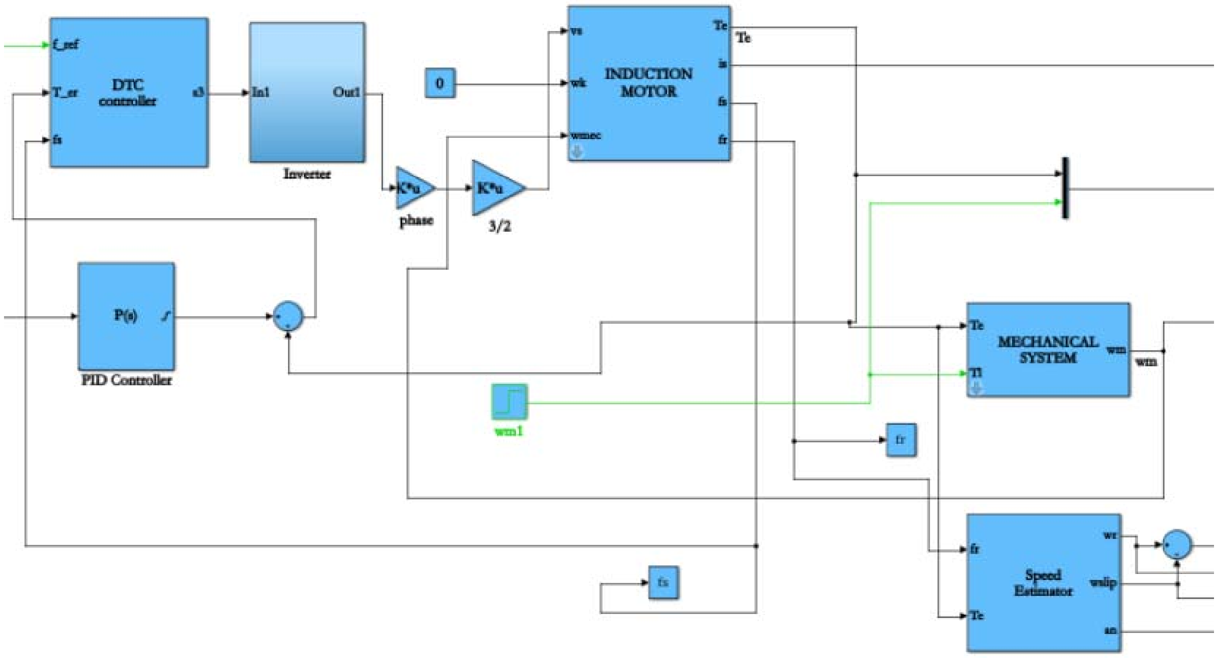


FIGURE 44 - CLOSED LOOP MODEL

Figure above shows a small section of an entire closed loop model we have made [5]. It explains how we will connect the different components together and how to control the speed of the induction motor in use.

<u>Conclusion:</u>

After analyzing the movement of the wheel suspension in Solidworks, we can verify that the desired movement is possible. We will bring forward this design for further analysis. The transmission however, is not working as we assumed. More specifically, the Ravigneaux gear set will not lock and rotate as we had intended it to do while designing. This issue needs to be addressed before we can move on with the stress-analysis.

5.4. A4

Plan:

- FEM analysis of A-arm
- Choose material
- Redesign the transmission
- Build prototype

Content:

Since the wheel suspension is ready to be analyzed, most of the iteration is used for this. To get the most accurate stress-analysis as possible, material must be chosen. Material selection consists of research about the different materials we have available. Transmission is also redesigned, as this is an issue in the last iteration. A simple prototype is in the making. The intent is to be able to control this prototype as well. This is done using Arduino microcontroller.

Resulting product:

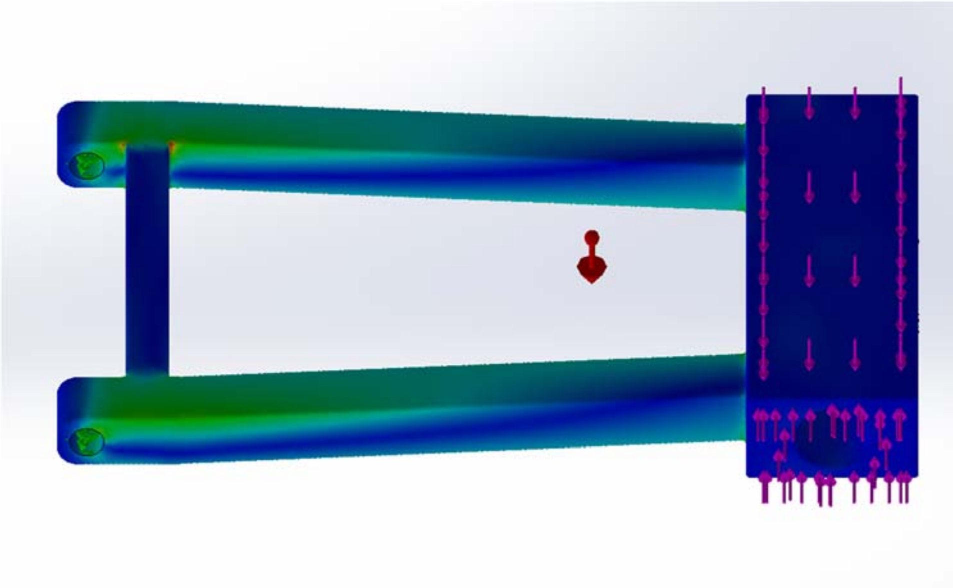


FIGURE 45 - TEST 1 OF A-ARM

FEM analysis results of the A-arm of the wheel suspension. Indicating that additional changes need to be made for the design to handle stress. Results show that the yield strength is higher than allowed.

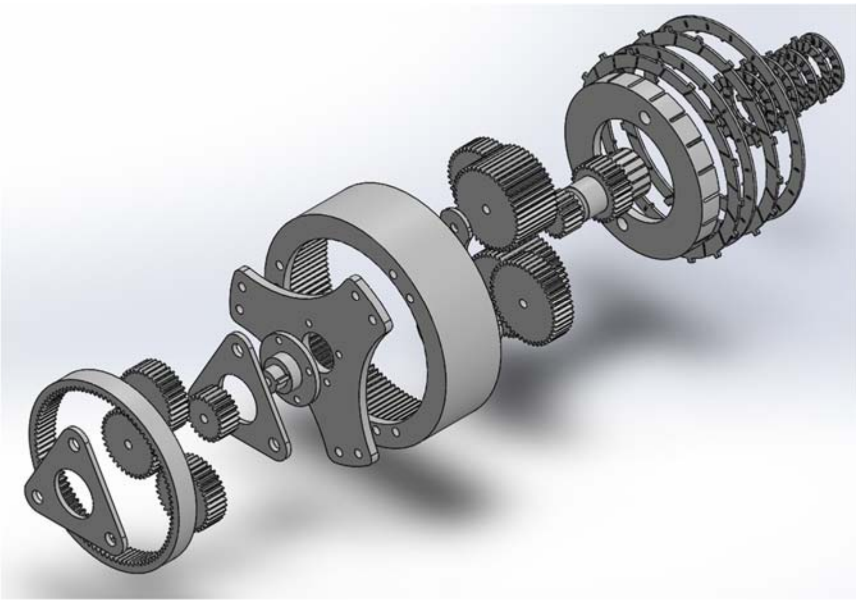


FIGURE 46 - TRANSMISSION DESIGN 2

Gears in transmission is increased in diameter and thickness. More teeth are added. Ravigneaux gear is placed opposite from the earlier design. Torque from shaft will also come from the opposite side than earlier.

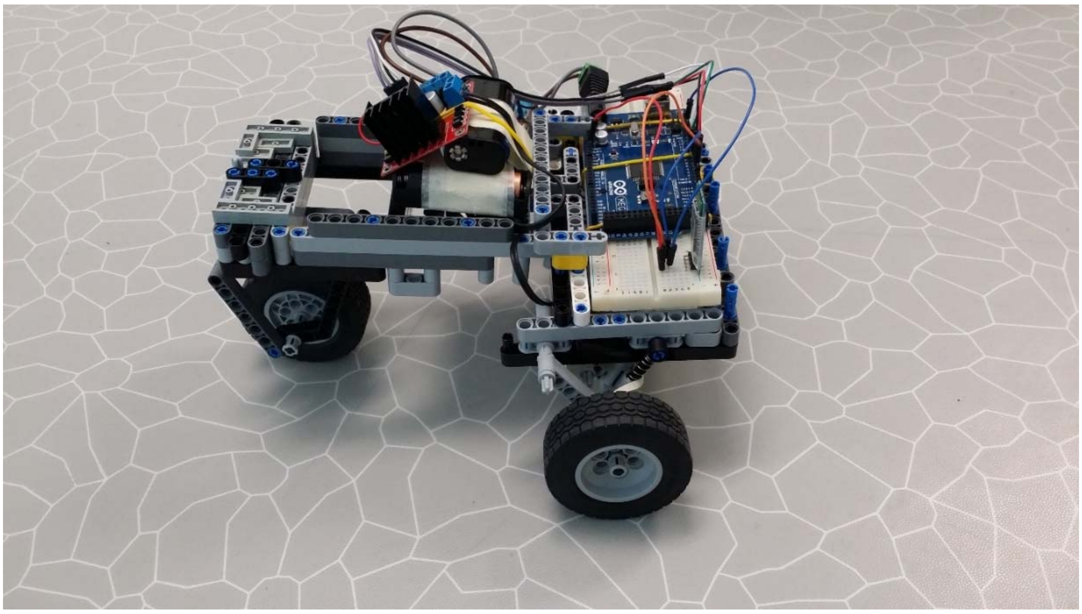


FIGURE 47 - PROTOTYPE

The prototype is built using Lego technic. Focus is on having a wheel suspension that resemble our chosen design. Coding in Arduino is done to control the prototype. Mainly to fulfill the optional torque vectoring requirement from KA.

<u>Conclusion:</u>

Analysis of the A-arm indicates that the acting forces are too great for the wheel suspension to handle. This could either be a result of the material not being strong enough, or poor design. After evaluating the results, we need to take actions accordingly.

5.5. A5

<u>Plan:</u>

- FEM analysis of wheel suspension and necessary redesign
- FEM analysis of transmission and necessary redesign
- MATLAB simulation

<u>Content:</u>

Issues regarding the design is focused on further. The wheel suspension design didn't handle the acting forces. Material is modified without giving a significant result. There is a lot of back and forth regarding the testing. To make the wheel suspension tolerable, the design is modified again. A new reinforcing beam is mounted underneath the A-arm. Besides not being sure about the specific material and design, a lot of challenges occurs with the FEM analysis program. Complex design and very few guidance resources makes the whole operation much more difficult than anticipated. Stress analysis of the transmission is initiated.

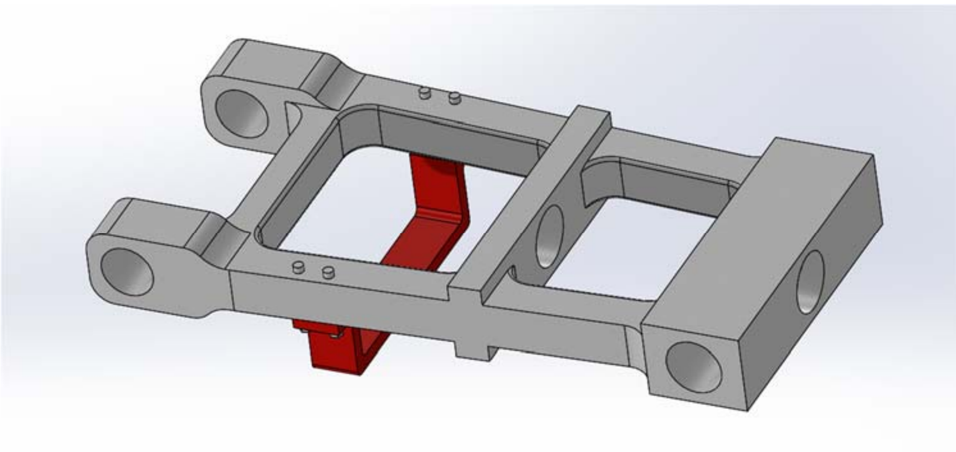


FIGURE 48 - MODIFIED DESIGN WITH REINFORCEMENT

New reinforcing design of the A-arm. Supporting beam is added and design is made much thicker.

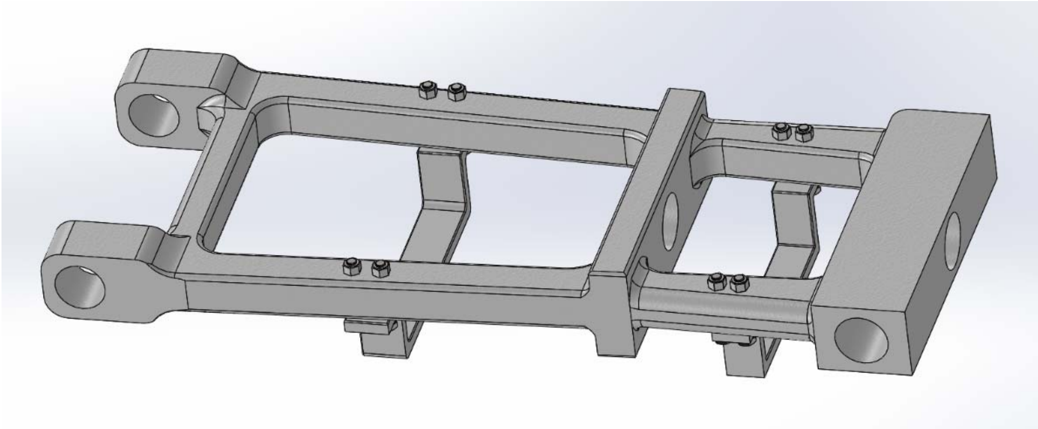


FIGURE 49 - FINAL DESIGN OF A-ARM

Figure 50 displays final design of A-arm. Entire design process and changes are available in the design document for detailed description [4].

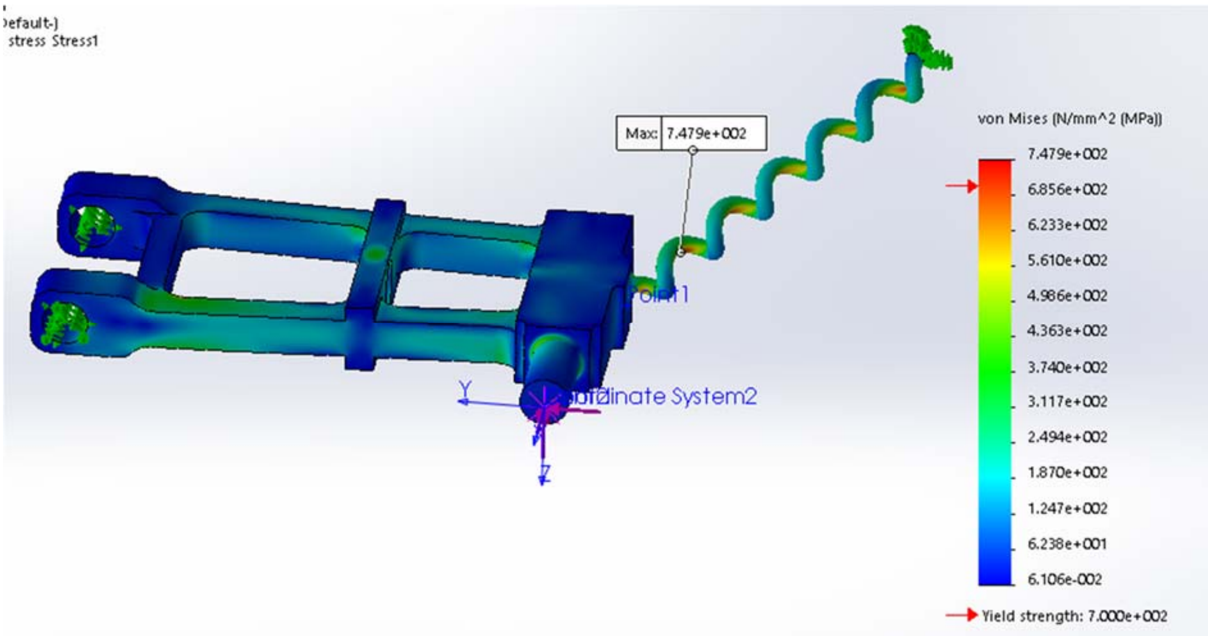


FIGURE 50 - ANALYSIS OF REINFORCED ARM

Analysis of A-arm with reinforcement and changed direction of acting forces.

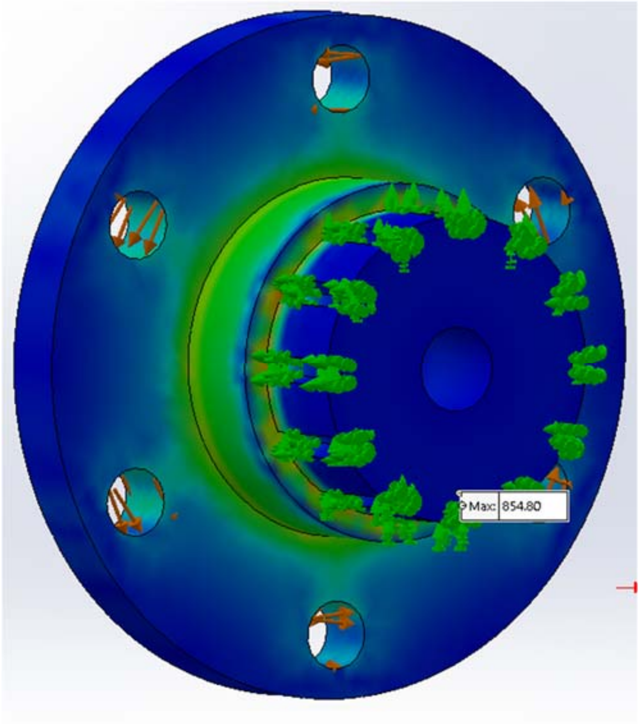


FIGURE 51 - FEM ANALYSIS OF TRANSMISSION PART

Figure 51 displays analysis of a part in the transmission which we have designed. Analysis shows that the acting torque is too great for the part to handle. Analysis is done several times with improvements and are described in detail in test document [8].

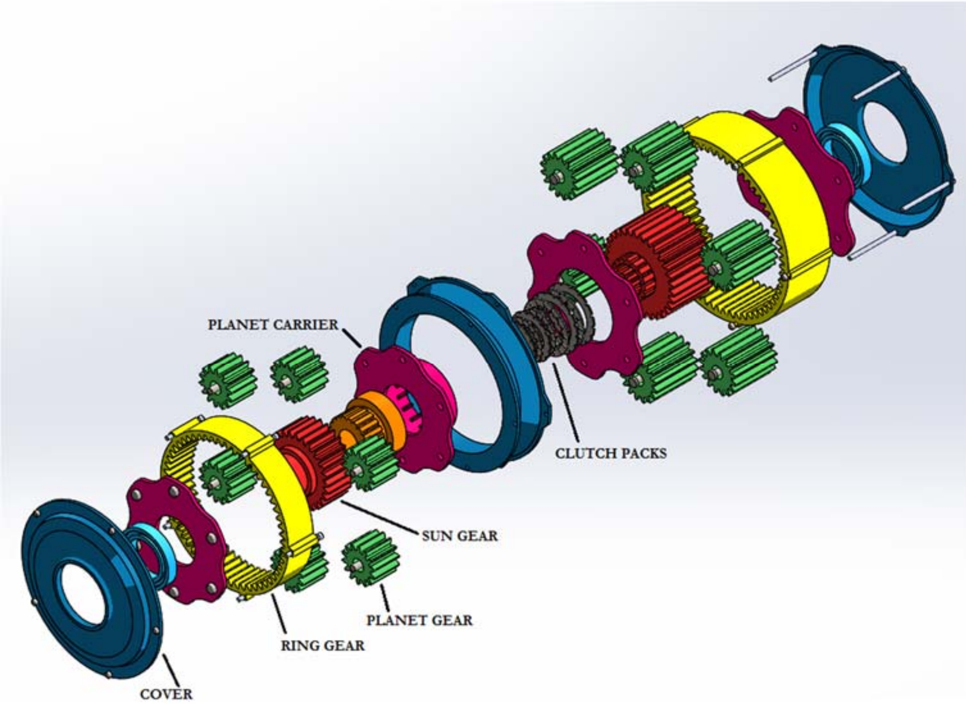


FIGURE 52 - FINAL TRANSMISSION DESIGN

Improvements are necessary on the transmission. Redesign process eventually leads to this final transmission design [4]. Parts are modified so that we can get the desired test results.

Conclusion:

Test analysis shows that both the wheel suspension and the transmission needs to be redesigned. Acting forces are still great for the designed parts. The good news is that since the max acting forces are more local, the design has potential to work. It simply needs more redesigning. Unfortunately, the architectural design phase is over, and according to plan we will be starting on the transition phase of our project.

6. TRANSITION

This phase consists of one iteration. This iteration will mainly be used to finish the necessary documentation for the bachelor project. All tests will be concluded and documentation will be finalized for hand-in.

- Start: 05.05.17
- End: 24.05.17

6.1. T1

<u>Plan:</u>

- Finalize documentation
- 3D print A-arm

<u>Conclusion:</u>

All planned documentation has got the necessary content to make the final hand-in paper as desired. Requirements that we haven't been able to meet, have been elaborated in the document. Grammar and references have been revised to make the document as good as possible. All that remains now is printing and binding before handing in the final report.

7. REFERENCES

[1] R. Software, "Website for IBM," 01 11 1998. [Online]. Available: https://www.ibm.com/developerworks/rational/library/content/03July/1000/1251/1251_bestpractices_TP026B.pdf. [Accessed 10 02 2017].

[2] E-Axle, "Calculations Document," E-Axle, Kongsberg, 2017.

[3] E-Axle, "Concept Document," E-Axle, Kongsberg, 2017.

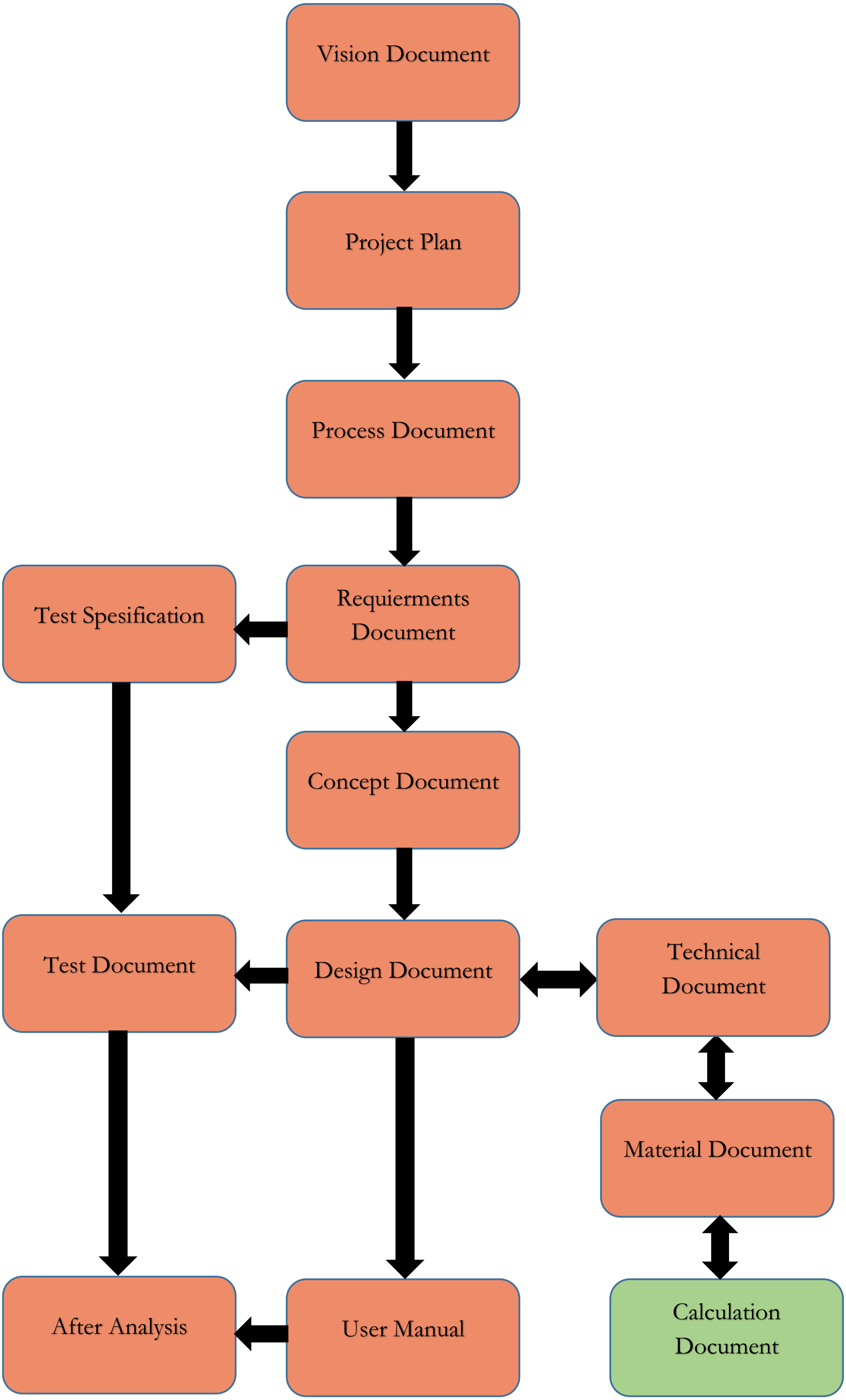
[4] E-Axle, "Design Document," E-Axle, Kongsberg, 2017.

[5] E-Axle, "Technical Document," E-Axle, Kongsberg, 2017.

[6] M. Doyle, "Website for PTC," 3 12 2014. [Online]. Available: http://blogs.ptc.com/2014/12/03/why-engineers-need-to-develop-t-shaped-skills/.

[7] J. Haugan, Formler og tabeller, Vigmostad & Bjørke AS, 2016.

[8] E-Axle, "Test Document," E-Axle, Kongsberg, 2017.



Vision Document
Project Plan
Process Document
Test Spesification
Requierments Document
Concept Document
Test Document
Design Document
Technical Document
Material Document
After Analysis
User Manual
Calculation Document

REQUIREMENT DOCUMENT

Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive

Employer	Kongsberg Automotive			
Group Members	**Name**		**Initials**	
	Abubakar Khan		AK	
	Ahat Turgun		AT	
	Anis Sadiq		AS	
	Egide Rubusa Bampo		ERB	
	Mustafa Moalim		MM	
	Pawan Bhatt		PB	
Document Information	**Version**	**Date**	**Approved**	**Pages**
	3.0	23.05.17	AS	34

24. januar 2017

REQUIREMENT DOCUMENT

Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive

TABLE OF CONTENTS

TABLES

REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
24.01.17	0.1	Document created Added abbreviations, introduction, scope and requirements criteria	MM
25.01.17	0.2	Added requirement template	MM
26.01.17	0.3	Updated requirements Added contents and list of tables	MM
27.01.17	0.4	Deleted 1.25 requirement	MM
31.01.17	0.5	Added Test ID	MM
01.02.17	0.6	Revised all requirements Added sources	MM
03.02.17	1.0	Finalized version	MM
22.03.17	1.1	Updated fonts and design	AS
22.03.17	2.0	Finalized version	AS
19.05.17	2.1	Finalized last version	MM
23.05.17	3.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATION	DEFINITION
BU	Battery unit
ED	Electric Drive
WS	Wheel Suspension
AC	Alternate Current
DC	Direct Current
KA	Kongsberg Automotive
OEM	Original Equipment Manufacturer
HDC	Heavy-Duty Customers

TABLE 2 – DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

The requirement document will give a detail of the functionality and characteristics the system must have. Most of our requirements are from KA, however, there are some requirements we as developers created to elaborate requirements from KA.

On the other hand, there are some requirements we have found after interviewing some of our users like heavy-duty vehicle drivers.

We have divided the requirements into two categories:

- System requirements
- User requirements

1.1. Scope

The scope of this document is to set foundation for our system. This document will elaborate on the requirements of our system and explain why these are important, to design a good system for our customer.

The document includes the following information:

- Criteria of writing a good requirement [1]
- Description of prioritization levels [2]
- All the requirements of the system [3]

2. REQUIREMENT CRITERIA

2.1. Background

For our system to satisfy our customer (KA) needs, we must describe in detail all the boundaries set by our customer. As mentioned above most of these requirements we got from KA, [3] but some of them we have created after several discussions around these requirements. For us to make a good system we must have fully defined and accurate requirements. This can be accomplished by looking at some of the criteria for a good system requirements.

2.2. Criteria [2]

2.2.1. Necessary

Can we make a good system, which can meet customer needs without this requirement? If yes, then we must either revise this requirement or eliminate it altogether.

2.2.2. Verifiable

A requirement must be verifiable to be a good requirement. If we cannot verify whether a requirement has been met or not in a system, then we should either revise or remove that requirement.

2.2.3. Attainable

A good requirement must be attainable during a development process. If that is not possible than we should remove the requirement or revise it.

2.2.4. Unambiguous

Requirements must not be interpreted in different ways. Should that be the case then the requirements must be clarified or removed altogether. A good requirement must be clear about its meaning, and a poorly written requirement can lead to misunderstandings or unnecessary work.

2.2.5. Complete

The requirement should be complete when reading, whereby the reader should not wait some information to understand the requirement

2.2.6. Consistent

Requirements should not conflict with each other. If this is not possible we should consider removing one of the two or revising them.

2.2.7. Traceable

The source of the requirement should be known and we should be able to locate the requirement throughout the system. It is also important to know where all the requirements are met in the system.

2.2.8. Allocated

We should be able to allocate requirements to an element in our system, where it is possible to implement that requirement. If this is not possible the requirement needs to be revised or removed.

2.2.9. Concise

The requirement shall be stated simply and clearly to avoid any misunderstanding or wrong interpretation of that requirement, which was not intended.

2.2.10. Implementation Free

A good requirement should tell us what we need to do for us to fulfill that requirement, without going into the solution or how we can do it.

2.2.11. Standard Construct

Imperative is used when writing a requirement like the statement "shall". Other statements using "will" for example, is not imperative form

2.2.12. Unique Identifier

Every requirement should be allocated with a unique identifier, which help us with tracing the requirement throughout the change history and as a form of identification.

2.2.13. Priority

The requirement is prioritized as follows:

Priority A: We must meet these requirements for the system to work. These requirements are absolute critical for the system to success.

Priority B: They are not the same level as "A" but we should accomplish these requirements. They do not decide if the system works or not.

Priority C: The system is not dependent on these requirements to be complete and function, but it makes the system better.

3. REQUIREMENTS

‘

3.1. System Requirements

ID	REQ1.01	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.17
DESCRIPTION The BU should be able to drive E-Axle for at least 10 hours.			**PRIORITY**
WHY	Because this is a standard driving time for a truck		A
COMMENTS			

TABLE 3 - REQUIREMENTS 1.01

ID	REQ1.02	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.18
DESCRIPTION BU can be swapped vertically.			**PRIORITY**
WHY	Easy to maintain and change BU.		C
COMMENTS			

TABLE 4 - REQUIREMENTS 1.02

ID	REQ1.03	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.18
DESCRIPTION ED shall be closer to the suspension chassis hinge point.			**PRIORITY**
WHY	To reduce the un-sprung mass.		B
COMMENTS			

TABLE 5 - REQUIREMENTS 1.03

ID	REQ1.04	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.19
DESCRIPTION Reduce overall weight.			**PRIORITY**
WHY	To reduce energy consumption.		C
COMMENTS			

TABLE 6 - REQUIREMENTS 1.04

ID	REQ1.05	SOURCE	KA
DATE CREATED	06.01.2017	TEST ID	TES 1.1
DESCRIPTION Electric motor should have a power of 150 kW per wheel.			PRIORITY
WHY	To supply enough power to the system to work.		A
COMMENTS			

TABLE 7 - REQUIREMENTS 1.05

ID	REQ1.06	SOURCE	KA
DATE CREATED	06.01.2017	TEST ID	TES 1.1
DESCRIPTION The electric motor should operate at 750V.			PRIORITY
WHY	For the motor to produce the desired power.		A
COMMENTS			

TABLE 8 - REQUIREMENTS 1.06

ID	REQ1.07	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.1
DESCRIPTION The electric motor should operate between 0-2000 RPM.			**PRIORITY**
WHY	Because the motor should have maximum and minimum rotational speed.		A
COMMENTS			

TABLE 9 - REQUIREMENTS 1.07

ID	REQ1.08	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.2
DESCRIPTION Transmission system should have two gears.			**PRIORITY**
WHY	To provide the system different speed and torque.		A
COMMENTS			

TABLE 10 - REQUIREMENT 1.08

ID	REQ1.09	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION Gear one should have a torque of 30000 NM.			**PRIORITY**
WHY	To give more torque to move the vehicle under low speed.		A
COMMENTS			

TABLE 11 - REQUIREMENT 1.09

ID	REQ1.10	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION Gear two should have a torque of 10000 NM.			**PRIORITY**
WHY	Give less torque to increase speed.		A
COMMENTS			

TABLE 12 - REQUIREMENT 1.10

ID	REQ1.11	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION The Gear ratio should be 30:1 and 10:1 respectively.			**PRIORITY**
WHY	To magnify torque from motor and give different acceleration.		C
COMMENTS	Though our motor generates enough torque, we do not need to fulfill this requirement to fulfill the two other requirements 1.10 and 1.09. In addition, priority will be C instead of A.		

TABLE 13 - REQUIREMENT 1.11

ID	REQ1.12	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION WS travel Lift should be100 mm.			**PRIORITY**
WHY	To make it easier to connect truck trailer and adapt to different road conditions.		A
COMMENTS			

TABLE 14 - REQUIREMENT 1.12

ID	REQ1.13	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION WS travel Drop should be 60 mm.			**PRIORITY**
WHY	To make it easier to connect truck trailer and adapt to different road conditions.		A
COMMENTS			

TABLE 15 - REQUIREMENT 1.13

ID	REQ1.14	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION WS carrying capacity should be at least 6 tons per wheel.			**PRIORITY**
WHY	To be able to withstand heavy load per wheel.		B
COMMENTS			

TABLE 16 - REQUIREMENT 1.14

ID	REQ1.15	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION WS carrying capacity should be at least 12 tons per axle.			**PRIORITY**
WHY	To be able to withstand heavy load per axle.		B
COMMENTS			

TABLE 17 - REQUIREMENT 1.15

ID	REQ1.16	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.5
DESCRIPTION Durability is 50 kN in both of x- and y-axis on each wheel.			**PRIORITY**
WHY	To withstand forces from different directions under driving on curved roads		A
COMMENTS			

TABLE 18 - REQUIREMENT 1.16

ID	REQ1.17	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.5
DESCRIPTION The wheel could make 200 000 cycles.			**PRIORITY**
WHY	It is the cycles before fatigue happen.		A
COMMENTS			

TABLE 19 - REQUIREMENT 1.17

ID	REQ1.18	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.5
DESCRIPTION Max force should be 100 KN in both of x- and y-axis on each wheel.			**PRIORITY**
WHY	To withstand max forces from different directions under driving on curved roads.		A
COMMENTS			

TABLE 20 - REQUIREMENT 1.18

ID	REQ1.19	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.19
DESCRIPTION The AC electric motor should be controlled via an inverter.			**PRIORITY**
WHY	Inverter can limit the power input to the motor and thus regulating the motor.		A
COMMENTS			

TABLE 21 - REQUIREMENT 1.19

ID	REQ1.20	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.3
DESCRIPTION Inverter should have differential gear functionality.			**PRIORITY**
WHY	To control the AC electric motor.		A
COMMENTS	We adjusted this requirement to use DTC to control the AC motor via inverter.		

TABLE 22 - REQUIREMENT 1.20

ID	REQ1.21	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.7
DESCRIPTION Varying wheelbase must be taken into account.			**PRIORITY**
WHY	To control and adjust varying distances between the wheelbase.		C
COMMENTS			

TABLE 23 - REQUIREMENT 1.21

ID	REQ1.22	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.8
DESCRIPTION Should be able to have a lift axle in front or behind the driven axle.			**PRIORITY**
WHY	To distribute the weight among several wheels under heavy load and to reduce friction under light load.		C
COMMENTS			

TABLE 24 - REQUIREMENT 1.22

ID	REQ1.23	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.9
DESCRIPTION The system should have optional torque vectoring.			**PRIORITY**
WHY	To have better handling and control of the vehicle		B
COMMENTS			

TABLE 25 - REQUIREMENT 1.23

ID	REQ1.24	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.3
DESCRIPTION The system should have an inverter.			**PRIORITY**
WHY	To convert DC to AC		A
COMMENTS			

TABLE 26 - REQUIREMENT 1.24

ID	REQ1.26	**SOURCE**	KA
DATE CREATED	11.01.2017	**TEST ID**	TES 1.2
DESCRIPTION The system should have one ED per wheel.			**PRIORITY**
WHY	To give room for more concepts and designs.		A
COMMENTS			

TABLE 27 - REQUIREMENT 1.26

ID	REQ1.27	**SOURCE**	KA
DATE CREATED	11.01.2017	**TEST ID**	TES 1.2
DESCRIPTION The WS should be of torsion beam type.			**PRIORITY**
WHY	To balance the wheels and stabilize the system.		A
COMMENTS			

TABLE 28 - REQUIREMENT 1.27

ID	REQ1.28	**SOURCE**	KA
DATE CREATED	11.01.2017	**TEST ID**	TES 1.2
DESCRIPTION The WS Should have an air suspension system with one bellow for each wheel.			**PRIORITY**
WHY	To give driving comfort, adjusting different way situation and withstanding heavy loads.		A
COMMENTS			

TABLE 29 - REQUIREMENT 1.28

ID	REQ1.29	**SOURCE**	KA
DATE CREATED	11.01.2017	**TEST ID**	TES 1.2
DESCRIPTION The WS Should have one shock absorber for each wheel.			**PRIORITY**
WHY	To reduce the oscillation of the wheel suspension during driving and under different road conditions.		A
COMMENTS			

TABLE 30 - REQUIREMENT 1.29

ID	REQ2.01	SOURCE	KA
DATE CREATED	11.01.2017	TEST ID	TES 1.10
DESCRIPTION The system shall be placed in standard truck frame.			PRIORITY
WHY	To fit all types of trucks.		B
COMMENTS			

TABLE 31 - REQUIREMENT 2.01

ID	REQ2.02	SOURCE	KA
DATE CREATED	09.01.2017	TEST ID	TES 1.1
DESCRIPTION Wheel size should be (315/80R22,5 twin assembly).			PRIORITY
WHY	To fit the standard truck.		C
COMMENTS			

TABLE 32 - REQUIREMENT 2.02

ID	REQ2.03	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.1
DESCRIPTION Standard brake disc should be 420 mm.			**PRIORITY**
WHY	To fit the wheel.		B
COMMENTS	This requirement is cancelled, instead we decided to use drum brakes.		

TABLE 33 -REQUIREMENT 2.03

ID	REQ2.04	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.1
DESCRIPTION WS hinge point should be rubber bushing design.			**PRIORITY**
WHY	To reduce noise and vibration created from metal to metal contact.		B
COMMENTS			

TABLE 34 - REQUIREMENT 2.04

ID	REQ2.05	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.1
DESCRIPTION Dimension of rubber bushing can preferably be Ø180*120 mm length.			**PRIORITY**
WHY	To fit the hinge point dimension.		C
COMMENTS	The dimension of this requirement is adjusted to (Ø80*90mm).		

TABLE 35 - REQUIREMENT 2.05

ID	REQ2.06	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.11
DESCRIPTION The BU should give 800 V DC current through two wire connectors.			**PRIORITY**
WHY	To make it possible to connect the BU and inverter and to supply required power to the ED.		A
COMMENTS			

TABLE 36 - REQUIREMENT 2.06

ID	REQ2.07	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.12
DESCRIPTION Water cooling should have two tubes for supply and return water respectively.			**PRIORITY**
WHY	To cool down the motor and other systems needed to be cooled.		A
COMMENTS			

TABLE 37 - REQUIREMENT 2.07

ID	REQ2.08	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.13
DESCRIPTION Pressurized air at 8-10 bar should be supplied to the air suspension.			**PRIORITY**
WHY	To have enough pressure to lift, drop and stabilize the system.		B
COMMENTS			

TABLE 38 - REQUIREMENT 2.08

ID	REQ3.01	SOURCE	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.3
DESCRIPTION Electric motor should be either pancake design or cylindrical design.			**PRIORITY**
WHY	These are standard motor designs for electrical vehicles.		A
COMMENTS			

TABLE 39 - REQUIREMENT 3.01

ID	REQ3.02	SOURCE	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.1
DESCRIPTION Electric motor of pancake design (Ø400*100 mm length), rotational axis around y.			**PRIORITY**
WHY	We choose if it is suitable for our design		C
COMMENTS	This requirement is cancelled, because the type motor we chose is not pancake design. Priority is reduced to C instead of B.		

TABLE 40 - REQUIREMENT 3.02

ID	REQ3.03	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.1
DESCRIPTION Electric motor of cylindrical design (Ø200*350 mm length) rotation around x.			**PRIORITY**
WHY	We choose if it is suitable for our design.		B
COMMENTS	This dimension of this requirement is adjusted to (Ø340*629mm length).		

TABLE 41 - REQUIREMENT 3.03

ID	REQ3.04	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.1
DESCRIPTION Integrated inverter, size flexible depending on packaging space.			**PRIORITY**
WHY	To save design space.		C
COMMENTS	We deleted this requirement, because we could not find integrated inverter, but we have separate inverter.		

TABLE 42 - REQUIREMENT 3.04

ID	REQ3.05	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.1
DESCRIPTION Torsion beam should be from hardened steel.			**PRIORITY**
WHY	Because the characteristics of hardened steel can withstand torsion forces better than other materials, as well as cost efficiency.		B
COMMENTS			

TABLE 43 - REQUIREMENT 3.05

ID	REQ3.06	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.1
DESCRIPTION Swing arms should be either from aluminum or cast iron.			**PRIORITY**
WHY	The characteristics of these materials can be subjected to several cycles before fatigue.		B
COMMENTS			

TABLE 44 - REQUIREMENT 3.06

ID	REQ3.07	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.2
DESCRIPTION Torsion beam and swing arms should be joined by screw flange connection or by weld.			**PRIORITY**
WHY	Must have a connection between torsion beam and swing arms		A
COMMENTS			

TABLE 45 - REQUIREMENT 3.07

3.2 USER REQUIREMENTS

ID	REQ4.01	**SOURCE**	USER
DATE CREATED	12.01.2017	**TEST ID**	TES 1.14
DESCRIPTION The WS system should be comfortable while driving on rough roads.			**PRIORITY**
WHY	The driver of the vehicle should have it comfortable while driving.		B
COMMENTS			

TABLE 46 - REQUIREMENT 4.01

ID	REQ4.02	**SOURCE**	USER
DATE CREATED	12.01.2017	**TEST ID**	TES 1.14
DESCRIPTION Shall be possible to disassemble and assemble the system.			**PRIORITY**
WHY	To make it easier to maintain and replace existing systems with our system.		C
COMMENTS			

TABLE 47 - REQUIREMENT 4.02

ID	REQ4.03	**SOURCE**	USER
DATE CREATED	12.01.2017	**TEST ID**	TES 1.15
DESCRIPTION The system should have efficient motor.			**PRIORITY**
WHY	To reduce energy consumption.		B
COMMENTS			

TABLE 48 - REQUIREMENT 4.03

<table>
<tr><td>ID</td><td>REQ4.04</td><td>SOURCE</td><td>USER</td></tr>
<tr><td>DATE CREATED</td><td>12.01.2017</td><td>TEST ID</td><td>TES 1.16</td></tr>
<tr><td colspan="3">DESCRIPTION
The system should be cost efficient.</td><td>PRIORITY</td></tr>
<tr><td>WHY</td><td colspan="2">To be affordable compared to current systems.</td><td rowspan="2">C</td></tr>
<tr><td>COMMENTS</td><td colspan="2"></td></tr>
</table>

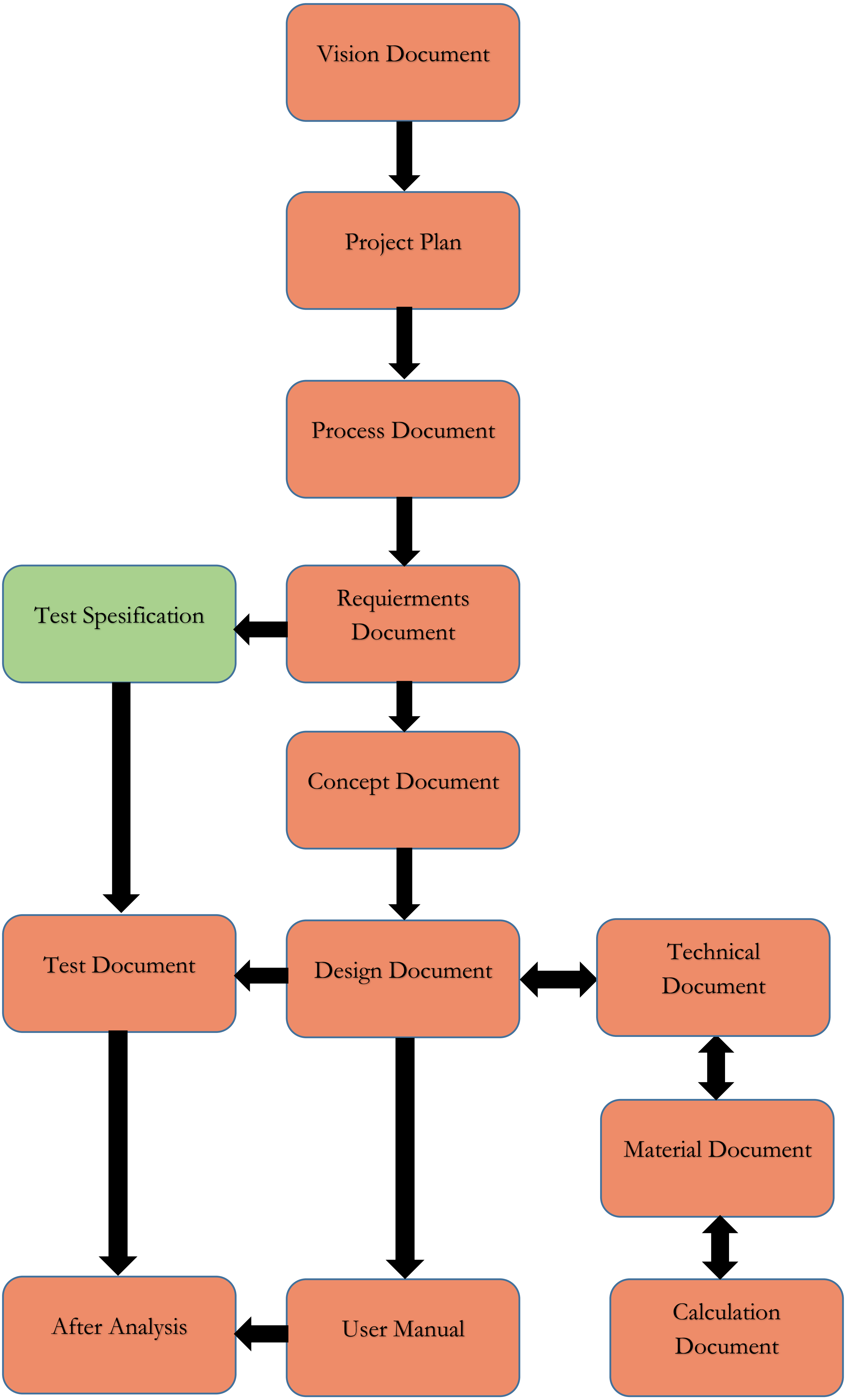
TABLE 49 - REQUIREMENT 4.04

4. REFERENCES

[1] "Collecting Requirements," [Online]. Available: https://www.youtube.com/watch?v=DVnqubzQqPk. [Accessed 24 01 2017].

[2] R. S. Smith, "writing a requirement," [Online]. Available: http://www.cdl.edu/uploads/Qd/S6/QdS615B1DcnwRZlnSuTDnQ/writing-requirements.pdf. [Accessed 24 01 2017].

[3] S. Bjørkgård, *Product Requirement Targets,* Kongsberg: KONGSBERG AUTOMATIVE, 2016.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TEST SPECIFICATION

Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive

<table>
<tr><td>Employer</td><td colspan="4">Kongsberg Automotive</td></tr>
<tr><td rowspan="7">Group Members</td><td colspan="2">Name</td><td colspan="2">Initials</td></tr>
<tr><td colspan="2">Abubakar Khan</td><td colspan="2">AK</td></tr>
<tr><td colspan="2">Ahat Turgun</td><td colspan="2">AT</td></tr>
<tr><td colspan="2">Anis Sadiq</td><td colspan="2">AS</td></tr>
<tr><td colspan="2">Egide Rubusa Bampo</td><td colspan="2">ERB</td></tr>
<tr><td colspan="2">Mustafa Moalim</td><td colspan="2">MM</td></tr>
<tr><td colspan="2">Pawan Bhatt</td><td colspan="2">PB</td></tr>
<tr><td rowspan="2">Document Information</td><td>Version</td><td>Date</td><td>Approved</td><td>Pages</td></tr>
<tr><td>3.0</td><td>23.05.17</td><td>AS</td><td>20</td></tr>
</table>

17. januar 2017

TEST SPECIFICATION

Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive

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TABLES

FIGURES

REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
17.01.17	0.1	Created the document	ERB
18.01.17	0.2	Format changes, language correction	PB
24.01.17	0.3	Updated the document with some theory.	ERB
25.01.17	0.4	Updated further with some test spec and theory	PB
26.01.17	0.5	Insert the test specification in test tables	ERB
31.01.17	0.6	Language correction	ERB
02.01.17	1.0	Finalized	ERB
23.01.17	1.1	Color and language correction, minor changes	PB
24.03.17	2.0	Changed title and finalized ver.	AS
19.05.17	2.1	Updated the document	MM
21.05.17	2.2	TES 1.7 and 1.2 Adjusted	ERB & PB
23.05.17	3.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
AC	Alternate Current
FEA	Finite Element Analyses
FEM	Finite Element Method
MATLAB	Matrix Laboratory

TABLE 2 - DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

Test plan is one of the most important document to have. Testing is very important, because it expose the weakness and defects in our system and show where we can improve. This will increase our chances of making a high-quality product.

1.1. Scope

The main purpose of this document is to give a framework of how to test our system, different strategies we can use and what kind of test methods are required. To test our system, we will be using SolidWorks and Simulink/MATLAB to simulate and validate our project. This is because most of our work will be purely analytical.

Our primary goal is to come up with several different solutions and models, while our secondary goal is to produce a prototype. Testing is required in every stage of the development process to verify that all the component and the subsystem of the product are compatible with each other. Verification and validation are the two-major component of testing a system. Verification means that our system complies with all specifications, while validation means that the system meets customer's requirements and expectations.

If validation fails, it means that the system specifications were not defined accurately and that the system is not functioning according to requirement specifications. However, if verification of the system fails, it means that the system is not working properly. This means that there are some errors in the design of the system or that the individual components are not compatible with each other [1].

2. TEST STRATEGY AND METHODS

There are many methods and strategies we can use to test our system and all of them are viable to some extent. Our test strategy is to use the Bottom-up testing method. This testing method is used by testing individual components first, then subsystem and finally the whole system. The method is a step by step method, where we test the system from the lowest level to the highest [2].

2.1. Black-Box Testing Method

Black-box is also known as functional testing, which treats system as a black box without considering the internal structure of the system. This type of testing compares the output signal to the input signal and verifies that the system is working as intended.

Some of the advantages of the black box testing are:

- The method is easier and time saving, as we only test if the system is working properly.
- The tester does not need to understand how the system is working.
- Can give us two different perspective (tester and developer).

The disadvantages of the black testing method are:

- It does not include many different scenarios, because of its simplistic approach.
- Incomplete testing, due to tester's lack of knowledge about the system's internal functionality.

2.2. White-Box Testing Method

White-box testing method deals (also called glass box or transparent testing method) with the internal functionality of the system, and use this knowledge during the testing phase. To use this testing method, detailed knowledge about the system is required.

The advantages of this testing white box testing are:

- Efficient in finding errors and problem.
- Covers main different scenarios, due to the knowledge of the internal functionality of the system.

The disadvantages of white box testing methods are:

- The method is time consuming and more complicated.
- It requires high level understanding of the system.

2.3. Unit Testing

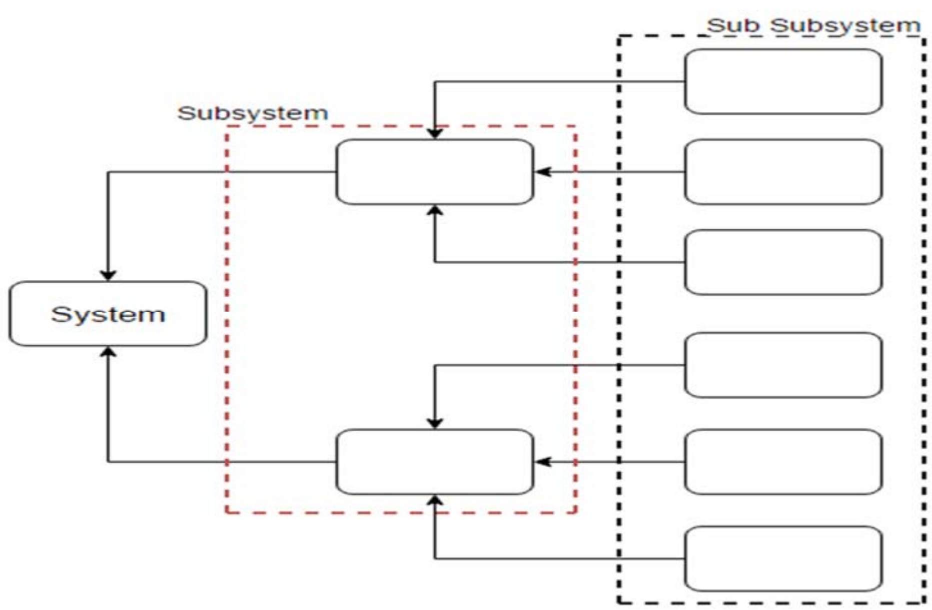


FIGURE 1 - BOTTOM-UP TESTING STRATEGY

Bottom Up testing method will be applied to test our product throughout the development process of this project. We will start by testing the smallest components independently to verify and validate that they meet their requirements specifications. The lowest building units of our system will include:

- Torsion Beam
- Air suspension
- Leaf spring
- Shock absorber
- Electric motors
- Inverters
- Transmission

At this level, we plan to test the components mentioned above by using SolidWorks and Simulations using Simulink MATLAB. Mechanical components, such as Torsion Beam, Air suspension, Leaf spring and Shock absorber will be tested and analyzed by using the FEA/FEM method in SolidWorks. The electronic components including AC motors, inverters and sensors will probably be tested by using calculations and simulations in Simulink.

2.4. Integration Testing

Integration testing will involve testing every newly integrated units to verify and validate that they interact with each other correctly. At this stage, testing will involve testing electric driving system to verify and validate that the motor, inverter, and transmission system function together as intended. This sub system will be tested by simulation in Simulink or by verifying the products datasheet.

Some calculations will be done to determine the controllability, observability, and the response of the system.

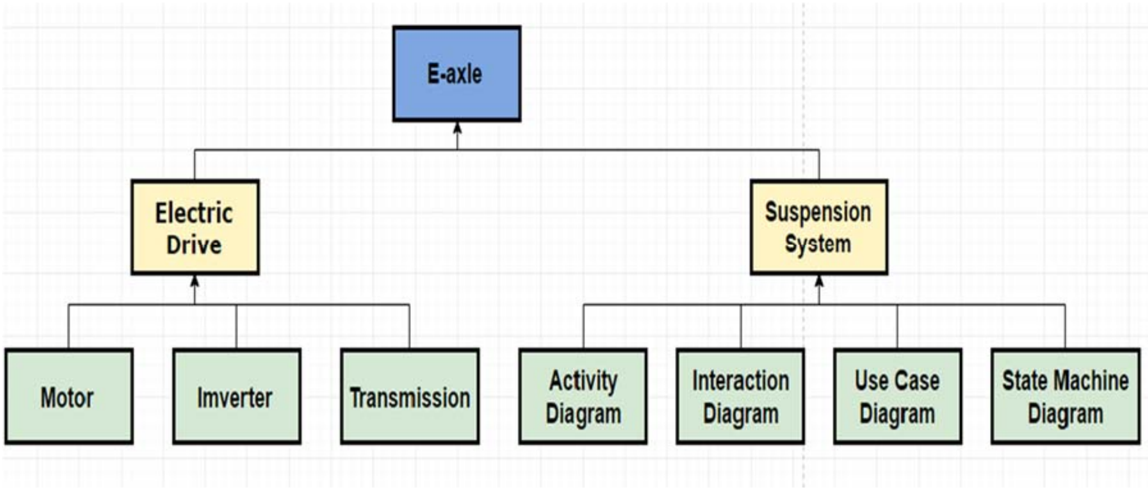


FIGURE 2: TOP DOWN TESTING METHOD

Testing at this stage will also involve testing the mechanical subsystem. This will be done to verify that the mechanical subsystems including torsion beam, air springs, leaf springs and shock absorber function together as planned. This subsystem will be tested in SolidWorks. The main objective of testing at this level is to verify and validate that interfacing and pathways between all the interfaced units satisfy requirement specifications.

2.5. Functional Testing

Functional testing will involve making sure that the functionality of the building units, the subsystem and the final system complies with the requirement specification. This is where we test the functionality of all the subsystems of our product to make sure that they satisfy the requirements specification.

Testing activities at this level will involve verifying and validating that the product work as the customer's required. We intend to perform the function testing to all the components and the systems of our prototype using various testing technique to verify that they comply the requirements specification.

2.6. System Testing

System testing will be performed to verify and validate that the newly developed product functions as required by the customer. This type of testing will be conducted on a complete, integrated Electric axle to verify and validate that the product functions as required by the customer. Various testing techniques will be used at this level to verify and validate the product.

3. TEST SPECIFICATIONS

This test specification document shows all the tests for this project listed in tables. Each test is given a unique ID, which makes it easier to trace it to the corresponding requirement from the requirement specification. The test tables give information about test verification method and the status of the test.

The status describes the situation of a requirement at the present date. The situation of requirement at time during the developing process will be given either tested or pending status. Tested means that a requirement has been tested and pending means that a requirement has not yet been tested. Testing results are discussed in the comments line after testing.

<table>
<tr><td>TEST ID</td><td>TES 1.1</td><td>REQ ID</td><td>1.05 - 1.06 - 1.07 - 2.02 - ~~2.03~~ - 2.04 - 2.05 - ~~3.02~~ - 3.03 - ~~3.04~~ - 3.05 - 3.06</td></tr>
<tr><td>DESCRIPTION</td><td colspan="2">All the requirements above are those we do not have to test because these are specifications we will get when we buy these materials or components. It is not necessary to test these requirements.</td><td>STATUS
Verified 1.05, 1.06, 1.07, 2.02 & 2,04</td></tr>
<tr><td>COMMENT</td><td colspan="2">We cancelled requirements 2.03, 3.02, 3.04 not needed to test.
We adjusted requirements 2.05, 3.03, but testing will be the same.</td><td></td></tr>
</table>

TABLE 3 - TEST 1.1

TEST ID	TES 1.2	**REQ ID**	1.08 - 1.26 - 1.27 - 1.28 - 1.29 - 3.07
DESCRIPTION	To test these requirements, we will make a 3d model which can show these different components to us as well as their functions in relation to each other.		**STATUS**
COMMENT			Verified 1.08, 1.26, 1.28 & 1.29

TABLE 4 - TEST 1.2

TEST ID	TES 1.3	**REQ ID**	~~1.20~~ - 1.24 - 3.01
DESCRIPTION	The requirements above will be fulfilled by reading the datasheet of each of the components related to a given requirement. We will find information from datasheets to verify and validate that the technical specifications in the data sheet satisfies the requirement as specified by requirement specification.		**STATUS**
COMMENT	Testing the requirement 1.20 is not needed, because it is changed.		Verified

TABLE 5 - TEST 1.3

TEST ID	TES 1.4	REQ ID	1.09 - 1.10 - ~~1.11~~ - 1.12 - 1.13 - 1.14- 1.15
DESCRIPTION	These requirements will be tested by using calculations and FEA Method.	STATUS	
		Verified	
COMMENT	The requirement 1.11 is canceled, therefore we do not need to test it		

TABLE 6 - TEST 1.4

TEST ID	TES 1.5	REQ ID	1.16 - 1.17 - 1.18
DESCRIPTION	These requirements will be tested using SolidWorks simulations.	STATUS	
		Verified	
COMMENT			

TABLE 7 - TEST 1.5

TEST ID	TES 1.6	REQ ID	1.19
DESCRIPTION	This requirement will be tested by calculating some values of a closed controlling loop and verify that the system is both controllable, observable and stable. Furthermore, some Simulink MATLAB simulations will be performed to test and verify that AC motors are adapted to variations in the load, as specified by the requirement specification. To verify and validate that the dynamics of the motors respond to the applied loads as required the MATLAB Simulations will be analyzed and commented.	STATUS	Verified
COMMENT	This requirement were tested by simulating the motor in Simulink, but we did not calculate to analyses the dynamic behavior of the closed loop system. This is because the motor we use has a suitable electric drive unit consisting of inverter and other necessary power electronics. The requirement is therefore satisfied without further tasting.		

TABLE 8 - TEST 1.6

TEST ID	TES 1.7	REQ ID	1.21
DESCRIPTION	To test this requirement we will calculate variation in the wheel base. After we can further test how this affect the driving characteristics of our system.	STATUS	
		Verified	
COMMENT			

TABLE 9 - TEST 1.7

TEST ID	TES 1.8	REQ ID	1.22
DESCRIPTION	This requirement will be tested in two different ways. First, we will test the mechanism for the dead axle, then we will test if the hydraulics of this system is working as intended or not.	STATUS	
		Pending	
COMMENT			

TABLE 10 - TEST 1.8

TEST ID	TES 1.9	REQ ID	1.23
DESCRIPTION	This requirement will be tested by demonstrating this feature with an RC car.	STATUS	
		Verified	
COMMENT			

TABLE 11 - TEST 1.9

TEST ID	TES 1.10	REQ ID	2.01
DESCRIPTION	This requirement can be tested by making a 3D model of our system.	STATUS	Verified
COMMENT			

TABLE 12 - TEST 1.10

TEST ID	TES 1.11	REQ ID	2.06
DESCRIPTION	This requirement can be tested using a Voltmeter and verify and validate that there is connection between the battery unit and the inverter through a two-wire connector.	STATUS	Verified
COMMENT			

TABLE 13 - TEST 1.11

TEST ID	TES 1.12	REQ ID	2.07
DESCRIPTION	This requirement can be tested by using hydraulic flow diagram.	STATUS	Pending
COMMENT			

TABLE 14 - TEST 1.12

<table>
<tr><td>TEST ID</td><td>TES 1.13</td><td>REQ ID</td><td colspan="2">2.08</td></tr>
<tr><td rowspan="2">DESCRIPTION</td><td colspan="3" rowspan="2">This requirement will be tested by calculation and hydraulics flow diagram.</td><td>STATUS</td></tr>
<tr><td rowspan="2">Pending</td></tr>
<tr><td>COMMENT</td><td colspan="3"></td></tr>
</table>

TABLE 15 - TEST 1.13

<table>
<tr><td>TEST ID</td><td>TES 1.14</td><td>REQ ID</td><td colspan="2">4.01- 4.02</td></tr>
<tr><td rowspan="2">DESCRIPTION</td><td colspan="3" rowspan="2">These requirements can only be tested after the system has been integrated into a heavy-duty vehicle.</td><td>STATUS</td></tr>
<tr><td rowspan="2">Pending</td></tr>
<tr><td>COMMENT</td><td colspan="3"></td></tr>
</table>

TABLE 16 - TEST 1.14

<table>
<tr><td>TEST ID</td><td>TES 1.15</td><td>REQ ID</td><td colspan="2">4.03</td></tr>
<tr><td rowspan="2">DESCRIPTION</td><td colspan="3" rowspan="2">This requirement will be tested by calculations, to verify and validate that the electric motor effect satisfies the customer's need.</td><td>STATUS</td></tr>
<tr><td rowspan="2">Pending</td></tr>
<tr><td>COMMENT</td><td colspan="3"></td></tr>
</table>

TABLE 17 - TEST 1.15

TEST ID	TES 1.16	**REQ ID**	4.04
DESCRIPTION	This requirement can be tested by verifying that the system we are developing is not heavily overpriced.	**STATUS**	Pending
COMMENT			

TABLE 18 - TEST 1.16

TEST ID	TES 1.17	**REQ ID**	1.01
DESCRIPTION	This requirement can be verified by calculating the average amount of energy we use while driving for 10 hours, and how much battery space we need for that amount of energy.	**STATUS**	Verified
COMMENT			

TABLE 19 - TEST 1.17

TEST ID	TES 1.18	**REQ ID**	1.02 – 1.03
DESCRIPTION	These requirements must be tested, by using SolidWorks or some other 3D modeling program, and design our system around these requirements.	**STATUS**	Pending
COMMENT			

TABLE 20 - TEST 1.18

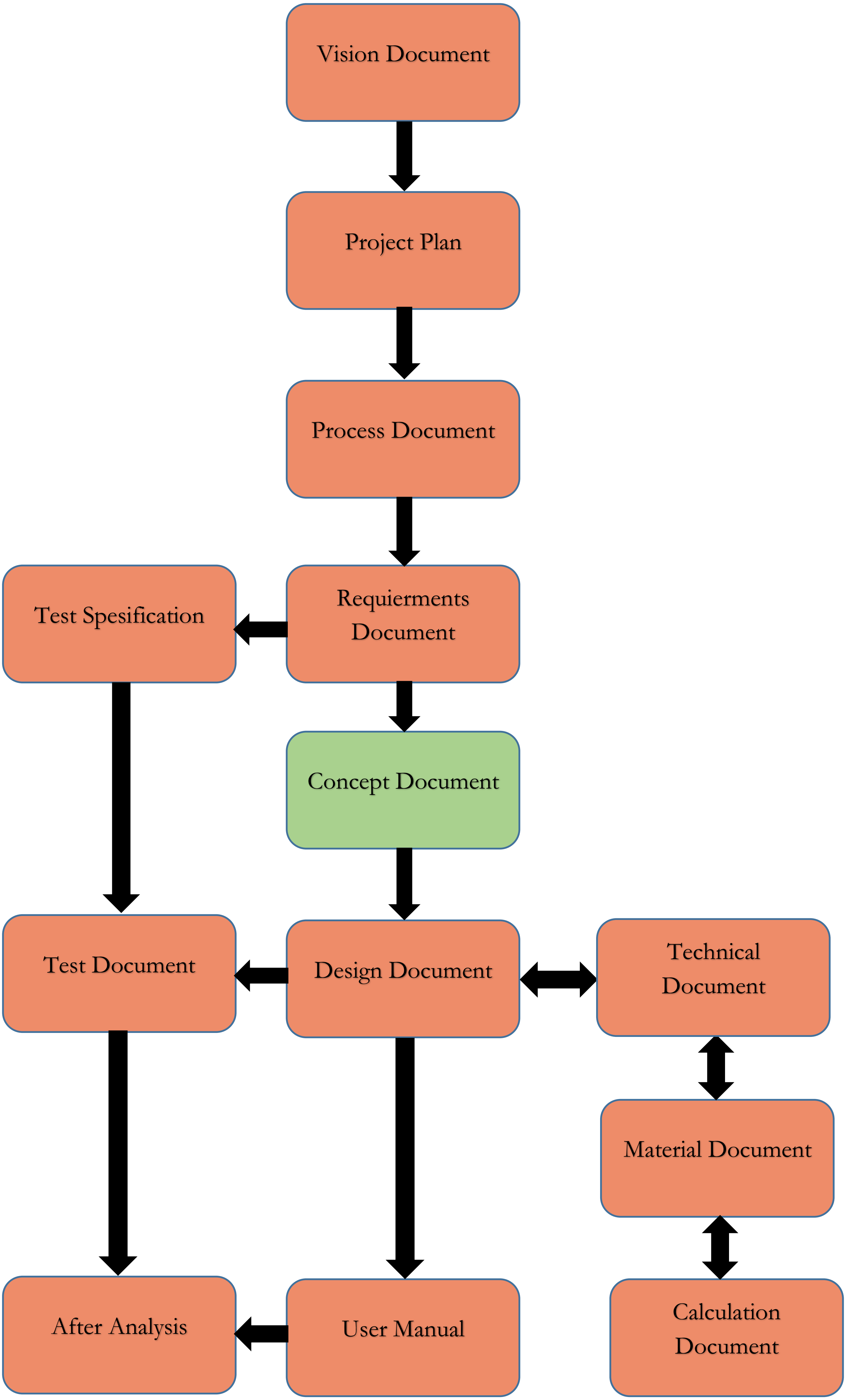
TEST ID	TES 1.19	REQ ID	1.04
DESCRIPTION	This requirement can be verified by using SolidWorks program, and calculate how much existing system weighs.	STATUS	Verified
COMMENT			

TABLE 21 - TEST 1.19

4. REFERENCES

[1] Oaldawud, "Software Test Specification," Oaldawud, [Online]. Available: http://www.cs.iit.edu/~oaldawud/Slides/Class12_ConfigurationManagement.pdf. [Accessed 22 01 2017].

[2] M. Beizer, "Dependable Software Systems," [Online]. Available: https://www.cs.drexel.edu/~spiros/teaching/CS576/slides/10.spec-testing.pdf. [Accessed 20 01 2017].


Vision Document
Project Plan
Process Document
Test Spesification
Requierments Document
Concept Document
Test Document
Design Document
Technical Document
Material Document
After Analysis
User Manual
Calculation Document

CONCEPT DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

<table>
<tr><td>Employer</td><td colspan="4">Kongsberg Automotive</td></tr>
<tr><td rowspan="7">Group Members</td><td colspan="2">Name</td><td colspan="2">Initials</td></tr>
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<tr><td colspan="2">Anis Sadiq</td><td colspan="2">AS</td></tr>
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<tr><td colspan="2">Mustafa Moalim</td><td colspan="2">MM</td></tr>
<tr><td colspan="2">Pawan Bhatt</td><td colspan="2">PB</td></tr>
<tr><td rowspan="2">Document Information</td><td>Version</td><td>Date</td><td>Approved</td><td>Pages</td></tr>
<tr><td>2.0</td><td>23.05.17</td><td>AS</td><td>48</td></tr>
</table>

18. mars 2017

CONCEPT DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
18.03.17	0.1	Document created	AK
21.03.17	0.2	Added info and concepts	AK
22.03.17	0.3	Stage 2 and 3 added	AK
23.03.17	0.4	Added stage 4	AK
23.03.17	1.0	Finalized	AK
18.05.17	1.1	Added transmission & lift axle	PB
21.05.17	1.2	Grammar and spelling check	AS
22.05.17	1.3	Corrections and minor updates	AK
23.05.17	2.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
C	Concept
S1	Stage 1
S2	Stage 2
S3	Stage 3
S4	Stage 4

TABLE 2 – DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

The purpose of this document is to give an overview of the different concepts for the wheel suspension system. It involves different types of ideas and concepts of possible design outcome, or how we can implement some of these concepts in to the final design of our product. The document also contains a brief explanation of the functionality of each concept.

Concepts are developed in four stages. We have given a unique ID to each concept. This ID is made up of Concept (C) followed by a number (X) and stage (S) also followed by a number (Y) e.g. (C1S1).

This document also gives a brief description of our ideas during design of concepts. It will give the necessary reasoning for the different concepts. These concepts do not cover a detailed design of the product, the detailed design of our product will be covered in the design stage.

1.1. Scope

The scope of this document is the following:

- Description of different concepts
- Placing of different subsystems
- Selection of independent or dependent axle for concepts

2. WHEEL SUSPENSION CONCEPTS

2.1. Concept Stage 1

Concept stage 1 is the first process of concepts design. This stage is the early and first stage in our process. Early concepts and ideas are created in this stage.

2.1.1. Sketches Overview

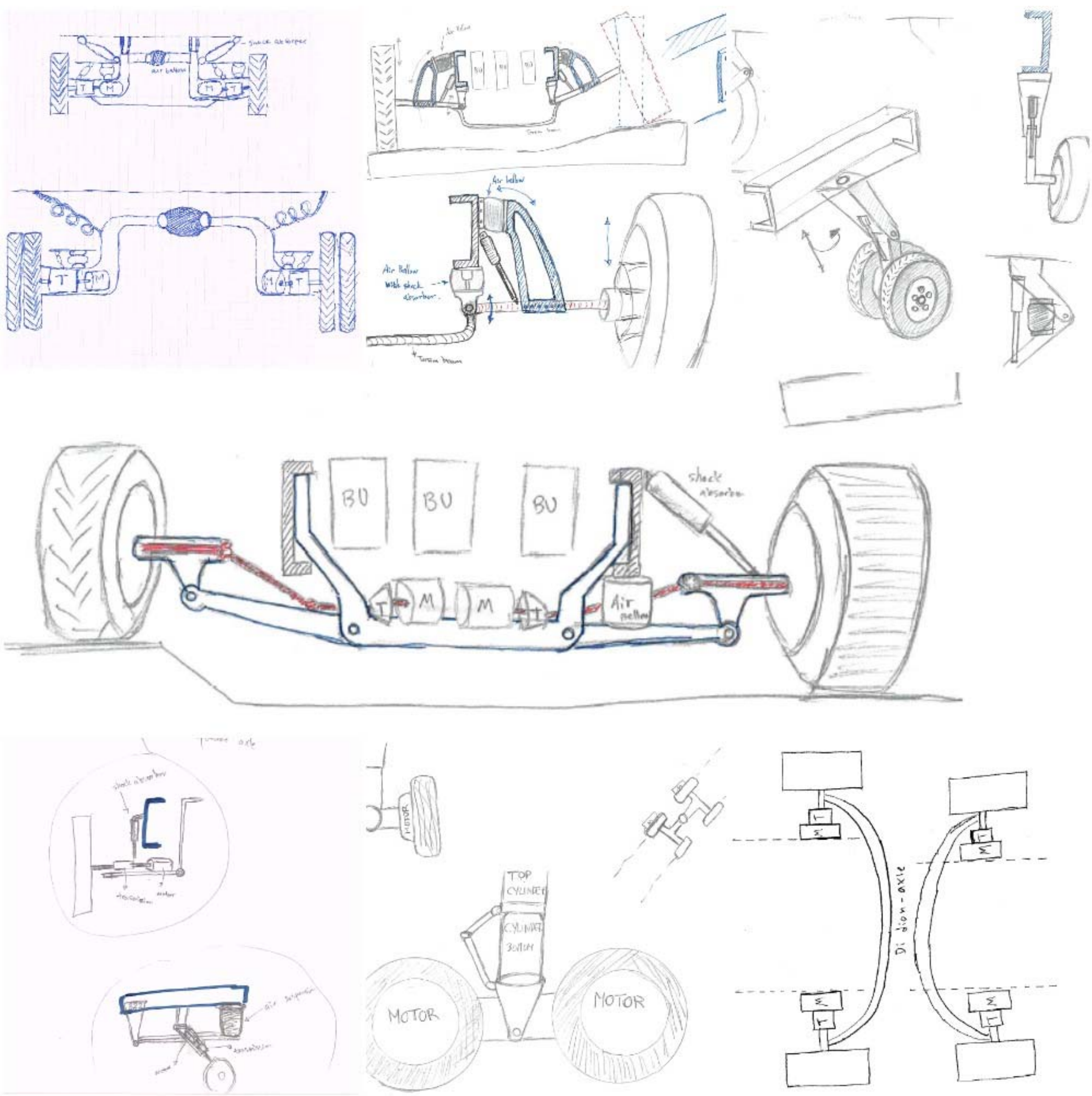


FIGURE 1 – OVERVIEW 1

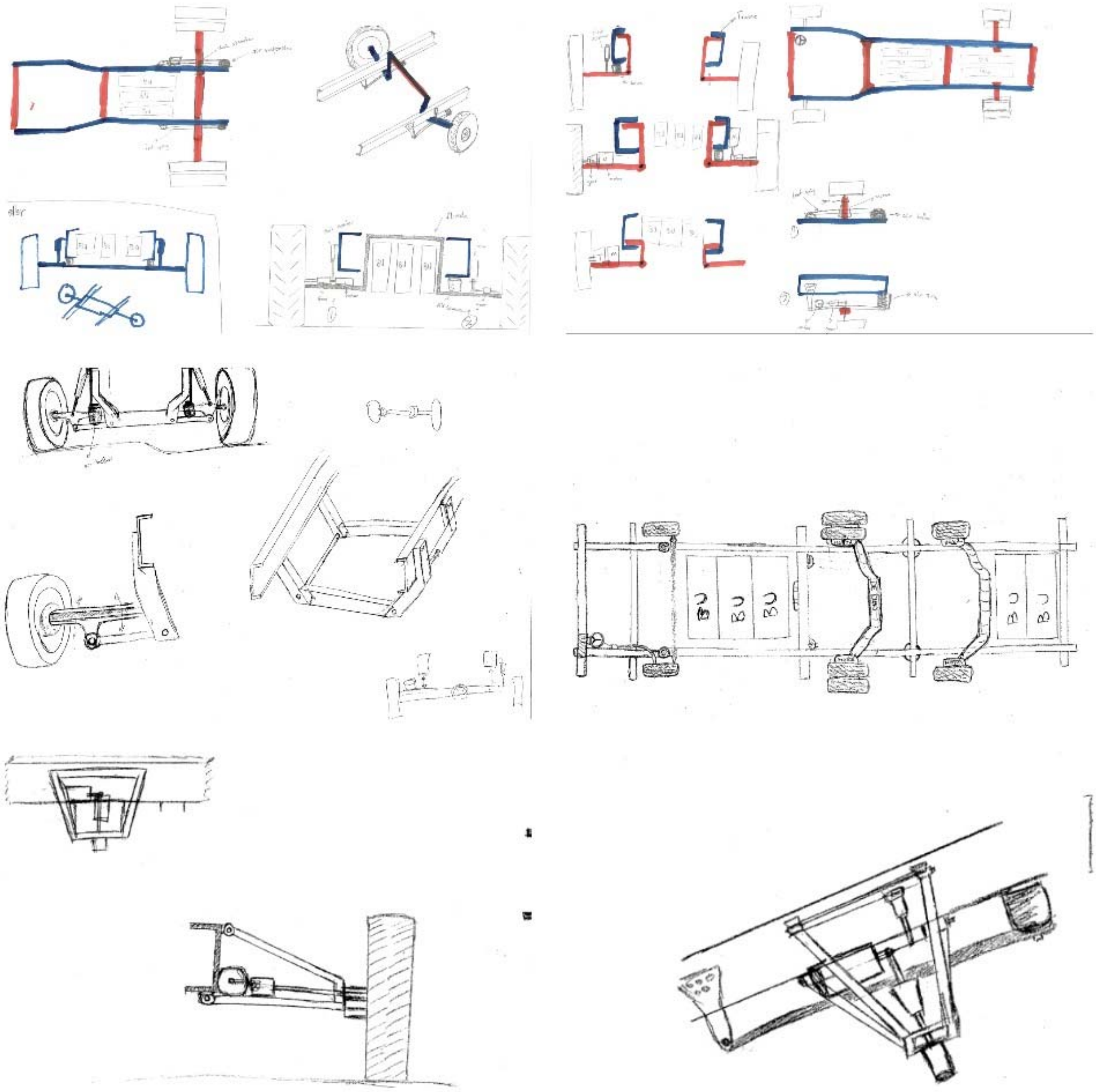


FIGURE 2 - OVERVIEW 2

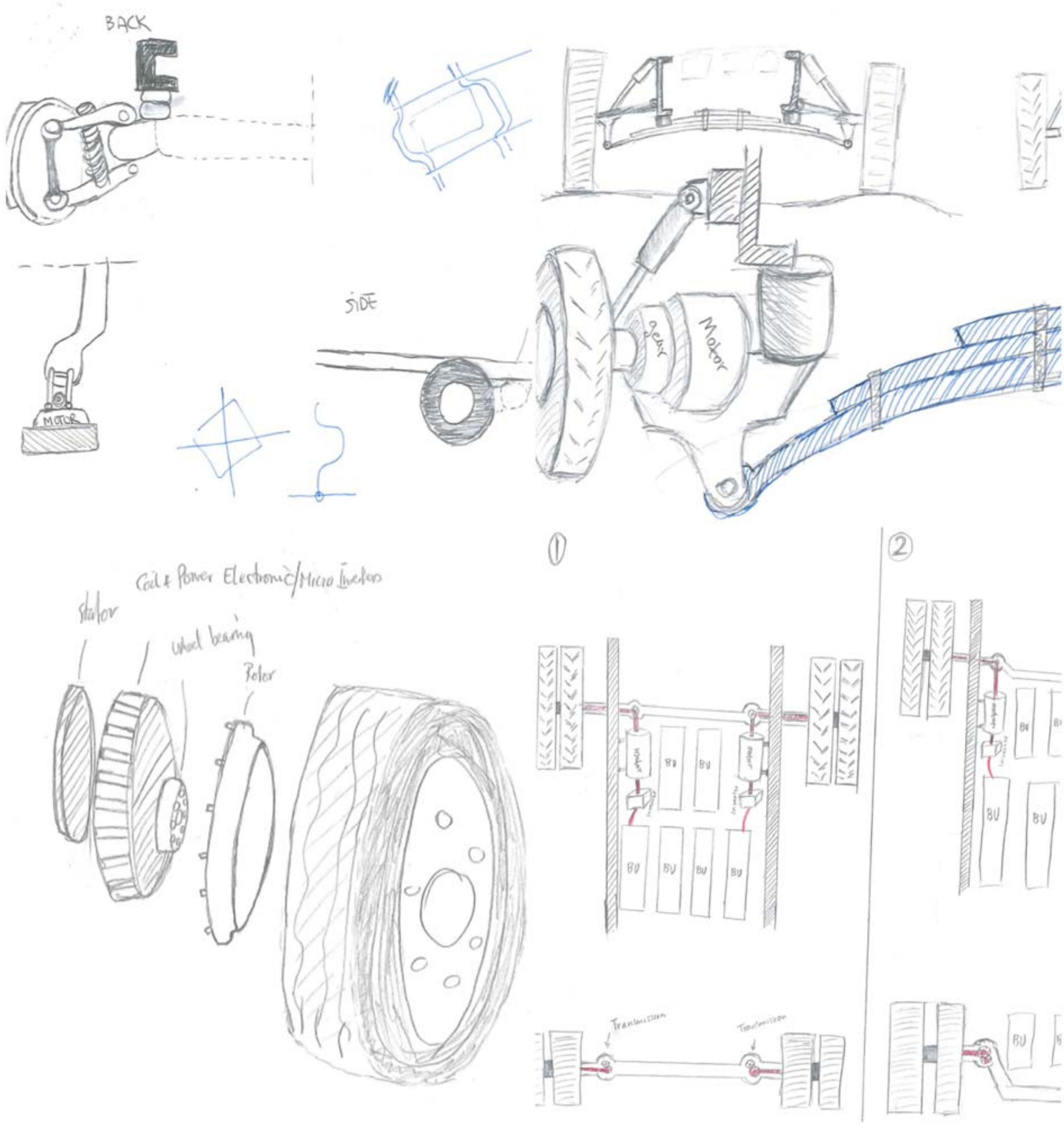


FIGURE 3 - OVERVIEW 3

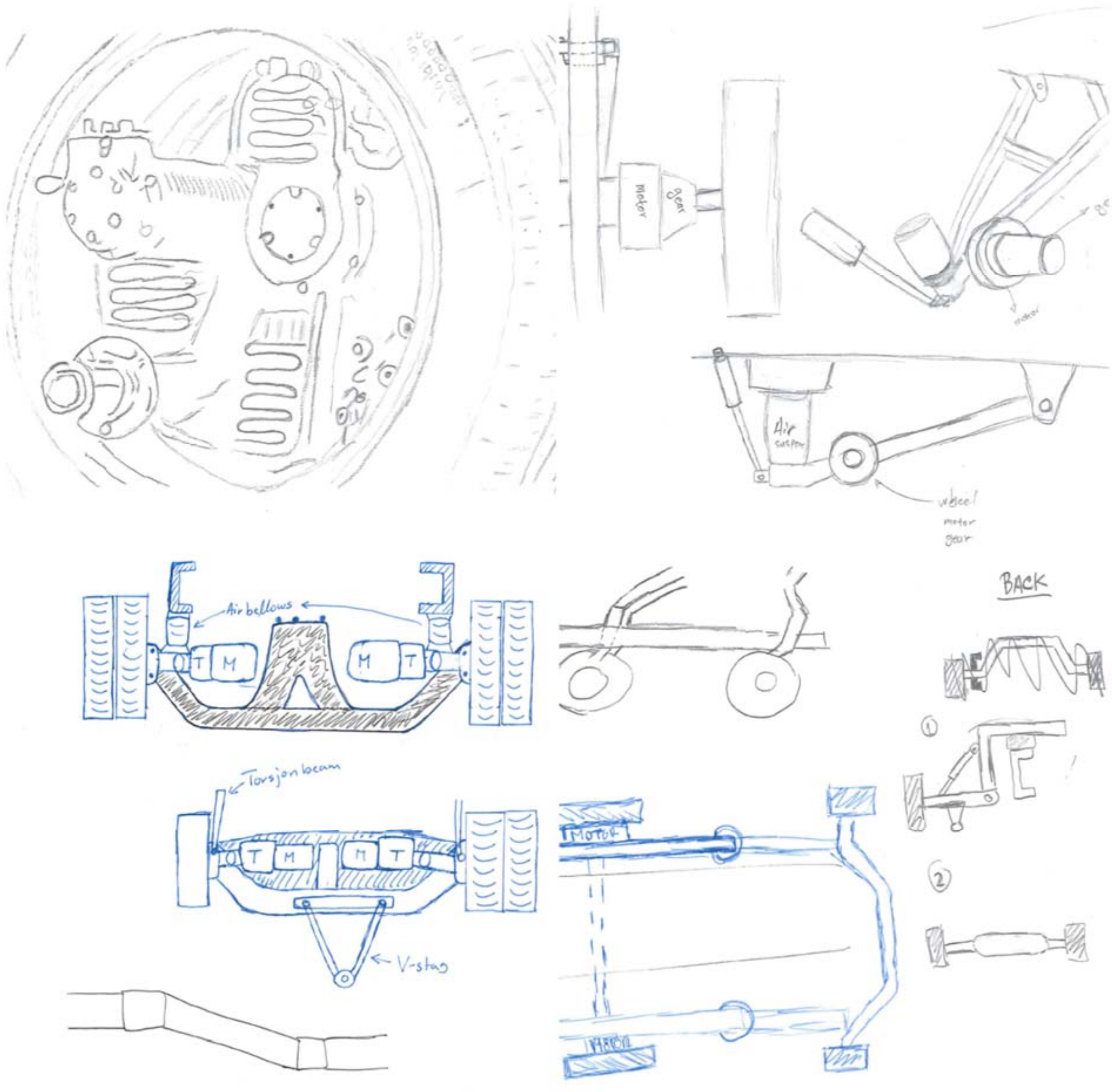


FIGURE 4 - OVERVIEW 4

Sketches above (fig. 1 - 4) are an overview of some of the early concepts by the group members. As we can see from figure 1 - 4, these drawings are early ideas and concepts of how the design of wheel suspension can possibly look. Some of these early idea-concepts will be described in further details.

2.1.2. C1S1

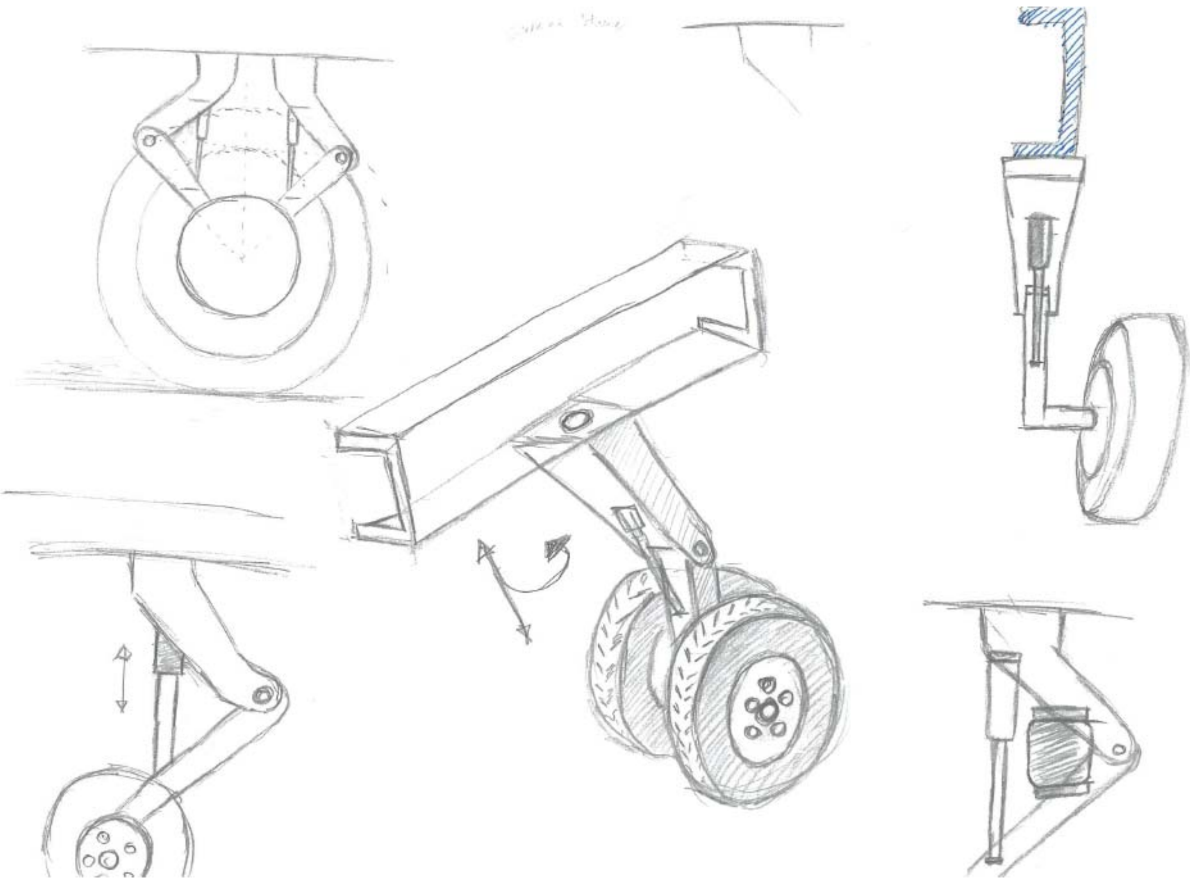


FIGURE 5 - CONCEPT 1 STAGE 1

The scissor-based concept is an idea inspired by the “Mammoet” company. Mammoet is a company which provides heavy transport and lifting service to their customers, meaning that the wheel suspension of their vehicles is very good engineered [1]. We think it can be a concept that can be implemented or combined with our possible design.

The suspension is a scissor shaped construction as we can see on the picture. The scissor shaped suspension is mounted to the frame and then connected to the wheels. In between the scissor shaped arm, we can see that it has been placed an air spring and a shock absorber. These are placed there so that the suspension is able to absorb the shock that comes from the road surface or any other forces.

2.1.3. C2S1

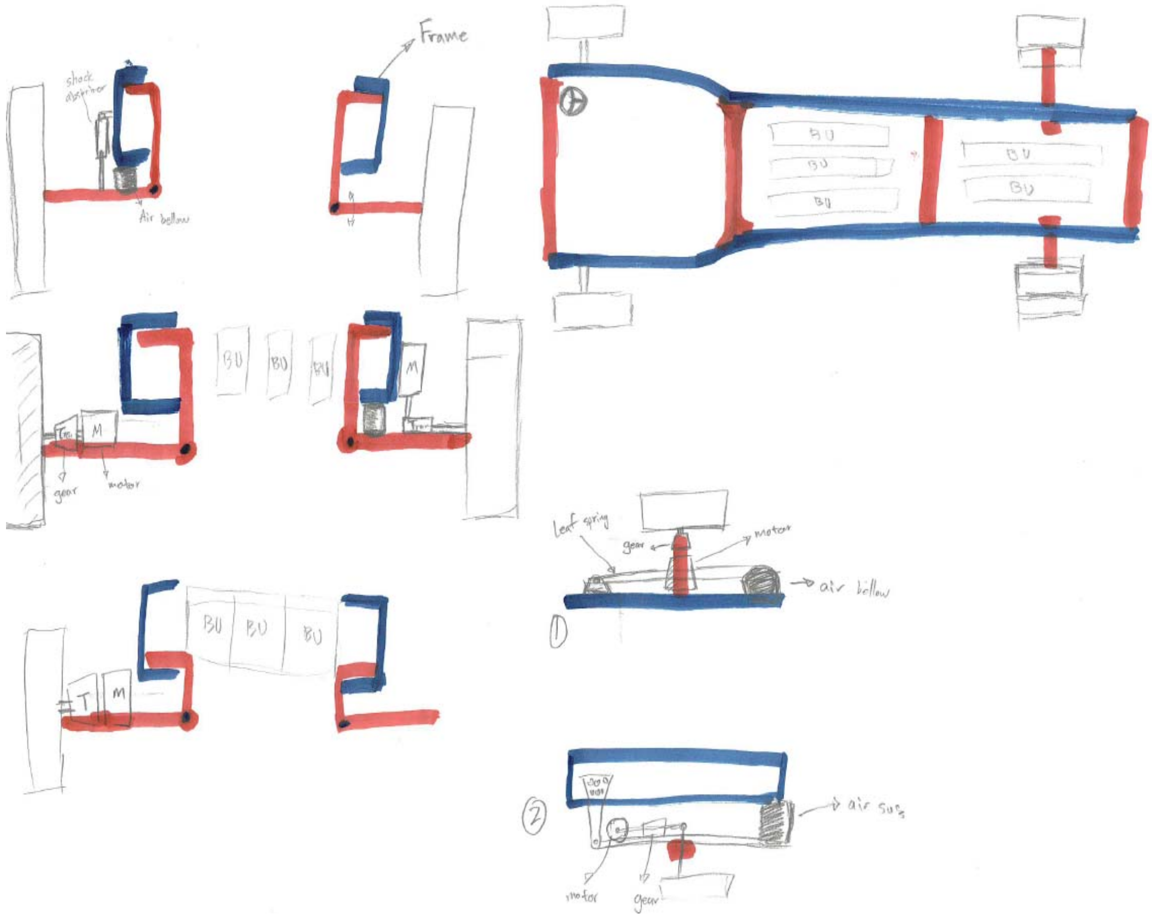


FIGURE 6 - CONCEPT 2 STAGE 1

The L-shaped concept is an independent axle. From the picture, we see that the arm connected from the wheels, is almost formed like the letter "L" when it is connected to the frame of the vehicle. The axle might not be so strong, because it is not a rigid connection between the wheels. The idea here is to save as much space as possible for the battery unit. For merely this purpose the space between the axles is empty.

Motor and transmission is mounted close to the wheels. Shock absorber is mounted from the axle to the frame to absorb the incoming shocks. Whilst air spring is mounted between the axle and the frame, this is so that the air spring can absorb and support the suspension, and be able to lift up the chassis if needed.

2.1.4. C3S1

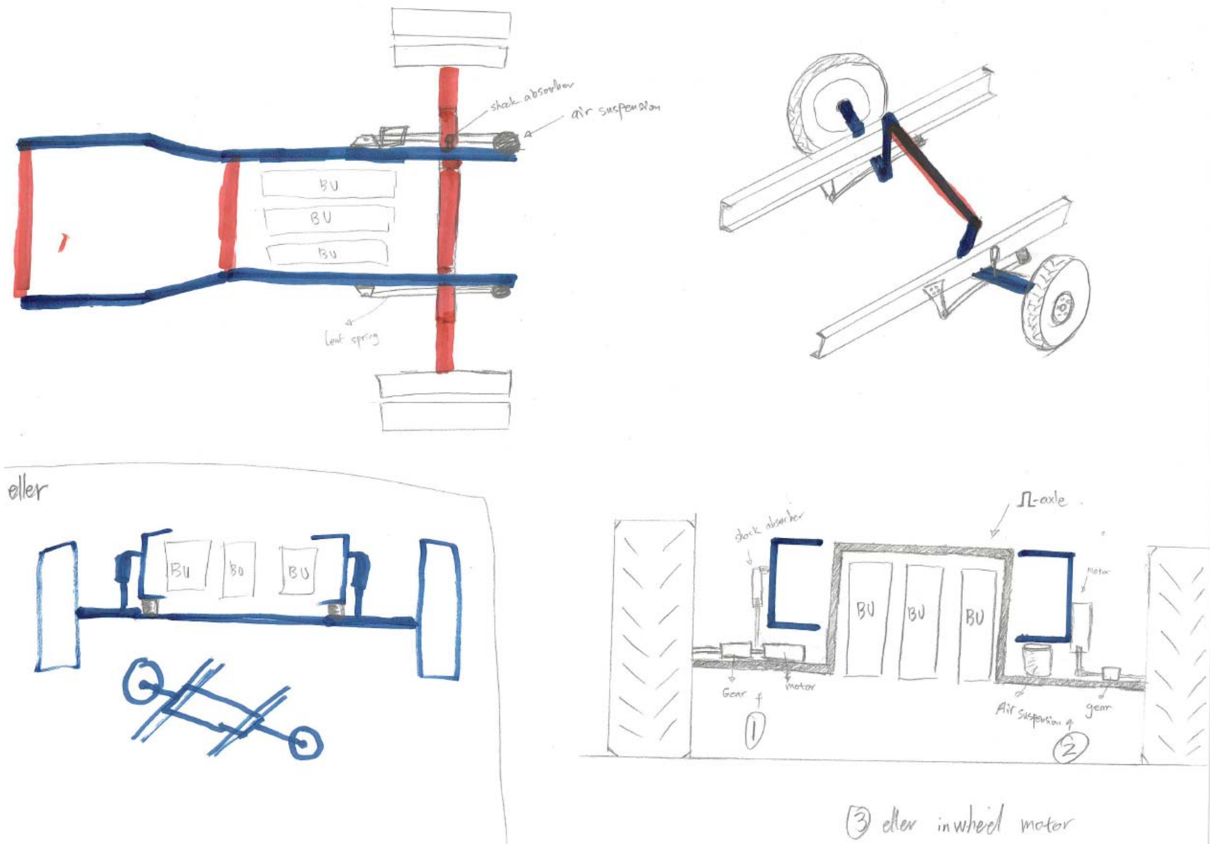


FIGURE 7 - CONCEPT 3 STAGE 1

This type is a dependent axle. There is a rigid connection between the wheels. It means that the connection is strong and can handle more forces compared to the L-shaped independent axle. The axle is a sort of reversed U-shape. The reason why the axle is designed as a reversed U-shape is so that the empty space between wheels is reserved for battery units. Another reason is so the battery unit can be swapped vertically from the bottom if needed, in case of maintenance.

2.1.5. C4S1

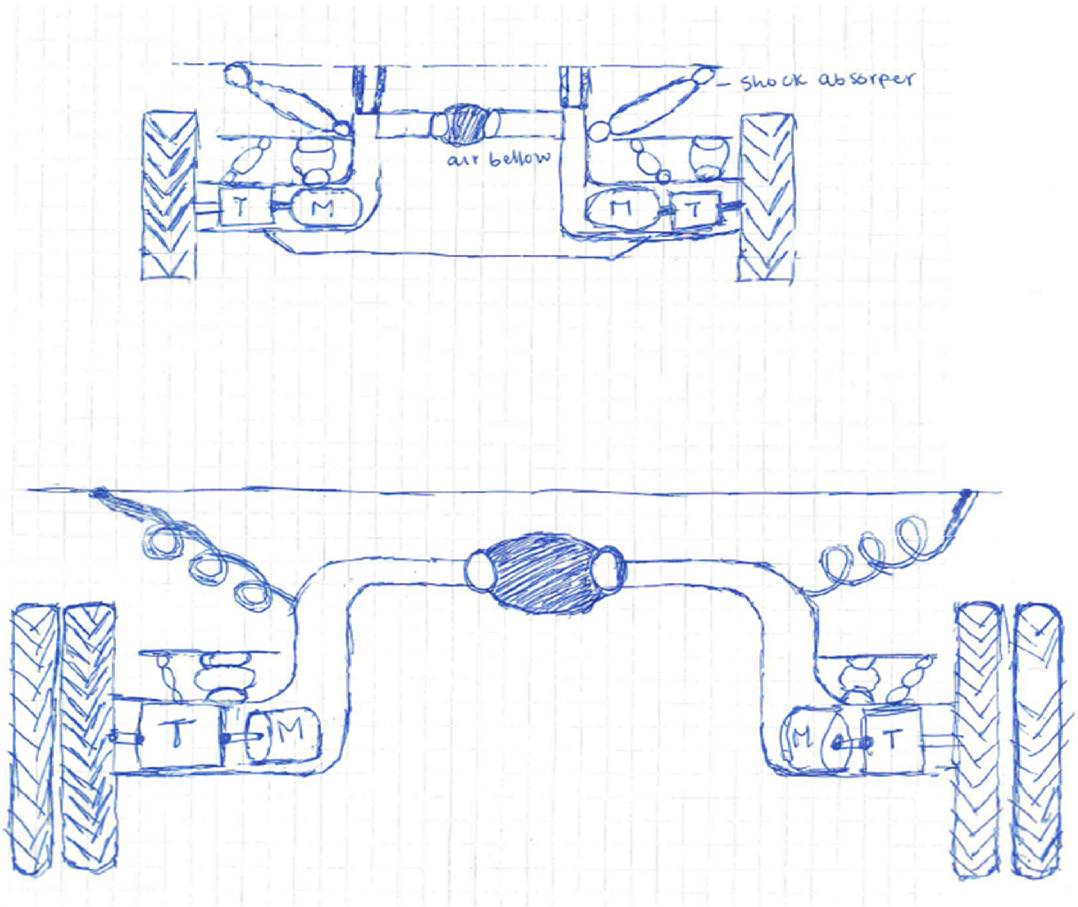


FIGURE 8 - CONCEPT 4 STAGE 1

This omega shaped axle, is another dependent axle type. The reason it is shaped like this is so that we can place battery unit under it, and take it out vertically from the bottom if needed. Construction is strong and rigid; meaning it can handle a lot of force.

Motor and transmission is placed inside the body of the omega shaped axle. It has been placed close to the wheels. In the middle of the axle, there is placed an air spring to control and stabilize the vehicle.

2.1.6. C5S1

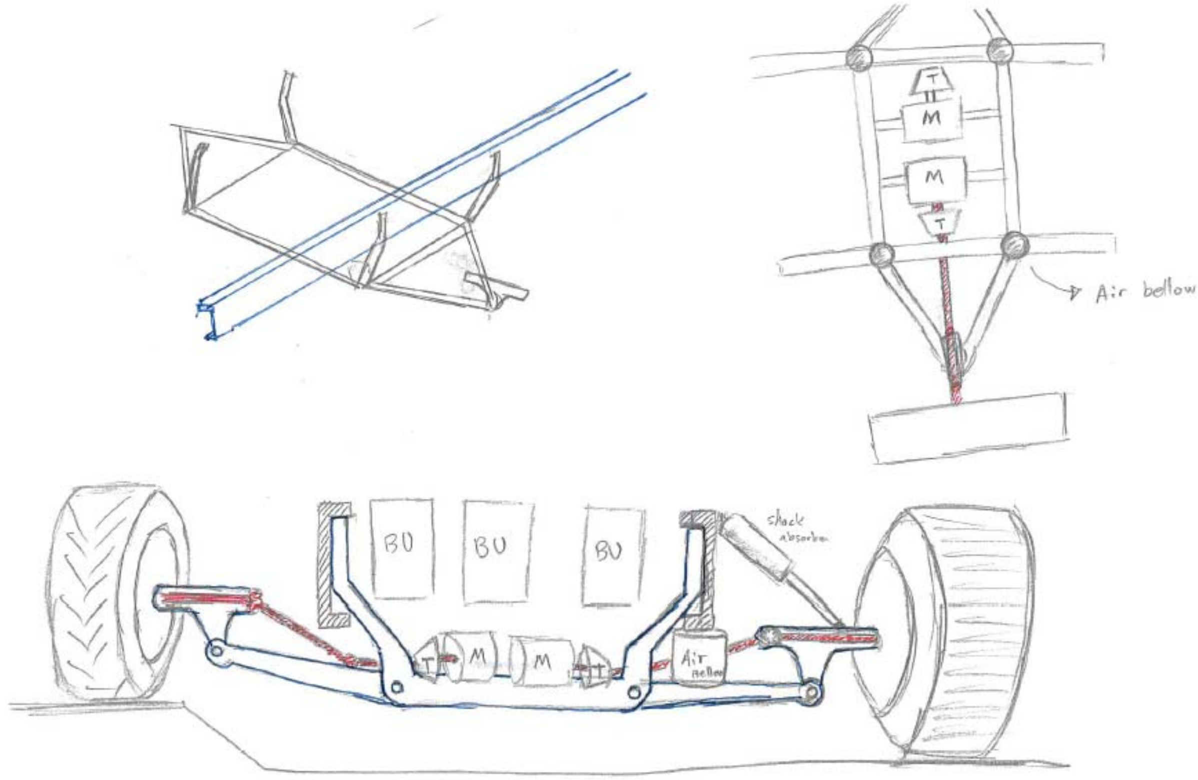


FIGURE 9 - CONCEPT 5 STAGE 1

This axle is independent and flexible. It’s shaped like the letter “V”. From the picture, we see that it is mounted to the frame of the vehicle. The V-arm is supported by two parts which is connected to the arm of the wheels. This construction is able to handle forces coming from both y and x axis.

Motor and transmission is placed between the V-arm. Close to the wheel there is placed a shock absorber, and under the frame there is placed an air spring, these components can absorb incoming shocks and bumpy surfaces on road. Over the transmission and motor there is space for battery units.

2.1.7. C6S1

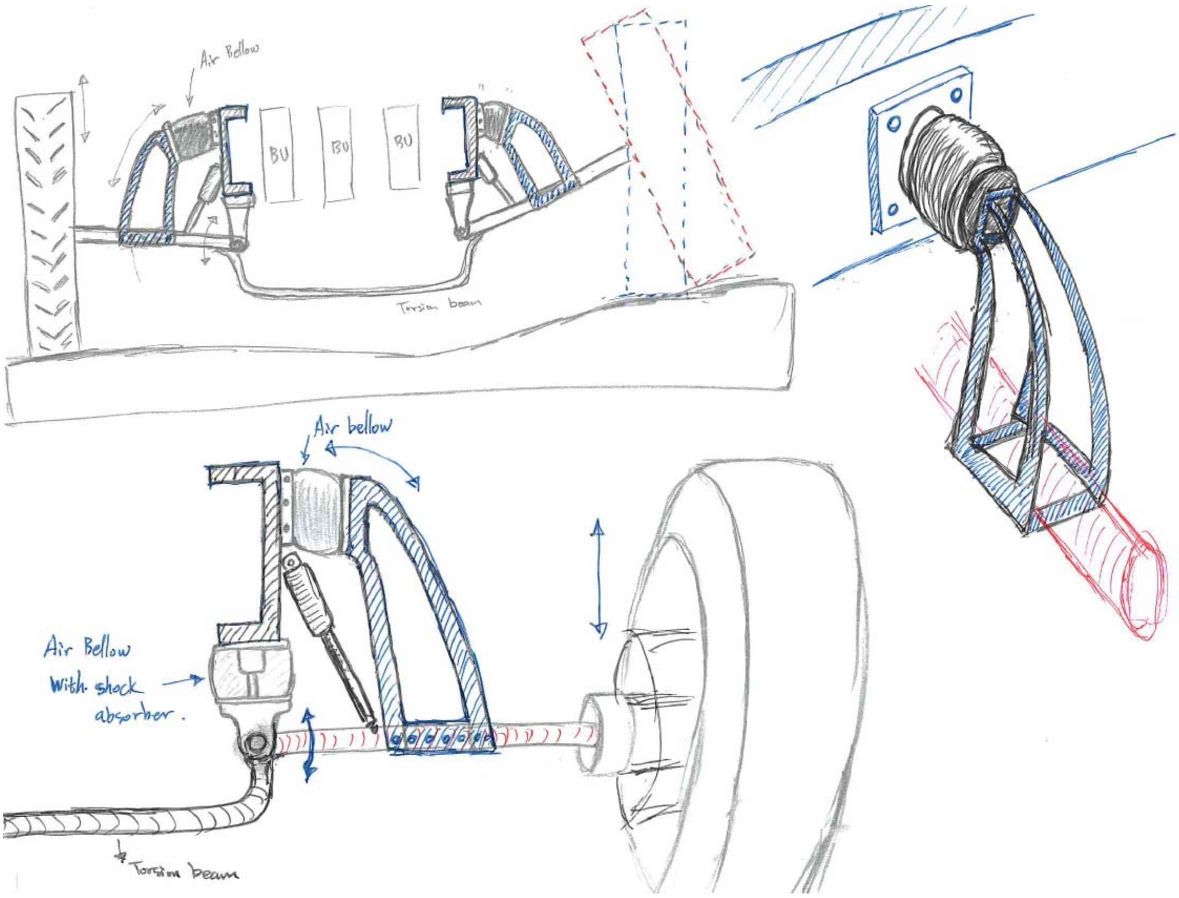


FIGURE 10 - CONCEPT 6 STAGE 1

This is another type of independent axle. This axle is not so strong constructed, because the only connection between the axles is a small torsion beam, and this torsion beam is not able to handle all the incoming forces on the axle.

From the axle, close to the wheel, there is an arm connected to the frame with an air spring in between them. This because, it is going to handle the horizontal forces working on the axle, so it does not break down. Under the air spring there is placed a shock absorber.

On the other concept, we can see that there is placed an air spring with shock absorber integrated under the frame. This is for extra support and too stabilize the vehicle.

2.1.8. C7S1

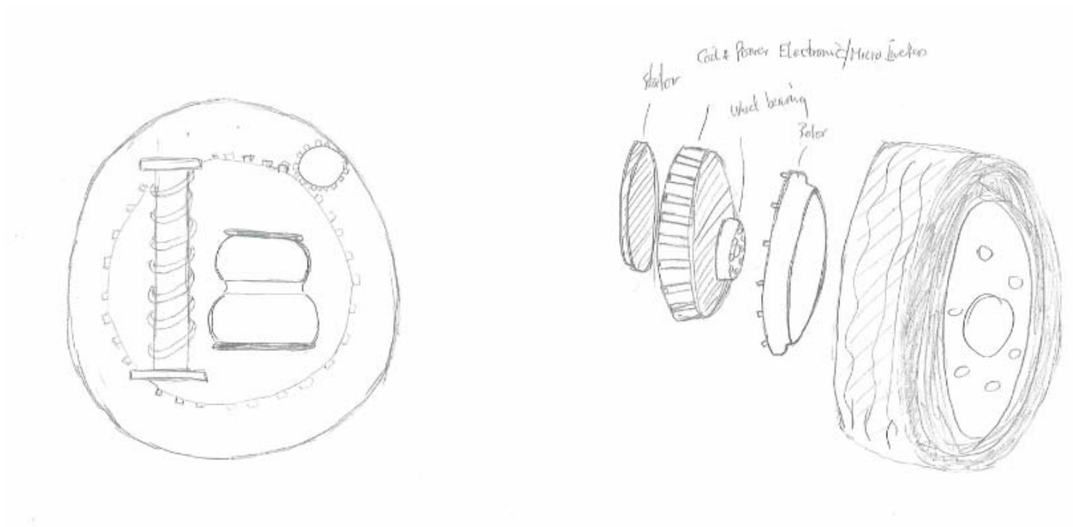


FIGURE 11 - CONCEPT 7 STAGE 1

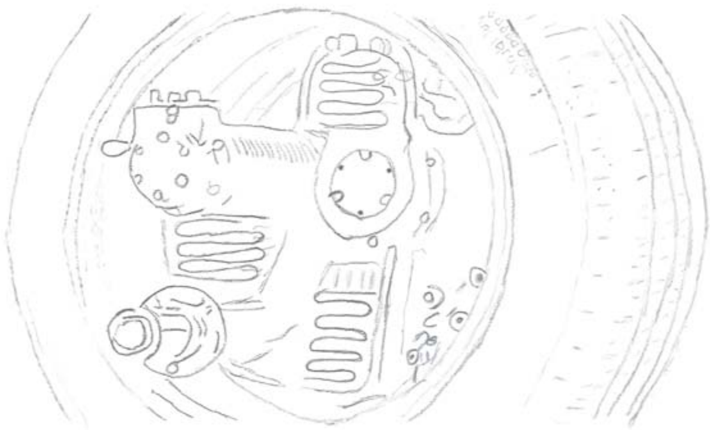


FIGURE 12 - CONCEPT 7 STAGE 1

This concept is everything integrated into the wheel. Both electric drive and suspension system. This concept is a technology which is still ongoing, but it has come to our minds while designing concepts. This is a concept which can save a lot of space in the vehicle. This means there will be a lot of empty space for the battery units. However, this concept is also very vulnerable. Vibration and shock forces working on the system can damage it over time.

2.1.9. C8S1

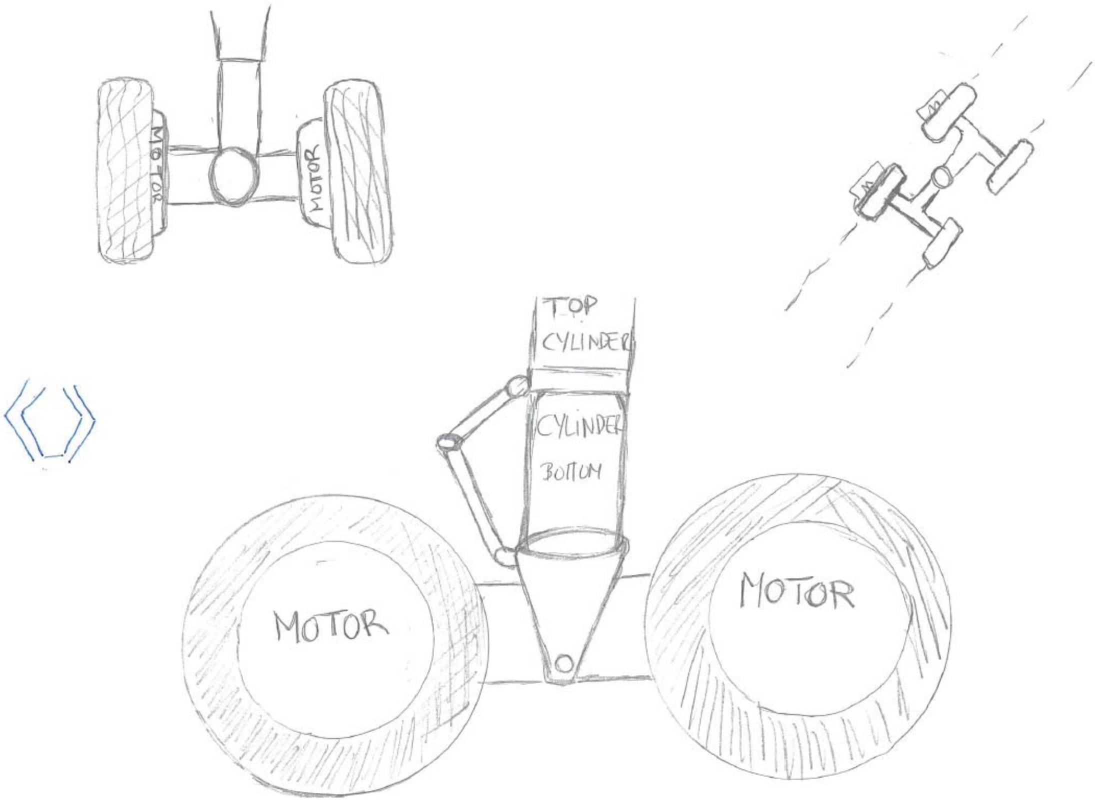


FIGURE 13 - CONCEPT 8 STAGE 1

This concept is based on aircraft suspension. There are four wheels on the suspension. In the middle, there is a cylinder which is hydraulic driven and absorbs incoming shocks and vibrations.

2.1.10. C9S1

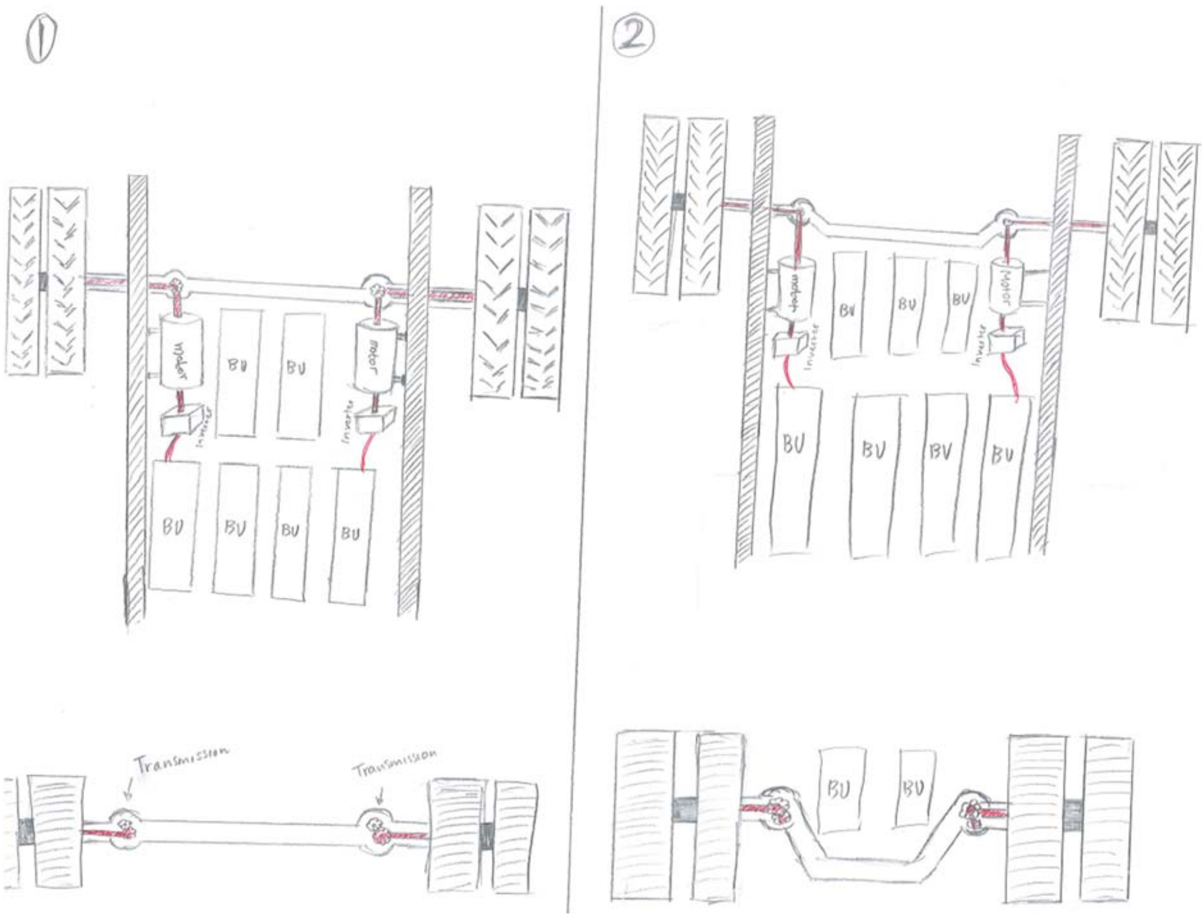


FIGURE 14 - CONCEPT 9 STAGE 1

In this concept, all components are placed at the same place. Main difference is the shape of the solid rigid axle. Both of these axles are dependent. Only difference is the shape of axle as we can see on the picture. Motor and transmission has been placed horizontally along the frame of vehicle.

2.1.11. C10S1

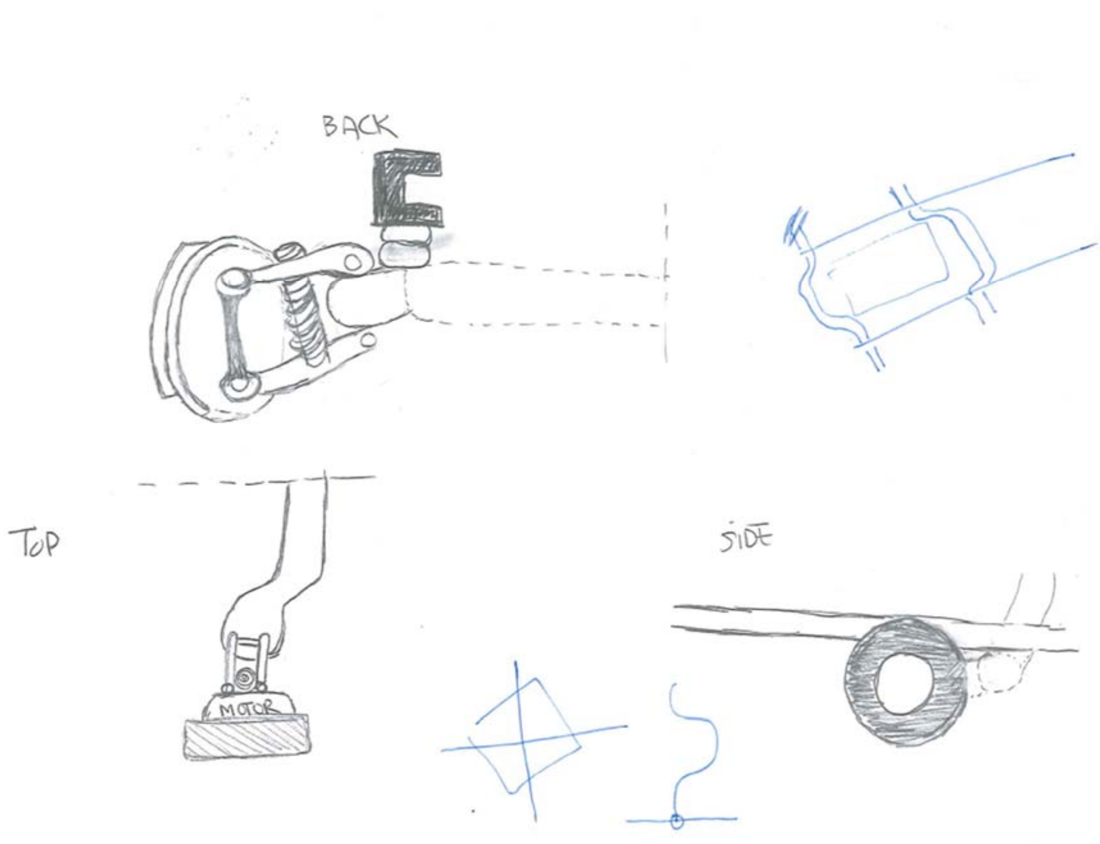


FIGURE 15 - CONCEPT 10 STAGE 1

This type of axle is inspired by a "de Dion axle". This axle is independent. On the back view we can observe that it has an arm connected to the axle which is independent. Motor and transmission is placed in-wheel. Air spring is placed under the frame, and shock absorber is mounted on the wheel and then connected to the frame.

2.1.12. C11S1

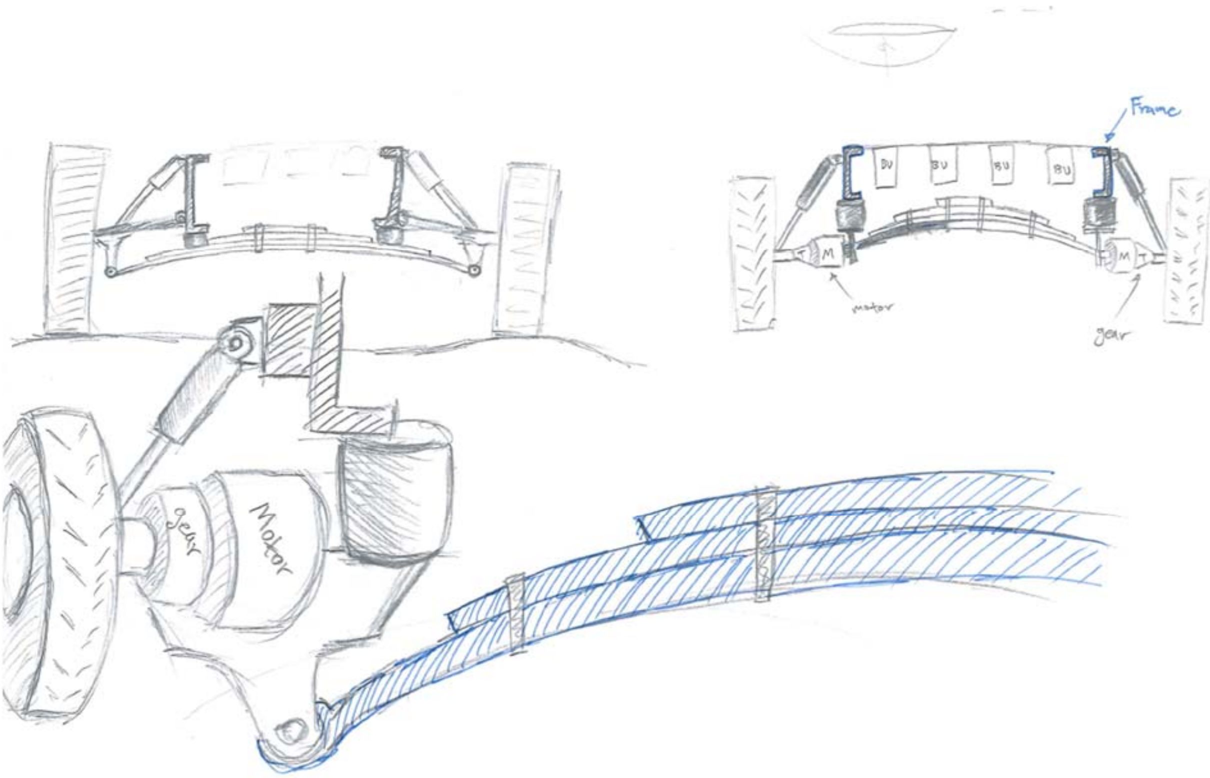


FIGURE 16 - CONCEPT 11 STAGE 1

This is a leaf spring based concept. This axle is semi-independent. It's based on using leaf spring as an axle connection between wheels. So the leaf spring works both as a support and can also absorb vertical shock forces.

Motor and transmission is placed on arm holding the leaf spring up. Shock absorber and air spring helps stabilize and absorb incoming shocks.

2.1.13. C12S1

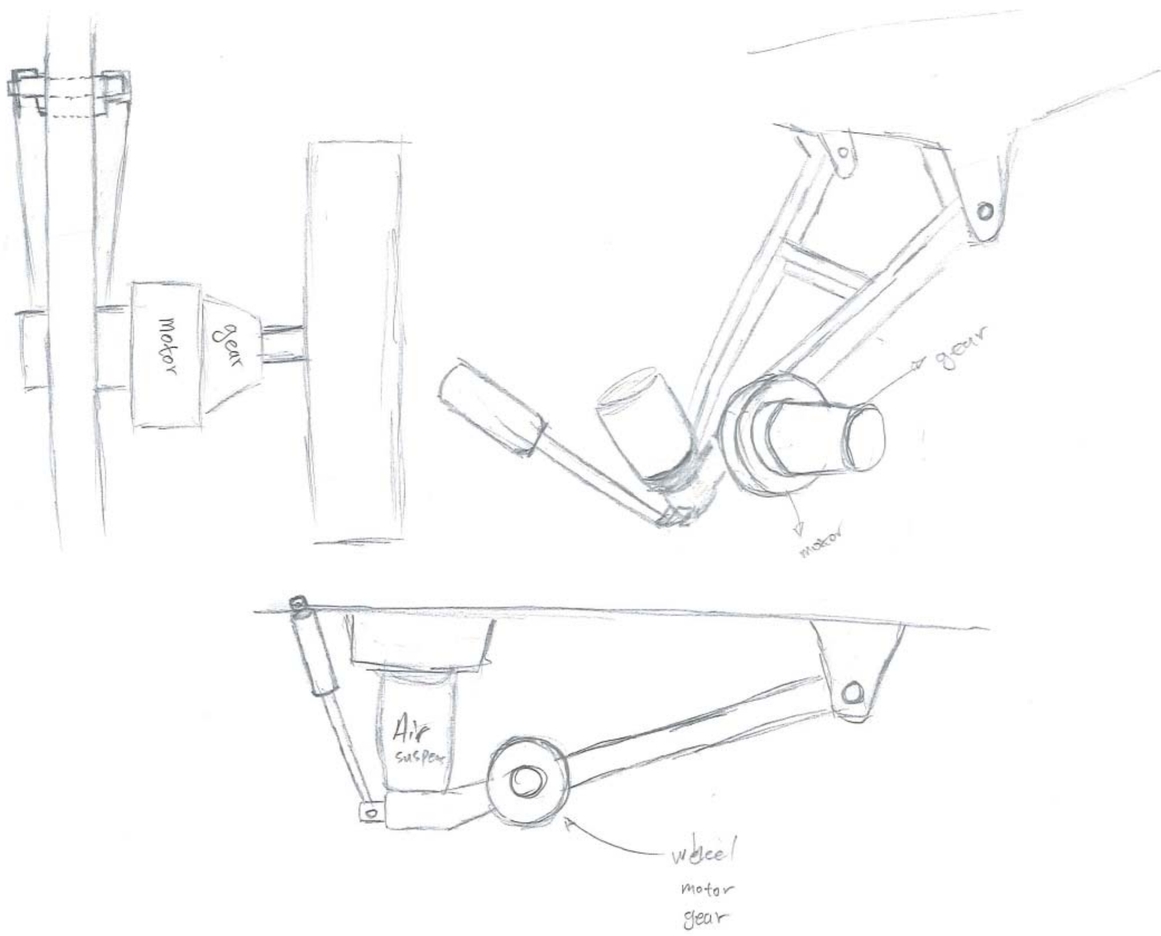


FIGURE 17 - CONCEPT 12 STAGE 1

This concept is formed like the letter "A". This axle is independent. Axle of this type is able to handle forces which comes from z, y and x- directions. Forces coming from y-direction can be a bit hard to handle, but it all depends on the width of the A-arm. The longer the width is, the more force it is able to handle. A disadvantage with this concept can be the change of wheel base during bumpy roads. Meaning; wheels will not move up and down smoothly, but move up and down in a more circular motion.

Shock absorber and air bellow is placed on the arm and then mounted to the frame of the vehicle to stabilize and absorb incoming forces. Motor and transmission is placed close to the wheels.

2.2. CONCEPTS STAGE 2

Concepts stage 2 is the next stage in our concept process design. In stage 2 we are making three new concepts which are a combination of different ideas from stage 1. We try to see how the ideas from stage 1 can be combined and made into new concepts. Three new concepts are presented in stage 2. These will be explained in further details.

2.2.1. C1S2

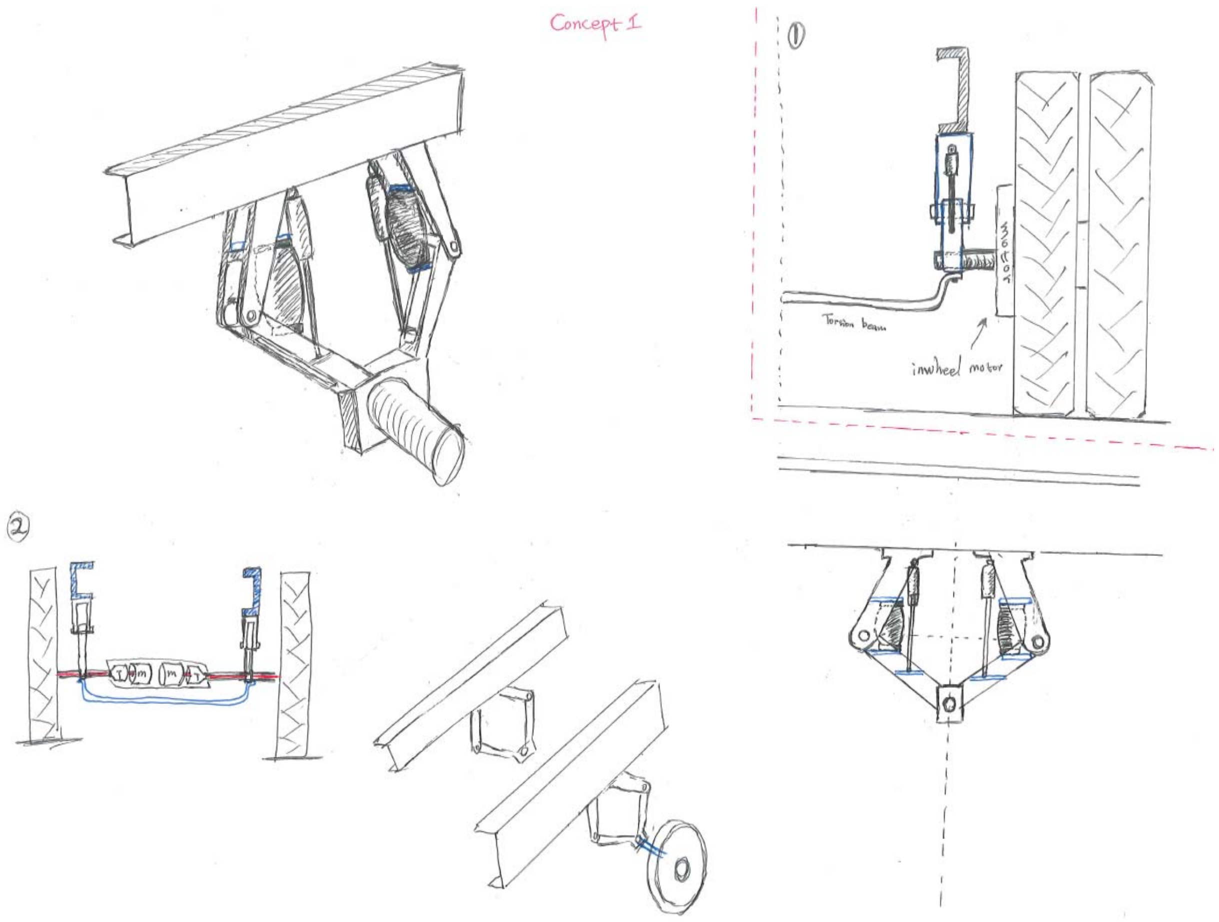


FIGURE 18 - CONCEPT 1 STAGE 2

This concept is the one inspired by the "Mammoet" company [1]. This concept has a scissor type of arm which is connected to the frame of vehicle. Scissor arm is then connected to wheels with a bearing sticking out to the wheel connection. Reason of inspiration by Mammoet is because they provide heavy-duty vehicle services to their customers, and since we are designing for heavy-duty vehicles it makes it relevant for our design.

Mammoet uses hydraulic system on their wheel suspension. This is because the heavy-duty vehicles they are using is driving on a very low speed. That's why they only use one scissor arm on their vehicles. We are designing for a heavy- duty vehicle which is going to drive on both low and high speed. What we are doing is, we put two scissor arms instead of one, to further increase the strength of the axle construction of our concept. We also don't use a hydraulic system. Instead, we use shock absorbers and air springs.

Shock absorber and air spring are placed inside the arm of the scissor. It has been placed on both sides to further stabilize vehicle against incoming forces. A torsion beam is placed between the wheels to stabilize it further against the forces working on the wheel suspension.

Motor and transmission has two concepts in this design. From the picture above we can see that on number one, it has been place in-wheel, and on number two it has been placed on a solid rigid axle which has a connection from one wheel to the other.

2.2.2. C2S2

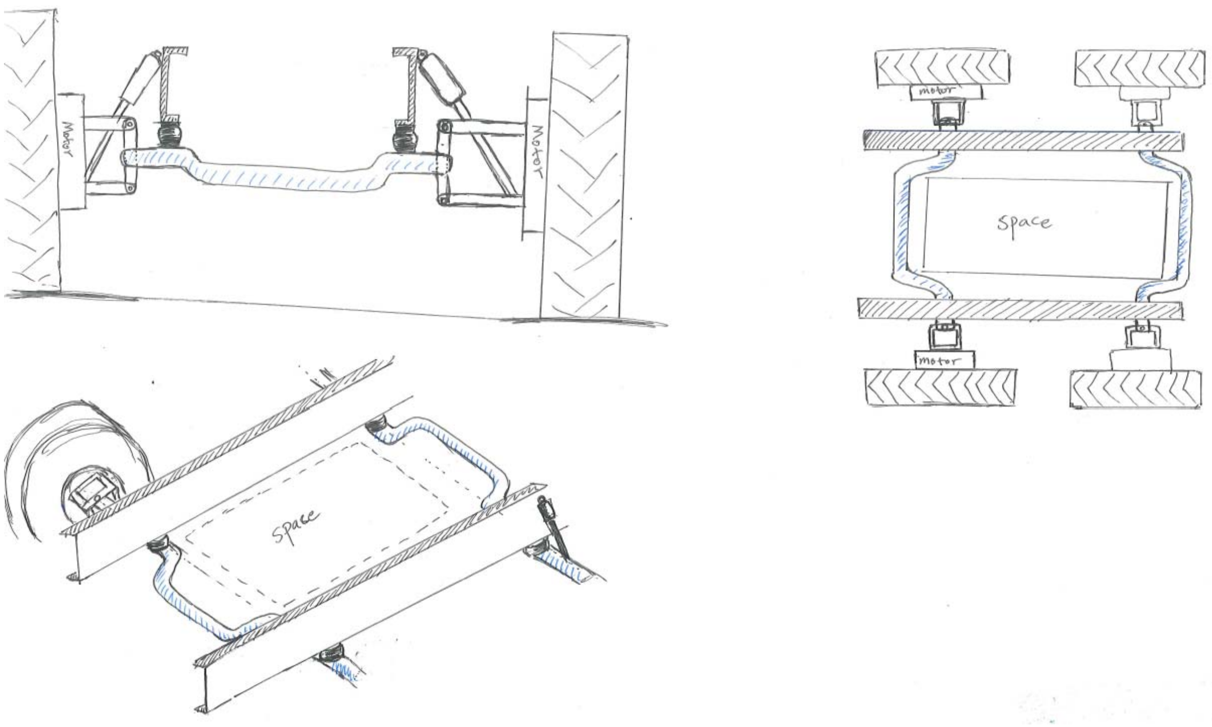


FIGURE 19 - CONCEPT 2 STAGE 2

Concept 2 is designed out of combining the shape of "de Dion axle" [2], with a solid type of axle. We are making the construction of the de Dion axle strong, but still independent as we can observe from the picture. The de Dion axle is connected to a double type of arm which is then connected to the wheels.

Shape of the de Dion axle on the dead axle (behind the drive axle) is reversed. This is to create empty space in the middle to store battery units. Shock absorber is placed between the double arm and the frame of the vehicle. Air spring is placed under the frame, so it can absorb incoming shocks working on the system.

Motor and transmission is placed in-wheel too save as much space as possible for battery units.

2.2.3. C3S2

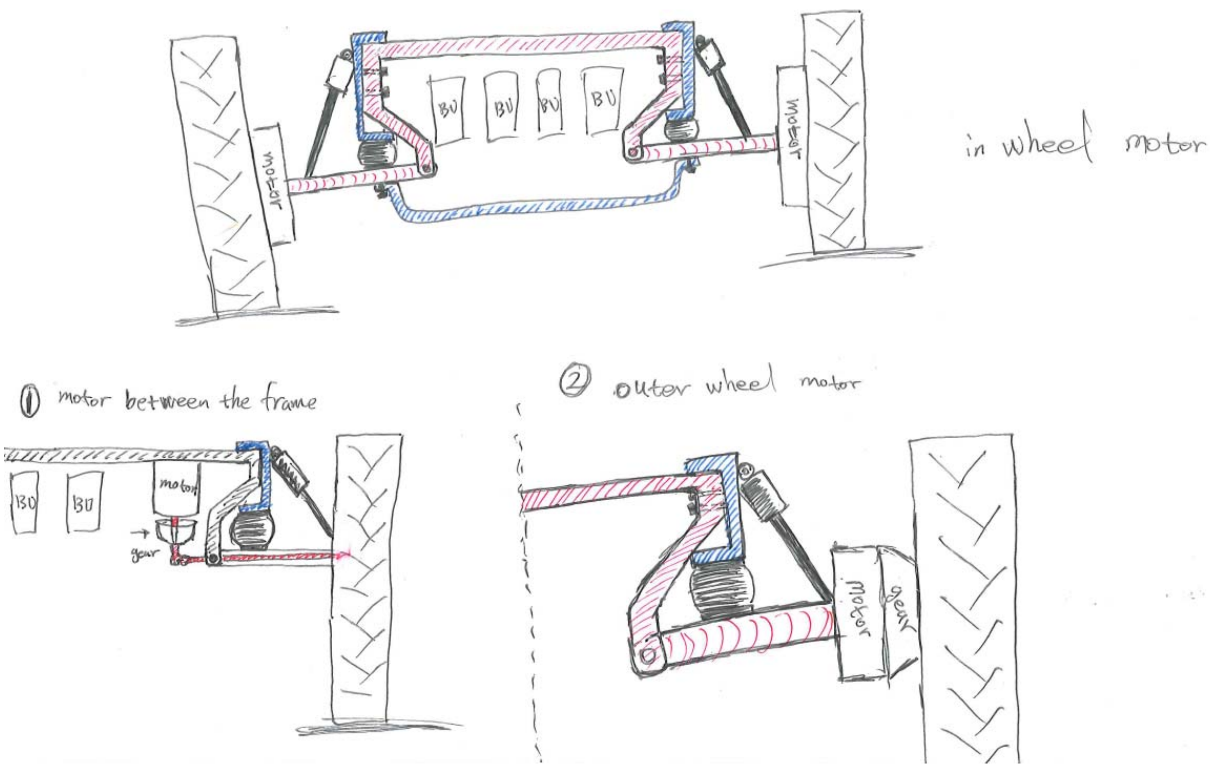


FIGURE 20 - CONCEPT 3 STAGE 2

This concept is a modified and better version of the omega shaped C4S1. This axle is independent. We want to make an independent type of axle which is better and smarter constructed than the omega shaped C4S1.

From the wheels there are two arms which are connected to the axle and then mounted to the frame of the vehicle. Between the connections there is a joint on each arm so it can move flexibly up and down, independently from the wheels. Shock absorber and air spring are placed on the arm connected to the wheel, to absorb incoming shocks and vibrations working on the system.

For the motor and transmission part, we have three separate concepts. First concept has in-wheel motors. Second concept has motor and transmission mounted and placed between the frame. On the third concept the motor and transmission is placed close to the wheel.

2.3. CONCEPTS STAGE 3

We made another stage in our concept process. The reason we did this is because we needed to modify and make some improvements to the concepts that was made in stage 2. After some discussion with our mechanical supervisor Lars, we had to reflect over the concepts that we made in stage 2. This lead to the creation of stage 3 in our concepts process. These concepts will be explained in further details.

2.3.1. C1S3

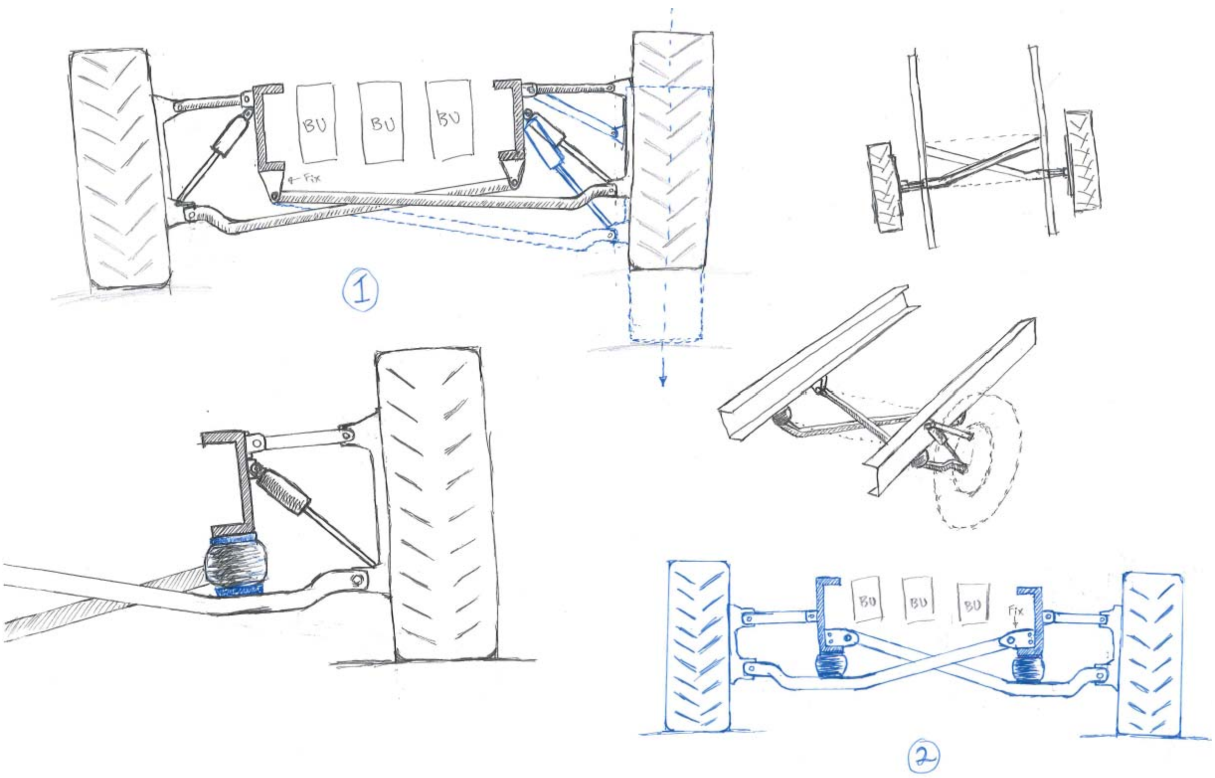


FIGURE 21 - CONCEPT 1 STAGE 3

Here we came up with an idea of creating a vertical type of scissor axle. This axle is flexible and independent. We thought that by making a vertical type of scissor axle, the axle will be able to handle horizontal and vertical forces working on the system.

Shock absorbers and air springs are placed traditionally like many of the other concepts to absorb incoming forces.

A disadvantage on this system is that the length of the arm which is connected from the frame to the wheel is limited. Meaning that the wheels can't move up and down as freely as we would like it too do. Also if the vehicle brakes heavily, forces working on axle can cause a lot of stress in x-direction.

There are two different concepts of how the scissor arms can be mounted. One is that the scissor arms are mounted from the wheels to under the frame of the vehicle. The other one is that scissor arms are mounted from the wheels to inside of frame on vehicle.

2.3.2. C2S3

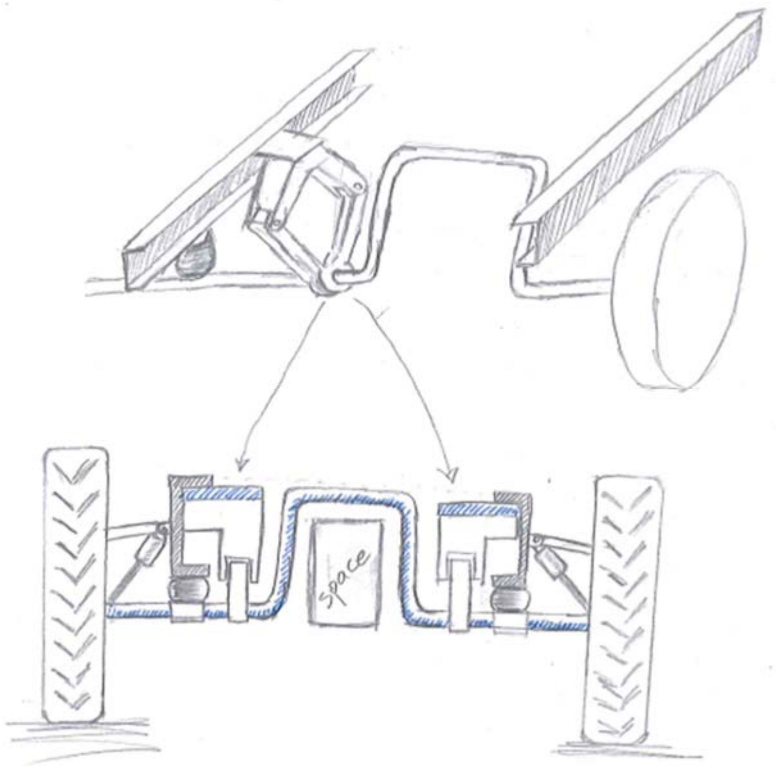


FIGURE 22 - CONCEPT 2 STAGE 3

This concept is modified in such a way that the vertical scissor arm has been placed inside the frame of vehicle. As we can see from the picture, we also use an omega shaped axle connection between the wheels. The scissor arm is placed on this axle and mounted on the inside of frame. Shock absorbers and air springs are traditionally placed like many of our other concepts to absorb incoming forces.

2.3.3. C3S3

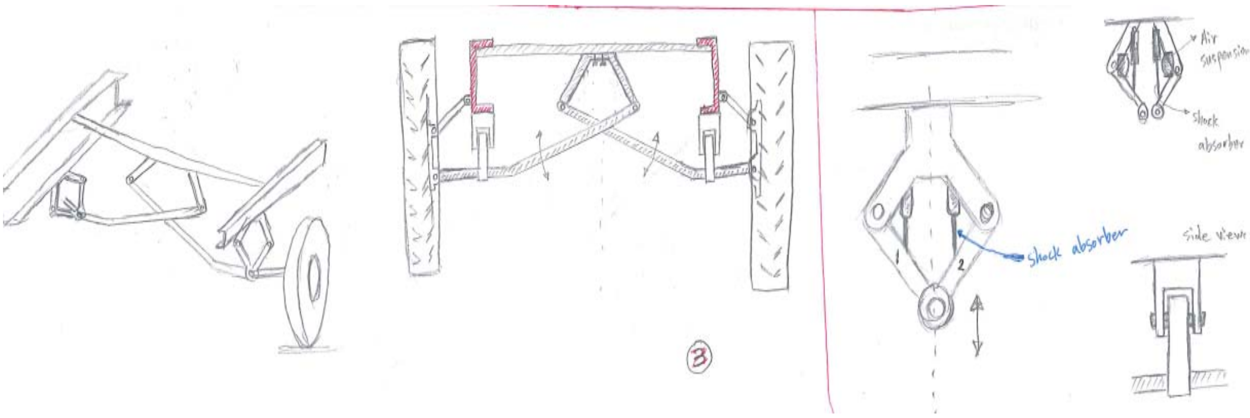


FIGURE 23 - CONCEPT 3 STAGE 3

The idea in this concept is to try to place another scissor arm under the frame of the vehicle. We still use the traditional scissors from the C3S3, but now these scissors are placed under the frame of the vehicle and not inside like the C3S3. Reason to place another scissor arm under the frame is because we want to increase stability and be able to handle more forces working on suspension system.

Air springs and shock absorbers are placed inside the arms of the scissor to absorb incoming forces.

2.3.4. C4S3

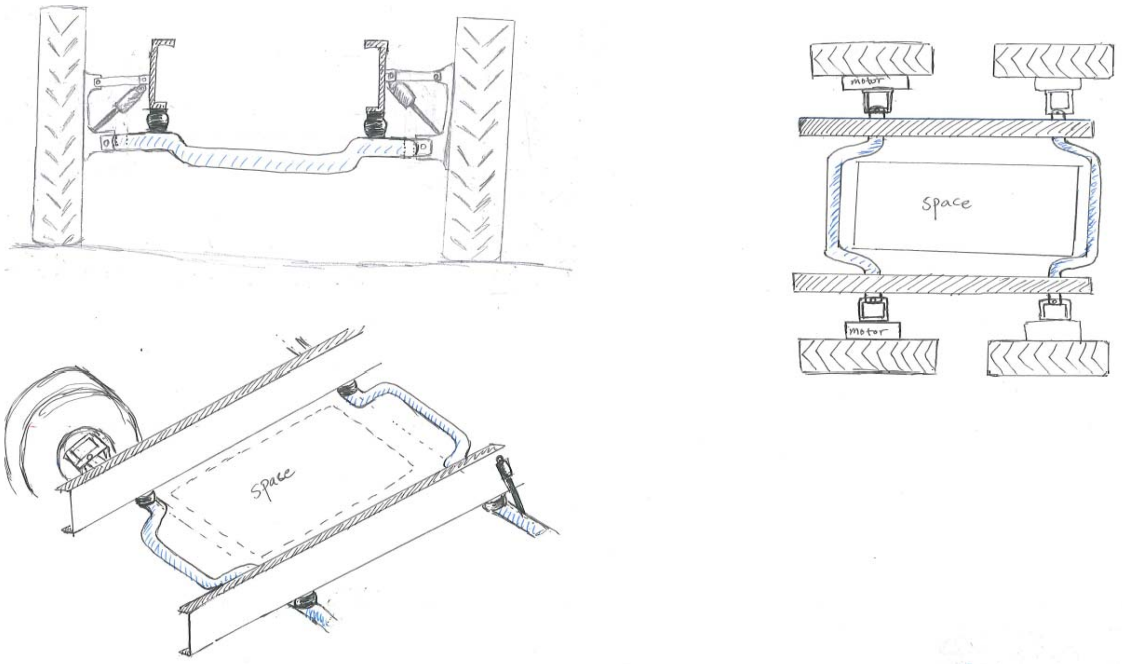


FIGURE 24 - CONCEPT 4 STAGE 3

This concept is a modified and improved version of the C2S2. The reason we are changing and modifying previous concept of this design, is because we do not have a fully understanding of how this mechanism would actually work in reality. From C2S2 the arms are at the same length. Meaning, the wheels will incline, and this is not something we want. We want the wheels to move up and down smoothly.

The major improvement we are making in this concept, is the change in length of the arms. Upper arm is shorter than the arm at the bottom as we can see from the picture above. The reason we do this is to avoid inclining of wheels. Having a longer arm placed at the bottom of the wheel, will further increase the flexibility, and reduce possibility of wheels inclining.

The air springs and shocks absorbers are placed traditionally like the previous concept of this design to absorb incoming forces. The motor and transmission is placed in- wheel.

2.4. CONCEPTS STAGE 4

We have to make yet another stage in our concepts process. The reason we end up making a new stage is because after some discussion and reflection with our external supervisor from KA, we realize that not all of our previous concepts are actually feasible. During design of concepts in different stages, we were not consequent about how feasible the concepts would actually be.

However, throughout the stages of our concepts we are gaining more knowledge and experience. All of these different stages are a learning process for us. It gives us more understanding of our system and how the mechanism and functionality of system and subsystems work.

In stage 4 we have chosen 3 concepts which are actually feasible. These 3 concepts are from the previous stages, and modifications are made if deemed necessary.

2.4.1. C1S4

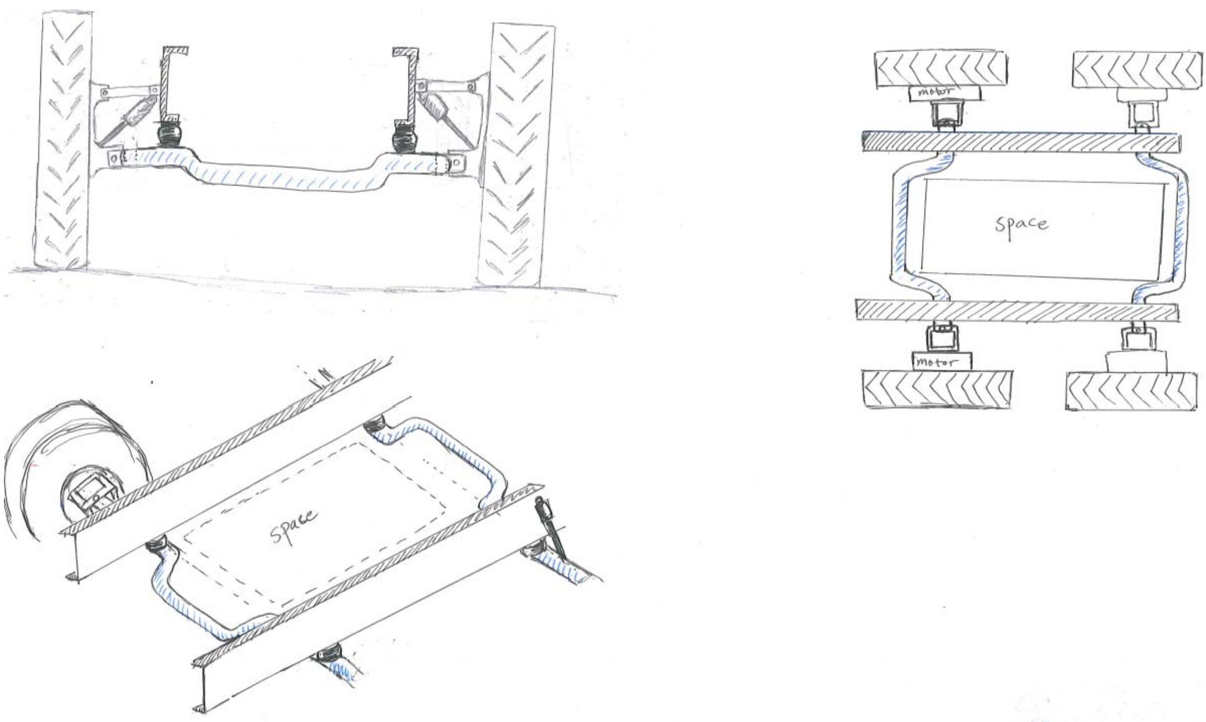


FIGURE 25 - CONCEPT 1 STAGE 4

This is a concept which is feasible and able to become a reality. All the details of this concept are explained in C4S3. That’s why this concept will not be explained in details here since no modification are made. This means the functionality and the mechanism is the same as the previous C4S3.

It’s simply constructed. There is no fancy type of axle between the wheels. It’s a solid type of “de Dion axle” [2] between wheels, which is independent. Concept is therefore an easy type of design which is not so difficult to make.

2.4.2. C2S4

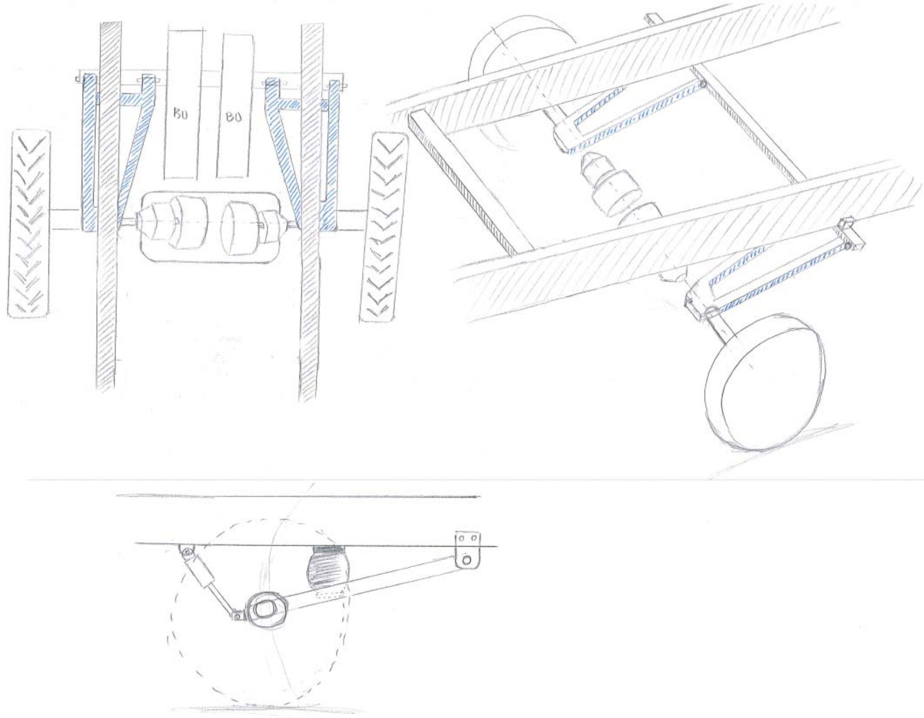


FIGURE 26 - CONCEPT 2 STAGE 4

This concept is a modified and improved version of C12S1. Yet another concept that is also feasible. The difficulty level of this concept is considered to be medium. In order to make this concept more solid some changes are made.

A major modification is increased width of the A-arms. Meaning that we are increasing tolerance to forces that the wheel suspension can handle in every direction.

Another change in this concept is the placing of transmission and motor. In the previous version C12S1, transmission and motor was placed close to the wheels. Resulting in transmission and motor to be exposed to a lot of vibrations. This has us reflecting on where to place these components. So, we are going to place motor and transmission under the frame of vehicle. There is also a support beam which is connected from one arm to the other.

2.4.3. C3S4

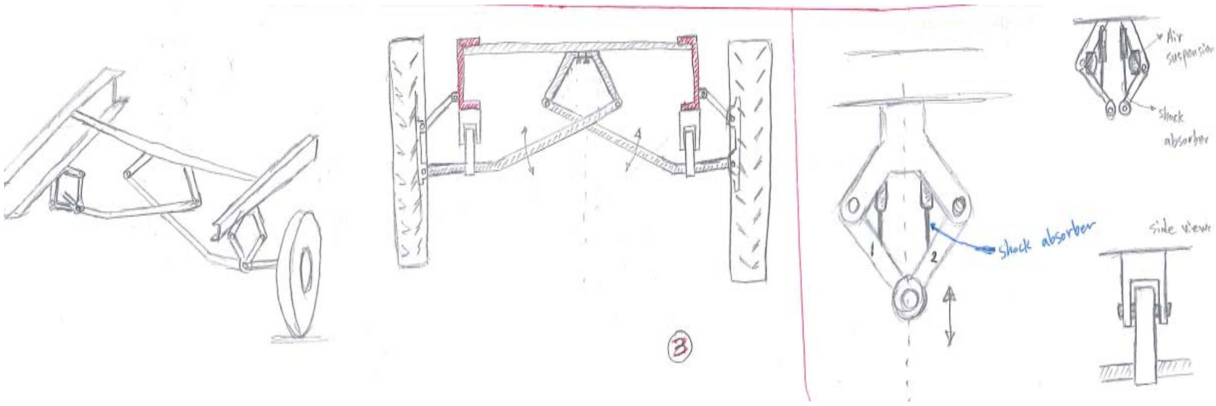


FIGURE 27 - CONCEPT 3 STAGE 4

This scissor type of axle is another concept which is feasible, however the difficulty level of this concept is very high. All the details of this concept has been explained in C3S3. That's why this concept will not be explained in details here since no modification is made to this concept.

One of the reasons why this concept is difficult is because of all the different types of components and mechanisms that are working together. There are two scissors placed under the frame on each side of the wheels, and another scissor placed under the frame of the vehicle. Getting all of those mechanisms to work together can prove to be a difficult task.

3. TRANSMISSION CONCEPTS

Transmission system is one of the components in our electric drive subsystem. The purpose of a transmission system is to control torque, speed and direction of rotation. The purpose of this paragraph is to give a brief overview of different concepts for our transmission system. These concepts are based on a planetary gear set and conventional automatic transmission. In addition this paragraph will also contain a brief explanation on what the idea is behind these concepts and how they were meant to function.

We have given a unique ID to each concept. This ID is made up of (T) which stands for transmission, Concept (C) followed by a number and stage (S) also followed by a number e.g. (TC1S1).

3.1. Concepts Overview

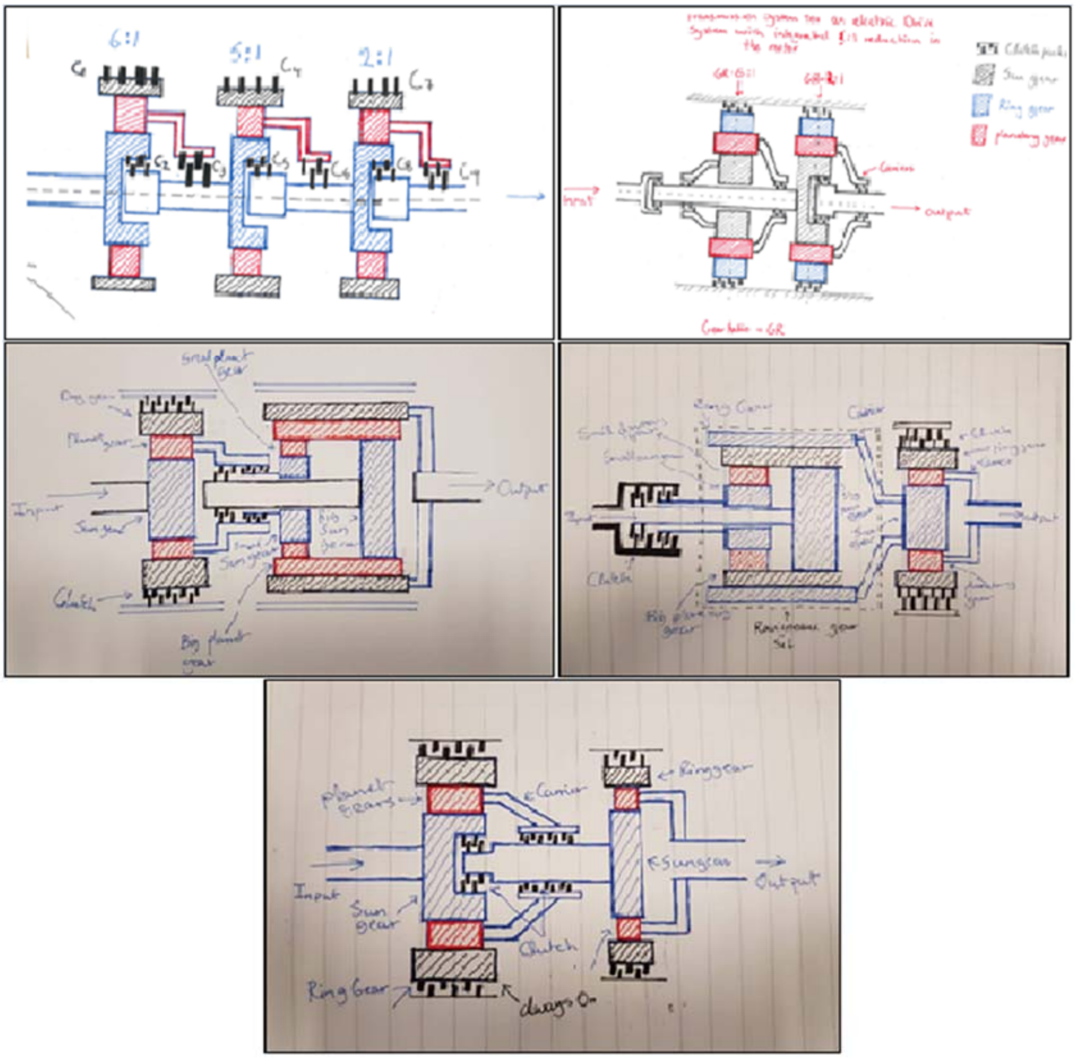


FIGURE 28 – CONCEPT OVERVIEW

Here we can see all the concepts which are made by the group. As we can see all of these are hand drawn and are early concepts for transmission system. Notice that these concept are made without much consideration of the inner workings of a transmission system, and are purely from a mechanical perspective.

3.2. Concept Stage 1

3.2.1. TC1S1

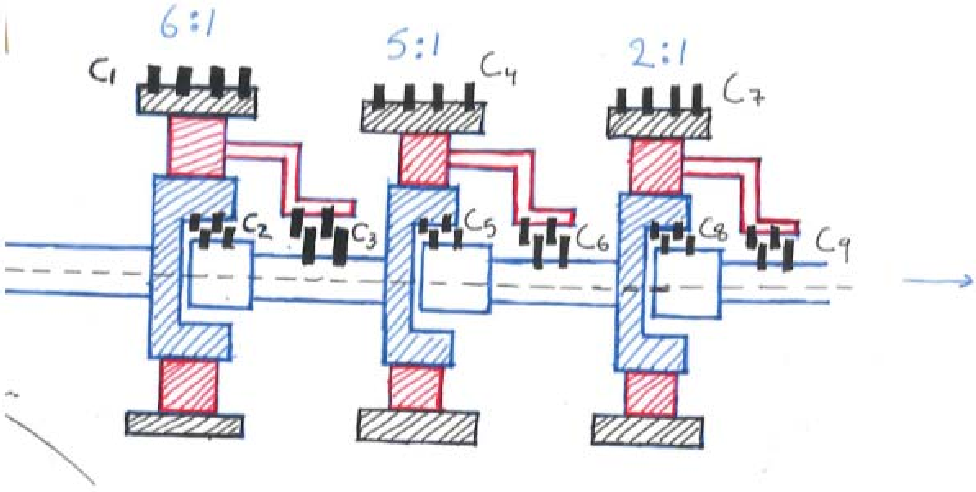


FIGURE 29 – CONCEPT 1 STAGE 1

This is the first concept we have come up with. The idea behind this concept is to use a multistage planetary gear transmission system, with 3 planetary gears in a row. Multi clutch packs control these planetary gears and the electronic and hydraulic components control these clutch packs and decide when to engage or disengage. Gear ratios are calculated based on a lot of assumptions and a lot of simplifications are made.

We have decided that this is not a very good concept simply because gear ratio 2:1 is not possible in a planetary gear. And compared to other concepts this is not the most optimal one, because of the amount of clutch packs we need to control and manage.

3.2.2. TC2S1

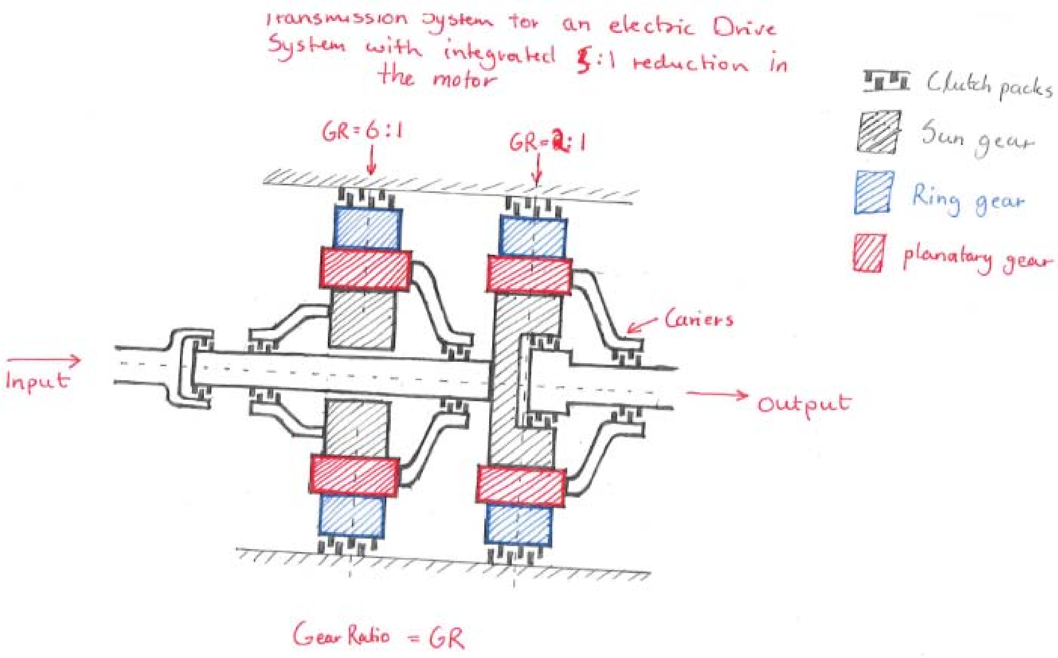


FIGURE 30 – CONCEPT 2 STAGE 1

Here we can see concept 2. As we can observe, this one is a bit more detailed than the previous one. At this point we have done a lot more research about planetary gears. However, on the image above, one gear set has a gear ratio 2:1 which is a mistake. The real ratio is 5:1.

The idea behind this concept comes from an instructor at HSN, who thinks that we can minimize our design if we can find an electric motor with integrated reduction gear of about 2:1. This means we have eliminated the need for a planetary gear set with gear ratio 2:1, which is impossible to begin with, as mentioned previously.

This concept is eliminated, since we have a different concept which we think is better in a lot of ways and which is not dependent on the type of motor we choose.

3.2.3. TC3S1

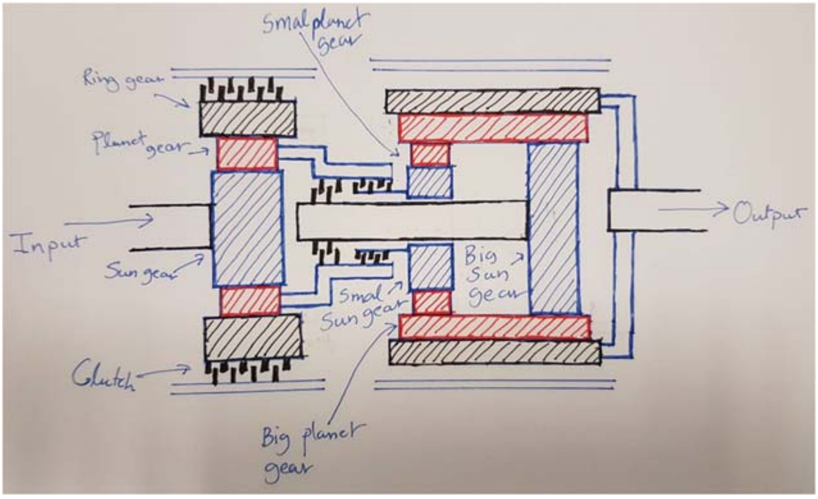


FIGURE 31 – CONCEPT 3 STAGE 1

The image above shows the third concept we have come up with. This concept is a bit different from the previous one since it consists of a Ravigneaux gear set and a planetary gear set. Ravigneaux gear set is a type of planetary gear which consists of 2 sun gear, 2 planetary gear of different length but equal teeth number, and a ring gear. For further explanation on Ravigneaux gear, check paragraph for transmission system in the technical document [3].

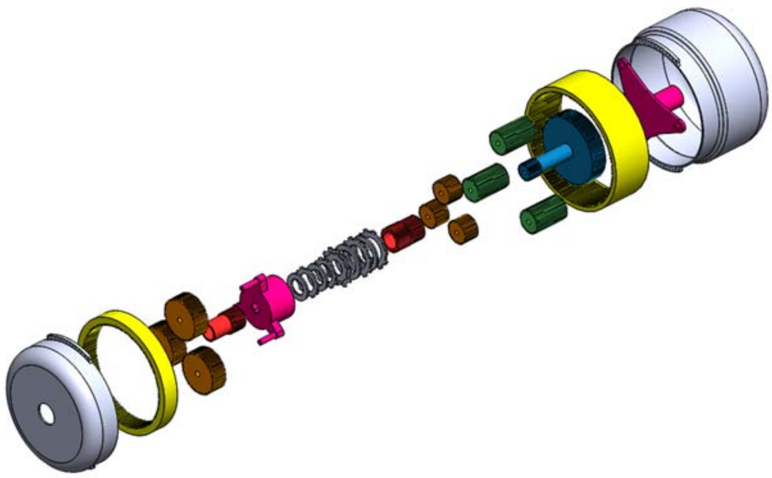


FIGURE 32 – 3D MODEL OF TC3S1

3.2.4. TC4S1

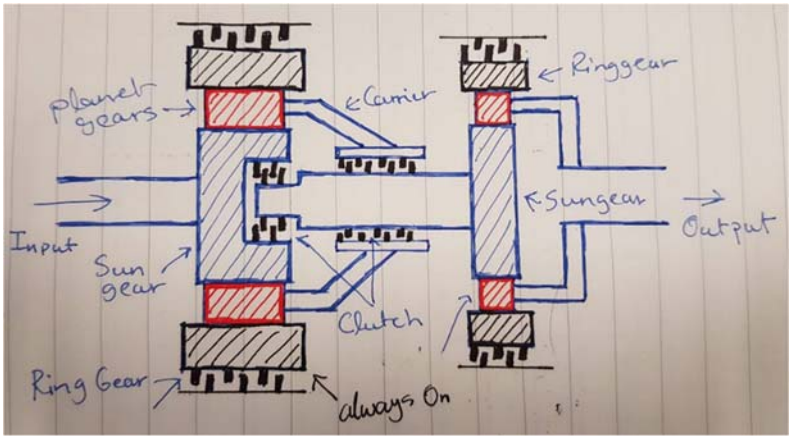


FIGURE 33 – CONCEPT 4 STAGE 1

Here we have the last concept which is developed by our group. As we can see it is heavily influenced by concept 2. The reason for this concept is a new electric motor for our electric drive, which can deliver much more torque than the previous one. The fact that this new motor is much more powerful than the previous, means that we have to adjust our transmission design accordingly.

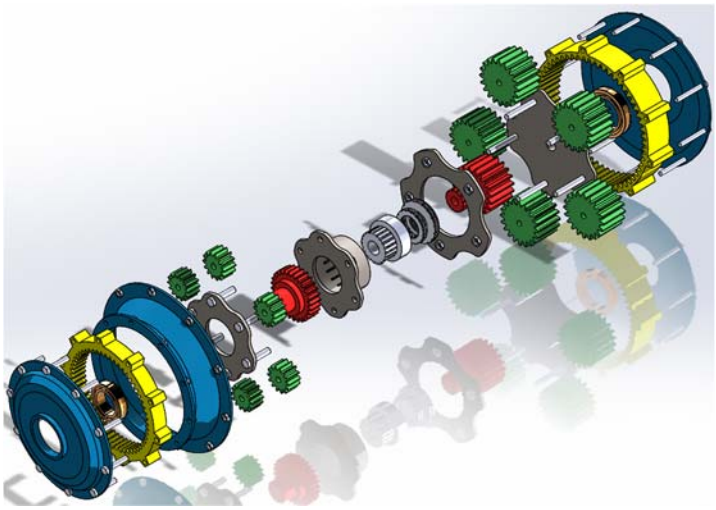


FIGURE 34 – 3D MODEL OF C4S1

This is the final concept selected as our transmission system. This concept is modified a bit further.

3.3. Concepts Stage 2

3.3.1. TC3S2

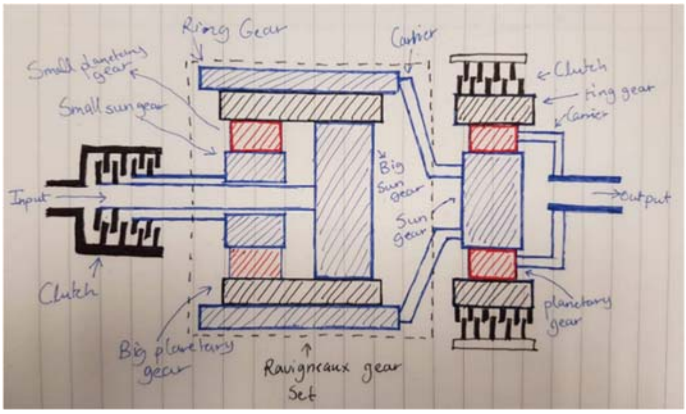


FIGURE 35 – CONCEPT 3 STAGE 2

Here we have a 2D drawing of concept 3 stage 2 after some changes in the previous design. In this design we are switching the location of the Ravigneaux gear and planetary gear. In addition we are also switching the location of big sun gear and small sun gear. This minor changes makes it much simpler and eliminates many of the problems with the previous design.

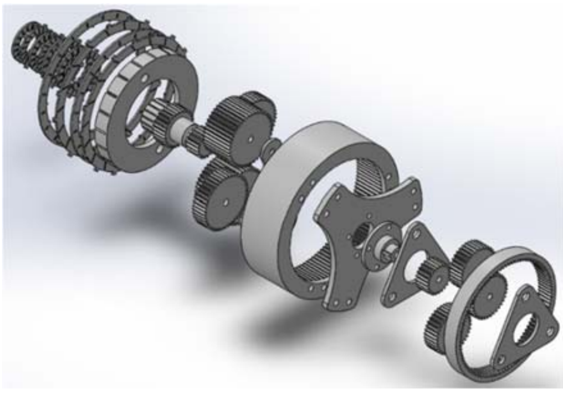


FIGURE 36 – 3D MODEL OF THE CONCEPT C3S2

This concept is the one we want to use in our electric drive, but ultimately it doesn't end up happening. The reason for this is the shear complexity of this concept and size. Since we have limited space in our suspension system we want a transmission system which is as compact as possible.

3.3.2. TC4S2

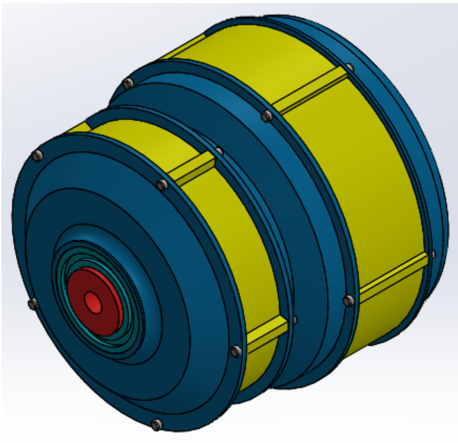


FIGURE 37 – CONCEPT 4 STAGE 1

This is the final stage of our transmission system and concept 4. We have refined and made some additional adjustment to concept 4 and this is the final concept. Down below we can see an exploded view of the concept in this stage.

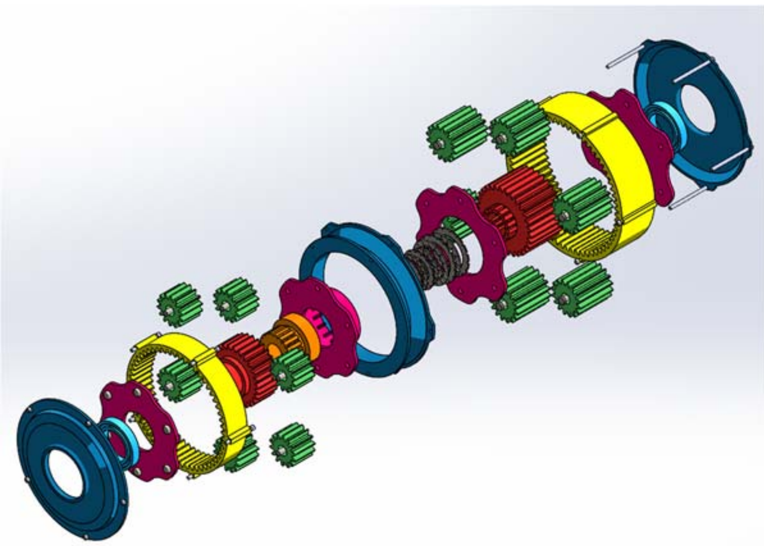


FIGURE 38 – CONCEPT 4 STAGE 2

4. LIFT AXLE CONCEPTS

Some heavy-duty vehicles are equipped with dead axles which can be raised or lowered to increase weight capacity or to distribute the load over more wheels. The axle is raised when not in need to prevent wear of the wheels and to provide increased traction in the remaining wheels.

FIGURE 39 – LIFT AXLE [1]

Several manufacturers like Meritor and Hendrickson produce computer controlled axles, which are lowered automatically when the vehicle reaches its maximum limit. The axle can still be raised manually by pressing a button.

Our concepts for lift axles are not developed further, because of time constraints. We have prioritized the main wheel suspension and electric drive system. Reasoning behind this is; if we don't have a solution for the main wheel suspension, we will have challenges delivering this subsystem.

We have given a unique ID to each and every concept. This ID is made up of (L) which stands for Lift axle, Concept (C) followed by a number (X) and stage (S) also followed by a number (Y) e.g. (LC1S1).

4.1. Concepts

4.1.1. LC1S1

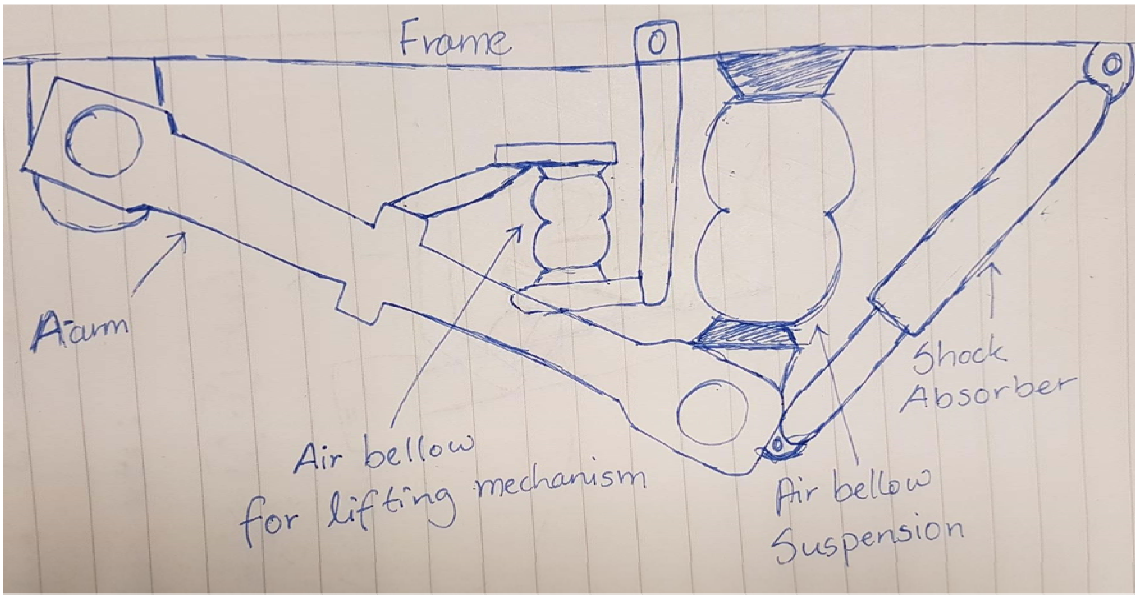


FIGURE 40 – CONCEPT 1 FOR LIFT AXLE

This is the first concept we have come up with for our lift axle system. As mentioned above due to limited time we cannot develop this concept any further. This concept is inspired by Hendrickson Toughlift FRT13 fixed axle suspension system [4]. This concept is developed after finalization of our wheel suspension concept. The idea behind this concept is that the small air bellow can inflate and push the axle up, while the other air bellow (used for suspension) will deflate, during lifting of axle.

As we can see we have chosen to integrate existing concepts into our wheel suspension axle concept. Many of the existing lift axle mechanisms deals with solid axles, but our concept is an independent one.

4.1.2. LC2S1

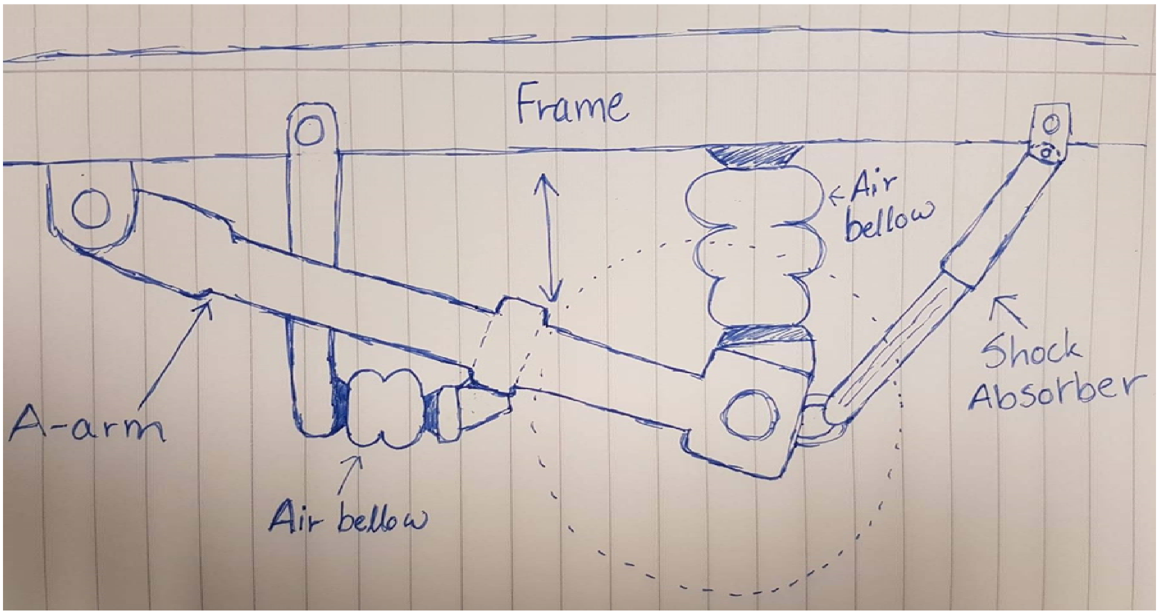


FIGURE 41 – CONCEPT 2 FOR LIFT AXLE

This is the second concept for lift axles which is developed by the group. This concept is inspired by a Ridewell non-steerable lift axle [5]. The concept is pretty much the same as concept 1, but the positioning of lift axle air bellow is a little different. The steering mechanism is also same as previous concept.

As mentioned above, since we have integrated existing lift axle concepts into our independent suspension, this will make the entire vehicle suspension independent.

5. REFERENCES

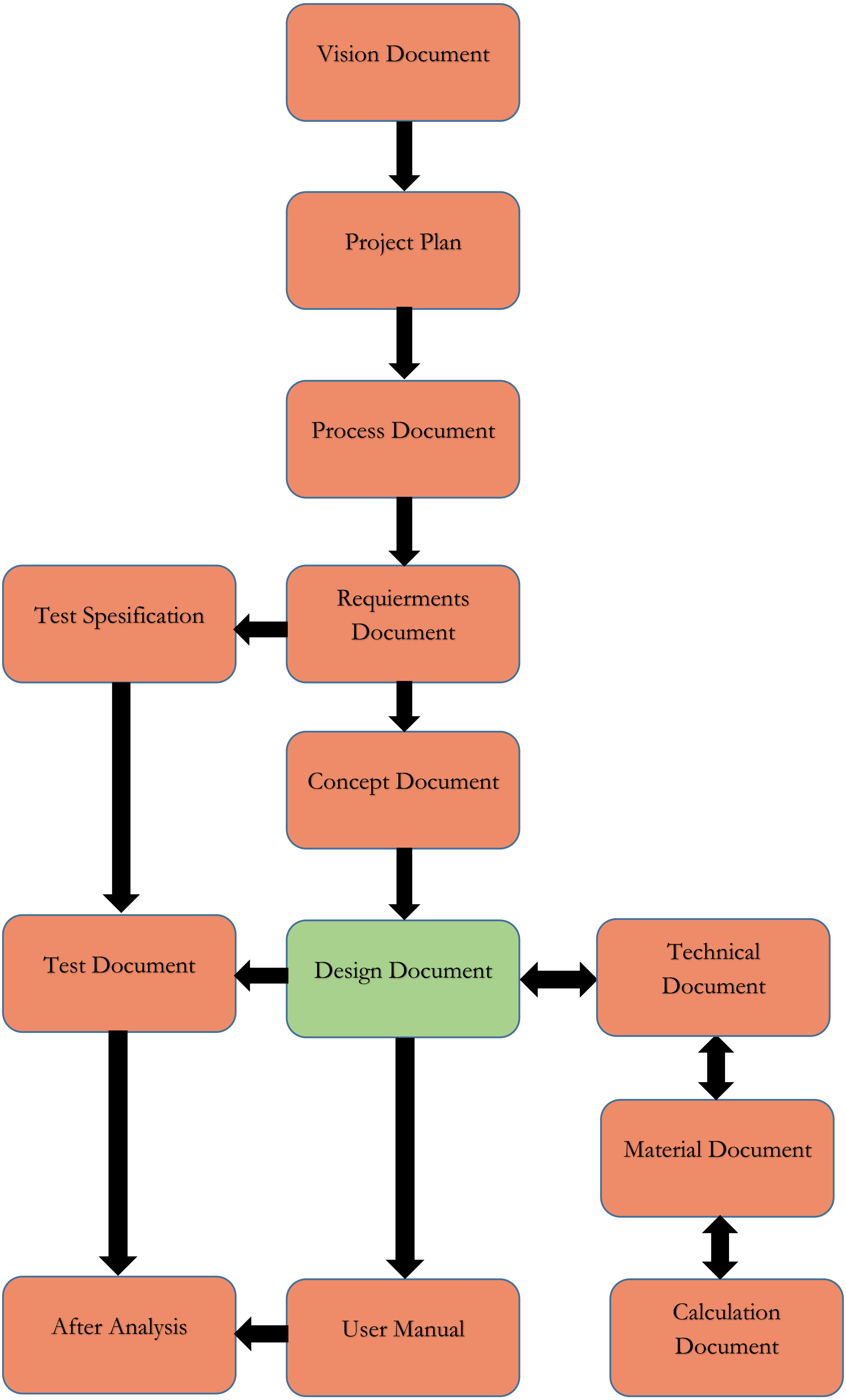
[1] Mammoet, "mammoet.com," [Online]. Available: http://www.mammoet.com/en/expertise/heavy-transport/. [Accessed 18 03 2017].

[2] Carbibles, "carbibles.com," [Online]. Available: http://www.carbibles.com/suspension_bible_pg2.html. [Accessed 18 03 2017].

[3] E-Axle, "Technical Document," E-Axle, Kongsberg, 2017.

[4] Hendrickson USA L.L.C, 16 04 2017. [Online]. Available: https://www.hendrickson-intl.com/Auxiliary/Truck_Non-Steer_Lift_Axle/TOUGHLIFT-FRT13.

[5] Stengel Bros. INC., 15 04 2017. [Online]. Available: http://www.stengelbros.net/2150015-Ridewell-132K-Non-Steerable-Lift-Axle_p_2941.html.


Vision Document
Project Plan
Process Document
Test Spesification
Requierments Document
Concept Document
Test Document
Design Document
Technical Document
Material Document
After Analysis
User Manual
Calculation Document

DESIGN DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

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Document Information	**Version**	**Date**	**Approved**	**Pages**
	2.0	23.05.17	AS	35

25. april 2017

DESIGN DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
25.04.17	0.1	Document created	AK
27.04.17	0.2	Introduction and scope added	AK
28.04.17	0.3	Sub-systems, list of components, exploded view added, and other minor updates	AK
04.05.17	0.4	Wheel suspension exploded view added	AK
05.05.17	1.0	Updates and changes	AK
07.05.17	1.1	Design development and designs added	AK
08.05.17	1.2	Design testing added, and minor updates	AK
09.05.17	1.3	Wheel suspension components added	AK
10.05.17	1.4	Added transmission design	PB
19.05.17	1.5	Updates and changes	AK
20.05.17	1.6	Torsion beam added	AK
23.05.17	2.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
UPM	Unified Process Model
KA	Kongsberg Automotive
FEM	Finite Element Method
C2	Concept 2
S4	Stage 4
3D	Three Dimensional
2D	Two Dimensional

TABLE 2 – DEFINITIONS OF ABBREVIATION

1. INTRODUCTION

The purpose of this document is to give a detailed overview of the design we have come up with.

The design of our system has changed at a varying degree almost every day. Our agile project model UPM allows us to make frequent changes to our design throughout our project.

In our design process, we are working with electro part, transmission and wheel suspension. Our design consists of multiple smart solutions the group members have come up with during the architectural stage. Our solutions are presented and thoroughly discussed with KA. It has been very important for the group to keep KA updated during the design process.

We are moving forward with C2S4 for the wheel suspension. For the transmission system we are moving forward with TC4S2 [1].

1.1. Scope

This document covers every detail of the design process. How the different components are evolving from initial concept to its outcome design. The selection of the components and materials are justified and explained in detail. The different components are going through different types of testing, e.g. the wheel suspension is going through FEM analysis and calculations are made to assure the relevant regulations.

2. WHEEL SUSPENSION WITH INTEGRATED ELECTRIC DRIVE

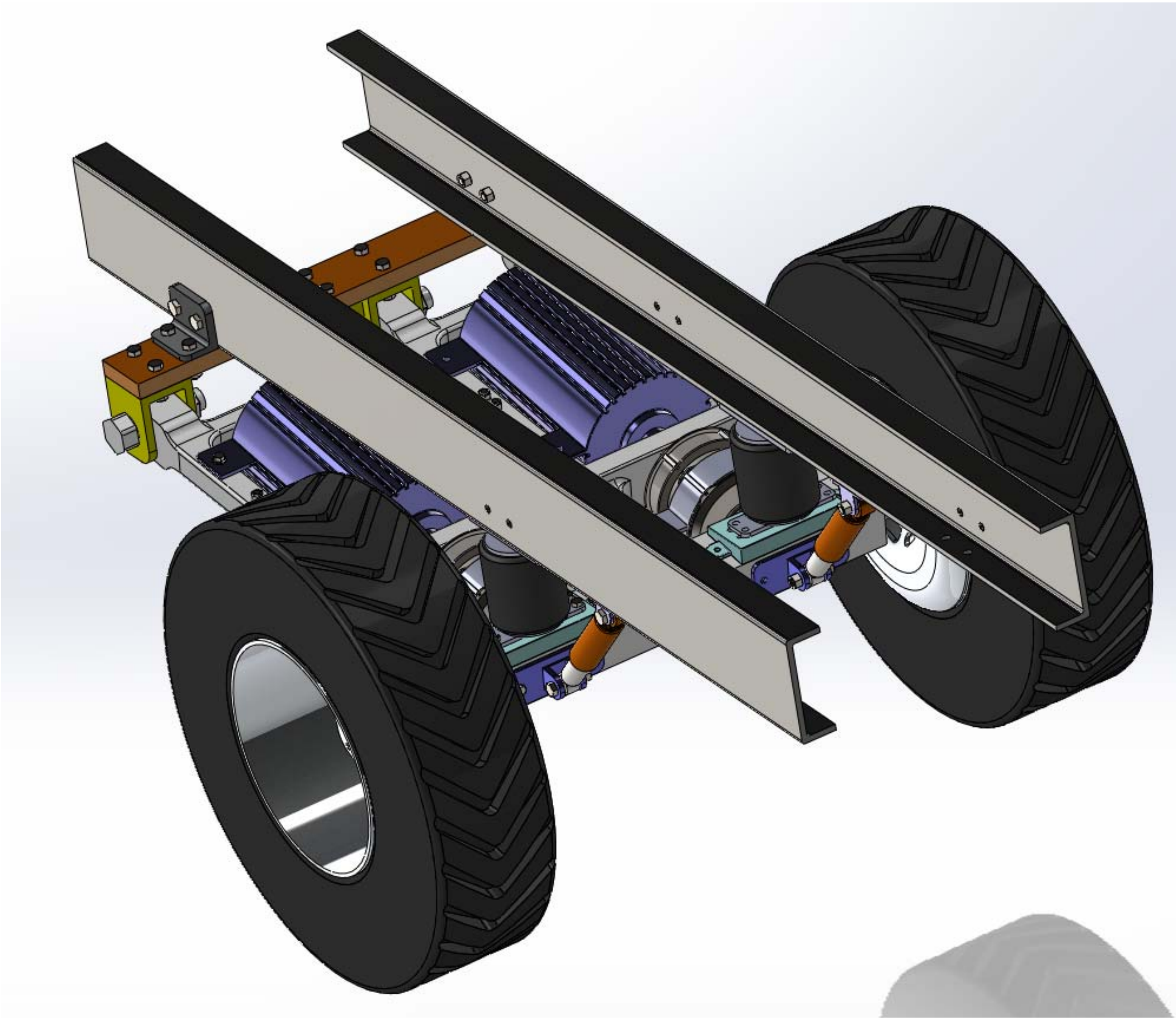


FIGURE 1 - ISOMETRIC VIEW OF SYSTEM

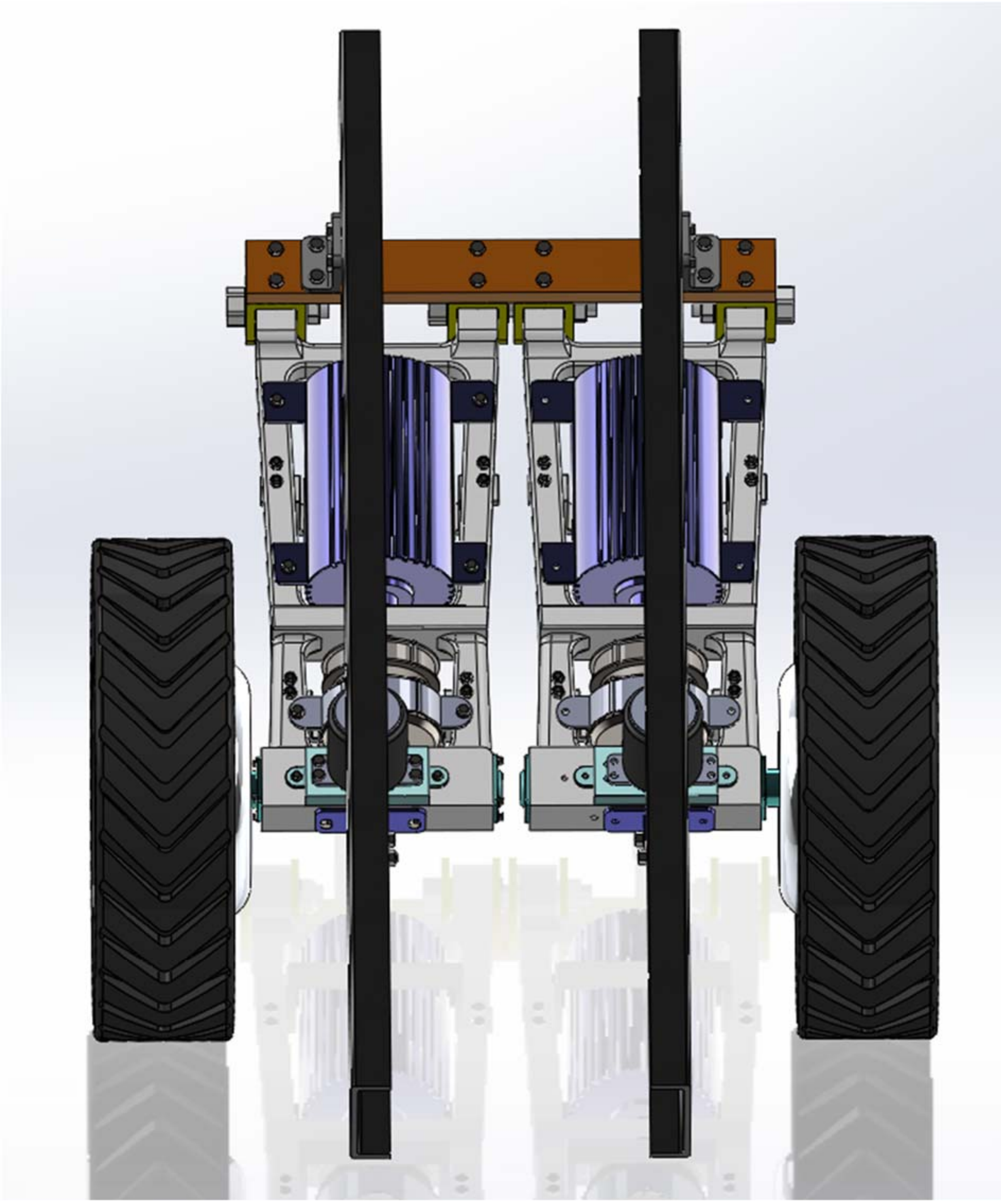


FIGURE 2 - TOP VIEW OF SYSTEM

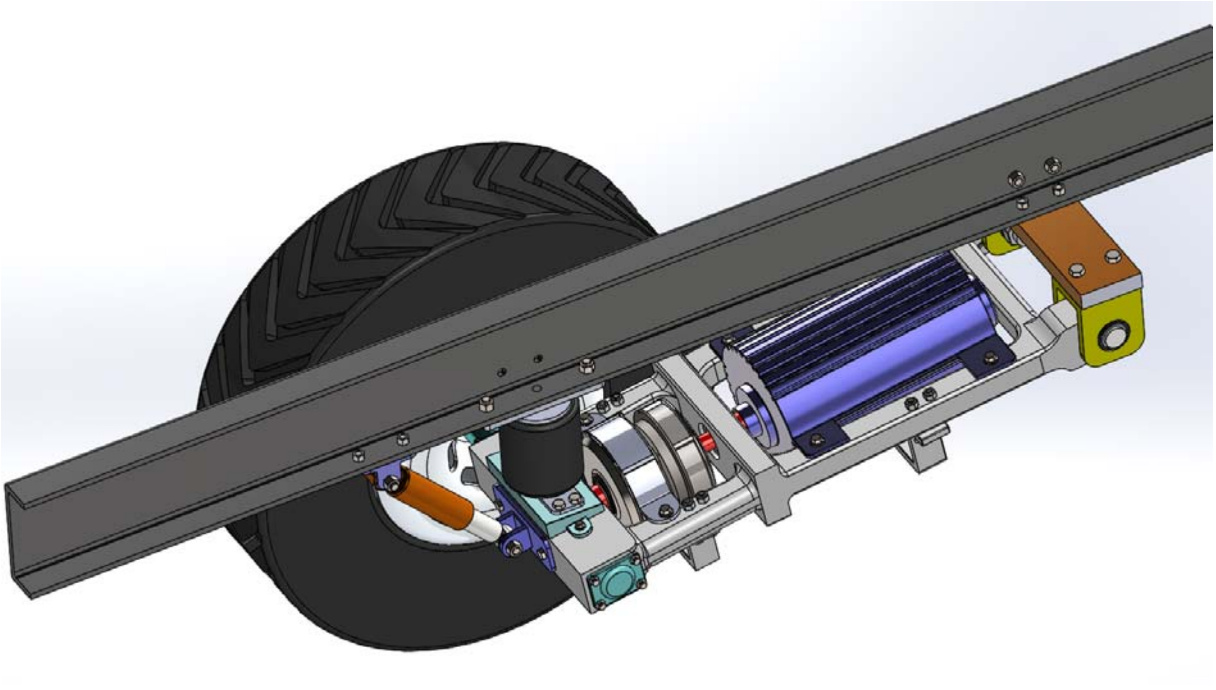


FIGURE 3 - DETAILED VIEW OF SYSTEM

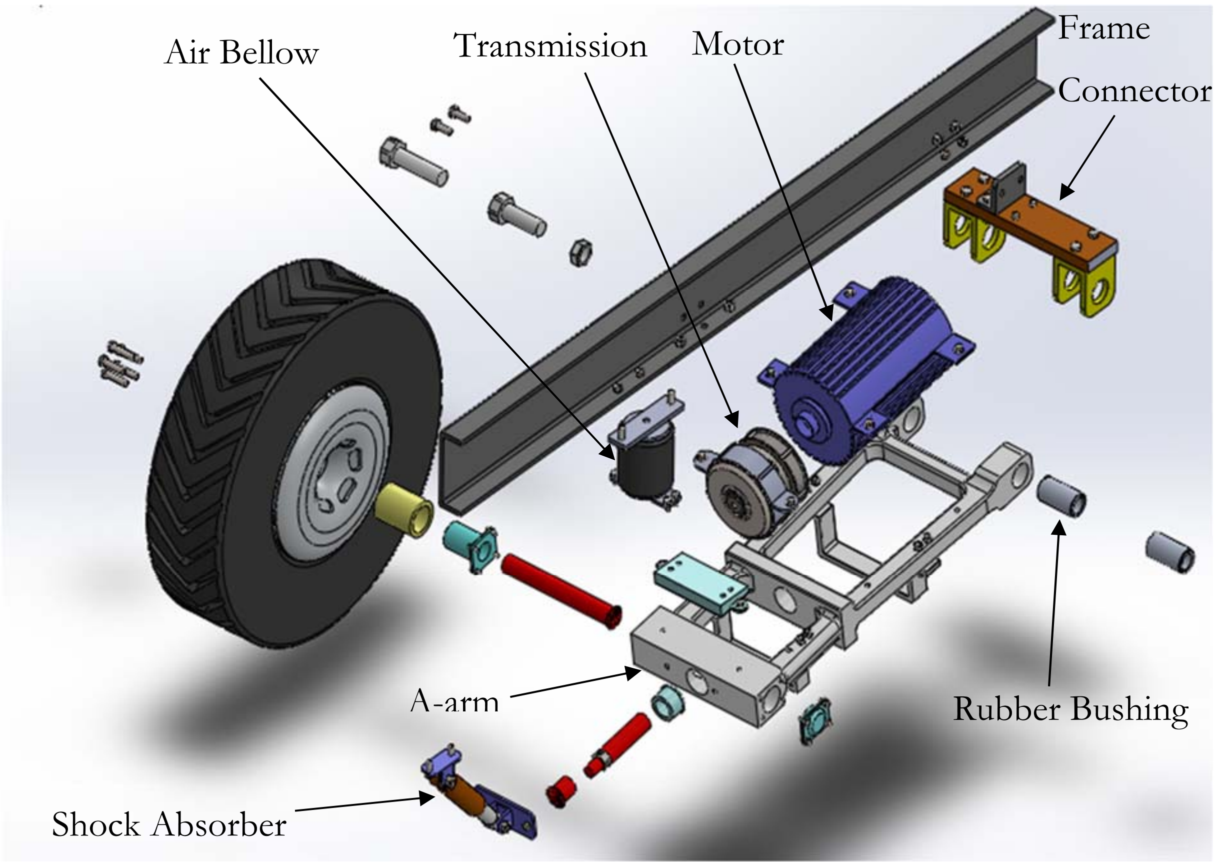


FIGURE 4 - EXPLODED VIEW OF SYSTEM

2.1. Properties of System

This system is made for heavy-duty vehicles. It is a wheel suspension with integrated electric drive. This means that the vehicle will be fully electric and only run on electricity. The traditional combustion engine will be replaced by this system.

The wheel suspension system has an independent axle. This gives more flexibility than the traditional dependent axle's.

2.2. List of System Components

WHEEL SUSPENSION	TRANSMISSION	ELECTRIC DRIVE	OTHER SYSTEMS
A-arm	Ring gear	Motor	Breaking system
Shock absorber	Sun gear	Inverter	Cooling system
Air bellow	Planet gear	Sensors	Dead axle lift mechanism
Rubber bushing	Carrier		Air suspension system
Torsion beam	Clutch pack		

TABLE 3 – LIST OF SYSTEM COMPONENTS

3. SUBSYSTEMS

Our design consists of a few different subsystems. The main subsystems that the group is working on are; wheel suspension, transmission and electric drive. The group is also working with other subsystems such as cooling system, air suspension system, breaking system and dead axle lift mechanism, but not on a detailed level such as the main subsystems.

3.1. Major Subsystems

The teams focus is on the three major sub systems. Wheel suspension, transmission and electric drive as mentioned earlier. These three systems are critical to work with and achieve a solution for.

3.2. Other Subsystems

There are also other subsystems that the teams is working on, but not in a detailed level such as the major subsystems. The other sub-systems are breaking system, air suspension system, cooling system and dead axle lift mechanism. These subsystems are a part of the bigger picture, which is why the team is also developing an understanding of how these subsystems work.

4. WHEEL SUSPENSION

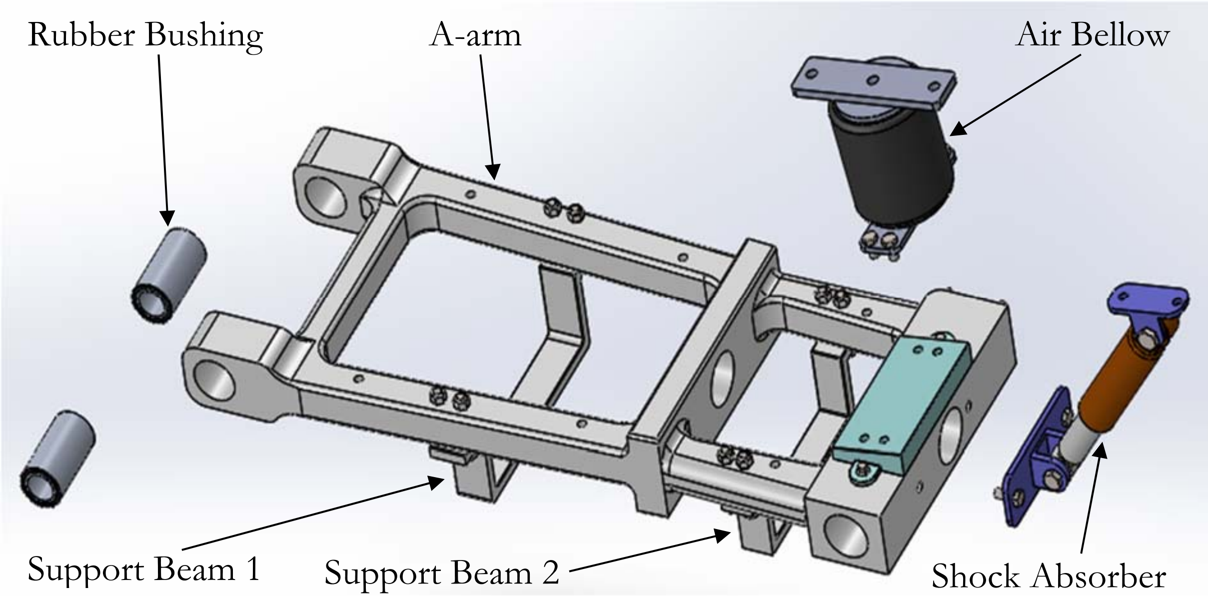


FIGURE 5 - EXPLODED VIEW OF WHEEL SUSPENSION

From figure 2, we can see the exploded view of the wheel suspension. As we can see, it consists of the main body which is the A-arm. The other components are air bellow, shock absorber and rubber bushing. These components have some sort of connection to the A-arm. That is why the A-arm is the main body in this sub-assembly.

This subsystem is mounted to the frame of the vehicle and connected to the wheel.

The wheel suspension system serves a purpose of holding the weight of the vehicle, good road grip and handling of vehicle. It functions as support and stabilizer for the vehicle. A good wheel suspension will give the driver a good and comfortable driving experience. The suspension also protects the vehicle itself and cargo from damage and wear [2].

Key functions:

- Support the weight
- Provide a smooth ride
- Keep tires in firm contact with the road
- Prevent excessive body dive [2]

4.1. A-arm

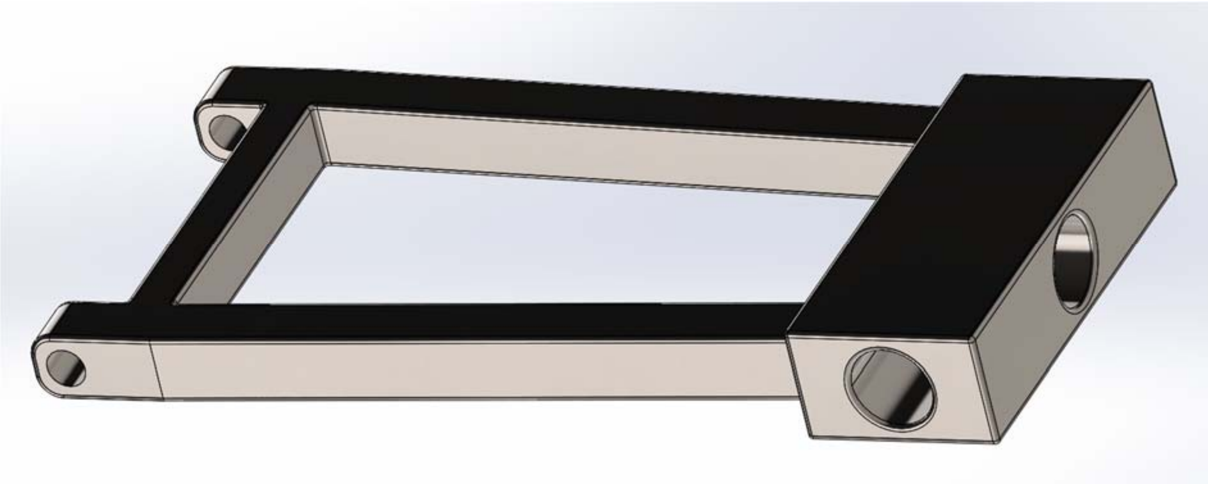


FIGURE 6 – A-ARM ILLUSTRATION, EARLY CONCEPT

The A-arm is one of the most critical parts. This because the component must be able to handle great forces. The incoming forces from wheels (x- y- and z- axis) will have a big impact directly on the A-arm.

Design of the A-arm is changing on a varying degree almost every day, this is because we have to make sure the design of the A-arm is in such a way, that it is able to handle the necessary forces applied to the system.

4.1.1. Initial Design

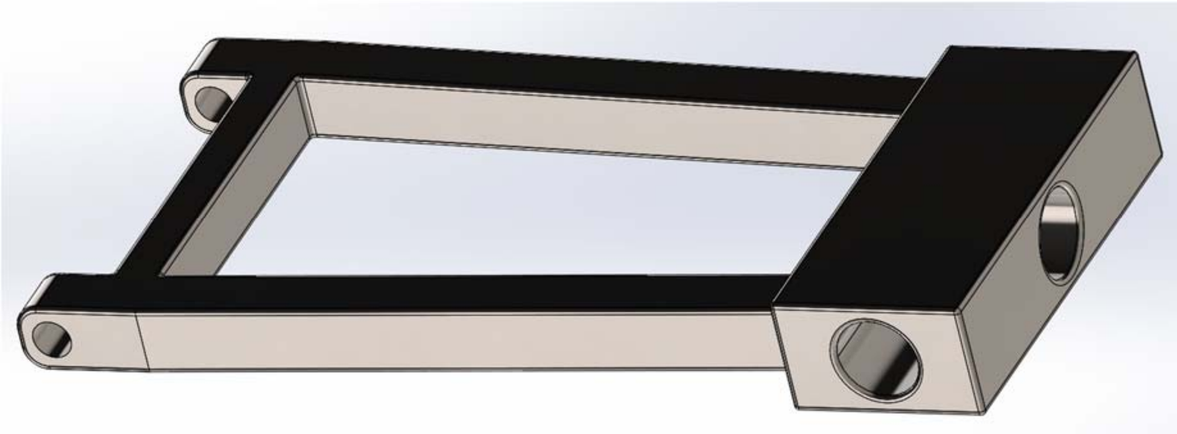


FIGURE 7 – INITIAL DESIGN A-ARM

From figure 3, we can see the initial design of the A-arm. This is how the design of the arm has started. When designing the A-arm we have to think about every aspect such as the material, thickness, length and width of the arm. This is how we end up with many different types of designs for the A-arm.

4.1.2. Design Development

When designing something, many factors are taken into consideration. One must think about the forces that are applied to the design, and how long the design is able to live throughout its lifespan.

When designing, we apply the “Design Thinking” method which is common for engineers when designing something [3]. We are more focused on solutions rather than problems.

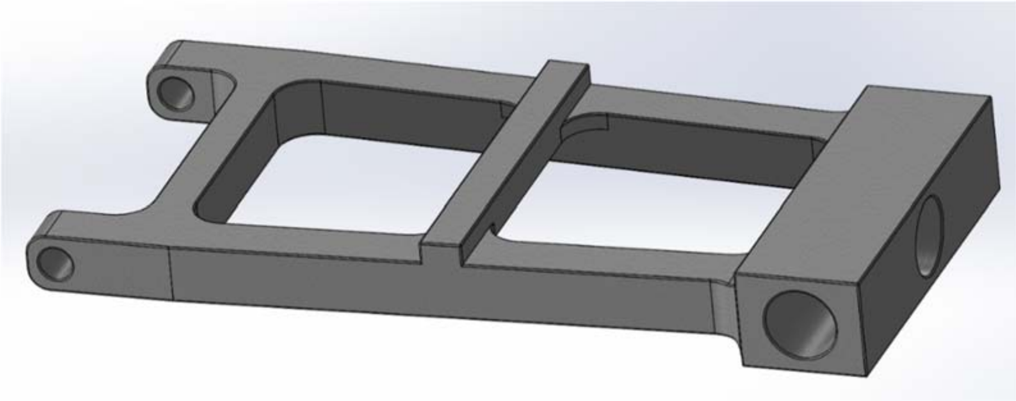


FIGURE 8 – DESIGN 2

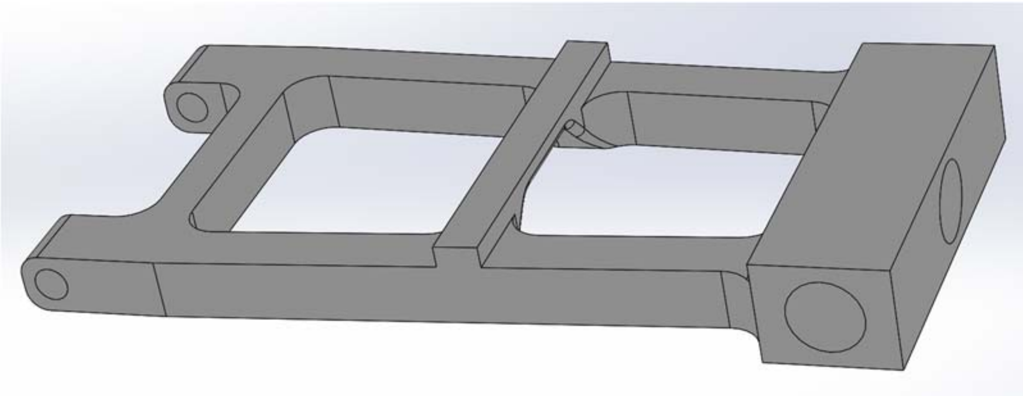


FIGURE 9 – DESIGN 3

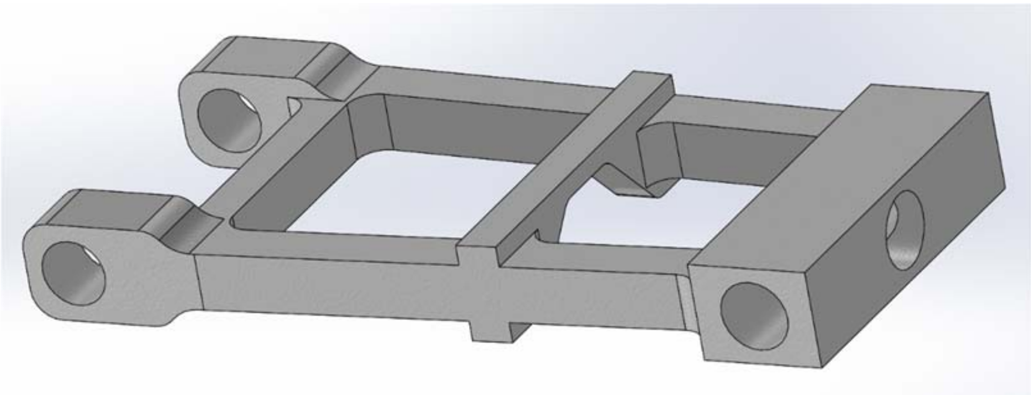


FIGURE 10 – DESIGN 4

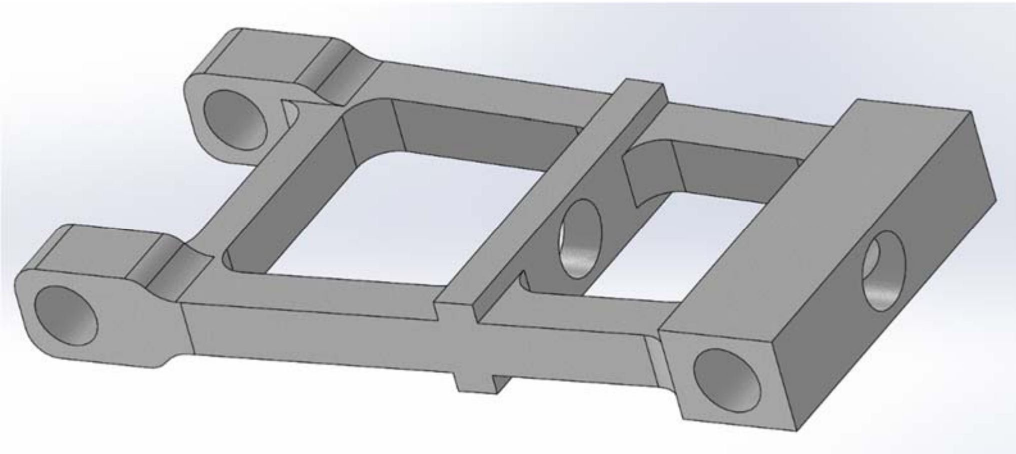


Figure 11 – Design 5

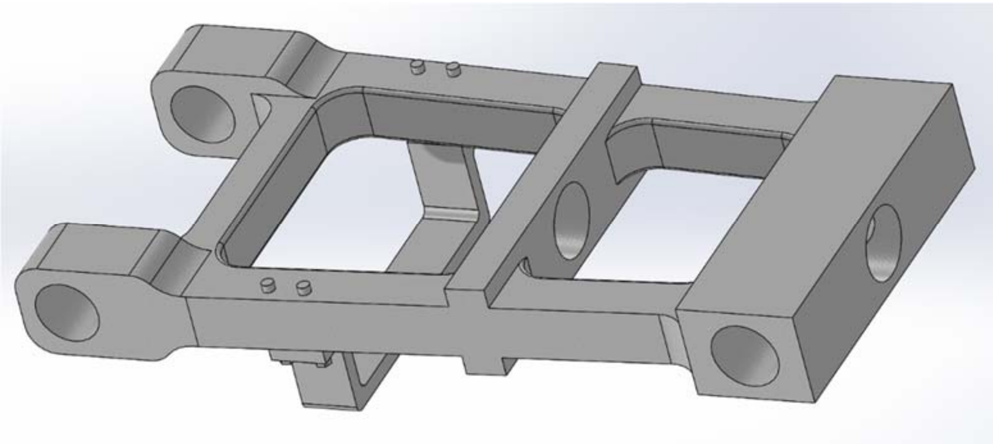


Figure 12 – Design 6

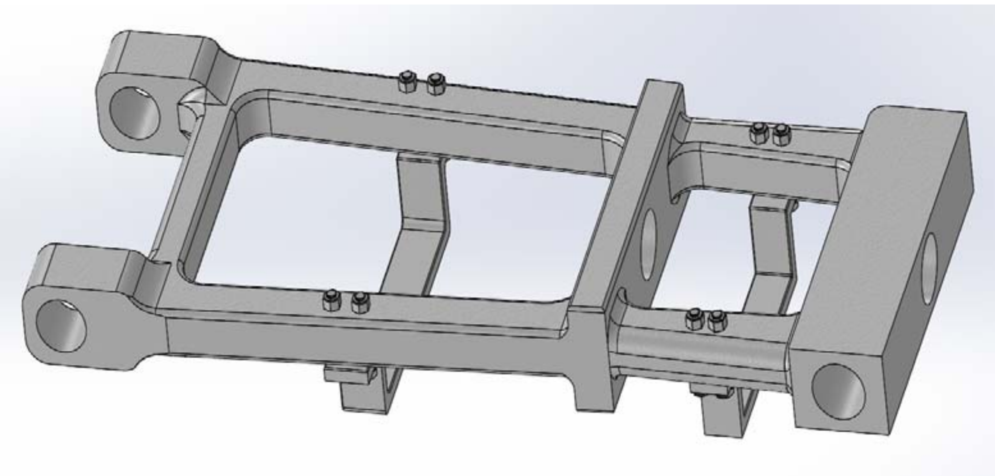


Figure 13 – Design 7

From figure 8 – 13, we can observe the development of the design, and how it is modified. A design is not only about how it looks, but rather about how it functions. The reason we come up with so many designs for the A-arm is because when we run tests on the design, we realize all the factors that must take into consideration. It is not necessarily about how fancy the design looks.

4.1.3. Design Testing

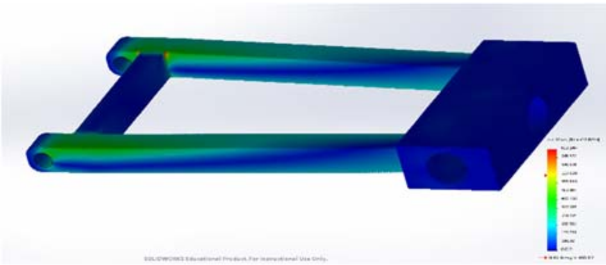


FIGURE 14 – INITIAL DESIGN FEM TEST

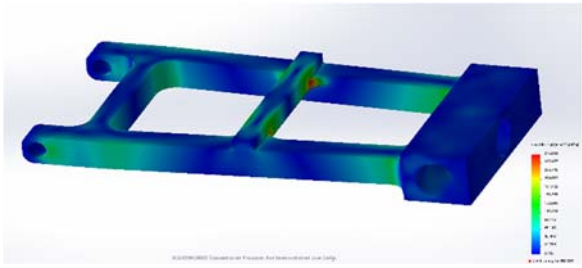


FIGURE 15 – DESIGN 2 FEM TEST

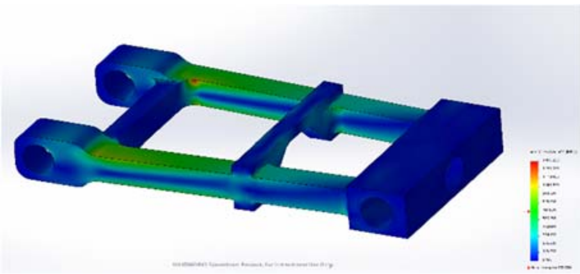


FIGURE 16 – DESIGN 3 FEM TEST

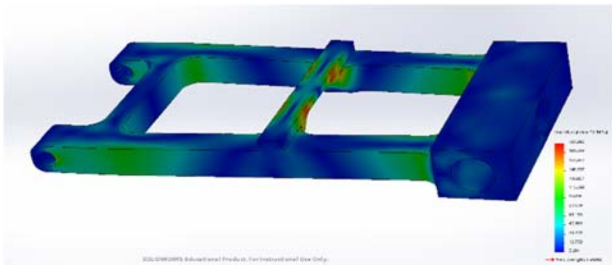


FIGURE 17 – DESIGN 4 FEM TEST

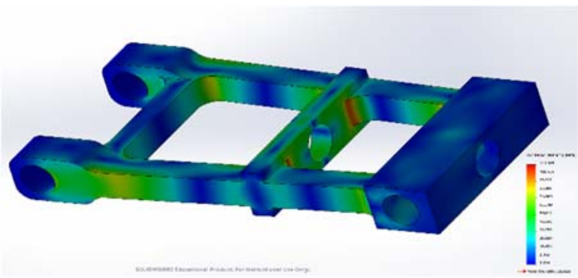


FIGURE 18 – DESIGN 5 FEM TEST

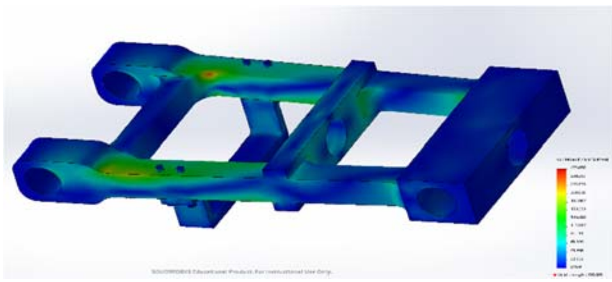


FIGURE 19 – DESIGN 6 FEM TEST

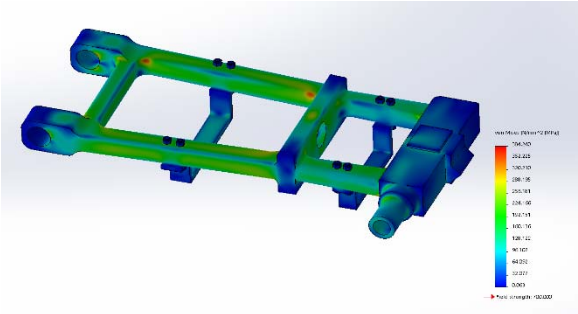


FIGURE 20 – DESIGN 7 FEM TEST

Figure 14 – 20 shows all the different designs that are going through a series of FEM analysis tests. This is how we frequently make changes too our design.

When a design of a component or a system is made, calculations and tests are conducted to verify the component.

After a design is made in CAD program, we run the design in FEM analysis to verify if the design can handle the applied forces. If the design can't handle the applied forces, and the stress is too high then we have to make changes to our design. The changes we make on the design are such as; length, width and thickness of the material. Sometimes changing angle and adding some fillets will increase the strength of the material. Our minds is always focused on finding solutions regarding the design.

4.1.4. Final Design

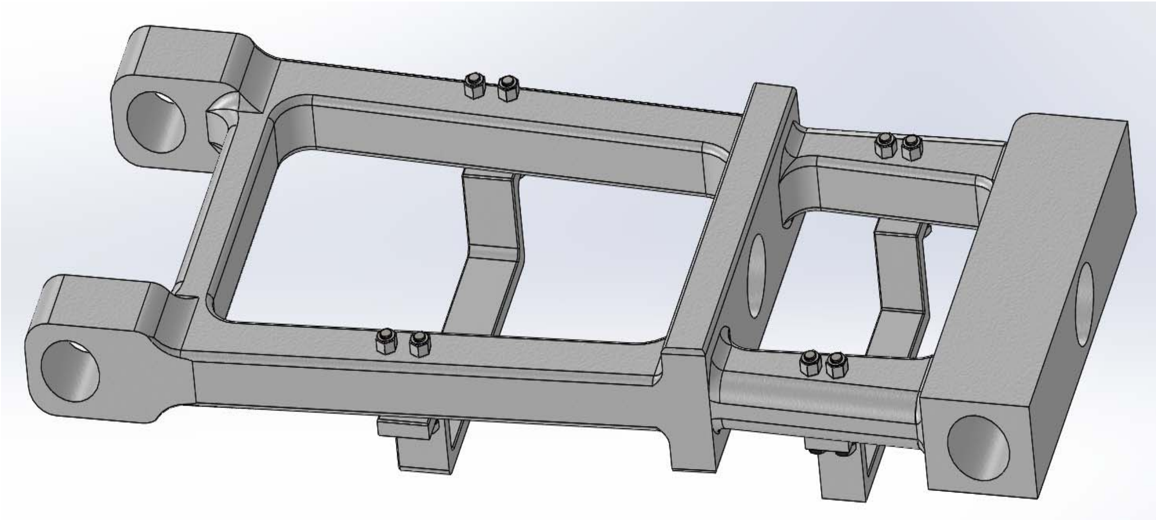


FIGURE 21 – FINAL DESIGN

Figure 21 is the final outcome of our design. This is the design we are moving forward with in our system. All of the different designs are going through several FEM analysis tests, too determine if the design is strong enough to handle the applied forces.

In the middle of the A-arm there is created a reinforced support with a hole inside. The reinforced support is not strong enough to handle the applied forces, so two support beams are added (fig. 21). These two support beams are added because the design is weak and can't handle the applied forces. This is discovered trough the FEM analysis tests we are running on all of our designs.

The outcome of the different tests is that the design on figure 21 is the most solid one. This design is able to withstand the forces that are working on the system.

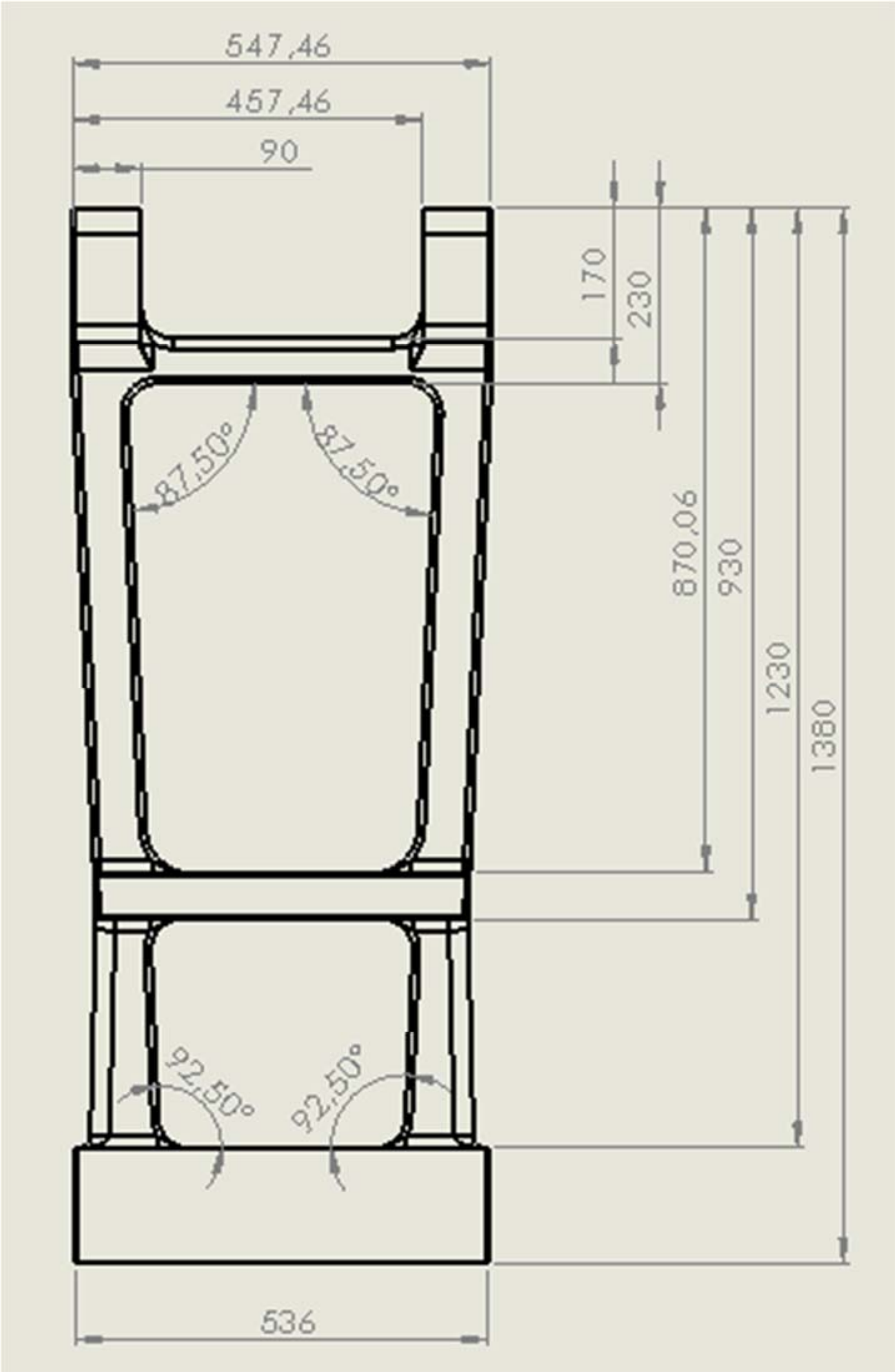


FIGURE 22 - DIMENSIONS OF A-ARM IN MILLIMETERS

For more 2D drawings view attachments (Att: C-G).

4.2. Air Bellow

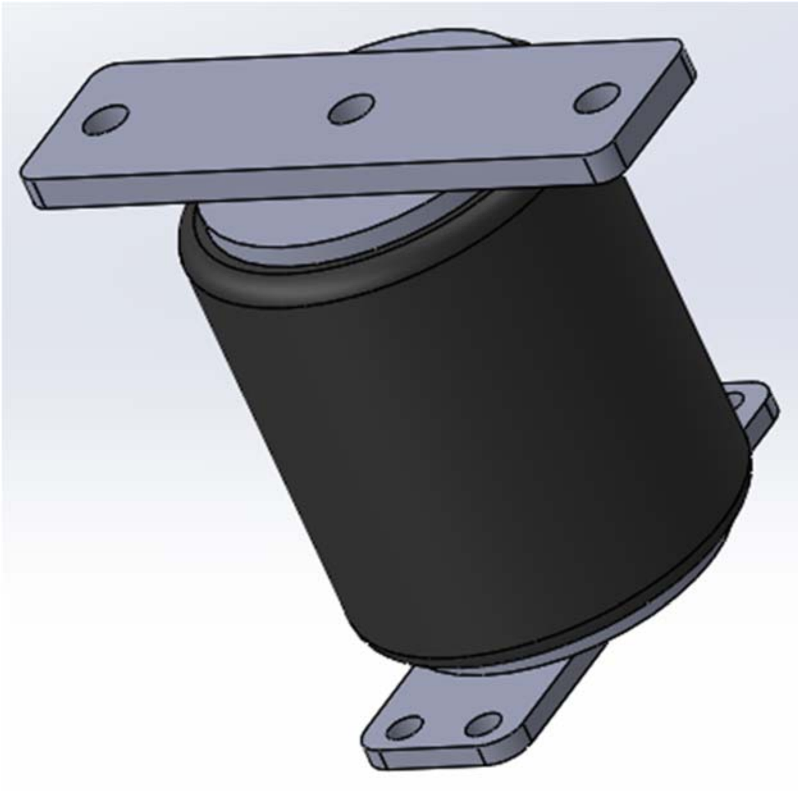


FIGURE 23 – AIR BELLOW ILLUSTRATION

Air bellow affects suspension of a vehicle. It's a type of suspension powered by engine driven or electric compressor. What happens is that the compressor pumps air into flexible bellows usually made of rubber. The air pressure then inflates the bellows, and raises the chassis from the axle [4].

We are not running any FEM analysis test on the air bellow, this is because the air bellow is a standard type of component which can be bought from vehicle retainers. It can be bought from the specification that is needed of the air bellow. We only design an air bellow to illustrate how it fits into our system

For our system, we are using "Airspring" air bellow from Goodyear [5].

4.3. Shock Absorber

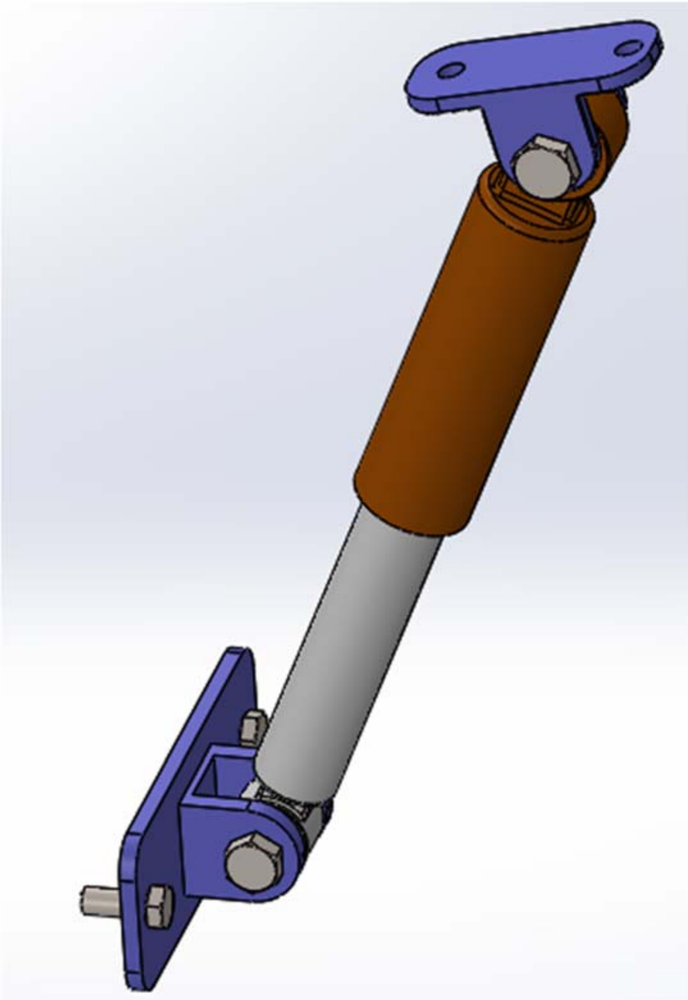


FIGURE 24 - SHOCK ABSORBER ILLUSTRATION

Shock absorber is a hydraulic or mechanical device that serves the purpose to absorb and damp shock impulses. It does this by converting the kinetic energy of the shock into another form of energy, usually heat, which is then dissipated [6].

In a vehicle, the shock absorbers reduce the effect of travelling over rough ground, which lead to improved ride quality and vehicle handling. Shock absorbers use valving of oil and gasses to absorb excess energy from the springs [6].

Shock absorber is a standard type of component which can be bought from vehicle retainers. It can be bought according to the needs of the vehicle. Meaning that one can buy a shock absorber for the specifications that is required.

For our system, we have chosen to use "GasSLX Shocks" [7] which is suitable for our system. This shock absorber fits for the class 7 – 8 vehicles [8].

4.4. Rubber Bushing

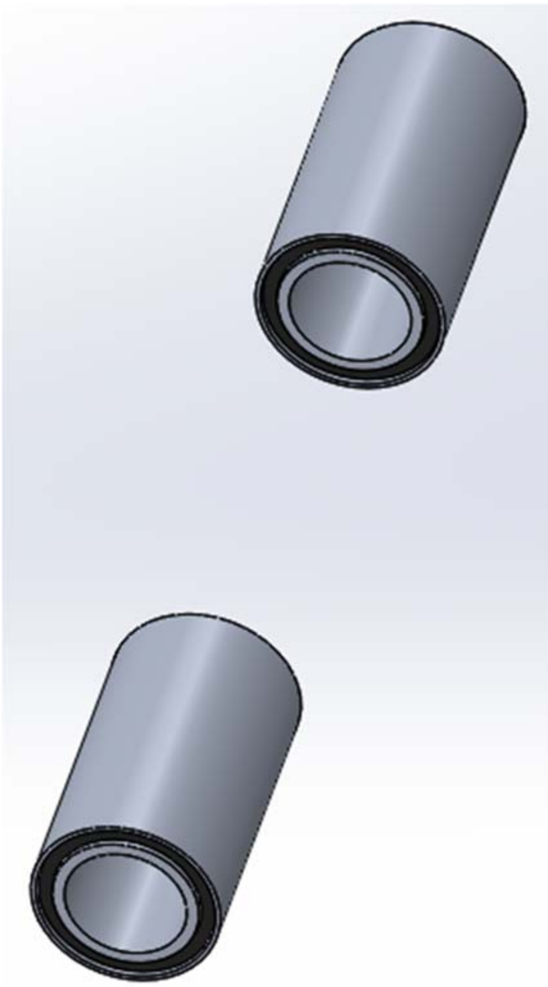


FIGURE 25 – RUBBER BUSHING ILLUSTRATION

A rubber bushing is a type of vibration isolator. It works as an interface between two parts, and it dampens the energy that is transmitted through the bushing. In our system, it separates the faces of two metal objects while at the same time allowing a certain amount of movement. It is usually made of rubber [9].

Rubber bushing is another type of component which can be bought from retainers according to the required specifications.

For our system, we have chosen to use a standard rubber bushing [10].

4.5. Design with Torsion Beam

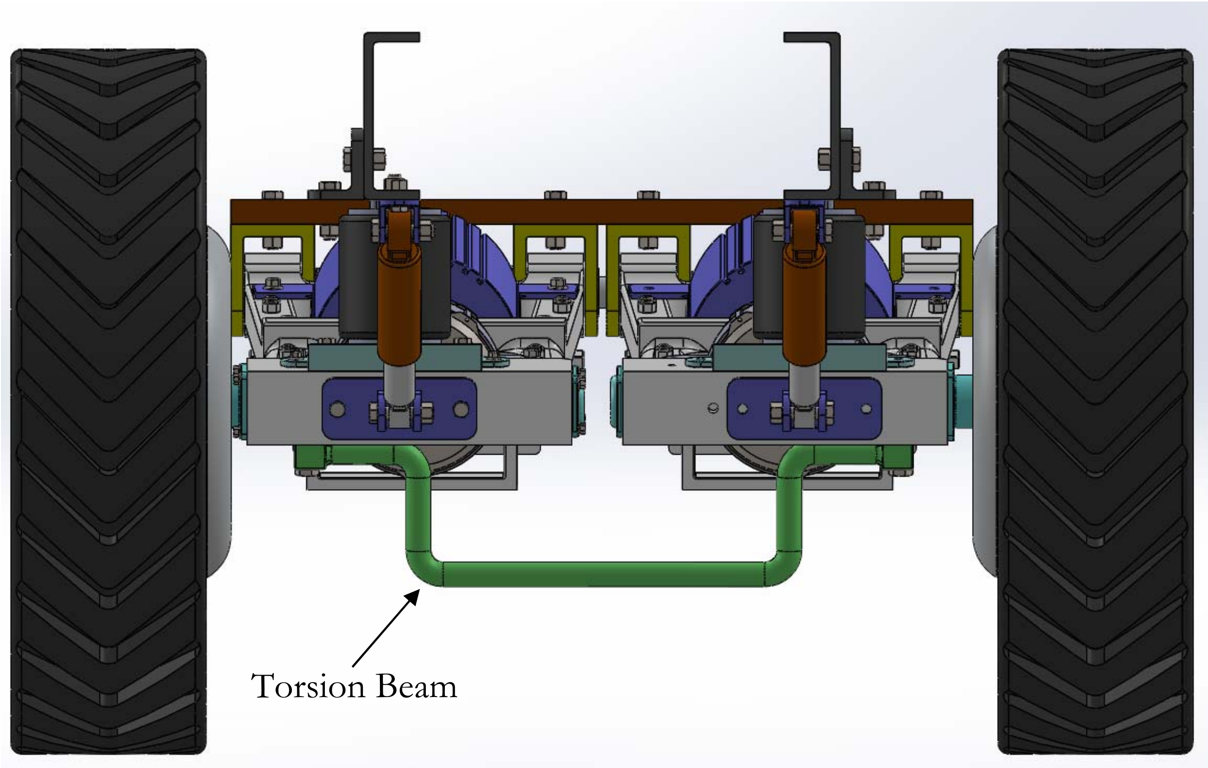


FIGURE 26 - SYSTEM WITH TORSION BEAM

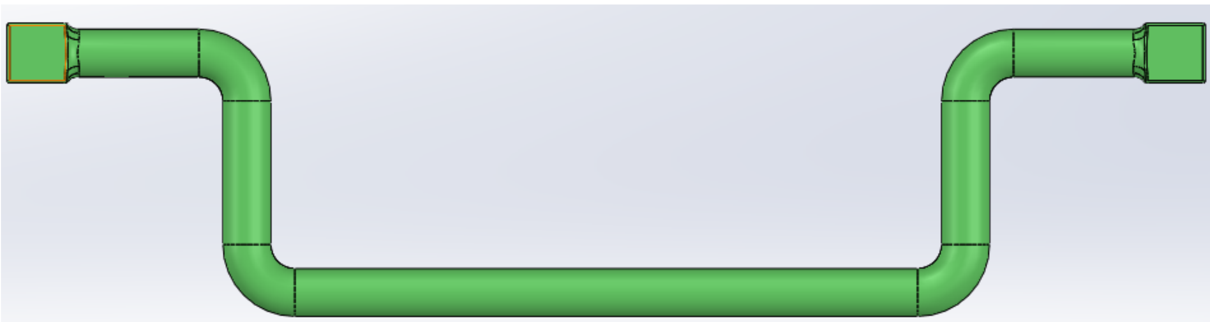


FIGURE 27 - TORSION BEAM ILLUSTRATION

Figure 26 gives an overview of system with torsion beam. As we observe, the torsion beam is mounted from one axle to the other. Torsion beam provides lateral stability to the vehicle when it comes to cornering, and when side forces are working on the vehicle.

We have designed the torsion beam for our system (fig. 27), however when testing it out in 3D program Solidworks it does not function as we desire. Solidworks doesn't allow us to make the design of the torsion beam flexible.

Furthermore, the torsion beam only locks down our independent type of axle in Solidworks, because when we connect it between the axles, it becomes a dependent axle instead of independent. Meaning, the independent function of our system is not functional anymore. We do not have any resources to test out the torsion beam physically, to verify if it will affect independency of our system or not. We assume that it will. That's why we decide to move forward without the torsion beam in our system.

5. TRANSMISSION SYSTEM

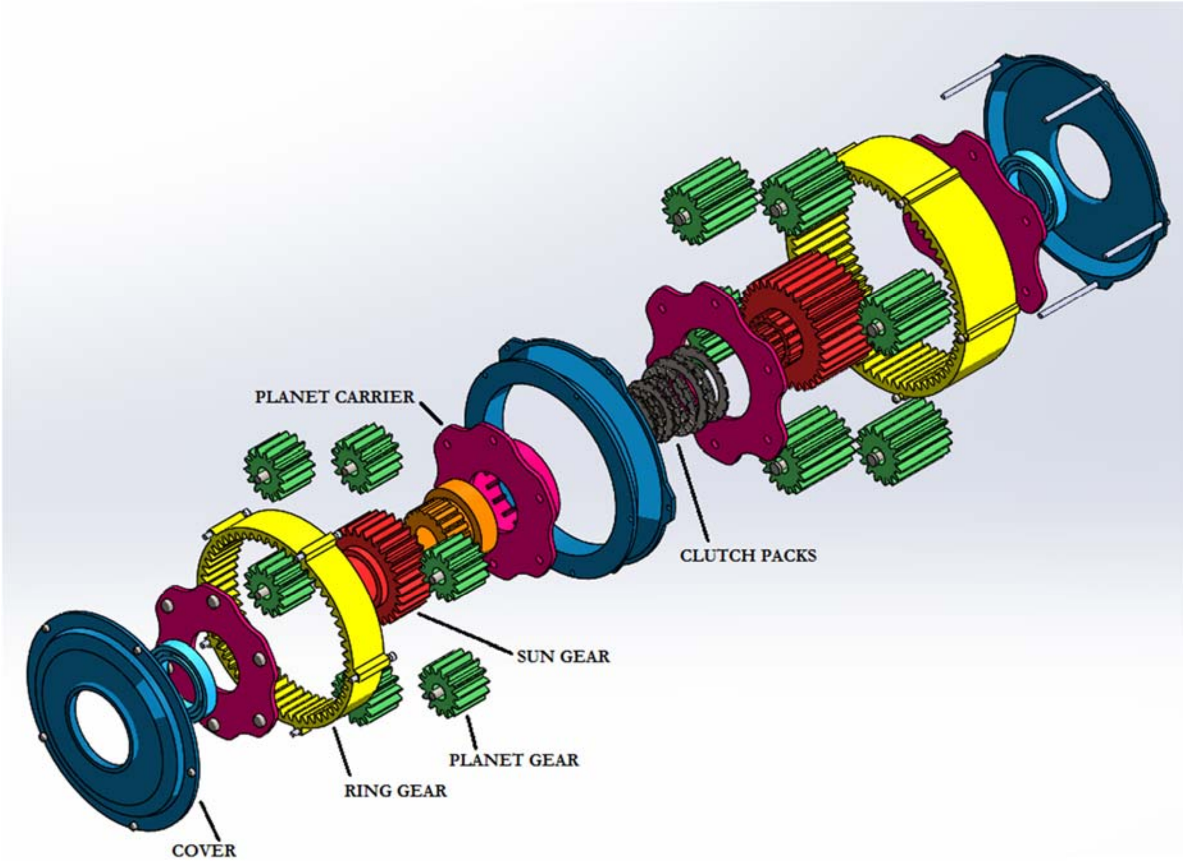


FIGURE 28 – EXPLODED VIEW OF TRANSMISSION SYSTEM

As mentioned previously, transmission system is one of the most important aspects of our electric drive system. The purpose of a transmission system is to control the power output to the wheel by adjusting speed and torque. In our system we are focusing on the gearbox aspect of a transmission system.

Figure 23, shows a 3D exploded view of our transmission system. It consists of 5 major components, sun gears, planet gears, ring gears, clutch packs and carriers.

5.1. Design Development

The concept chosen for our transmission system is concept 4, which is based on two planetary gear sets in a row. Figure 29, shows us concept stage 2 and stage 1 side by side. As we can see, the form of the transmission has changed quite a bit and has changed in size as well. This is done to make the transmission system more durable and to allow it to withstand more force/torque.

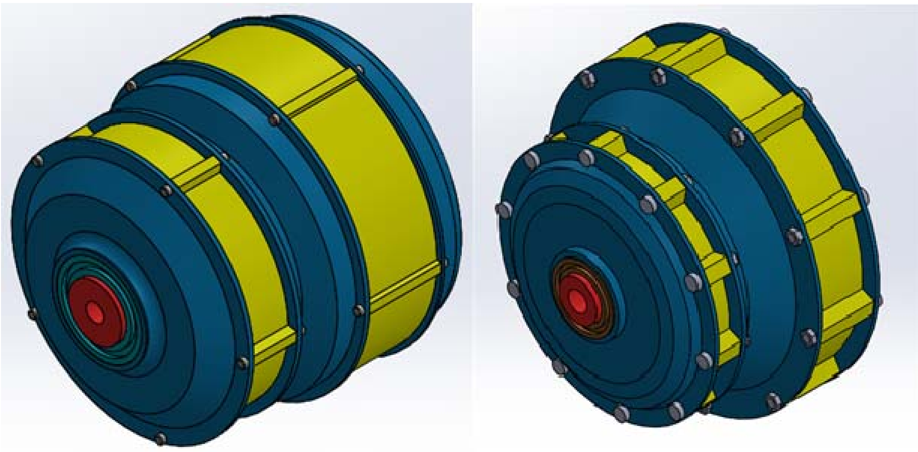


FIGURE 29 – COMPARISON BETWEEN STAGE 2 AND STAGE 1

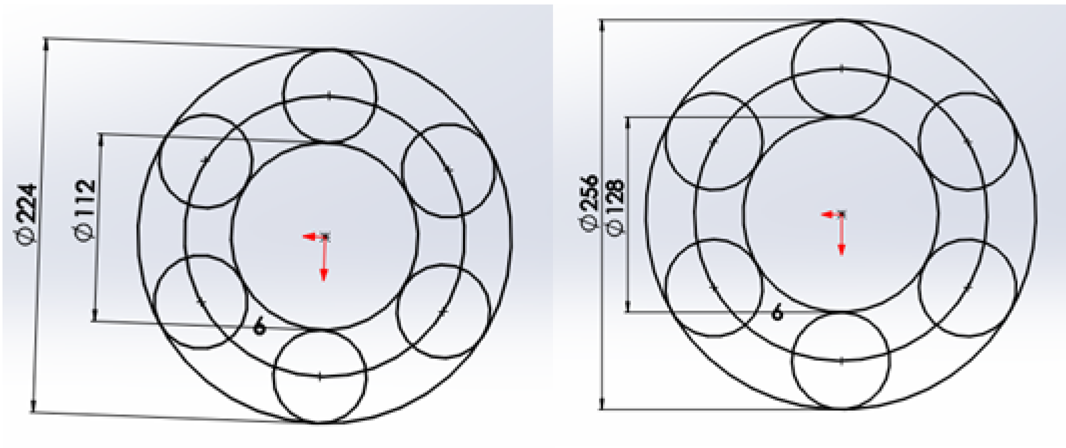


FIGURE 30 – 2D SKETCHES OF PLANETARY GEAR SETS

5.2. List of Components

Name	Number	Material
Small sun gear	1	Ferrium C61
Big sun gear	1	Ferrium C61
Small planet gear	6	Ferrium C61
Big planet gear	6	Ferrium C61
Small carrier input	1	AISI 4340
Small carrier output	1	Ferrium C61
Big carrier input	1	AISI 4340
Big carrier output	1	AISI 4340
Planet pin big	6	AISI 4340
Planet pin small	6	AISI 4340
Roller Bearing	2	
Ball bearing	24	
Small sun output	1	Ferrium C61

TABLE 4 – LIST OF COMPONENTS FOR TRANSMISSION SYSTEM

5.3. Sun Gear

In our transmission we are using 2 different sun gears. One small and one big. The reason for this is because the second sun gear has to withstand a lot more torque/forces than the first one. As mentioned above the primary objective of a transmission system is to control the speed and torque. In our system which consists of two different planetary gear sets, the first one will amplify the torque from the motor. This means that the second gear set has to be sturdier to withstand these forces.

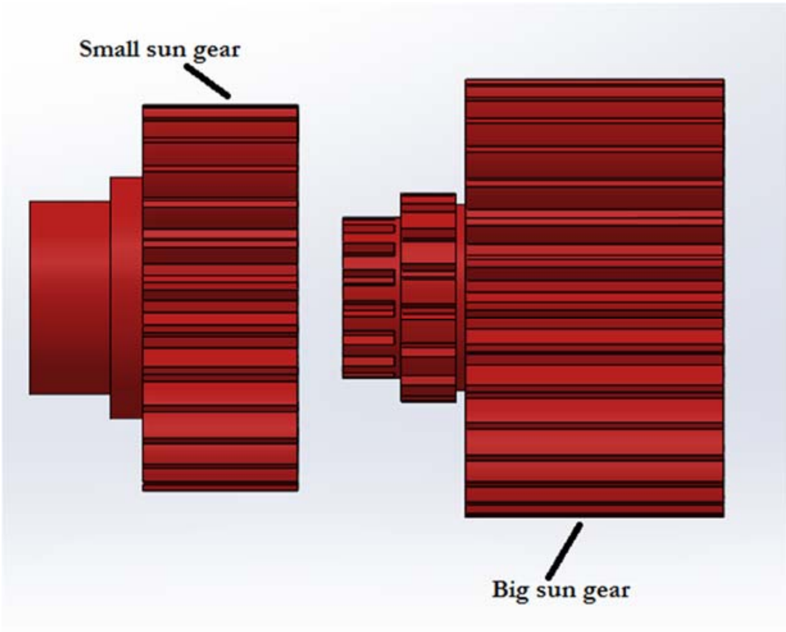


FIGURE 31 – COMPARISON BETWEEN SMALL SUN GEAR AND BIG SUN GEAR.

These sun gear are in mesh with planet gear of different sizes. The amount of planet gears affect how much torque the sun gear can transmit, but the amount of planet gears are limited by the gear ratio of a planetary gear set.

5.4. Planet Gears

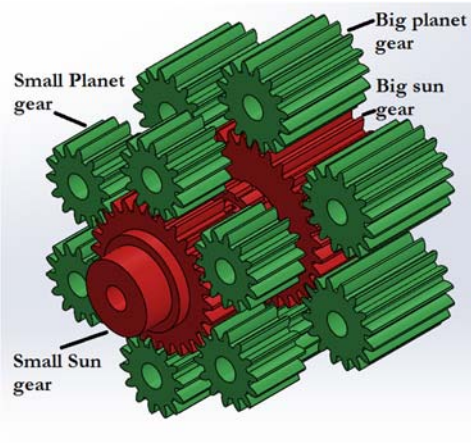


FIGURE 32 – PLANET GEARS IN MESH WITH SUN GEARS.

In our planetary gear sets, there are 6 planet gears each. This helps to reduce the force/torque on a single gear tooth, which means that the gear set can withstand more force than it would with fewer planet gears.

These planet gears are connected to the carrier which either transmit power/torque to the next gear set or to the output shaft.

5.5. Carriers

Carriers are components used to transmit power/torque from planet gears. In our transmission system there are 4 different carrier, but only two of them are used to transmit power. The other two are to ensure that the planet gears are in constant mesh with sun gears.

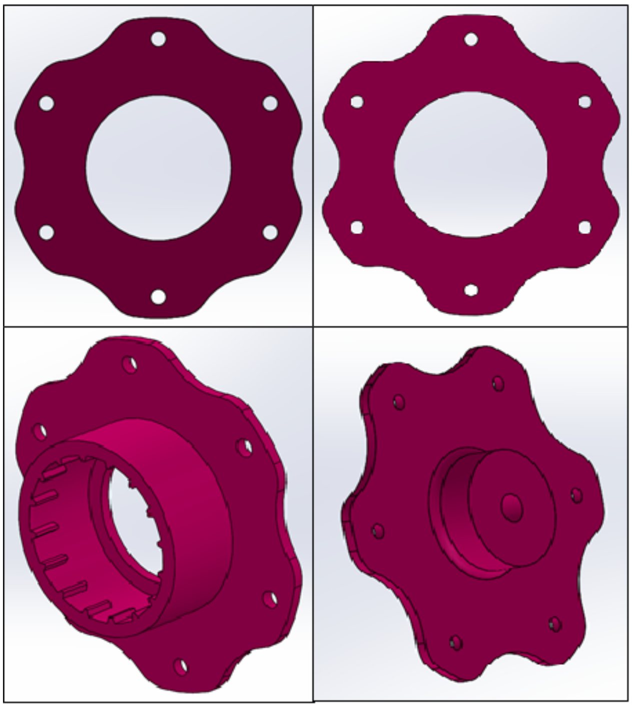


FIGURE 33 – CARRIERS FOR TRANSMISSION

Figure 33, shows all the different carrier we are using in our system. The two at the bottom are the ones used to transmit power.

Small planet output (bottom left) have groves to transmit power from carrier to big sun gear, similar to an internal gear. This means that these groves must withstand the same amount of force.

There are also 6 holes on each carrier, which connect them to the planet gears.

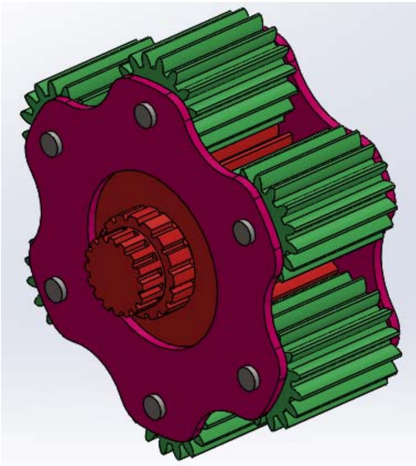


FIGURE 34 – PLANET CARRIER IN ASSEMBLY

5.6. Clutch Packs

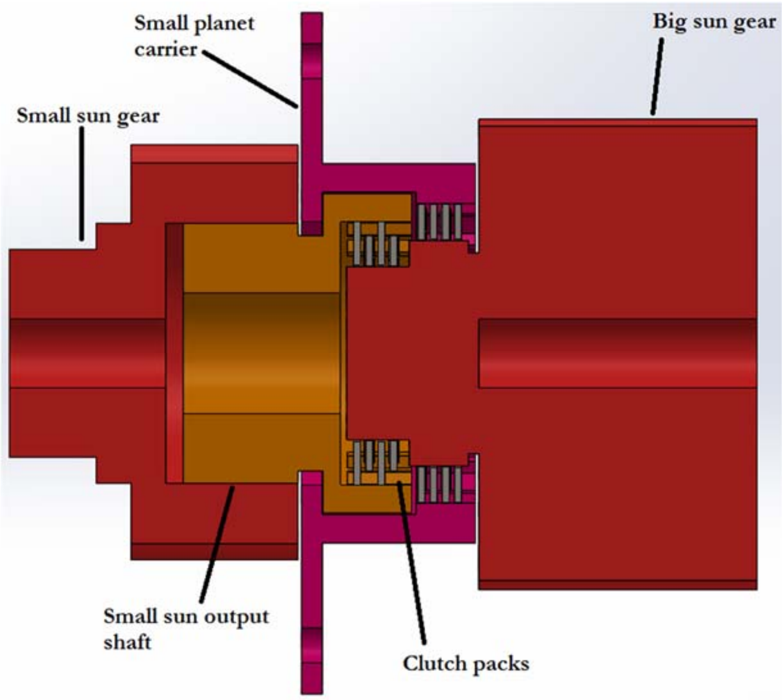


FIGURE 35 – ASSEMBLY OF CLUTCH PACKS

Clutch packs are an essential part of any elliptical gear system. They are used to engage or disengage different components together and to control the power flow. Additionally in transmission system with multiple elliptical gear sets, multi plate clutches are used to change gear ratios. This is the main purpose of clutch packs in our system.

FIGURE 36 - CLUTCH PLATE DESIGN

6. REFERENCES

[1] E-Axle, "Concept Document," E-Axle, Konsberg, 2017.

[2] W. Harris, "howstuffworks.com," [Online]. Available: http://auto.howstuffworks.com/car-suspension1.htm. [Accessed 23 04 2017].

[3] L. Naiman, "creativityatwork.com," [Online]. Available: http://www.creativityatwork.com/design-thinking-strategy-for-innovation/. [Accessed 06 05 2017].

[4] Wikipedia, "wikipedia.org," 02 03 2017. [Online]. Available: https://en.wikipedia.org/wiki/Air_suspension. [Accessed 08 03 2017].

[5] Ryder Fleet Products, "ryderfleetproducts.com," [Online]. Available: https://www.ryderfleetproducts.com/goodyear-air-springs-1r12-432/air-bag-p-u71-1r12432. [Accessed 19 05 2017].

[6] Wikipedia, "wikipedia.org," 09 03 2017. [Online]. Available: https://en.wikipedia.org/wiki/Shock_absorber. [Accessed 10 03 2017].

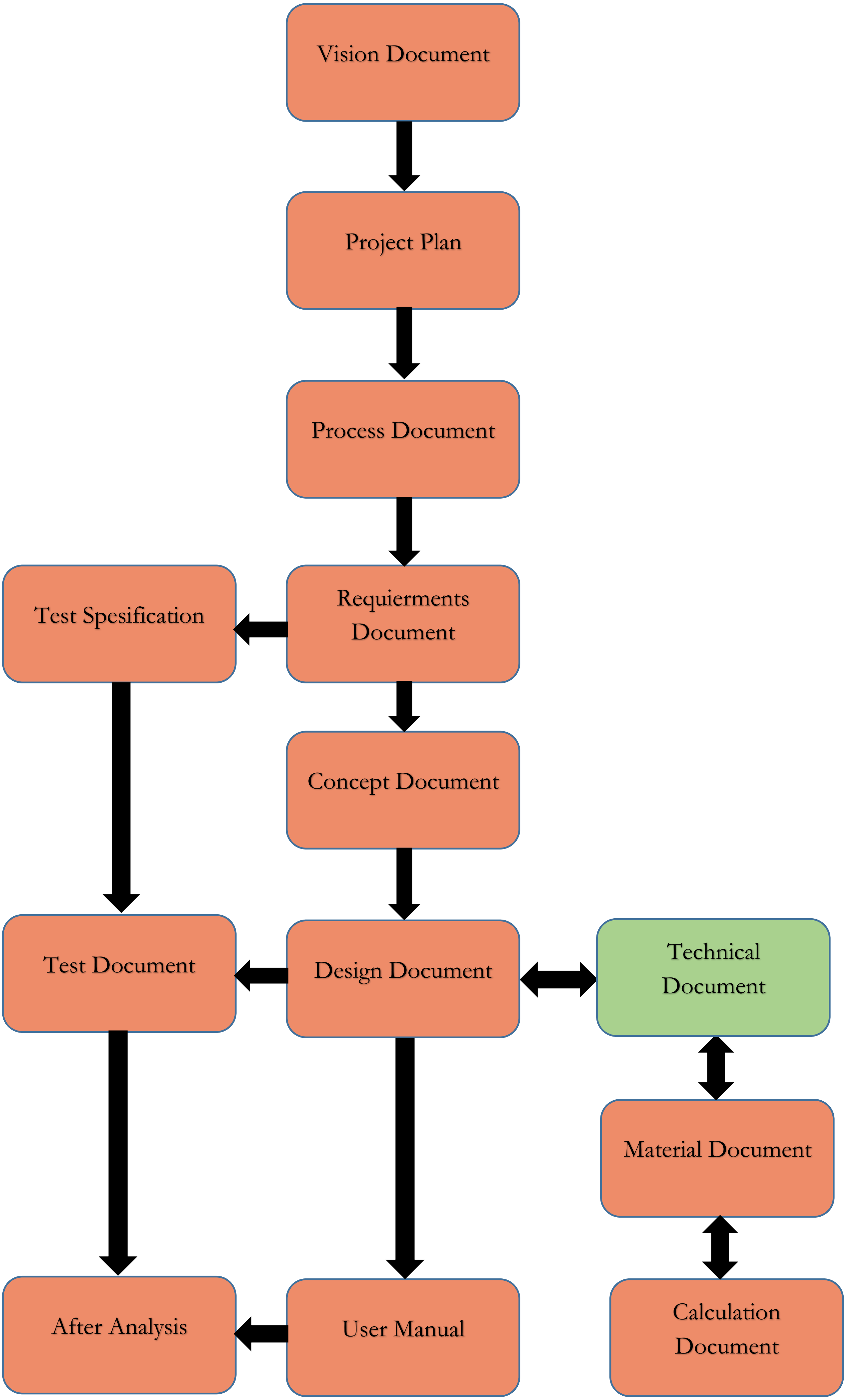
[7] Gabriel The Original, "gabriel.com," [Online]. Available: http://gabriel.com/heavy-duty/products/gasslx/. [Accessed 19 5 2017].

[8] Gabriel The Original Product Guide, "gabriel.com," [Online]. Available: http://gabriel.com/wp-content/uploads/2011/06/Gabriel_2016_Heavy-Duty_Product_Guide.pdf. [Accessed 19 5 2017].

[9] Wikipedia, "wikipedia.org," 30 03 2017. [Online]. Available: https://en.wikipedia.org/wiki/Bushing_(isolator). [Accessed 10 04 2017].

[10] Alibaba, "alibaba.com," [Online]. Available: https://www.alibaba.com/product-detail/OE-no-1135080-VOLVO-FH12-FM12_60220431245.html. [Accessed 19 5 2017].

[11] E-Axle, "Test Document," E-Axle, Kongsberg, 2017.


Vision Document
Project Plan
Process Document
Requierments Document
Test Spesification
Concept Document
Test Document
Design Document
Technical Document
Material Document
After Analysis
User Manual
Calculation Document

Høgskolen i Sørøst-Norge

KONGSBERG AUTOMOTIVE

TECHNICAL DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

Employer	Kongsberg Automotive			
Group Members	**Name**		**Initials**	
	Abubakar Khan		AK	
	Ahat Turgun		AT	
	Anis Sadiq		AS	
	Egide Rubusa Bampo		ERB	
	Mustafa Moalim		MM	
	Pawan Bhatt		PB	
Document Information	**Version**	**Date**	**Approved**	**Pages**
	2.0	23.05.17	AS	87

23. mars 2017

TECHNICAL DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

REVISION HISTORY

DATE	VERSION	CHANGES	AUTHOR
23.03.17	0.1	Document created	PB
24.03.17	1.0	Finalized	PB & ERB
18.05.17	1.3	Electro part integration	AK & ERB
19.05.17	1.4	Updated the document	ERB
20.05.17	1.5	Updated the document	PB
21.05.17	1.6	Grammar check	AS
22.05.17	1.7	Cooling system reference added	AK
23.05.17	1.8	Correction and updates	AK
23.05.17	2.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
BU	Battery Unit
ED	Electric Drive
AC	Alternate Current
CTS	Coolant Temperature Sensor
EM	Electric Motor
CVT	Continuously Variable Transmission
AC	Alternating Current
DC	Direct Current
ED	Electric Drive
DTC	Direct Torque Control
VSI	Voltage Source Inverter
CSI	Current Source Inverter
SVM	Space Vector Modulation
DSC	Direct Self-Control
SVM	Space Vector Modulation
DFOC	Direct Field-Oriented- Control
IFOC	Indirect Field-Oriented Control
IGBT	Insulated Bipolar Gate Transistor
PID	Proportional Integral- Derivative

TABLE 2 – DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

The purpose of this document is to give an overview of the technical aspect of our system. The reader is introduced to the detailed functionality of transmission system, electric drive system and the cooling system. It's important to understand the system as a whole and to understand how our system functions. In addition the document describes working mechanism of different components in our system.

1.1. Scope

The scope of this document is to introduce:

- Transmission system
- Cooling system
- Electric drive system and various control concepts

2. TRANSMISSION SYSTEM

Transmission system is a very important part of a vehicles drivetrain. Key objective of a transmission system is to control the power output to the wheels, by adjusting speed and torque from engine. It is commonly identified or referred as a gearbox. In vehicles, a clutch system or a torque converter is used to engage or disengage power flow from the engine.

Today, a transmission system is used widely in many different applications and in different forms. Most commonly used in vehicles, but also wind turbines, constructions, mining and agricultural equipment. In this document, we are focusing on systems used in vehicle industry.

Today most of the gearboxes (transmission system) are used to increase torque, while reducing speed of the output shaft. We can find different kind of transmission systems, and group these into 4 categories, manual, automatic, semiautomatic and continuously variable transmission (CVT) [1].

3. GEARS

Before understanding transmission system it is important to understand gears, which are used to construct almost every type of transmission system.

Gears are a wheel-like construction, with teeth uniformly spaced around the outer edge (sometimes on the inside). Gears are used to transmit power and rotation from one axis to another. They can be used to convert rotational motion into linear motion and even reverse the direction of rotation. Gears teeth mesh together to create a relationship between the rotations of two axis. If two gear of different size are meshed together, they will rotate at different speeds [2].

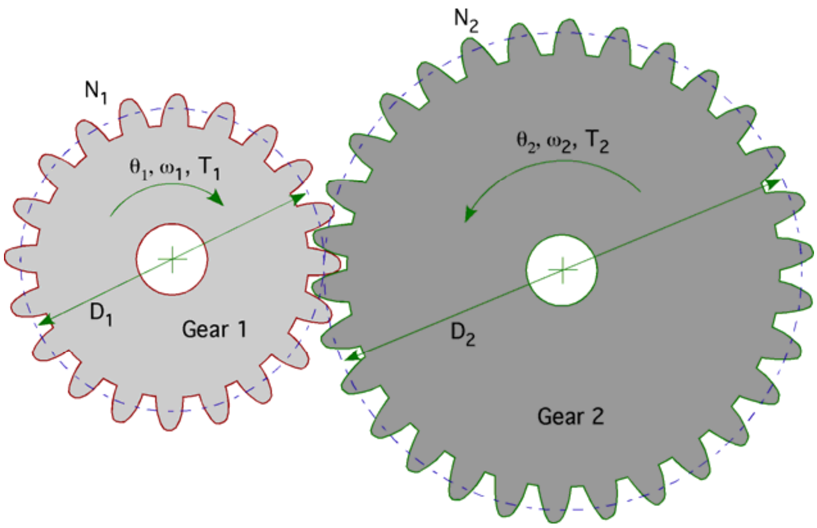


FIGURE 1 - TWO GEAR IN MESH

3.1. Application and Utility

Today we can find gears everywhere, from mechanical clocks, vehicles, bicycles, to manufacturing industry. Gears are required wherever we need to adjust the speed and power from an engine or motor. As mentioned above if gears of different size are meshed together they will rotate at different speed, and transmit different amount of torque [2].

In our project we look into applications of gears used for transportation purposes.

3.2. Gear Terminology

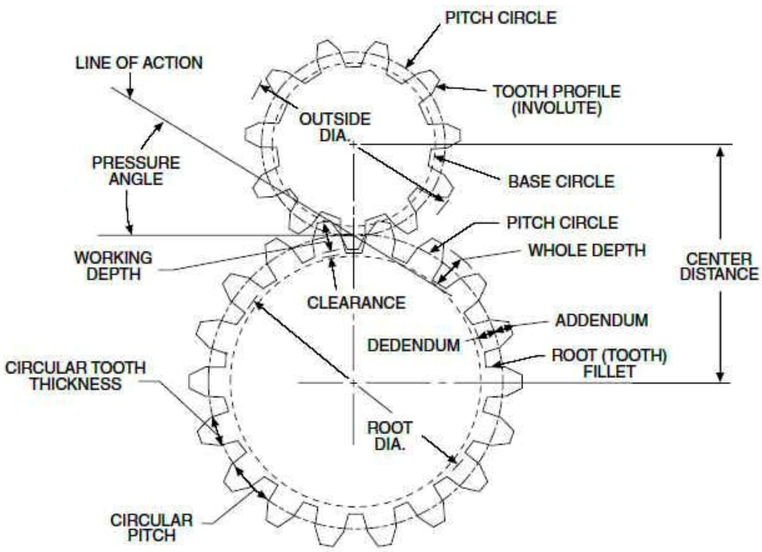


FIGURE 2 - GEAR TERMINOLOGY [3]

There are quite a few descriptive terminologies we must to be aware of while dealing with gears. It is crucial to understand these if when we design a transmission system, and to calculate certain parameters.

Some of the gear terms are [4]:

- **Pinion** is the small gear in a mesh and the bigg one is called gear, regardless of which one is doing the driving.
- **Gear ratio** is the number of teeth on the gear, divided by number of teeth on the pinion.
- **Pitch diameter (D)** is the basic diameter of the pinion and gear, which gives us gear ratio when divided with each other.
- **Module (m)** is a measure of tooth in the metric system. This can be obtained by dividing pitch diameter with number of teeth on a gear or pinion.
- **Pitch circle** is the circumference of the pitch diameter.

- **Circular pitch** is the distance from a point on a tooth to the same point on the adjacent tooth, which is measured along the pitch circle.
- **Addendum** of a tooth is its height above the pitch circle.
- **Dedendum** of a tooth is its depth below the pitch circle.
- **Whole depth** is the sum of addendum plus Dedendum.
- **Pressure angle** is the slope of the tooth at the pitch circle.

3.3. Gear Types

There are many different types of gear today and here we will look at some of them [5].


FIGURE 3 - SPUR GEAR [36]

- **Spur gears** are the most common type of gear used today. They have teeth which are cut parallel to the axis of the rotation. These are so common because they can be manufactured very easily, while other type of gears require more complicated procedures.


FIGURE 4 - HELICAL GEAR [37]

- **Helical gears** are another very common gear type. They have teeth which curve around, instead of running straight. This makes them one of the most efficient gear types and much quieter than spur gears.

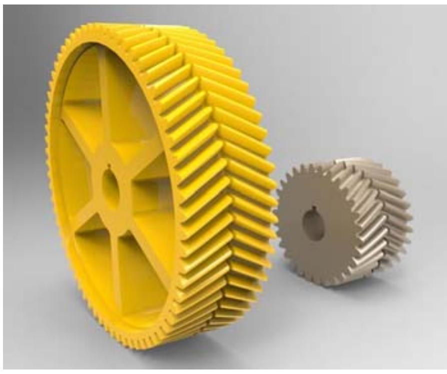


FIGURE 5 - HERRINGBONE GEAR [38]

- **Herringbone gears** are essentially two helical gear joined together. They are difficult to manufacture because of their complex geometry.

FIGURE 6 - BEVEL GEAR [39]

- **Bevel gears** are gear types which are used to transmit power from one axis to another non-parallel axis. These are used in transmission system and differentials. Teeth on bevel gear can be either straight or helical.

FIGURE 7 - RACK AND PINION GEAR [40]

- **Rack and pinion gears** converts the rotational motion of the gear into a linear motion of the rack. In a vehicle they are used in steering mechanism to control the vehicle.

FIGURE 8 - INTERNAL GEAR [41]

- **Internal gear** are gears which have teeth on the inside surface rather than the outside. They can reduce the size of a construction, because they can allow thing to pass in between. Internal gear rotate in the same direction as the gear driving them, and are extensively used in planetary gear and other elliptical gearing.

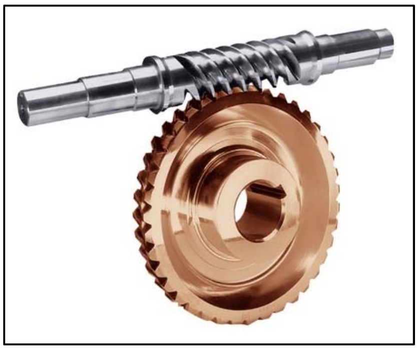


FIGURE 9 - WORM GEAR [42]

- **Worm gear** is a gear driven by a worm, which is a screw type gear. The gear rotates on an axis perpendicular and on a different plane than the worm gear. Worm gear can reduce the speed of a system and increase the torque drastically. One disadvantage is that they have low efficiency.

There are many other types of gears but, these are the one we are focusing on.

4. TYPES OF TRANSMISSION

As mentioned above we have 4 different types of transmission systems. Manual, Automatic, Semiautomatic and Continuously Variable Transmission. We will look at each of these transmission systems, and identify some of their advantages and disadvantages.

4.1. Manual Transmission

Manual transmission is one of the most common and widely used transmission system in the vehicle industry. It is cheap, lightweight and easy to maintain. Additionally, manual transmission gives the best performance compared to any other transmission. The reason that some people dislike manual transmission is because of its high learning curve, and shift-shock which new drivers might experience [6].

Manual transmission can be of two basic types, either a **sliding mesh** or a **constant mesh** type. The latter is the most commonly used in manual transmissions today, where gears are meshed together, and cannot be moved. In addition, a clutch system is used to engage or disengage power from engine to the transmission.

Since this is the most common type of transmission system, it has been considered for our system. But because of its simplicity, it is not suitable for our system since we have a requirement saying our system should have one transmission for every electric drive. Meaning that if we have 2 or more electric drives, we must have equal amount of transmissions.

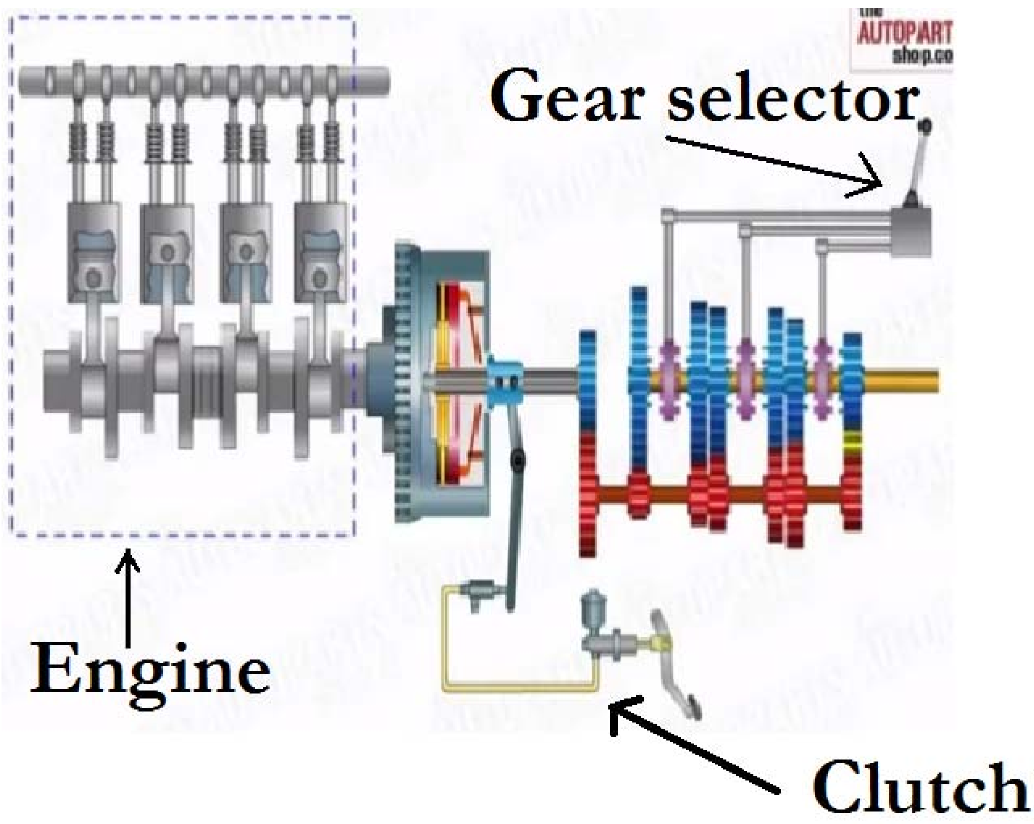


FIGURE 10 - MANUAL TRANSMISSION [7]

4.2. Automatic Transmission

Automatic transmission has been one of the most popular transmission system in recent years. Since it is very easy to use, it's very popular amongst people who want a smooth driving experience, without the need to interact with the transmission system frequently. It is not possible to select a specific gear in automatic transmission (though it is possible to limit the amount of gears). It selects appropriate gear, by considering different driving conditions.

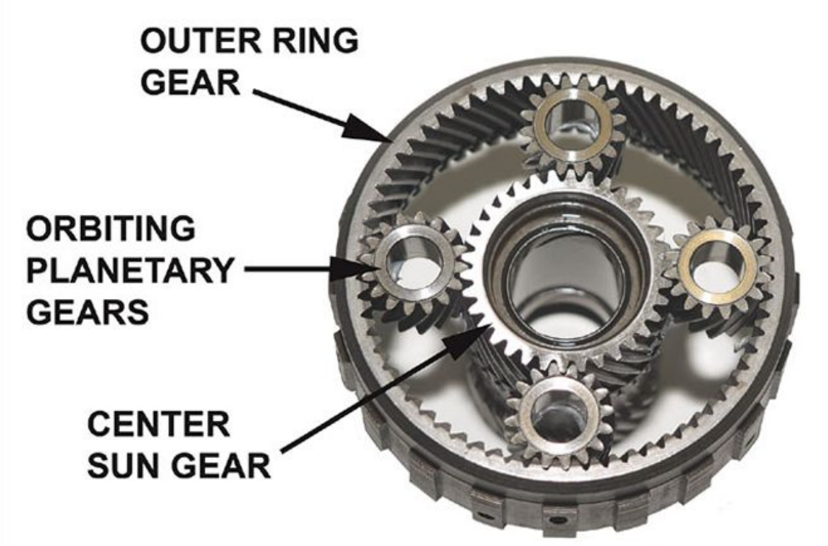


FIGURE 11 - PLANETARY GEAR SET [8]

Hydraulics are used to change gears in automatic transmission, and to connect engine/motor to the transmission system (fluid coupling or torque converter instead of a clutch). This caused older automatic transmissions to lose against manual transmission in terms of efficiency, but current system can compete and sometime even outperform manual transmission system.

Automatic transmission use elliptical gearing in their system, and planetary gear is one of the most used one. With some changes we can get different types of planetary gear or compound gear set.

4.3. Semi-automatic Transmission

Semi-automatic transmission (Clutch-less manual transmission or automated manual transmission) is a system, which facilitates manual transmission by eliminating the need to press the clutch while shifting gears. This transmission system uses different sensors, actuators and pneumatic system to shift gear, after a command from the operator/driver. This makes the driving experience much more relaxing, but keeps the driver engaged, unlike fully automatic transmission [6].

Since semi-automatic transmission is a combination of both manual and automatic transmission, it makes the system much more complicated and expensive. Some semi-automatic systems also provide fully automatic modes, which functions just like a normal automatic transmission system. Most known type of transmissions are dual clutch transmission systems, where we have 2 clutches which interact with even or odd numbers of gears.

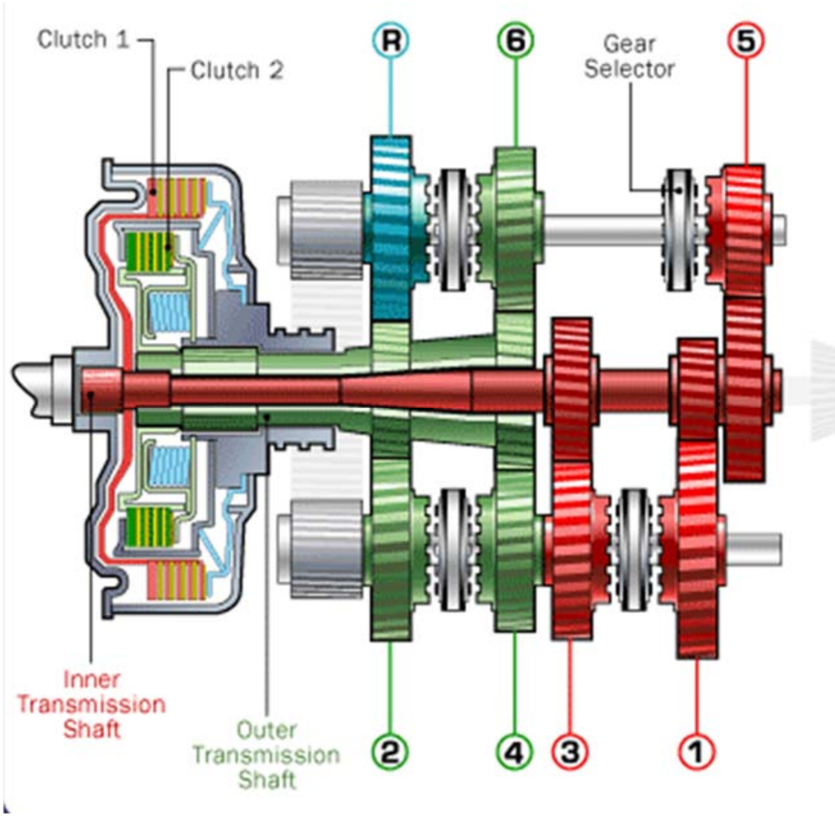


FIGURE 12 - DUAL CLUTCH SEMI-AUTOMATIC TRANSMISSION [9]

During elaboration phase, we considered this type of transmission, and majority of the group were in favor of it. We concluded that this was too complicated compared to the other type of systems, and that it wasn't compatible with our system.

4.4. Continuously Variable Transmission (CVT)

CVT's are transmission systems totally different from traditional systems. Simply because they don't have fixed gear ratio. It means they are not based on tooth based gears. CVT's, also called step-less transmission, are commonly pulley based and can seamlessly change between different gear ratios.

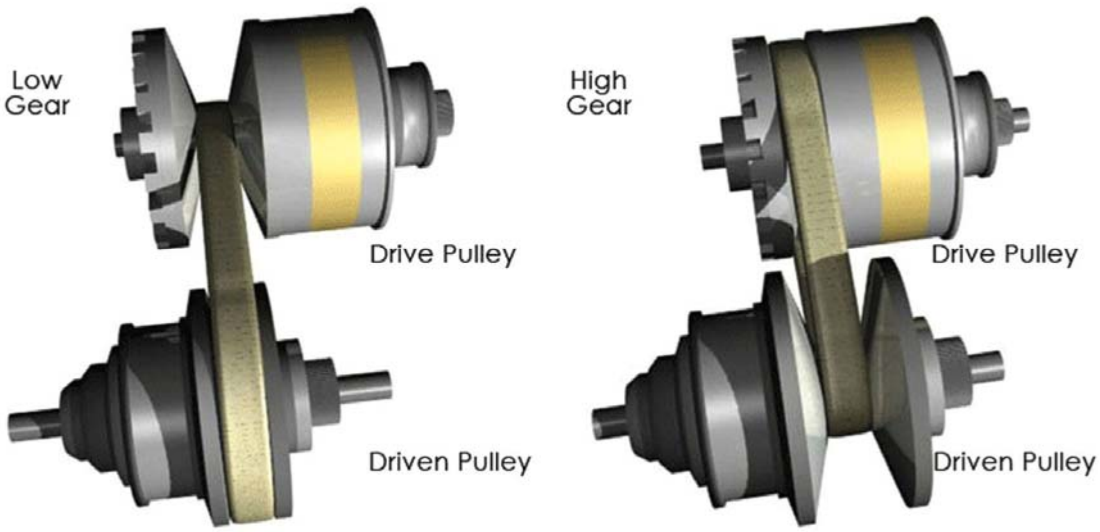


FIGURE 13 - A PULLEY BASED CVT SYSTEM [10]

CVT transmission is the simplest form of transmission which can be used in automobile industry. Even though CVT has a lower efficiency than a conventional manual transmission, it can be ignored due to its lower production cost [10].

As mentioned above the most common type of CVT is pulley based, but there are two other types; toroidal [11] and hydrostatic [12]. We are not considering these other two because of its complexity and since CVT's are not suitable for heavy-duty applications. Since they operate with friction-forces there is a limit to how much torque a CVT can transfer. After much discussion and research, we have discovered that we can't use CVT since the torque we need to move our vehicle is too high for any currently existing CVT system.

5. PUGH MATRIX FOR TRANSMISSION TYPE

6.			Transmission Type			
Nr	**Criteria**	**Weight (1-5)**	**Manual**	**Full Auto**	**Semi Auto**	**CVT**
1	Ease of use	4	-	+	+	+
2	Cost	3	+	-	-	S
3	Efficiency	5	S	S	-	+
4	Shift time	1	S	-	+	+
5	Torque load	4	+	-	S	-
6	Size	2	S	S	-	S
7	Comfortable	3	-	+	+	+
8	Complexity	2	+	-	-	+
Sum of Positive			3	2	3	5
Sum of Negative			2	4	4	1
Sum of S			3	2	1	2
Weighted sum			**2**	**-3**	**-4**	**11**

TABLE 3 - PUGH MATRIX FOR TRANSMISSION

A Pugh matrix has been created to determine which one of these transmission systems are the best suited. We use manual transmission as a standard (0) measurement, since we compare every other type of system with manual. Meanwhile if any system performs better in some area they get 1 point, but if they perform worse they get a -1 point.

We have discovered that CVT is the one that is best in many areas, but the ones it is lacking are very important. As I mentioned previously, CVT transmission is not suitable for heavy-duty applications, since it cannot handle a high amount of torque. That's why, even though we want to go ahead with CVT, we don't and instead focus on developing a transmission system around planetary gear.

7. TRANSMISSION CONCEPT

The concept we have chosen for our system is based on a planetary gear set. It consists of two planetary gear sets. Here we explain the technical aspect of our transmission system. We explain how our concept is intended to work. Later we also look at an earlier concept, which was also developed quite a bit, and we compare these two concepts.

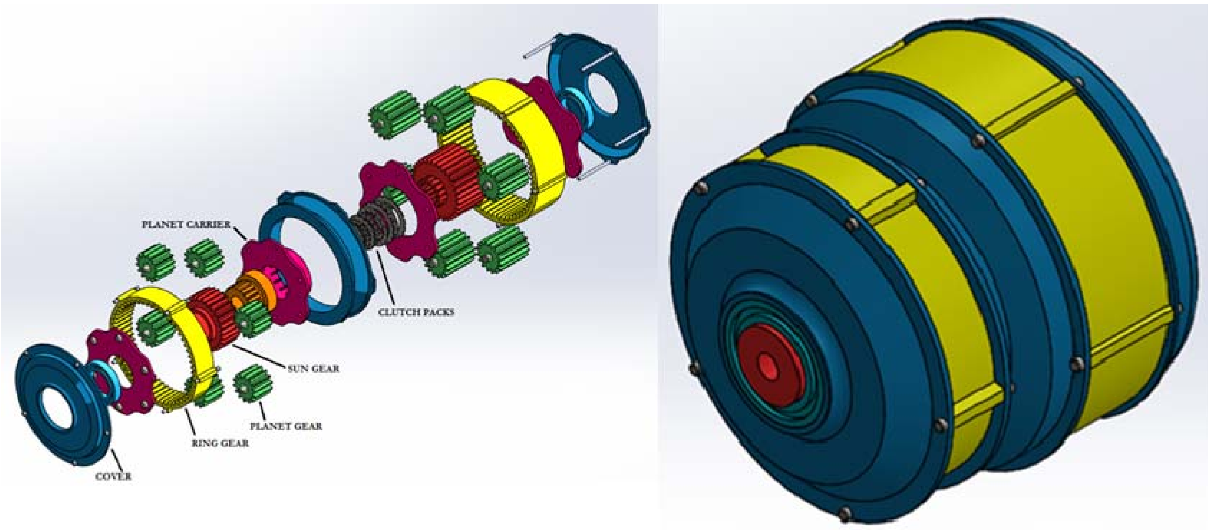


FIGURE 14 - OUR TRANSMISSION CONCEPT

Here we can see the final form of our transmission system. To the left we can observe an exploded view of our design, and we can see all the components our transmission system is made of.

As mentioned earlier, our transmission system is made of two planetary gear sets. In addition we have carriers, which transmit power from planet gears and clutch packs, which engage or disengage different gear sets to meet desired gear ratio.

7.1. Planetary gear set

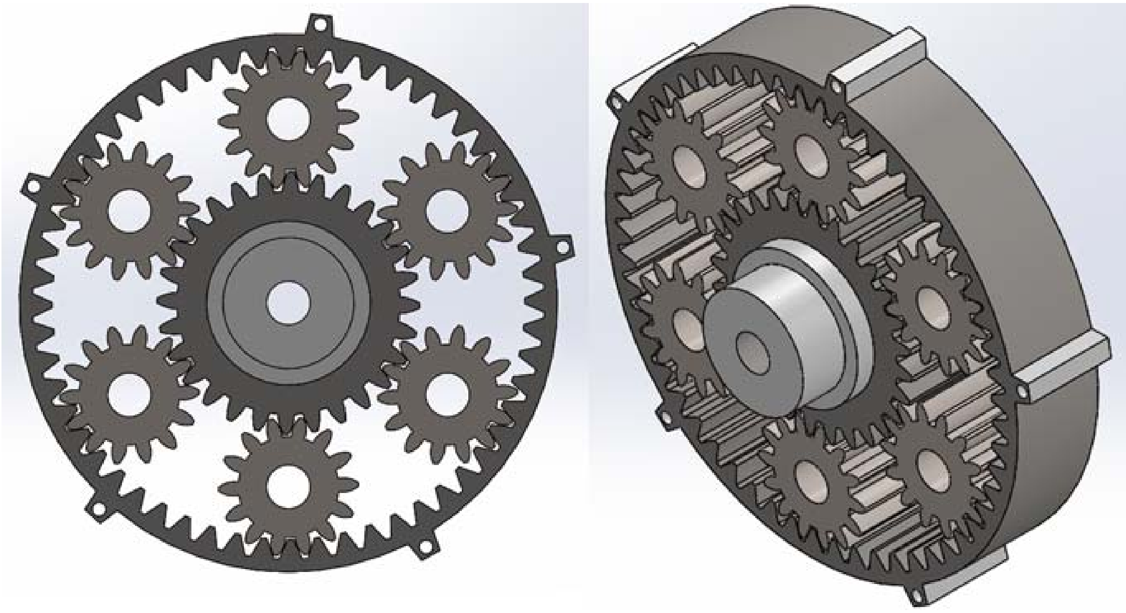


FIGURE 15 - PLANETARY GEAR SET

Figure above shows the planetary gear setup for our transmission. There are two of these in our system. This is the first and small one, while the other one is larger. The idea behind planetary gear set is that we can get different gear ratio by making one gear stationary and supply power in other gears.

The maximum gear reduction we get in a planetary gear is when the ring gear is fixed and the sun gear has input. Figure 16 below shows us how the gear set reacts, in such a scenario.

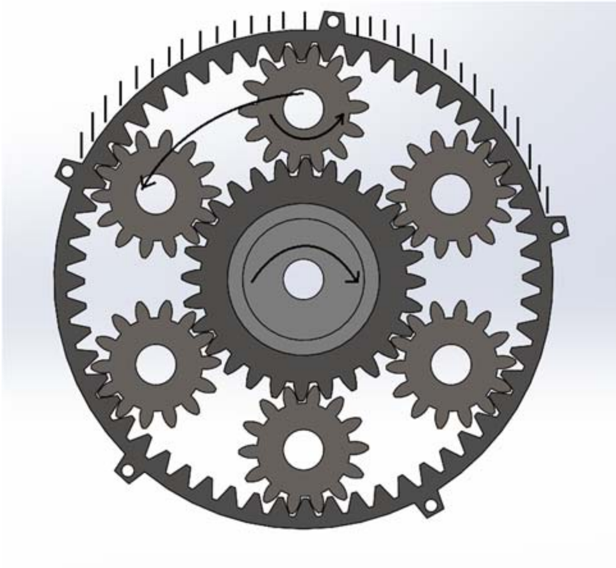


Figure 16 - Planetary movement

7.2. Power Flow in Our Concept

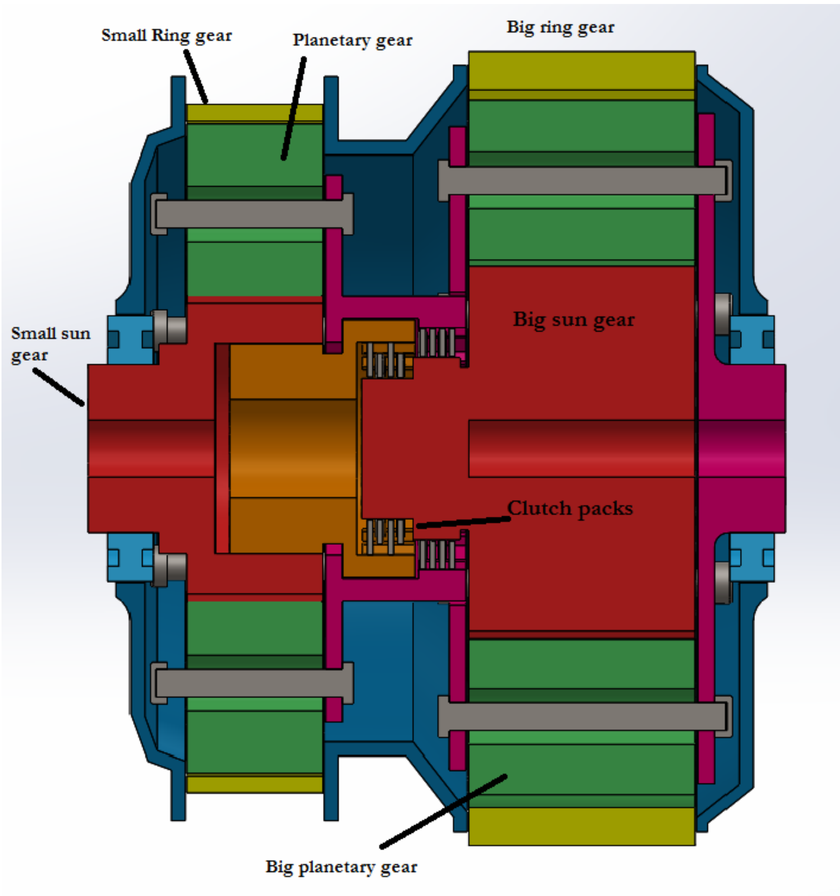


Figure 17 - Section view of transmission system

Figure 17 above shows a section view of our system. We can see where each component is located. This view can also help us illustrate the power flow in each gear.

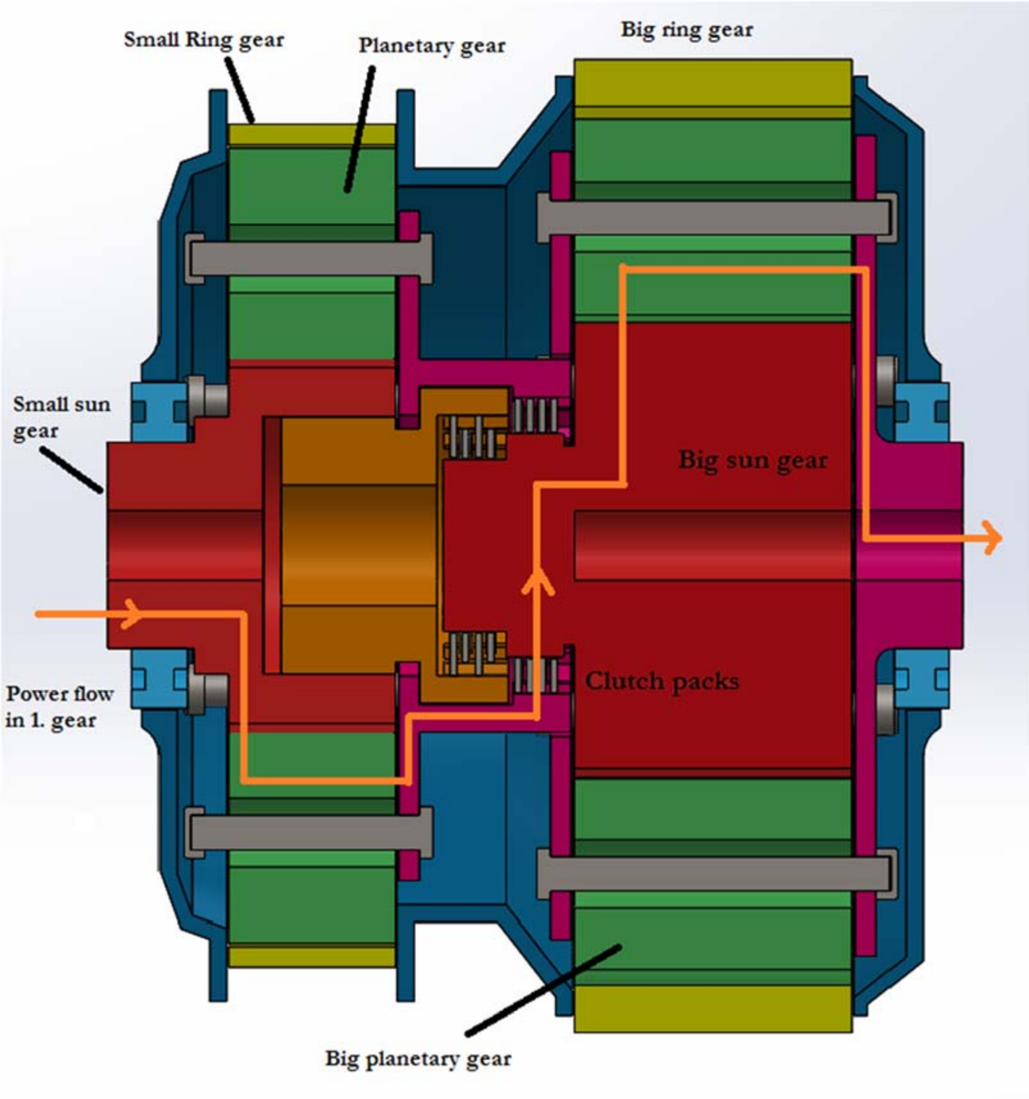


FIGURE 18 - POWER PLOW IN 1ST GEAR.

We can see that in 1st gear the power/torque comes from the motor into the small sun gear, which transmit it to the small planetary gears. The power flows from the planetary gears to the carrier and on to big sun gear through second clutch pack. The big sun gear transmit the power to the big planetary gears and finally to the output carrier.

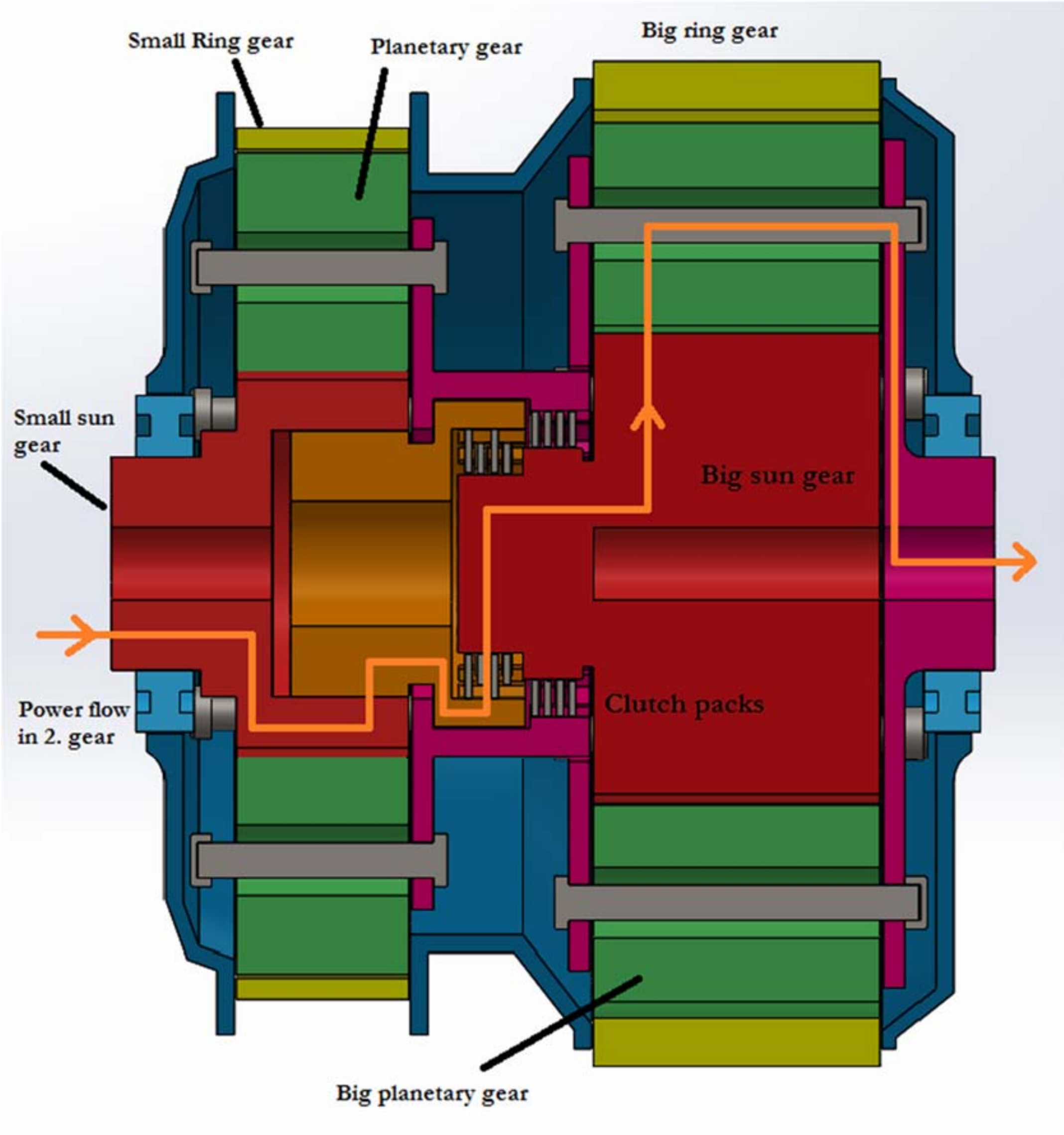


FIGURE 19 - POWER FLOW IN 2ND GEAR

In 2nd gear we don't need a high amount of reduction, therefor we disengage the second clutch pack and engage the first one. This means that the power flows directly from small sun gear to the big sun gear. After that the power flows from big sun gear to the big planetary gears and finally to the output carrier.

8. COOLING SYSTEM

Cooling system is critical for the truck because most of the energy from the ED becomes heat. The battery and motors generate heat, which can overheat the system making it unusable. That's why it's important to avoid all this rising heat in the electrical system. In addition, heat can damage the batteries and electric motors and reduce their effective life time. There are different types of cooling systems, but we will use water-cooling system, because liquid coolers possess better thermal capacity and are quite good at carrying the heat away. However, a water-cooling system is much more complex than air cooling system.

In our system, we divide the cooling system into two separate cooling systems. One for the electrical motors and the other for batteries.

8.1. Cooling System for EM

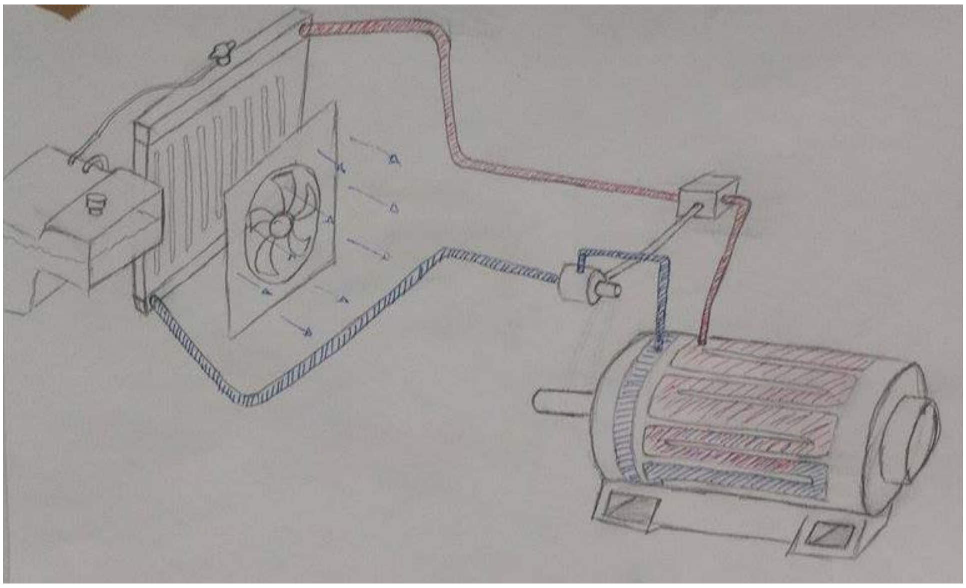


FIGURE 20 - CONCEPT FOR EM COOLING SYSTEM

We have an AC motor, an electric pump, a radiator with a fan, expansion tank, a thermostat, a CTS for the motor and hoses supplying/returning water-cooling [13].

The electric pump, pumps coolant in to the motor through the supplying hole, then the coolant absorbs heat from the windings and rotor of the motor. The coolant circulates in the motor in a zigzag circulation and gets out from the returning hole to the radiator, to cool down the hot coolant and circulate again.

FIGURE 21 – RADIATOR [14]

The hot coolant in the radiator will release its heat to the atmosphere with the help of the fan. Therefore, the radiator cools down the hot coolant and produces a cold coolant, which will absorb heat from the motor in the next cycle.

FIGURE 22 - RADIATOR-CAP TO REGULATE PRESSURE INSIDE THE RADIATOR [15]

FIGURE 23 - EXPANSION TANK [16]

There is an expansion tank next to the radiator. Since it is a closed system, the hot coolant coming in to the radiator expands and pressure builds up inside the cooling system. Then reaching a pressure about 103 KPa, the radiator cap lifts against the spring and allows coolant to escape to the expansion tank, to stop rising pressure. When the system cools down the water contracts and the pressure drops down inside the cooling system. The vacuum inside the system sucks back the coolant in the expansion tank. The radiator cap will act in this situation like a one-way valve and lets the coolant inside the expansion tank back to the system. It is not possible to suck the coolant back into the system because of interruption or defect in the system, the coolant pushes out through the overflow hose.

FIGURE 24 – ENGINE COOLANT THERMOSTAT [17]

The thermostat is a valve, which regulates the flow of the coolant. It covers the coolant from the motor, so the thermostat can sense the temperature. When the coolant is cold it bypasses the radiator and recirculates the motor without going to the radiator, which helps the temperature of the coolant to rise. Since the coolant absorbs heat from the motor quickly, it will reach temperatures between 71°C - 90°C and over, very fast. This causes the bypass valve to close and the main valve to open, then the hot coolant flows to the radiator and the cold coolant from the radiator flows directly to the motor through the pump.

CTS (coolant temperature sensor) is used to monitor the motor temperature. The temperature sensor measures the temperature that the thermostat or coolant is giving off. The data is then sent to the motor control system. The temperature sensor is responsible for registering high temperatures so that the fan at the radiator can start.

8.2. Cooling System for BU

Cooling system for battery unit contains [18]:

Battery unit, insulators, a heater, a radiator with fan, an electric water pump, temperature sensor and valves.

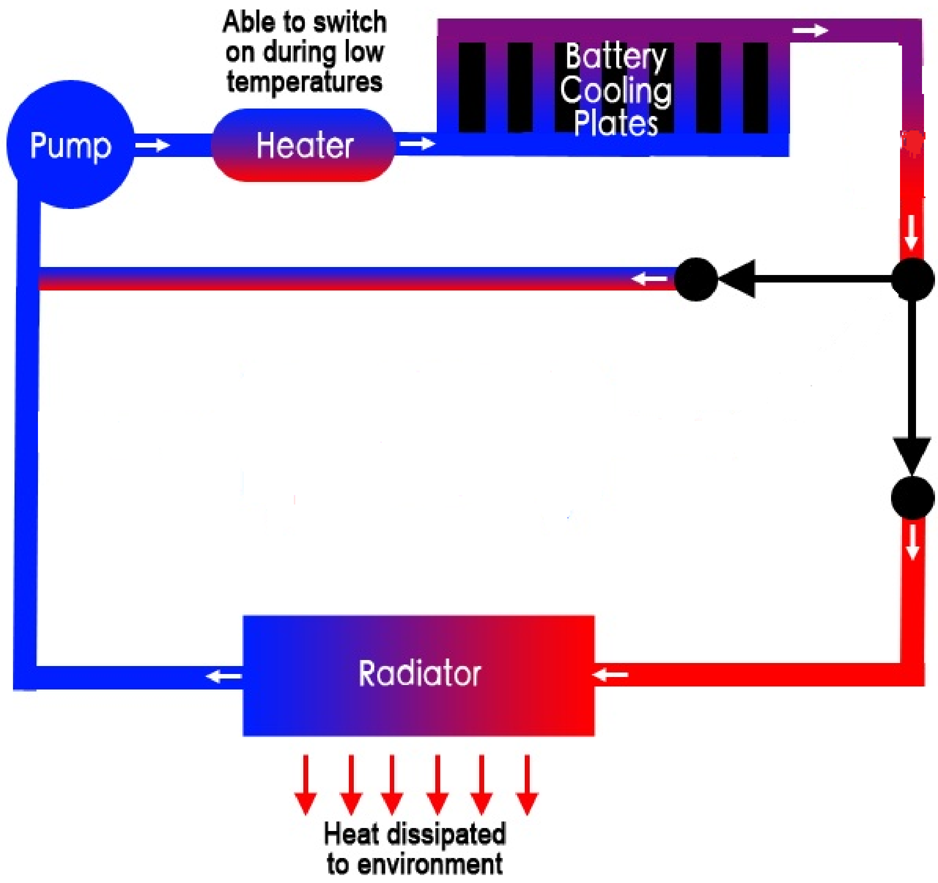


FIGURE 25 - BATTERY COOLING SYSTEM

A heater is optional and can be operated when needed. Heater is for cold climates when the temperature of the BU can fall below the lower temperature limit, thus the heater assists the BU to reach the proper temperature range in short time.

The BU is the source of energy for our system. The battery unit contains of cells. Battery cells will not only generate electricity but also heat. This heat should be removed from the battery unit, when the battery temperature reaches the optimum temperature or even in advance. Thus, a cooling function is required.

There are tubes through the cells of the BU that allows us to send the coolant through and remove the generated heat without mixing or damaging the BU. The water pump, pumps coolant in to the BU through the supplying hole, then the coolant absorbs heat from the cells of the BU. The coolant passes through the BU in a waveform to make sure that it cools or removes heat from all the individual cells and gets out from the returning hole to the radiator, to cool down the hot coolant and circulate again.

Insulator is helpful for the BU. In extreme cold or hot weather, the temperature difference between the inside and outside of the battery pack is much larger than that in mild weather. Battery temperature will thus fall (cold) or rise (hot) sooner out of the proper temperature range when the vehicle is at standstill. To prevent this, good insulation can slow down the falling or rising of battery temperature, especially when the vehicle is parked.

The hot coolant in the radiator will release its heat to the atmosphere with the help of the fan. Therefore, the radiator cools down the hot coolant and produces a cold coolant which will absorb heat from the BU at the next cycle.

The sensors monitor the temperature of the BU and sends the data to the control system. It can enable the fan of the radiator if needed.

Valves plays an important role to the flowing of the fluid and regulating it when and where it is intended. Different valves are participated in the cooling system as bypass valve, 4-way valve etc.

ELECTRIC DRIVE

This paragraph discusses some electric drive techniques used to control industrial and home applications today. This paragraph focuses on the techniques that are used to drive electric motors, since our project includes controlling the speed and torque of an AC motor.

The project involves driving a heavy-duty vehicle with two independently driven AC motors. We will therefore focus on electric drive used to drive electric motors, particularly those used to control AC motors.

The main objective is to discuss different methods we can use to control different electrical components (Motors, inverters etc.) in our project.

One of the main objectives of the project is to select and implement an electric drive that improves both the stability and the safety of an electrically driven heavy-duty vehicle.

Our integrated electric drive will consist of two induction motors equipped with one transmission each. The transmission which is of planetary type will provide the needed propulsion to the rear wheels.

For steering and acceleration, an electronic differential method is implemented. The implementation of the electric differential is done by simulating the developed driving system in Matlab/Simulink and by modeling the system mathematically. A remotely controlled small vehicle is programmed in Arduino as the proof of concept to demonstrate the functionality of electric differential.

An electric drive is a technique used to convert electric energy from one form to another and give possibilities to control the machine processes. Electric drives are designed to control the functionality of electric motors, converters and generators. They convert power from one form to another form which is more suitable for machines they're designed to drive [19, 20].

To achieve the desired results from an electric motor, we must be able to control the motor’s speed and torque. Electric drivers gives us the possibilities to control the parameters of an electric motor, so that it can be suited to load variations.

Parameters of an electric motor can be: the rotor’s speed, rotor voltage, rotor current, input frequency, amplitude, rotor torque, stator’s current, motor vectors etc. By varying one or more of these parameters we can be able to suit machines to our application requirements. The machines controlled by electric drive includes: conveyer belts, water pumps, washing machines, electric vehicles and many domestic appliances [21].

9. ELECTRIC MOTORS

An electric motor is a device that converts electric energy into mechanical energy. Electric motors operate on the principle that when an electric current- carrying conductor is placed in a magnetic field, a mechanical force is developed. The development of this force depends on the interaction of magnetic field and electrical current [20].

When a magnetic field interact with an electric current, a mechanical force is developed. The magnitude of this developed force is given by Lorentz's law, which states that when a conductor carries a current through a magnetic field, a force acts on the conductor and the force is given as the vector cross product of the current and the magnetic field. The force is mathematically modeled as:

$$\mathbf{F = IBL} \qquad [22]$$

Where **I** is the current vector, **B** is the magnetic flux vector and **L** is the length of the wire given in meters. Electric motors convert the forces mentioned above into a useful mechanical energy which is used to do some work. These are classified in two main categories depending on which type of electric currency they use.

The two categories are: Alternating current motors (AC Motors) and Direct current motors (DC Motors). Alternating current motors can be sub-classified into asynchronous and synchronous motors. This document focuses on alternating current electric motors, since this is the type of electric motor we intend to use for our electric drive system.

9.1. AC Motor

Alternating current motors, are a type of electric motors that use alternating current. These motors are used to convert an alternating electrical energy into mechanical energy. The mechanical energy is created from a magnetic force that is exerted by the rotation of magnetic field.

The rotation of the magnetic field is caused by an alternating current that flows through the magnetic coil. AC motors are mainly made of two components, namely: a stator that is stationary and has some coils supplied with AC current and a movable rotor that sits inside the stator and has a means to be connected to a load through an output shaft.

AC motors operate on the principle of magnetism. They contain magnetic coil wires and several fixed magnets surrounding a shaft. When an alternating current AC flows through the coil wires, the wires are magnetized and generate a magnetic field.

The generated magnetic field causes the fixed magnets to interact with each other and initiate the rotational movement of the shaft and the coil of wires. AC motors are classified into three main categories, namely: Asynchronous AC Motors, Synchronous AC motors and Industrial AC Motors.

9.2. Asynchronous Motors

Asynchronous motors are commonly known as induction motors. Induction motors are the most used type of ac motor in industrial applications and domestic applications. These type of motors uses an electromagnetic induction to rotate a shaft. When an induced current flow through a magnetic coil it creates a magnetic field that surrounds the rotor of the induction motor and cause the shaft to rotate. Induction motors are designed in one or three phases.

9.3. Synchronous AC motors

This type of Ac motor has a permanent magnet like permanent magnet DC motor. When a current flow through a magnetic coil surrounding the permanent magnet, a magnetic field is crated around the rotor and makes it to rotate and produce a mechanical energy. These type of AC motors have rotors that rotate at the same rate as the alternating current which is supplied to them.

9.4. Industrial AC Motors

Industrial AC motors are mainly induction motors designed for application requiring high driving power. Most of the industrial AC motors are three-phase induction motor ranging from 220 watts to 3000 watts and operating at the voltage range of 220 VAC to 380 VAC.

10. SELECTION OF AN AC MOTOR

Our system needs a supply of torque to drive the heavy-duty speed vehicle. Selecting a type of ac motor for our system is crucial. There are many type of motors we can use. Some of the AC motors are capable of driving our system but aren't able to satisfy our requirement's specification.

To select a suitable AC motor for our electric drive system, we use the Pugh matrix concept selection method to compare different types and select the suitable result. First we determine the three concepts and there after weigh them accordingly. The three concepts are:

- One phase induction motor
- Three-phase induction motor
- Permanent magnet AC motor.

Pugh matrix used to to compare between these three ac motors check (Att: I). The comparison result shows that a three-phase induction motor has higher advantage over the remaining motors and it satisfies our requirement specifications. We therefore use a three-phase induction motor for our electric driving system, and focus on this further.

10.1. Three-Phase Induction Motor

Three-phase AC induction motor is the most popular type of ac motors and is used in most industrial and vehicle driving systems. This type of motor is maintenance free, has higher efficiency and less noisy. The stator of our system's induction motor will be supplied by a controlled three-phase AC power from a three-phase voltage source inverter. The synchronous speed of the motor is modeled using the general AC speed formula shown in equation below.

$$\mathbf{N}_{r} = \frac{(Ns - Nr)}{Ns} \ \mathit{in} \ \mathbf{RPM.} \qquad [23]$$

The equation show that the speed of AC motors can be controlled by varying the stators frequency with the influence of the load torque or by varying the voltage input. The speed of our AC motors will be controlled via an inverter with electronic differential functions.

Generally, the speed of any AC motor depends on the frequency of applied voltage and the number of magnetic poles the stator of the motor contains.

To be able to control an induction motor we must make sure that the supply voltage changes with the frequency. To control the speed of our induction motor in a way that satisfies our requirement's specification, we determine different controlling methods that may be suitable for our project and use a pugh matrix to select the best suitable controlling method for our project.

11. INVERTOR SLECTION

Inverters are used to convert direct current DC to an alternating currency AC. They convert DC to AC using different components working with the switching transistors. There are many types of inverters, but the most used ones are voltage source inverter and current source inverter. Five phase inverter, which is commonly known as the five-leg inverter, is slowly replacing other type of inverters as it can be used to control more than one motor at the same time. The input and the output voltage of an inverter depends on the construction of the inverter's circuit. Since our project will involve controlling the speed of three-phase induction motors, we focus on three-phase inverters.

Three-phase inverters are used on applications whose frequency vary from time to time. These types of inverters consist of three single phase inverters integrated together. They contain of three switches, each connected to a three-load terminal. The switches are controlled in such a way that they operate at 60 degrees each. They divide into current source three-phase inverters and voltage source three-phase inverters.

11.1. Voltage Source Inverters

Voltage source inverters can be classified according to different criterions. They can be classified according to number of phases they output. Accordingly, there are single-phase or three-phase inverters depending on whether they output single or three-phase voltages. It is also possible to have inverters with two, five or any other number of output phases [19].

11.2. Current Source Inverters

Current source inverters are used to convert direct current into alternating current. These types of inverters are fed by a constant direct current instead of direct voltage. Current source inverters are well suited to control an induction motor. The advantages of these inverters are: They use constant input current which is adjustable, unlike voltage source inverters which use adjustable voltage. CSI requires no feedback diode like voltage source inverters.

11.3. Five Phase Inverters

Five phase inverter is a type of inverter which use 5 phases ac voltage source. This type of inverters has an ability to control the speed and torque of two different three-phase induction motors at the same time. For our project, we can use this type of inverter, to control two three-phase induction motors directly placed on the wheel. This type of inverter can replace the need to use more than one inverter and minimize the cost and installing time. To select a suitable type of inverter we use Pugh matrix and compare between three different inverter types. We compared between the following inverter types are :

- Three-phase voltage source inverter
- Three-phase current source inverter
- Five phases voltage source inverter.

Pugh matrix used to compare between these three types of inverter (Att: J). The comparison results show that three phase voltage inverter is suitable for our project. We therefore choose to use three phase inverter for this project.

11.4. Variable Stator voltage control method

This method is performed by varying the stator's voltage at a constant frequency. This is achieved by controlling the inverter's switching interval. The technique produces a torque which is proportional to the square root of the stator's input voltage. An increase in stator's voltage will produce an increase in motor's speed and a reduction in stator's voltage will produce a decrease in speed.

However, speed range of this controlling method is very low compared to the speed range needed by our product. Beside the technique has a poor power fact, which makes the technique unsuitable for this project. This method is the cheapest and the easiest of all the controlling methods, but is suitable for applications with lower power range rating appliers like the ones used in homes. This technique is not suitable for our project's requirements specifications.

11.5. Variable Frequency control

By varying the input frequency for an induction motor, we can be able to control the speed and the torque of an induction motor. If the EMF of an induction motor is changed in the same ratio as the frequency, the flux of the motor will remain constant. This makes it possible to control the speed of an induction motor by varying the input frequency. The advantages of this technique are: Smooth starting, smooth acceleration, increased power factor and less harmonics. The disadvantage of technique is very high motor heating at low speed. For our system we need a technique, which produces high starting torque and minimal motor heating. We therefore considered this technique unsuitable for heavy-duty truck.

11.6. Variable Voltage/Hertz control

This method is known as Volts per Hertz, because it involves variation of both the frequency and the voltage. The method is performed by varying the ration of stator's voltage to the frequency. By varying the ratio of these two parameters, we can be able to control the speed and the torque of our induction motors. This method requires a constant stator flux density to work effectively. To maintain a constant flux density, the supply voltage must be changed in the proportional as frequency stated by "Faraday's law" of flux and magnetic field.

11.7. Direct torque control (DTC)

Direct torque control is done by directly controlling the stator flux and torque. The two parameters are controlled by selecting an appropriate inverter state. The method has the following advantages:

The methods require less components compared to other controlling methods.

Controllers like PID for flux and torque and voltage modulator blocks are not needed in this controlling method. This method has minimum torque response time compared to other driving methods. The disadvantages of the direct torque control are: The method requires the torque and flux estimators. The method causes some torque and flux ripples into system.

11.8. Direct self-control (DSC)

The direct self-control (DSC) is a method used to control the torque of most ac motors. This technique makes it possible to achieve accurate results of an induction motor. The speed and torque of an induction motor are controlled by sampling the motor's voltage and current. The sampled parameters are then used to estimate the motor flux and torque. Based on estimates of the flux position and the instantaneous errors in torque and stator flux magnitude, a voltage vector is selected to restrict the torque and the flux errors.

The control strategy "direct self-control" (DSC) of inverter fed induction machine offers a good basis on which a speed-proportional quantity can easily be derived alone from signals that are already needed for direct control of torque and stator flux in the stator reference frame. DSC was successfully optimized for traction drives. Because of economic reason, in this field of high-power applications, the switching frequency of GTO thermistors must be restricted to 200-300 Hz.

Therefore, the signal processing of DSC is rather different from those methods directly controlling torque and stator flux, which are optimized for medium power applications and utilize much higher switching frequencies.

11.9. Space Vector Modulation (SVM)

Space vector modulation is a technique used to control most types of AC motors. This method controls AC motor by creating a hexagon rotating voltage reference. The speed of the rotating hexagon voltage reference is then used to determine the frequency of the motor rotation.

11.10. Direct Field-Oriented Control (DFOC)

Field oriented control (FOC), is a method used mainly to control induction motors. This method function by decoupling between the current components used for generating magnetic flux and torque. This decoupling allows motor's speed to be controlled as a DC motor. This method is best suited to Permanent magnet ac motors, since they have the same features as the DC motors. However, the method can be still used to control an induction motor like the one used in our project.

The Field Orientated Control consists of controlling the stator currents represented by a vector. This control is based on projections which transform a three-phase time and speed dependent system into a two coordinate (d and q coordinates) time invariant system.

11.11. Indirect Field-Oriented Control (IFOC)

The indirect field oriented control technique, is one of the most used methods to implement induction motors controlling methods. This technique is implemented by adding a measured shaft speed to a slip speed that is calculated. The two motor parameters are added together to define the angular frequency of the rotor's flux vector. The disadvantage of this technique is that it uses a closed loop controlling model with feed forward scheme, which may be dependent to parameters that vary with the changes of the sounding environments e.g. temperature. The technique requires measurement of the motor's shaft speed, which means that some more components are required. We used pugh matrix to chose a switable control technique for this project. The pugh matrix is used to weigh and compare between four different control methods namely :

- Voltage/Hertz control
- Direct self-control (DSC)
- Direct field-oriented control (DFOC)
- Direct torque control (DTC)

Pugh matrix used to compare betweem these four control techniques check (Att: K).The comparison between the four control methods shows that the direct control has higher advantages over the other controlling methods.

We therefore have decided to use direct torque method to control the speed and the torque of a three-phase induction motor via a source voltage invertor and other controller devices. The stability control of two separate electric vehicle (EV) motors by using only single five-leg inverter (FLI) is the motivation of this study.

This paper proposes an electric differential (ED) in a FLI to serve dual separate induction motor (IM) drive-based wheels of an EV traction drive system. FLI is developed to replace the two normal three-phase voltage source inverters that need to independently control the two motors.

The next stage of this section is to determine the controlling closed loop system for the whole system. After a controlling closed loop system is determined, we will use space state method to determine the location of the dynamic system's poles and zeros to determine if the system is stable, controllable and observable. If the dynamic system is not stable we will need to replace the poles and zeros to a place where the system will be stable, controllable and observable.

12. INTEGRATED ELECTRIC DRIVE SYSTEM

Our driving system consists of a three-phase induction motor driven via a three-phase voltage inverter. The three-phase voltage inverter converts power input from the battery unit from direct current DC to three-phase alternating current AC. The differential input of the inverter is fed by differential signals from the electric differential system for traction and stability improvement.

The whole heavy-duty vehicle is considered as a load. The vehicles torque will vary with changing road conditions and varying load. There are different motion resistive forces acting on our vehicle. Resistive forces acting on our vehicle will include: the aerodynamic forces, vehicle's upper hill driving force**,** the vehicle's rolling resistance force and the vehicle forward force, which is developed by the electric motors.

The aerodynamic force results in friction from the vehicle body, driving through the air. This force is developed due to the structure protrusion of the vehicles outer parts like the side mirrors and the frontal area shape. This force is calculated using the equation below and the calculations are shown in calculation document.

$$F_{aero} = \frac{1}{2} C_d AV^2 \quad [24]$$

This is the force needed by the vehicle to drive up a slope. The force is calculated by the formula defining the components of the vehicle weight that act along the slope. We calculate this force using the equation below. We use the equation below to calculate the total motion resistive forces acting on our vehicle.

$$\boldsymbol{F}_{tot} = F_m Ma + MgCrr + \frac{1}{2} pAC_d V^2 \quad [24]$$

The rolling force is a resistive force that acts on vehicle due to the traction of the tires on the driving road. The force depends on the vehicle's speed and vehicle's weight.

13. PID CONTROLLERS

Proportional Integral-Derivative controller (PID), is a feedback loop based mechanism used to control systems. This mechanism controls a system by continuously calculating the difference between a reference variables and a measured process variable [25].

PID controllers are one of the most common controllers used universally in different industrial control, domestic and automotive control. These types of controllers are attractive because they produce a robust performance in a wide range of operating conditions. Additionally, these controllers are simple to operate compared to other controllers. PID controllers correct the system's error by the means of proportional, integral and derivative. To satisfy our system's requirement of electric drive and vehicle's dynamic control, PID controllers are used in all the closed loop controlling systems. These controllers help us to truck and improve the response of our closed loop controlling systems [25].

We use PID controllers to control the closed loop speed control model of our three-phase induction motor using DTC. Additionally, we use this type of controller to control all other processes that are required to act automatically. The figure below (fig.26) shows a PID controller Simulink model created in Simulink.

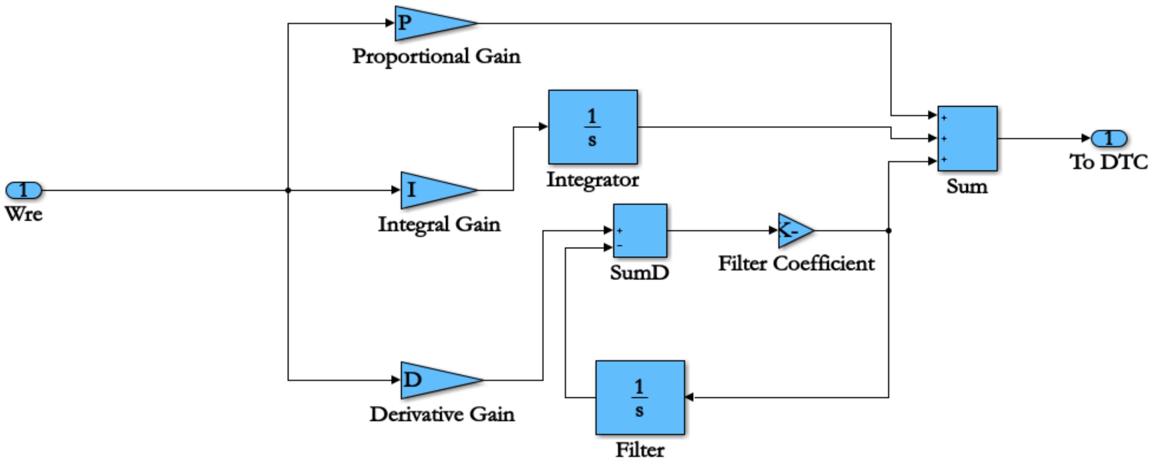


FIGURE 26 - SIMULINK MODEL OF PID REGULATOR

Our PID controller consists of three algorithms with three basic coefficients, namely: proportional, integral and derivative. These coefficients are varied for us to get an optimal response for our system. The main objective of using PID controller is to get an optimal performance for our closed loop DTC control model. This controller has an input which is the mathematical difference (error) between the reference speed ω_{re} and the actual measured induction motor speed ω_{m}. The figure below shows the position of our PID controller in our closed loop speed control model using DTC.

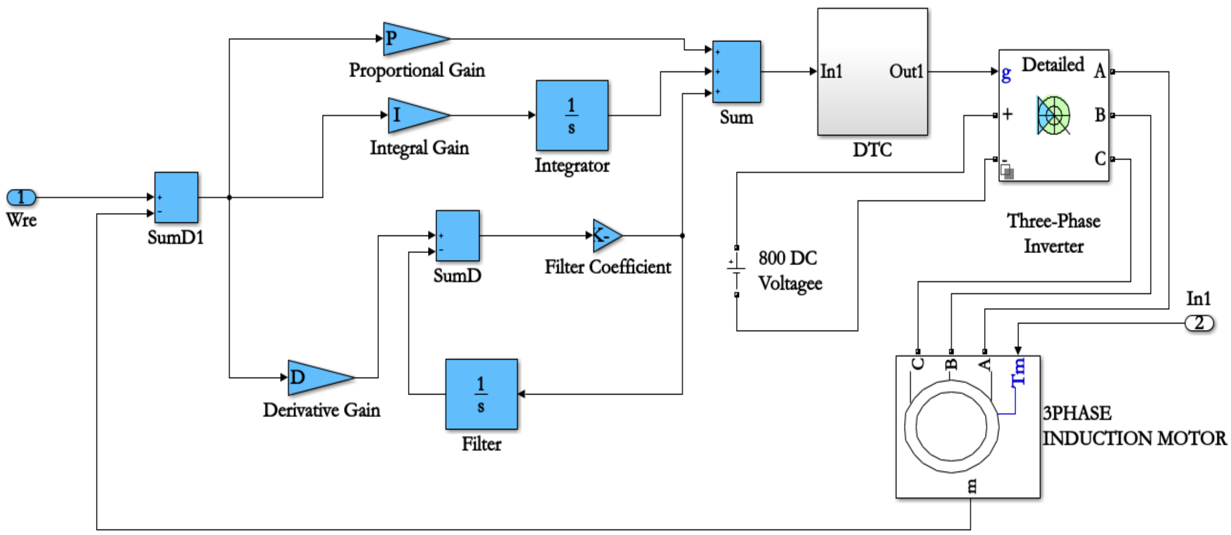


FIGURE 27 - PID CONNECTED TO DTC

The output of the PID controller is applied to the entry of the direct torque controller. The P, I and D gains of PID are turned using mat lab.

14. THE OVERALL ELECTRIC DRIVE SYSTEM

The overall electric drive model of our system consists the electric drive and an automatic transmission system. Two three-phase induction motors, each operating at 700 V/ 200 Kilo Watts are used to drive the rear wheels of the vehicle. Each of the induction motors is driven and controlled by a motor controller comprising of a three-phase voltage source inverter. The three-phase voltage source inverter is controlled via a direct torque controller which process an electric signal from an electronic differential unit.

The inverters convert DC voltage from the battery unit to an AC voltage type. Additionally, the inverter is fed with a signal from an electronic differential via DTC. Different sensors and transducers are used to measure physical changes in different parts of our system. These includes brake pedal position sensor, steering wheel angle sensor, accelerator pedal angle sensor, vehicle height sensor, cooling temperature sensor etc.

The steering wheel angle sensor is used to measure the angle of the steering wheel, while the accelerator pedal sensor is used to calculate the steering wheel turning angle and determine the driver's intention. The steering wheel sensor's output is used as an input variable of the vehicles electronic differential controller alongside with acceleration pedal position sensor's output signal. The accelerator pedal position sensor is used to determine the longitudinal force acting on the acceleration pedal and determine the driver's intension during cornering. The accelerator pedal position's output signal is used as an input signal of the vehicle's electronic differential controller.

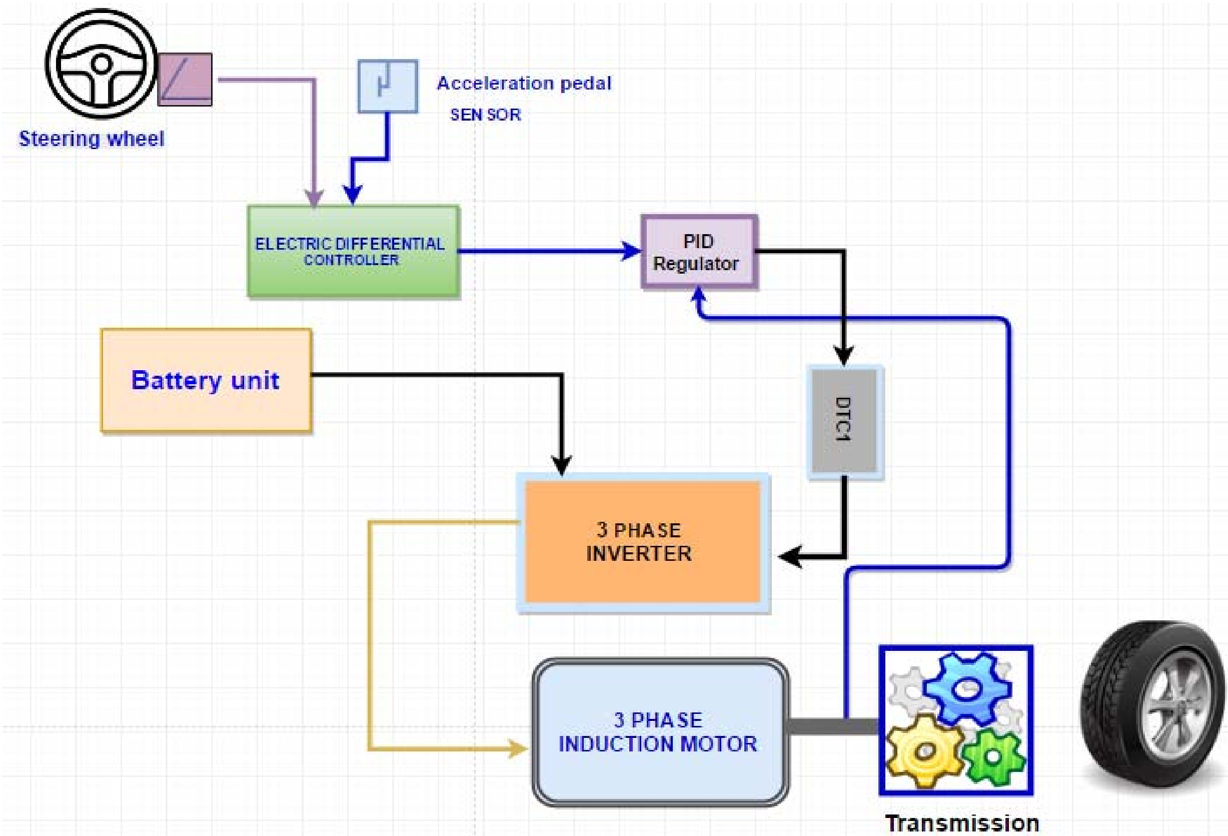


FIGURE 28 - ONE SIDE ELECTRIC DRIVE

Our proposed electric drive system functions as follows: Each rear wheel is driven by a three-phase induction motor via a transmission. The speed and torque of the induction motors, is controlled by electric drive system. The speed of the rear wheels is controlled and compensated using speed and steering wheel difference signals through a feedback loop.

Power conversion is done by a three-phase's voltage inverter, which is directly connected to the battery unit. These inverters are integrated with differential gear functionality. The inverters are also used to control and traction of the vehicle.

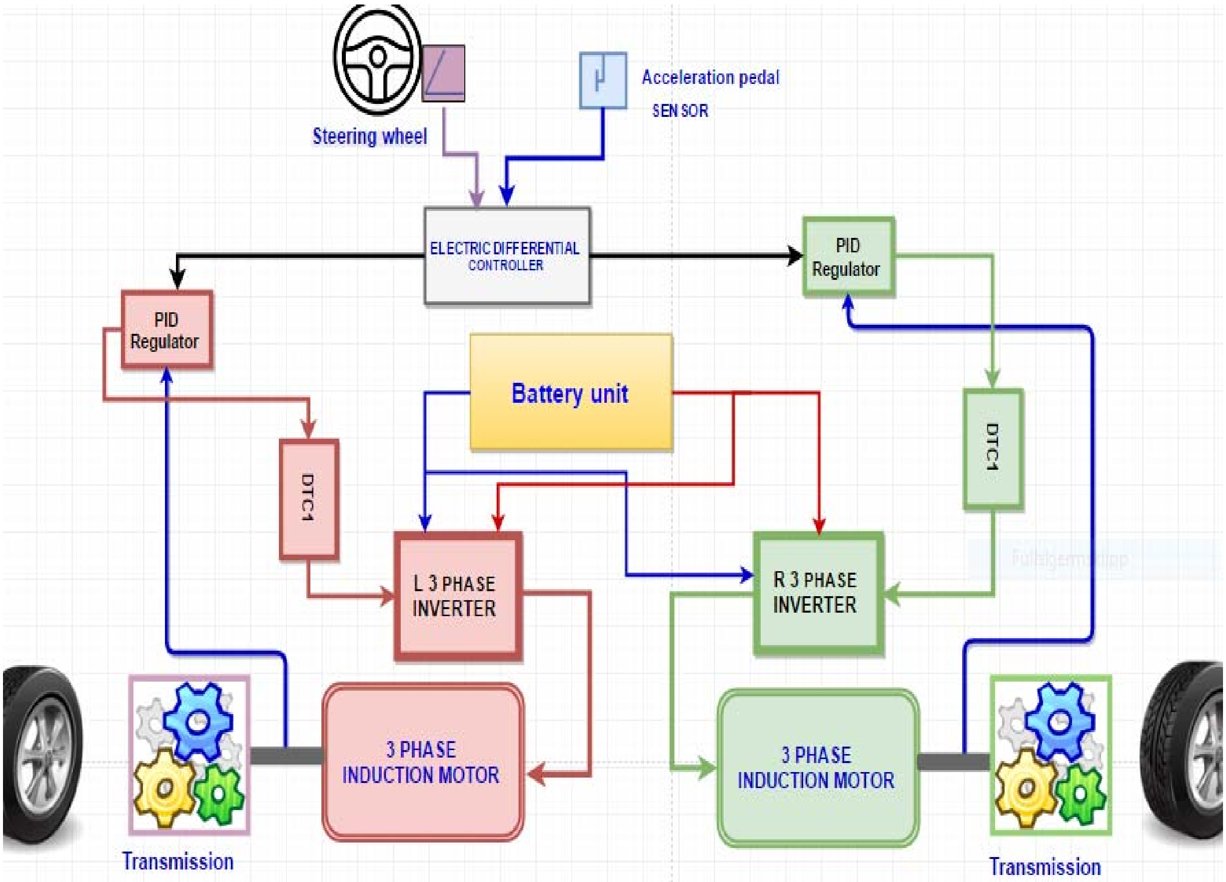


FIGURE 29 - ELECTRIC DRIVE SYSTEM BOTH SIDES

Since our heavy-duty vehicle will be driven by electric motors, which operate independently. The speed of the outer wheels will need to be higher than the speed of the inside wheels, to increase stability and reduce the turn radius of the vehicle. This condition will be met, using electronic differential controller and a network of speed and flux estimators, integrated in DTC controller.

The accelerator pedal position sensor sets the reference speed of the closed loop controlling system. On the other side the steering turning angle is set as the reference position signal of the system. The electronic differential system process and conditions the signals difference together with the steering wheel's output signal. The reference signal is compared to the actual induction motor's speed and the obtained error is fed to the PID controller, which sets the speed of the system.

For the stability and maneuverability of our vehicle, the two rear driven wheels should spin at different rotary speeds during cornering and under uneven road conditions. In classical vehicles, the differential is achieved mechanically through a conventional mechanical differential.

Our project involves driving a heavy-duty vehicle using two three-phase induction motors that are controlled independently. We will therefore need to have an electronic differential unit to avoid losing control of the vehicle during cornering.

For us to model it, this requires an electric differential in Simulink. We use Ackermann's steering differential model and create mathematical models to help for this purpose [26].

Based on the Ackermann steering differential model [27], we make a mathematical model needed for us to create a Simulink model of the required electronic differential (fig. 30).

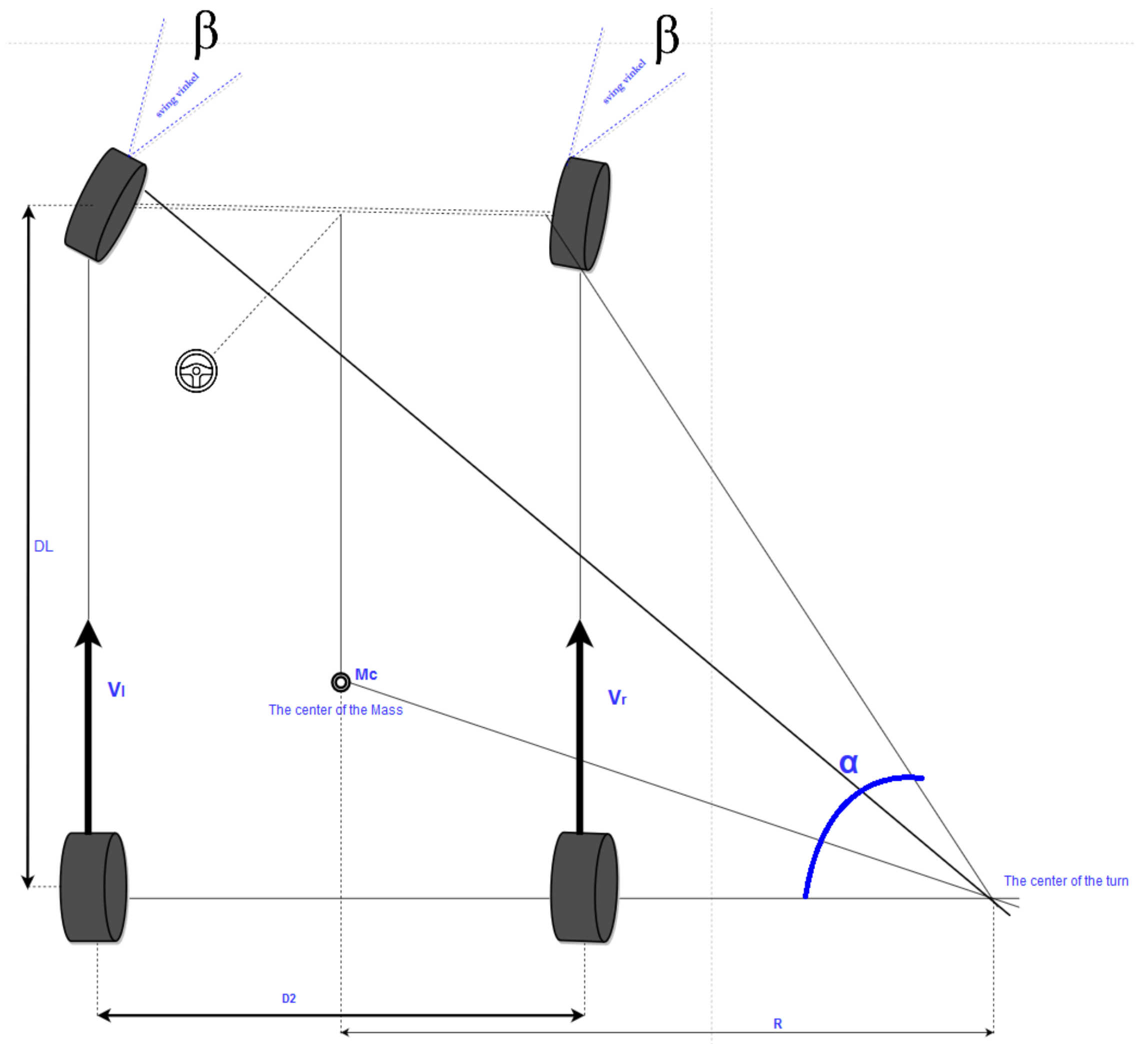


FIGURE 30 - STEERING MODEL BASED ON ACKERMAN PRINCIPLE

The actual reference speed for the right electric drive unit V_{right} and the left drive unit V_{left} are obtained by regulating the common reference speed $\boldsymbol{\omega}_v$ using the output signal from the direct torque controller [1]. If the vehicle is making a turn to right, the left wheel speed will be multiplied by a constant and increased while the right wheel speed is remaining equal to the reference speed $\boldsymbol{\omega}_{re}$. We calculate to determine ß, which is the steering angle of our heavy-duty vehicle [2]. The following calculations help us to determine ß.

Based on the model shown in figure 30 we do calculations to determine the steering mathematical model of our vehicle. The mathematical model of our vehicle steering system is shown below.

$$Lw\ R = ß$$

$$Vr = \alpha\ (R + \frac{D2}{2})$$

$$Vr = \alpha\ (R - \frac{D2}{2})$$

$$R = \frac{DL}{\tan ß}$$

$$\Delta\omega = \frac{D2 * \tan}{DL} * \alpha$$

The induction motor speed reference is obtained using the following mathematical models.

$$\omega_{rim}\ G_{retio} * w_{Lr}$$

$$\omega_{Lim}\ G_{retio} * w_{Rr}$$

The functioning principle of our vehicle's steering system can be summarized as follow. Speed sensors are used to sense the angular speed of the steering wheel. The common reference speed of our vehicle ω_C is determined by the accelerator pedal position controller. The speed of the right electric drive unit V_{right} and the speed of the left electric drive unit V_{left} are determined by the output signal from DTC Speed controller.

When ß is greater than zero it means that the vehicle is making a turn to right. When ß is less than zero it means that the vehicle is making a turn to the left. When ß is equal to zero it means that the vehicle is driving straight forward. From the mathematical model above, we modeled an electronic differential in Simulink. The created Simulink model is shown below (fig. 31)

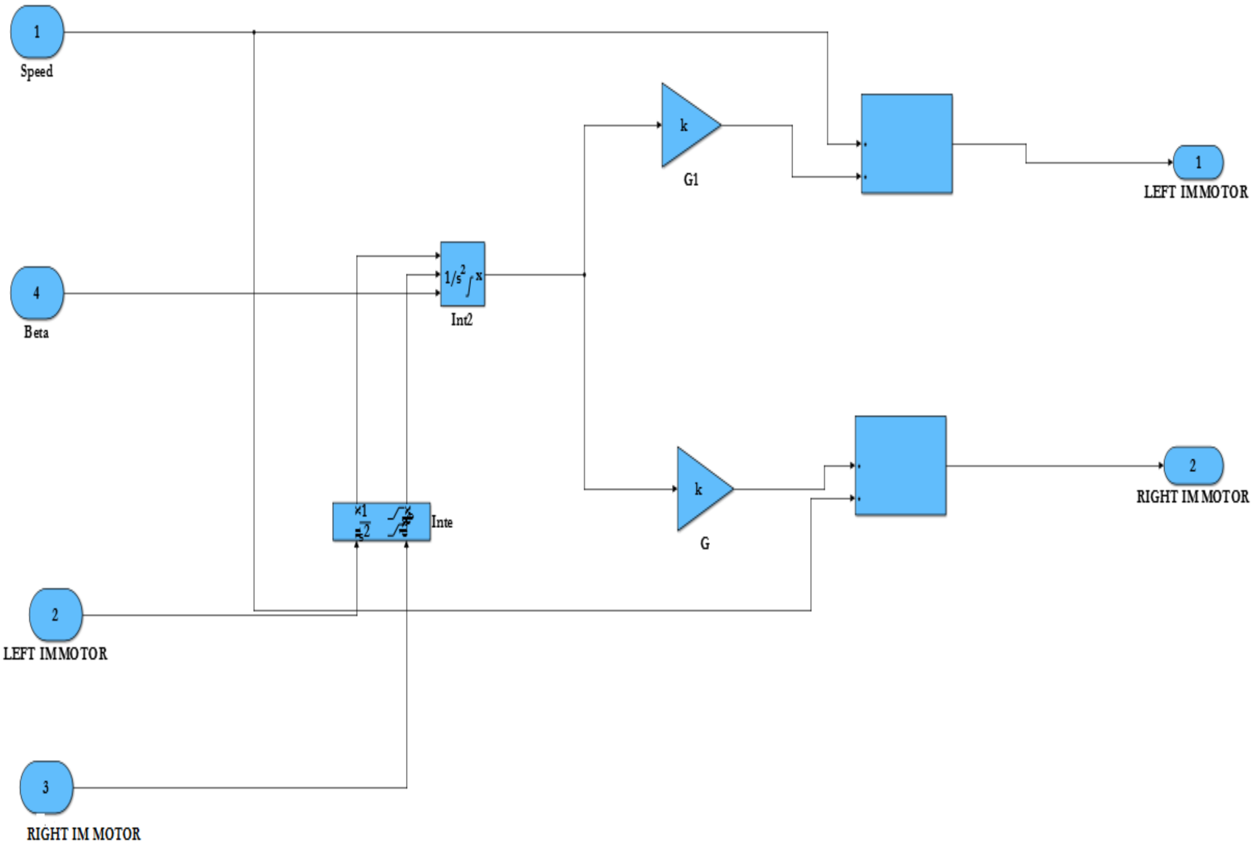


FIGURE 31 - SIMULINK MODEL OF ELECTRONIC DIFFERENTIAL

The speed controllers are used to control each motor torque. The speed of each rear wheel is controlled using feedback of difference in speed. Figure 32 below shows how our electronic differential is connected to the closed loop model.

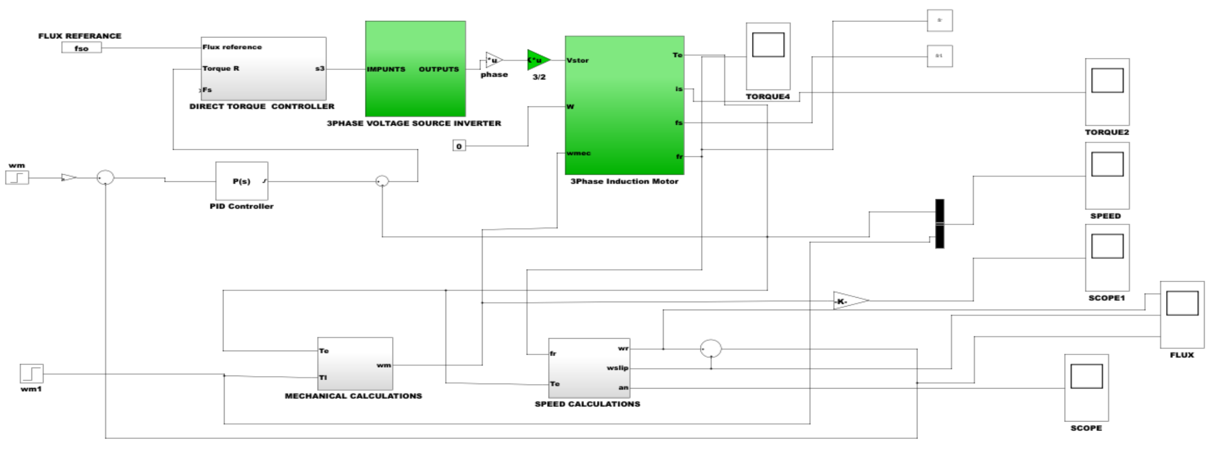


FIGURE 32 - CLOSED LOOP CONTROLLER WITH ELECTRONIC DIFFERENTIAL

Since the two rear wheels are directly driven by two separate three-phase induction motors, the speed of the outer wheel need to be higher than the speed of the inner wheel during steering maneuvers (and vice-versa).

15. INDUCTION MOTOR MATHEMATICAL MODEL

Before we can model and simulate an induction motor in Simulink, we must first determine the mathematical model of the induction motor [28]. The mathematical models for the induction motor's torque and flux must be determined in order for us to be able to model a Simulink model for an induction motor.

These mathematical models are equations based on Clarke transformation, which involves converts all the measured three-phase parameters of the induction motor to a two phase parameters based d and q planes [29]. The induction mathematical models needed to create an induction motor model are shown below.

$$\Psi ds \frac{d}{dt} = \mathbf{R_s i_{ds}} + Ws\Psi qs + Vas$$

$$\Psi qr \frac{d}{dt} = - \mathbf{R_s i_{qs}} - Ws\Psi qs + Vqs$$

$$\Psi dr \frac{d}{dt} = - \mathbf{R_r i_{dr}} (W_s - W_r)\Psi d$$

$$\Psi dr \frac{d}{dt} = - \mathbf{R_r i_{dr}} + \mathbf{-(Ws} - Wr)\Psi dr$$

The Equations above are to be used to model our induction motor in Simulink. The main objective of the mathematical model is to estimate the flux and torque based on the observed currents and the control voltage inputs. We can further expand the above equations to yield the following equations.

$\Psi ds = L_{is}\, i_{ds} + L_m\, (i_{ds} + i_{dr}) = L_{is}\, i_{ds} + L_m\, i_{dr}$

$\Psi dr = L_{ir}\, i_{dr} + L_m\, (i_{ds} + i_{dr}) = L_{ir}\, i_{dr} + L_m\, i_{dr}$

$\Psi dm = L_m\, (i_{dr+}\, i_{ds})$

$\Psi qs = L_{is}\, i_{qr} + L_m\, (i_{qs} + i_{qr}) = L_{is}\, i_{qs} + L_m\, i_{qr}$

$\Psi qr = L_{ir}\, i_{qr} + L_m\, (i_{qs} + i_{qr}) = L_{ir}\, i_{qr} + L_m\, i_{qr}$

$\Psi qm = Lm\, (i_{qs\,+}\, i_{qr})$

$T_e = \frac{d}{dt}\frac{3}{2} \quad (\Psi_{ds}\, i_{qs\,-}\, \Psi_{qs}\, i_{ds})$ [29]

From the mathematical models above we can determine the stator flux linkage by using the formula:

$\int_s^{\infty} \Psi(s) = Vs - i_s Rs$ [29]

The stator resistance R_s is neglected whenever the stator voltage V_s is dropping.

We can then calculate the stator flux linkage vector by modifying the equation above to: $\int_s^{\infty} \Psi(s) = Vs$ [29]

The equation can be further modified to:

$\Delta\Psi s \;= Vs\Delta t$

Where Δt stands for the sampling period. The voltage space vector Vs can occupy any of the 8 switching vectors of the inverter. From the equations above it can be noted that the stator flux linkage will have the increased speed whenever an active switching vector is applied to the three-phase voltage inverter.

If one of the two inactive vectors of the inverter switching vectors are applied to the v-voltage source inverter, then the stator flux linkage space vector will stop functioning.

In three-phase induction motors, electromagnetic torque is proportional to the product of rotor flux linkage space vector and the stator flux linkage space vector. To control the speed of a three-phase induction motor a simulation is done by modeling a three-phase induction motor model in Simulink.

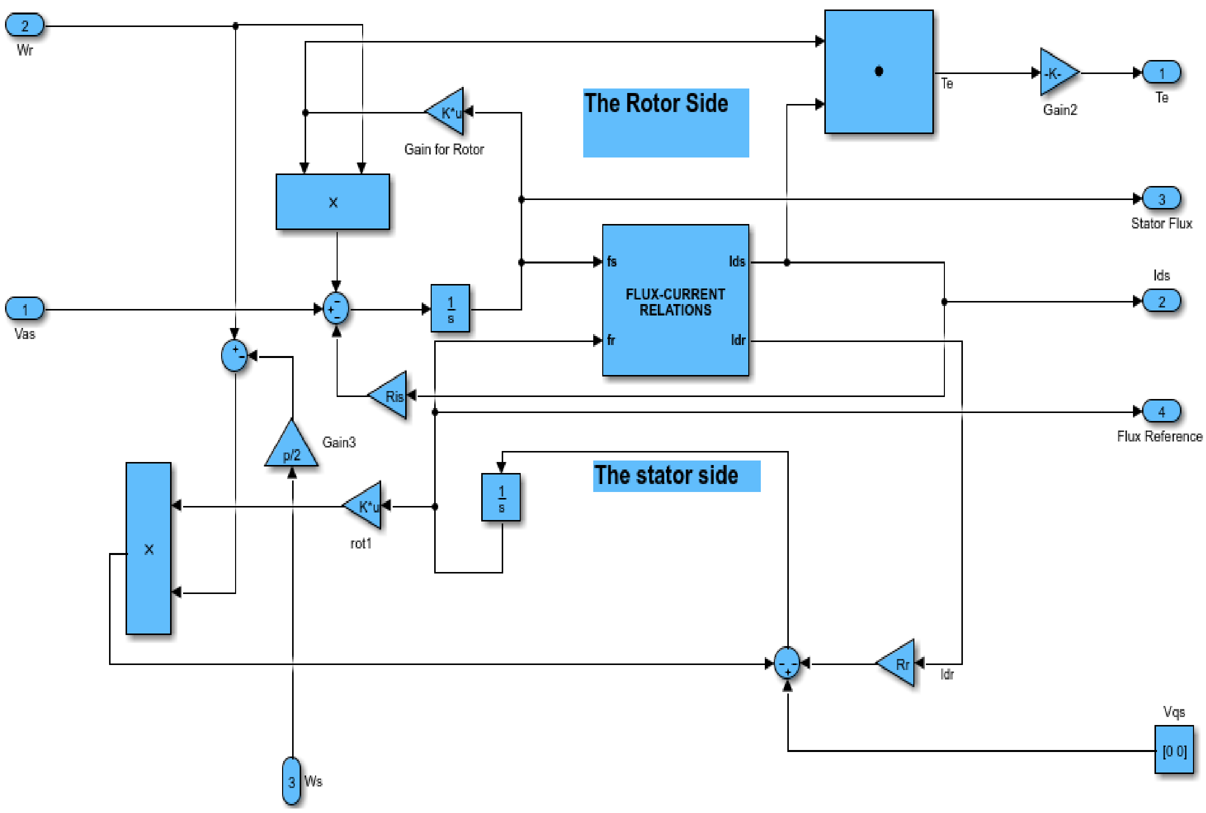


FIGURE 33 - SIMULINK MODEL OF THREE-PHASE INDUCTION MOTOR

From figure 33 we can notice that stator voltages are used as the control input and the rotor voltages are connected to zero voltage source. The stator currents are output signals of the model, which means that we can calculate the output signals using space state method as shown below.

$$\Psi qs = L_{is}\, i_{qr} + L_m\, (i_{qs} + i_{qr}) = L_{is}\, i_{qs} + L_m\, i_{qr}$$

$$\Psi qr = L_{ir}\, i_{qr} + L_m\, (i_{qs} + i_{qr}) = L_{ir}\, i_{qr} + L_m\, i_{qr}$$

15.1. Stator Flux Control

Torque control is done by changing the amount of slip angle $\Delta\theta$s, which we can control directly by using controlling the stator flux. We control the motor's flux directly by decoupling the amplitude and angles of flux vectors. In our closed loop control the reference torque is driven through the PI controller, which controls the speed.

The change in torque ΔTe, which is the torque error is compensated by increasing the magnitude of the stator flux angles from θs to θs + $\Delta\theta$s. Where the $\Delta\theta$s is the desired changes in stator flux angles. The change in stator flux angle can be then calculated the required stator flux vectors as:

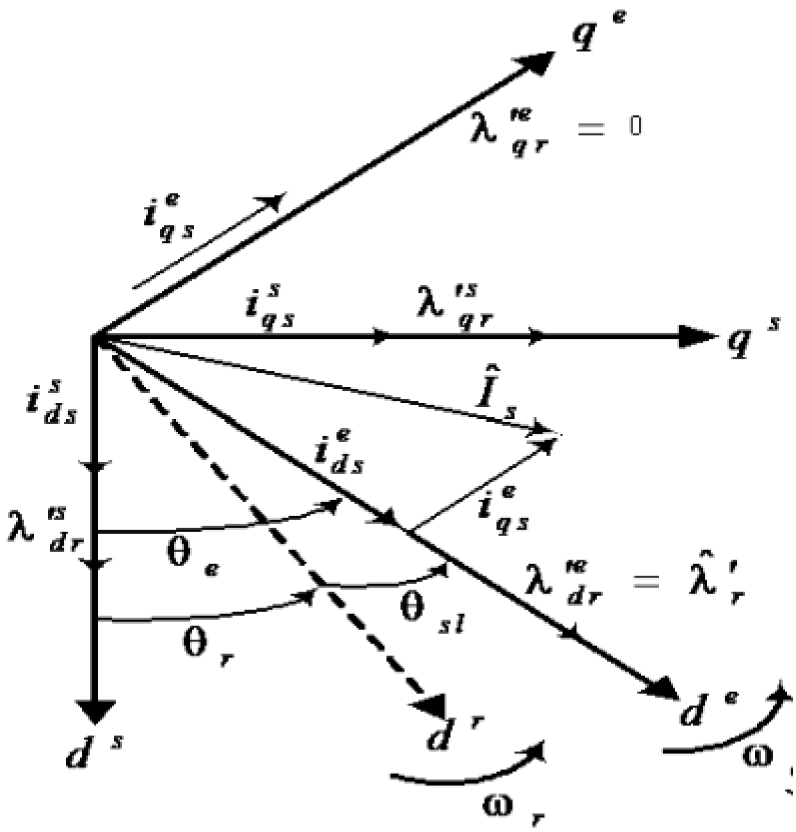


FIGURE 34 - CONTROL OF STATOR FLUX LINKAGE IN IN D-Q PLANE [30]

The estimated flux magnitude vector are calculated using:

$\Psi d \int (Vs - idRd)dt$ [29] [31]

$\Psi q \int (Vs - iqRq)dt$ [29] [31]

To find the actual flux magnitudes we can use the following equations.

$$\psi_{sd} = \int (v_{sd} - i_{sd}R_s)\,dt$$ [31]

$$\psi_{sq} = \int (v_{sq} - i_{sq}R_s)\,dt$$ [31]

The reference flux vector is given by:

$$\psi_{sd}^* = \psi_s^* \cos(\theta_s^*)$$

$$\psi_{sq}^* = \psi_s^* \sin(\theta_s^*)$$

The flux error is given by:

$$\Delta\psi_{sd} = \psi_{sd}^* - \psi_{sd}$$ [31]

$$\Delta\psi_{sq} = \psi_{sq}^* - \psi_{sq}$$

The reference space voltage vector is given by:

$$v_{sd}^* = \Delta\psi_{sd}/\Delta t + i_{sd}R_s$$ [31]

$$v_{sq}^* = \Delta\psi_{sq}/\Delta t + i_{sq}R_s$$

Where Δt is the sampling time. Reference flux components are calculated with the equations above where $\Delta\psi_s$ stands for the flux error between reference flux and estimated actual flux. In order to compensate for the flux error, the voltage components have to be calculated from the model of voltage space vector.

Using this reference voltage components, time signal is calculated [8]. Time signals generate the pulses for control the voltage source inverter (VSI). Within this sample, the inverter is switched and made to remain at different switching states for different durations of time such that the average space vector generated within the sampling period is equal to the sampled value of the reference value.

16. VOLTAGE INVERTER MATHEMATICAL MODEL

We use the technique of space vector modulation for us to determine the required stator flux for our three-phase voltage inverter. The space vector modulation method helps us to describe the mathematical model of our three-phase voltage inverter, which is used to convert the direct current DC from the battery unit to a three-phase alternating current AC. We use this method in order for the induction motor to be provided by the necessary voltage from the voltage source inverter [32].

Our inverter convert the DC to AC with a help of switching elements such as transistors. Usually each switching element of a voltage source inverter is supplied by a voltage at a given sampling time and the voltage angle is at 180 degrees. To avoid having unstable air gap flux of our three-phase voltage.

For us to be able to get the desired flux, we must control the inverter in a way that helps us to achieve good dynamic behavior of our system. We use a space vector modulation technique to achieve this. The technique is applied in order to improve the sampling time and the system response. Our inverter is modeled using IGBT.

Neglecting the stator resistance which is usually very small, we can obtain some equation describing the flux states of the inverter.

The flux equation of each of the inverters three phases can be described by the formula. Each of the three phases is represented by a coil in star or y connection method. We can therefore represent the flux of each of the three coils using the following formula.

$$\Psi ds \frac{d}{dt} = R_S \, i_{ds} + Wds\Psi qs = Vas$$

Neglecting the rotor's resistance, we can integrate the equation above and get

$$\frac{d\Psi s}{dt} = V_s$$

Neglecting the rotor resistance, we can integrate the equation above to become

$$\frac{d\Psi s}{dt} = V_s \frac{d}{dt}$$

$$V_s = \frac{3}{2} Vds \, (S_a \, \Psi e^{\frac{-2i\omega t}{3}} + S_b \, \Psi e^{\frac{-4i\omega t}{3}} + S_C \, \Psi e^{\frac{-8i\omega t}{3}}$$

The mathematical models above are used to develop a Simulink model for our voltage source three phases inverter. The Simulink model of the three-phase is shown by the figure below.

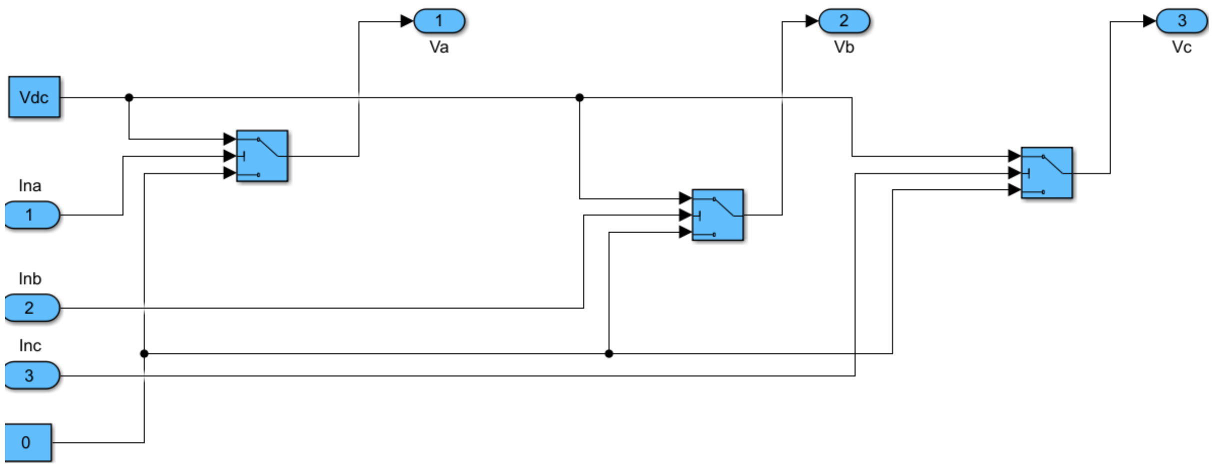


FIGURE 35 - A SIMPLE SIMULINK MODEL A THREE-PHASE INVERTER

For a six-leg voltage source inverter like the one used in our project, the stator flux linkage vectors flow a six-cornered path at a constant speed. To obtain the required flux linkage's root locus we must apply a switching parameter combination of active and inactive switching vectors.

Table 4 below shows the possible switching vector depending on the location of the flux vector. In every sampling period, the stator flux and torque flux errors are kept within the limits of the used two level hysteresis.

Since the stator voltage is proportional to the stator flux. With the help of the calculations above we can develop a table containing the possible switching states of our voltage source inverter. Our three-phase voltage inverter will produce 23 voltage vectors, but two of the vectors will be zero voltage vectors since they lie at the origin. This means that the inverter will produce six active voltage vectors and two inactive voltage vectors. The truth table below shows how our three-phase inverter converts the DC supply voltage three phase AC via an optimal switching table [33].

Vectors	-A	-B	-C	+A	+B	+C	V_{AB}	V_{BC}	V_{CA}	
V_0 (000)	OFF	OFF	OFF	ON	ON	ON	0	0	0	Inactive vector
V_1 (100)	ON	OFF	OFF	OFF	ON	ON	$+V_{dc}$	0	$-V_{dc}$	Active vector
V_2 (110)	ON	ON	OFF	OFF	OFF	ON	0	$+V_{dc}$	$-V_{dc}$	Active vector
V_3 (010)	OFF	ON	OFF	ON	OFF	ON	$-V_{dc}$	$+V_{dc}$	0	Active vector
V_4 (011)	OFF	ON	ON	ON	OFF	OFF	$-V_{dc}$	0	$+V_{dc}$	Active vector
V_5 (001)	OFF	OFF	ON	ON	ON	OFF	0	$-V_{dc}$	$+V_{dc}$	Active vector
V_6 (101)	ON	OFF	ON	OFF	ON	OFF	$+V_{dc}$	$-V_{dc}$	0	Active vector
V_7 (111)	ON	ON	ON	OFF	OFF	OFF	0	0	0	Inactive vector

TABLE 4 - TRUTH TABLE OF POSSIBLE SWITCHING VOLTAGES OF INVERTER

We achieve an optimal switching state vector for inverter by increasing or decreasing the magnitude of space vector angles depending on the position of the stator flux magnitude. The stator flux magnitude M^{th} can lay in different positions within the limit of hysteresis band.

If we need to increase the magnitude in order for us to compensate, we can use the switching vectors V_M, VM+1, V_M+2 to V_M+_N depending on the sampling time, where M is a number between 0 and 7, which stands for the range of the switching vector 2^3, where 3 stands for the number of phases the used inverter has.

Since our inverter is a three-phase inverter, we have 2^3 possible switching vectors, but two of the switching vector lie at the zero axis and they are inactive switching vectors. This means that M is a number between 1 and 6. These six active vectors of our system will affect the toque of our system as well.

16.1. Direct Torque Simulink Model

Figure 36 shows the block diagram of direct torque control we created in Simulink. The block diagram shows that the direct torque control method is performed by estimating both the torque and the flux of stator and rotor respectively [1].

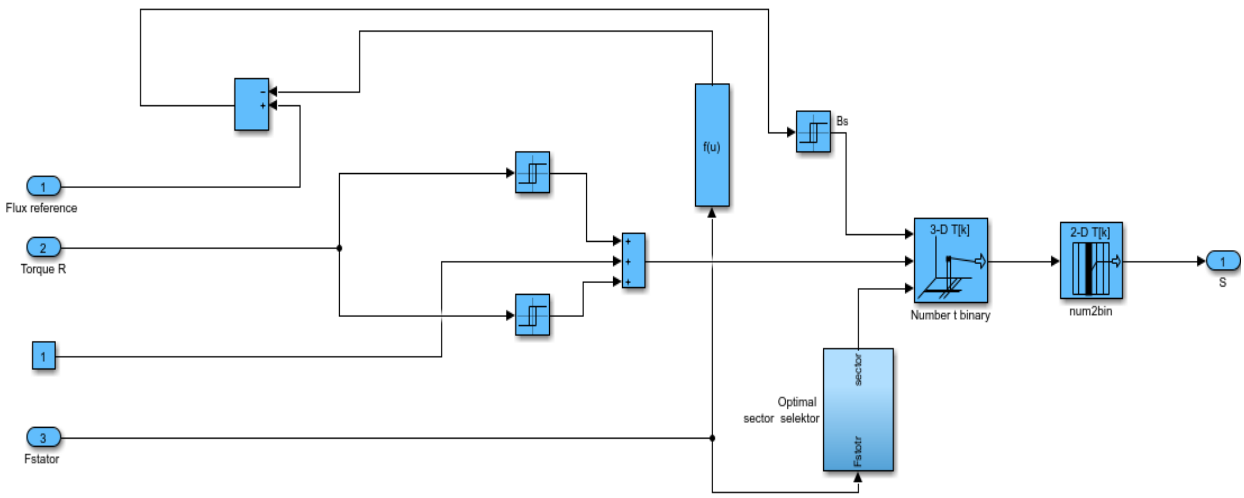


FIGURE 36 - SIMULINK MODEL OF DTC

The reason we need to control these two parameters is that they have to remain within the hysteresis bands. We can manage to hold the torque and stator flux within the desired hysteresis bands by choosing an appropriate sector in space vector modulation. The torque produced by the induction motor can be calculated using the equation below:

$$\mathbf{T_e} = \frac{d}{dt}\frac{3}{2}\,(\Psi_{ds}\, i_{qs})$$

From the equation, we can notice that the torque depends on the stator flux Ψ, the rotor flux and the angle between the vectors of stator and rotor flux. We intend to control these two parameters independently. Using the d-q axis format we can express the voltage across the induction motor stator using the same equation:

$$\mathbf{T_e} = \frac{d}{dt}\frac{3}{2}\,(\Psi_{ds}\, i_{qs}) \qquad [2]$$

The parameters represent the change in the stator flux in d and q axis respectively. We can further expand the equation to obtain the flowing formula. We are able to estimate the stator flux as long as the stator current is observable [3].

We need to determine the d-q stator currents before we can calculate the stator flux vector and electromagnetic torque of our induction motor. Figure 37 below shows a torque flux estimator Simulink model created to estimate the torque and flux of our system.

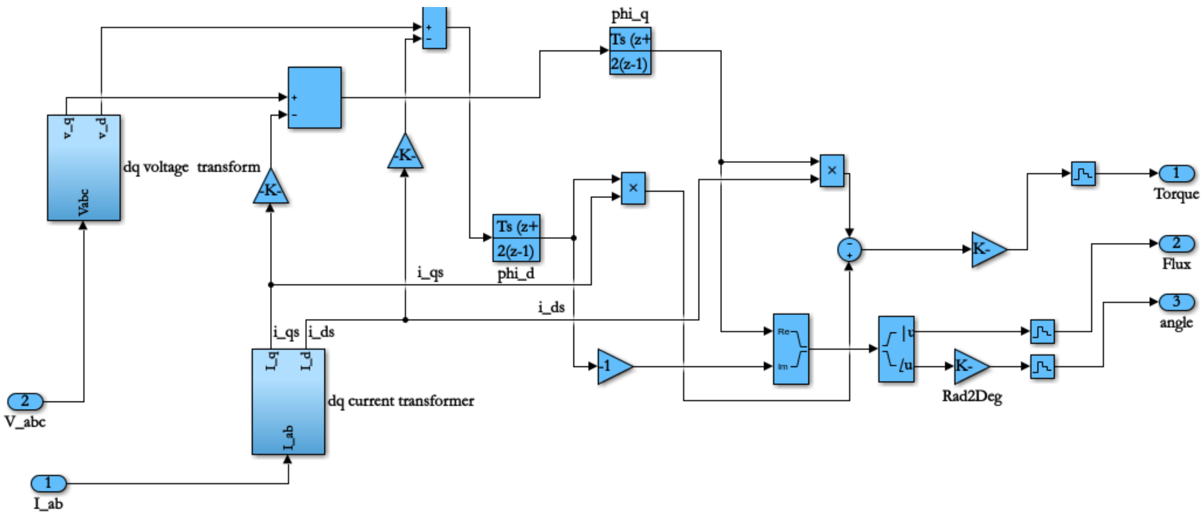


FIGURE 37 - SIMULINK MODEL OF TORQUE AND FLUX ESTIMATOR

The estimated flux and torque will be controlled separately. They is stator variation due to stator voltage variation. The controllability of the stator flux depends on the selection of an optimal voltage vector.

The stator flux state is divided into six voltage sectors having six different sets of voltage. The estimated flux is increased or decreased to much the required reference stator flux. A two level hysteresis comparator is used to compare the estimated and reference flux. The signal from the hysteresis is has to be controlled somehow to avoid the saturation of the flux and torque.

We therefore decide to include a component that can control the flux to avoid saturation. Figure 38 shows the flux controller Simulink model used to control the flux of our induction motor.

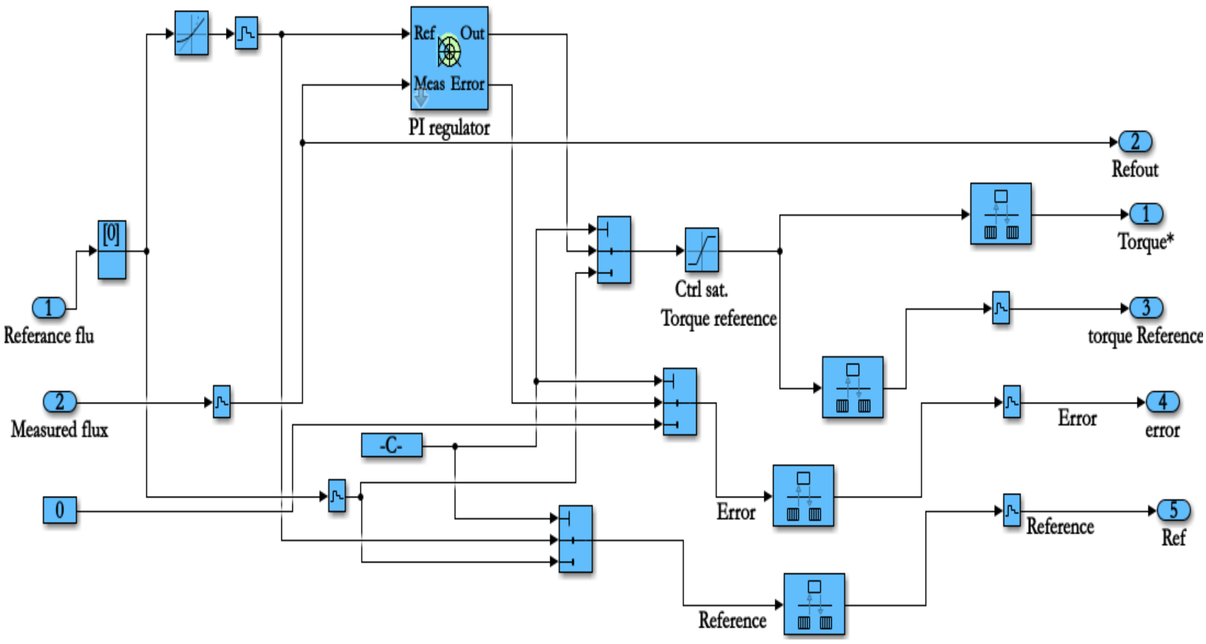


FIGURE 38 - FLUX SIMULINK MODEL OF AND TORQUE CONTROLLER

The flux error which results from the mathematical difference between the estimated and desired flux is fed to the two level hysteresis comparator which determine their error status.

Changing the stator flux very quickly, will result in great variation in the torque output. We therefore have to select an optimal inverter voltage vector to avoid this happening.

An optimal inverter voltage vector will help us produce much faster speed, which will help us improve the dynamic response of the system. For us to be able to get the desired flux, we have to control the inverter in a way that helps us to achieve good dynamic behavior of our system. Space vector modulation techniques can be used to avoid this.

The space vector technique is applied the three-phase voltage inverter to improve the sampling time and the system response. Our inverter is modeled using IGBT (Insulated bipolar gate transistor).

Our three-phase voltage inverter will produce 2^3 voltage vector, but two of the vector will be zero voltage vectors. This means that the inverter will produce six active voltage vector and to inactive voltage vectors. The diagram below shows the position of the switching vectors in d-q plane.

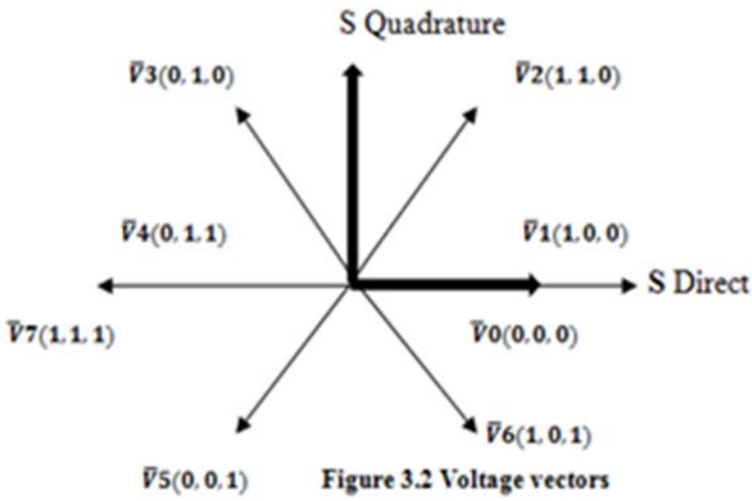


FIGURE 39 - POSSIBLE VOLTAGE VECTORS OF INVERTER IN S PLANE

16.2. Stator Flux Control Direction Control

Before we can select an appropriate voltage vector for our three-phase voltage source inverter, we have to first determine the direction and the position of the stator flux. To determine the direction or the position of the stator flux we divide the flux's root locus into six sector representing the six possible active voltages of the inverters switching transistors [34].

The root locus is divided in six sectors because the inverter being used in our project is a six step inverter. To control the toque of our induction motor directly, we have to make the motor's flux follow a circular path by limiting the flux magnitude from exiting the two level hysteresis bands [35].

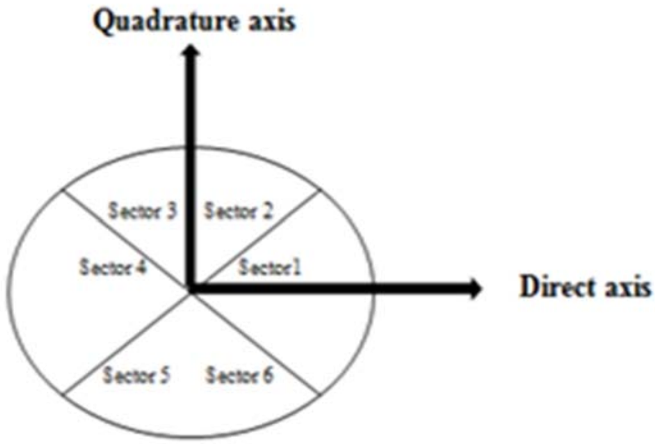


FIGURE 40 – SIX ACTIVE SWITCHING VECTORS

We can achieve this by increasing the flux magnitude to compensate, when the stator's flux touches the lower band limit of the hysteresis. And decrease the stator's flux magnitude when it reaches the upper limit of the hysteresis band. Using two level hysteresis comparators we can be able to determine when we need to increase or decrease the magnitude of the stator flux [35].

17. DTC CLOSED LOOP SIMULINK MODEL

The figure below represents the bloc of our closed loop direct torque induction motor speed control system modeled in Simulink for simulations. This closed loop electric drive system model, features controlling the speed of a three-phase induction motor using flux, torque and hysteresis-band controllers. The system outputs the torque, the angular motor speed, the motor flux and the motor power.

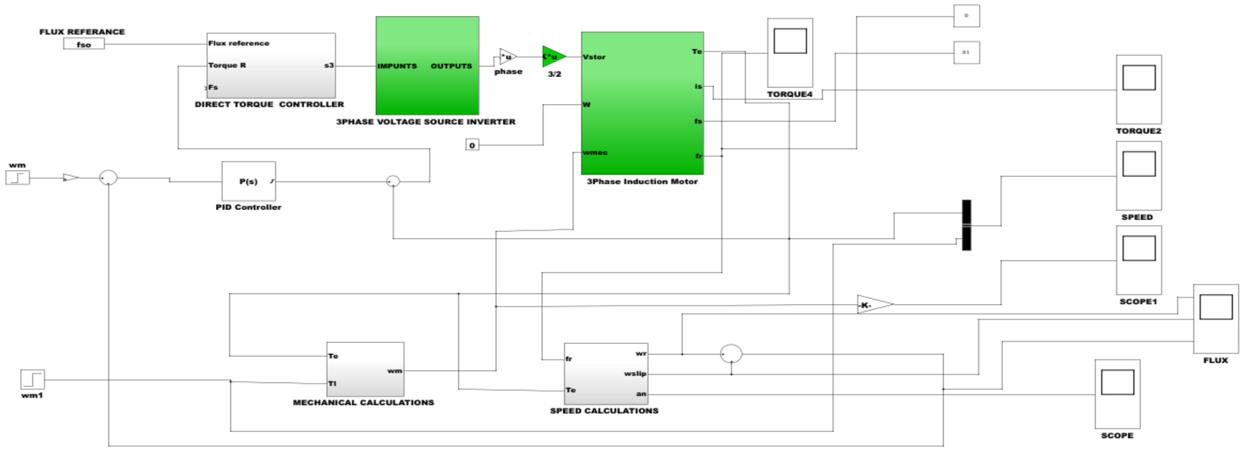


FIGURE 41 - THE OVERALL CLOSED LOOP MODEL OF OUR ELECTRIC DRIVE

The speed control subsystem outputs the reference torque and the stator flux of our induction motor. The torque and flux references are compared to the estimated values, respectively. The resulting errors are processed by the hysteresis-band controllers. This closed loop speed controlling model consists of different subsystems assembled together function as an integrated closed loop.

The closed loop system outputs the reference torque and the stator flux of our induction motor. The torque and flux references are compared to the estimated values, respectively. The resulting errors are processed by the hysteresis-band controllers.

Additionally, this technique can also help us reduce the torque variation of the stator torque and stator flux through the inverter's switching table. We use Matlab to calculate the parameters of the induction motor (Fig. 42).

17.1. Simulation Results

After modeling of our closed loop system, we simulate the system to study and analyze how our DTC closed loop system will affect the induction motors used to drive the heavy-duty vehicle. We choose a three-phase induction motor that is suitable for our system before we can start simulating the closed loop controlling system. The motor chosen to be used in this project is an induction motor [36] with an integrated electric drive consisting of an inverter and other necessary power electronic components. Additionally, the induction motor is a liquid cooled induction motor, which means that it satisfies the requirement that requires as to use liquid for motor and the battery unit cooling system [36].

The figure below show some of the function specifications given on the datasheet of the chosen induction motor.

Motor Type	Induction Motor
Torque (Motor Shaft) Torque (Gear Box Shaft)	815 Nm 2215 Nm
Power	200kW peak, 85kW continuous
Speed (Motor Shaft) Speed (Gear Box Out)	7200 RPM (FWD or REV) 2645 RPM (FWD or REV)
Weight	176 kg
Input Voltage (See CEU160)	MV: 250-450 V_{DC} HV: 450-700 V_{DC}
Cooling	-40 °C to 65°C (50/50 WEG, 1" fitting)
Shaft Flange	DANA 4-1-3101 or Rockford 02067368
Efficiency	93%
Isolation resistance	**> 1** MΩ at 700V_{DC}
Parking Brake	ZEMARC (Optional)
Environment	IP65 rated (IP-67 optional)
Mounting	Integrated Flange

FIGURE 42 - FUNCTION SPEC. OF THE CHOSEN MOTOR [36]

The main reason we choose this motor is the fact that the motor has high torque, high power and high efficiency. From the information given about the function specifications of the induction motor, we can conclude that this motor has power enough to drive our vehicle in different road conditions. To analyze and study how suitable the chosen motor is for our project, we simulate torque speed characteristics of the motor using Matlab. The figure below shows the torque speed characteristics of the chosen induction motor. The simulation results are shown on the figure below.

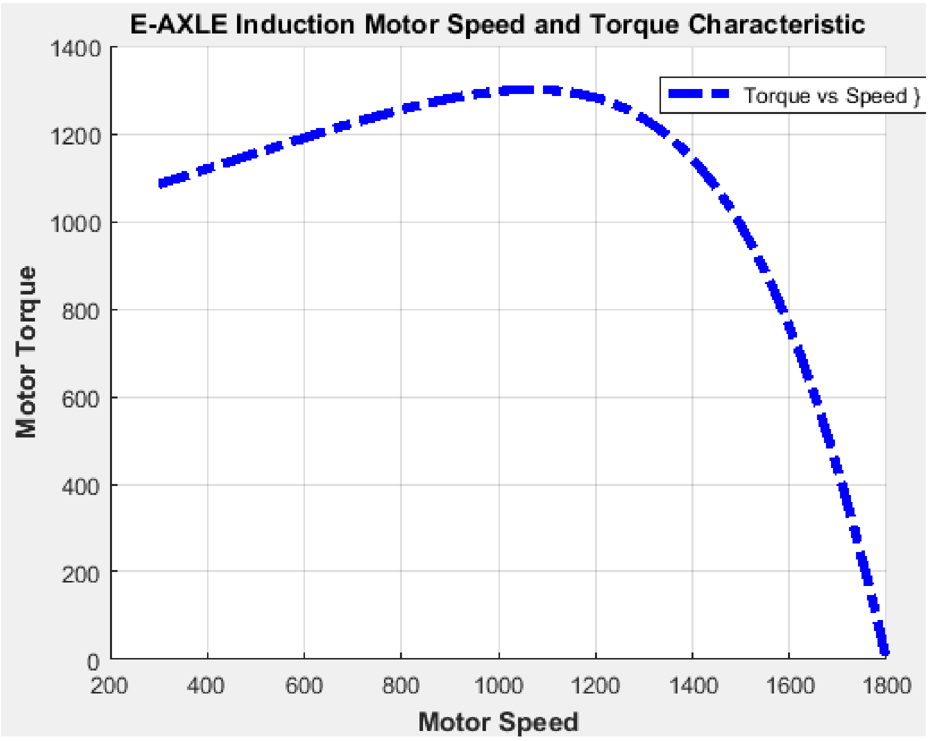


FIGURE 43 - SIMULATION OF SPEED AGAINST TORQUE

The torque speed characteristics of our induction motor simulation results verifies that the chosen induction motor is suitable for our project. From the simulation result we can conclude that the chosen motor will be able to provide the vehicle with both the required torque and power in different road situations. The Matlab code used to plot motor's torque speed curve check attachment (Att: H).

With such torque and power the motor is able to provide the required torque to the transmission and drive the vehicle in different road conditions with heavy loads

After we analyze the torque speed characteristics of the chosen motor, we start simulating the closed loop induction motor speed control Simulink model of our system.

Some of the needed parameters are corrected from the datasheet of the chosen motor, while other are extracted using Matlab. The table below shows the parameters we used to simulate our closed loop speed controlling system using DTC.

PARAMETERS	VALUES
Rated motor power	200 K watts
Rated motor voltage	700 Volts
Number of Poles	4 poles
Stator resistance	4 .19Ω
Rotor resistance	4 .16Ω
Rated motor frequency	60Hz
Torque	2215 Nm
Rotor inductance	6.8 mH
Stator inductance	6.7 mH
Mutual Inductance	7.45 mH
Rated motor speed	1800 RPM
Motors load torque	Variable
Moment of Inertia	0.015Kg*m^2

PARAMETERS	VALUES
Friction Factor (F)	0.08 N
Rated motor speed	1800 RPM

TABLE 5 - PARAMETERS USED TO SIMULATE CLOSED LOOP CONTROL WITH DTC.

After determining the simulation parameters we do our first simulation. Where the output of the model simulation parameters are: induction motors stator speed, induction motor's rotor speed and induction motor's slip. We simulate our closed loop induction motor speed control with DTC, by varying some of the parameters to analyze the behavior of our system in different conditions.

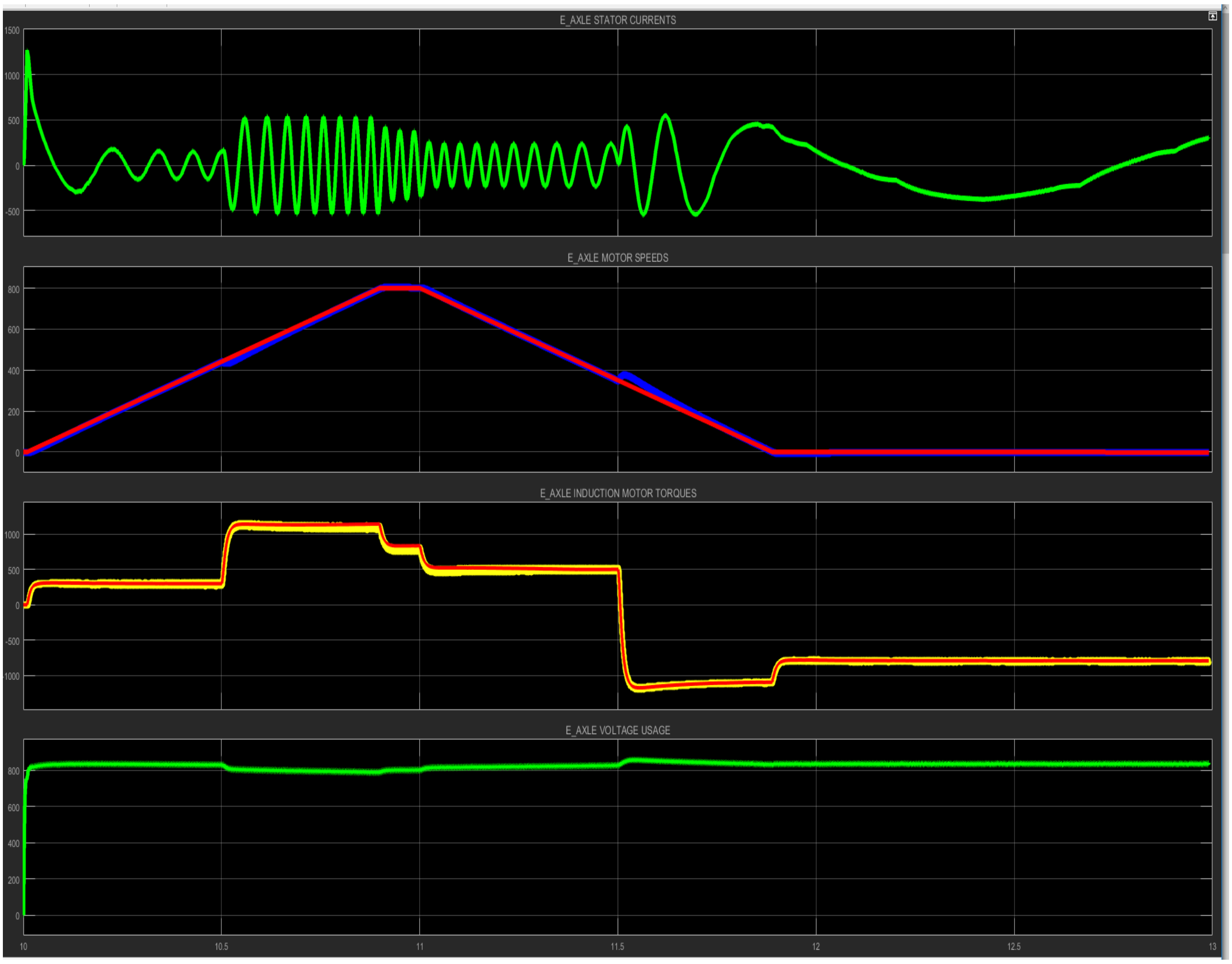


FIGURE 44 - SIMULATION OF STATOR SPEED, MOTOR'S SLIP AND ROTOR SPEED

The simulation results shown in figure 44 are the result we get when we variate the the load torque of our system. This simulations are done to study the relationsheep between the input voltage, load torque, desired torque, desired speed and the referanse speed. The results show that increasing load torque leads to an increase in voltege consumption. Additionally the simulation show that the motor

From the simulation results we can notice that the motor produces no torque until we apply a step input signal to act as desired torque. After we apply the step input, the motor torque increases to match the load conditions. We are using the step input as referance torque input of our closed loop control system.

Mechanical load is applied in order to test the transient performance of the developed DTC model. The flux is kept at required value as well as the torque.

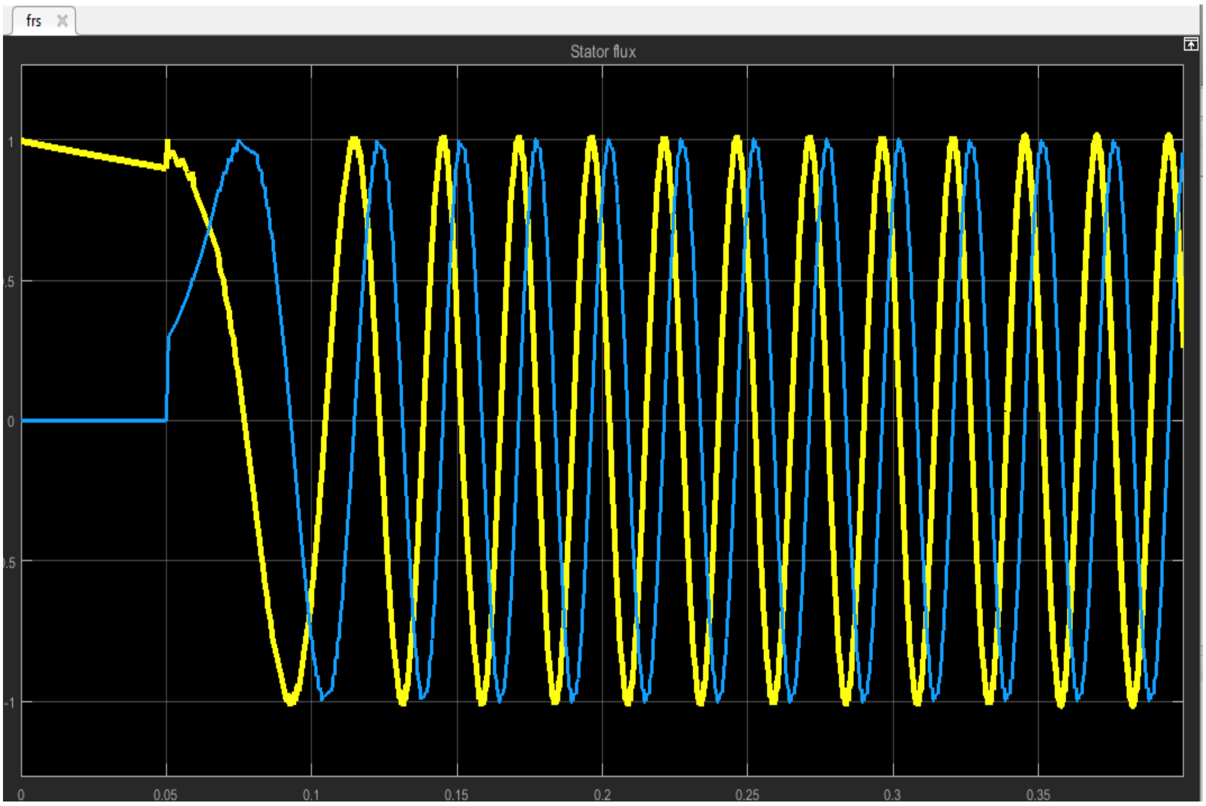


FIGURE 45 - SIMULATION OF STATOR FLUX

This simulation result shows the stator flux of motor against time. Comparing the stator flux results with the torque results, we can observe any small variation of stator flux affects the torque in the induction motor. Any small variation in stator flux is enough to cause a significant change in the motor torque. Using hysteresis limits and determining the optimal switching values of our voltage source inverter, we can limit unnecessary variation of the stator current. Conclusively the figure shows that the flux control of an induction motor using DTC is effective and has better performance. The simulation results shows that the DTC method reduces oscillation to a reasonable value.

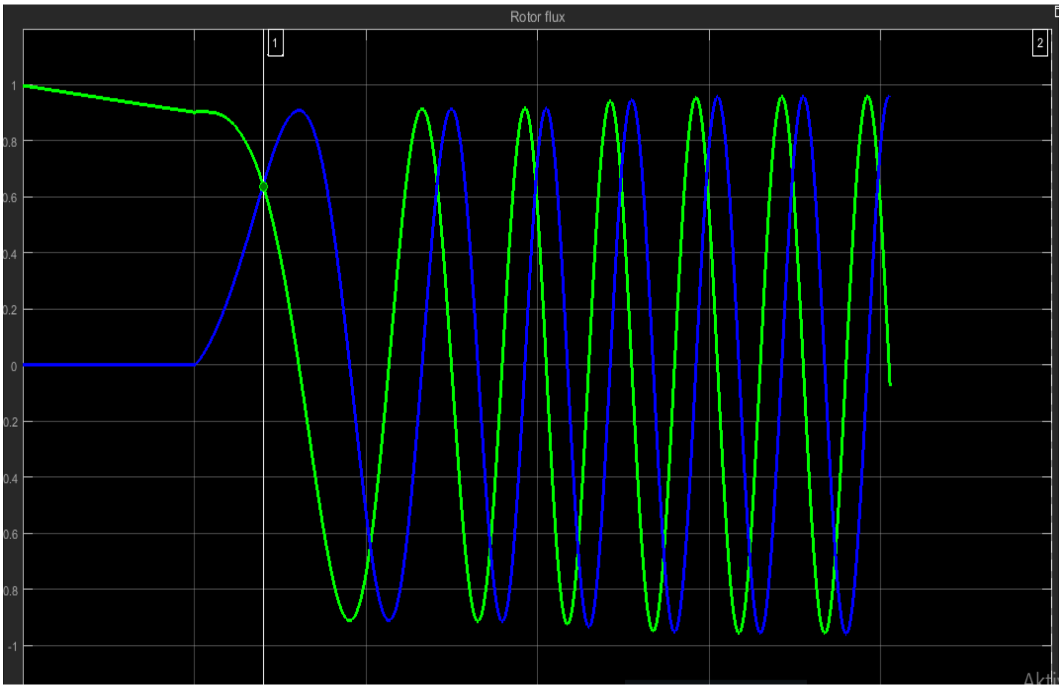


FIGURE 46 - SIMULATION OF STATOR FLUX

Figure 46 is a simulation of the stator flux to analyze the functionality of our induction motor's stator side. The simulation result shows that our system being controlled by DTC, has constant and rotor flux, which means that the DTC model we created is increasing the stability of the induction motor.

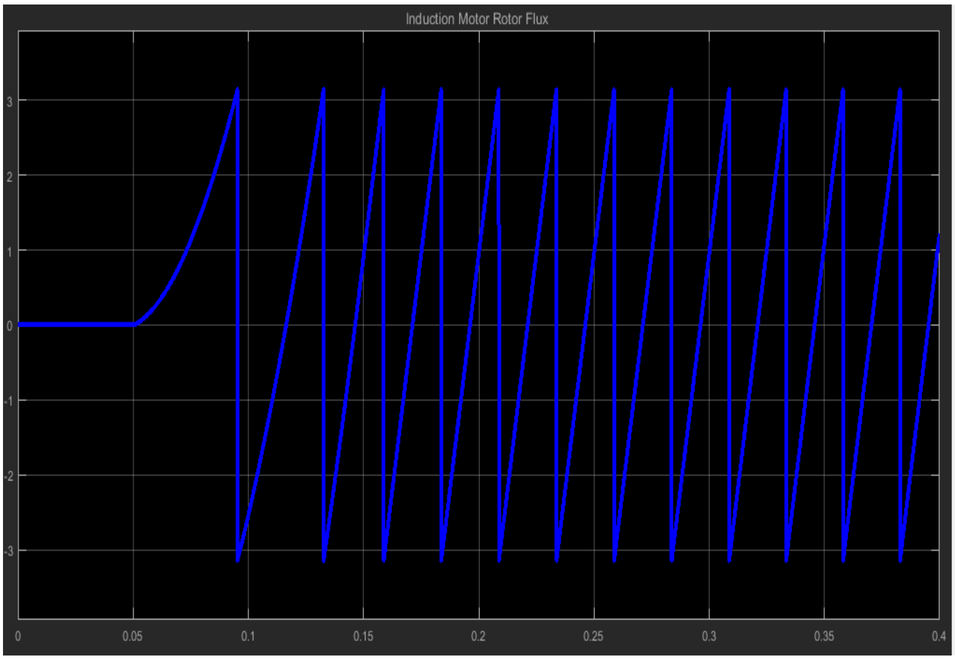


FIGURE 47 - SIMULATION OF ROTOR FLUX ANGLES.

Figure 47 simulates the rotor flux angle so we can analyze the stability of our induction motor. The simulation results show that our system being controlled by DTC is pretty stable with no fluctuations in rotor flux angle graph.

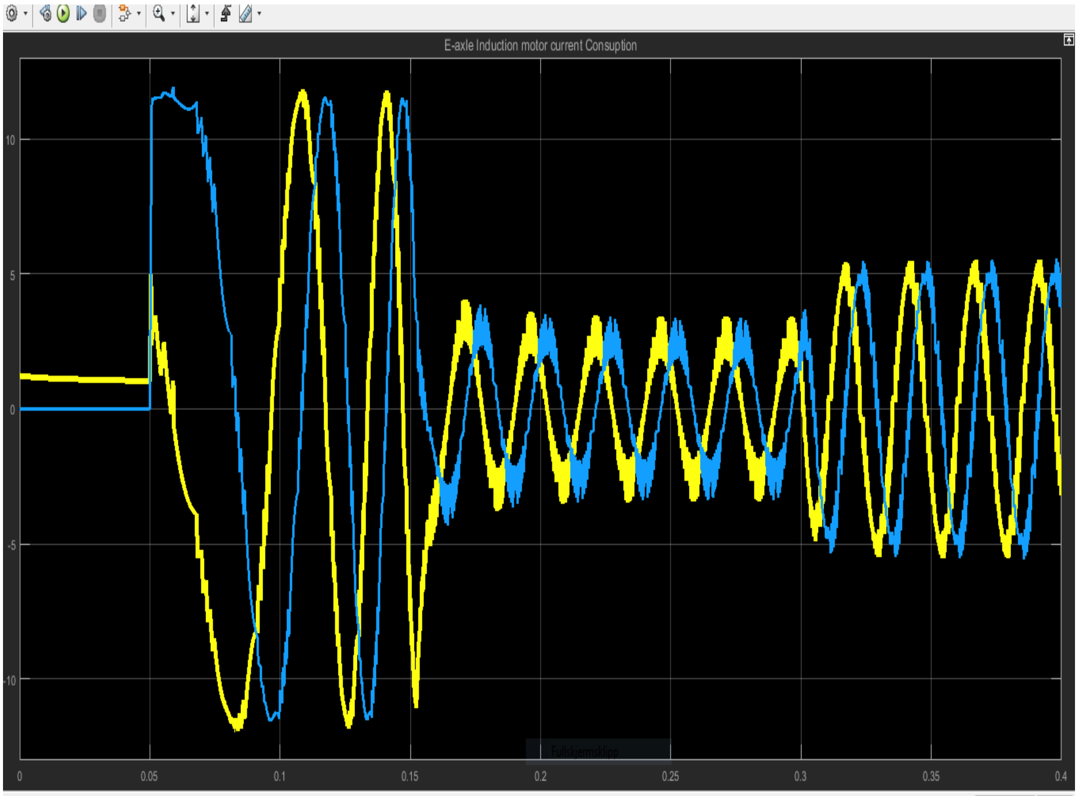


FIGURE 48 - SIMULATION OF MOTOR CURRENTS.

Figure 48 shows a simulation of the induction's motor's internal currents. The simulation shows that by varying the load of our induction motor, the current consumption is also variant. From the figure we can notice that when we increase the motor load, motor current consumption increases proportionally with increase of the motor load. The simulation results show that when we decrease the motor load from 0.15 seconds to 0.30 seconds, the current consumption also decreases. According to result it shows that operating voltage is near to 750 Volts. The simulation results show that the current consumption of the motor is fairly constant and low. When the load is low, the current consumption increases with increasing load.

FIGURE 49 – SPEED TIME SIMULATION OF USED MOTOR

This simulation shows how the speed of our induction motor is affected by variation of the the load. This simualation is done by varying the torque load and the results show that the speed of the motor is directly affected by the load variation.

From this simulation result of our induction motor it is observed that the speed of our motor changes with the varying load. The peak torque occurs at the starting of the motor. This is because our transmission needs more torque at the starting point, while the torque need decreases over time. The fi presents the desired speed and the speed developed by the EV, as well as the speed error. The results show that the desired speed stable. The stability is increased by the use of a PID regulator, the PID controller corrects the speed errors developed and increase the stability of the vehicle. We can increase the stability and minimize the speed errors even more by using an adaptive PID controller instead of conversional PID controller, which we used in this project.

The simulation results of our system shows that the closed loop control of an induction motor using direct torque and PID controllers achieves the satisifying resultst The simulation result show that the reponse of the system is improved by using PID regulators. We could have increased the stablity, controlablity and the respons of the system even more by using Fuzzy adaptive PID regulators insead convetional PID regulators.

We can however conclude that the chosen contro technic is suitable for our system and satisfies or requirements.

18. INTERFACES

The interfaces between the electric parts and the mechanical parts, are mainly based on sensory system. Our system uses different type sensors that rapidly sense and transduce change in the environment and send this information to the electric control module. The control module, which is a microcontroller, performs signal conditioning to the signal and activates different actuators to compensate for the signal difference. The signal conditioning is done by the microcontroller.

The signal conditioning which is performed by the micro controller includes linearization, signal amplification, signal filtering, signal digitalization and signal analyzation. After signal conditioning, the controller module activates the appropriate actuator to compensate the difference between the sensed valuables and the actual variables.

19. AIR SUSPENSION

The air suspension of our system is controlled by the control module through an actuator that controls an electric air compressor. A height sensor measures the distance between the suspension and the vehicle wheel surface. The height sensor sends the transduced signal to the electric control module for signal conditioning, linearization and digitalization.

Electric control module activates an actuator in suspension system, which in turn commands an air compressor to increases or reduces the amount of air in the system depending on the road conditions the vehicle is driving on.

The electronic control module helps to compensate for the chassis height automatically depending on road condition the vehicle is driving through. The diagram below shows a block diagram of how we think to use a closed loop control with a PID controller to regulate the height of the vehicle.

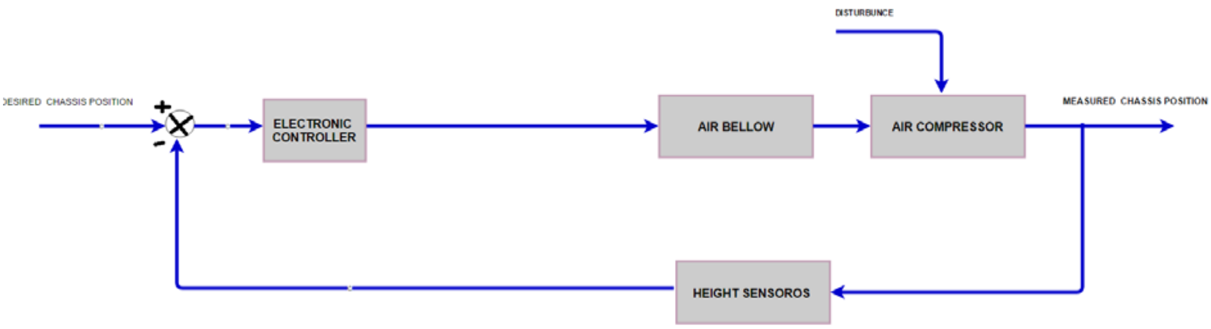


FIGURE 50 - CLOSED LOOP BLOCK OF AIR SUSPENSION CONTROL

When the vehicle reaches uneven road, the system mentioned above reacts and adjust the suspension system to adapt to the road condition. The air suspension in our heavy-duty truck performs lifting and dropping of the chassis to comply with the vehicle driving road conditions and helps stabilize the vehicles.

One of our requirements from KA was to develop an electronically controlled air suspension for the heavy-duty truck. The electronically controlled air suspension would help to increase the stability of the heavy-duty vehicle and the comfortability of the driver.

20. COOLING SYSTEM

Coolant temperature sensors (CTS) are used to transduce the temperature of the coolant liquid, which is water in our case. The coolant sensors work by sensing the temperature changes of the coolant liquid and an open close valve called thermostat. The sensed temperature difference is then sent to an electric control module. The electric control module linearizes, conditions and digitalizes the signal to remove errors and unwanted noise. The figures below shows the block of the closed loop control of the motor and battery unit cooling systems.

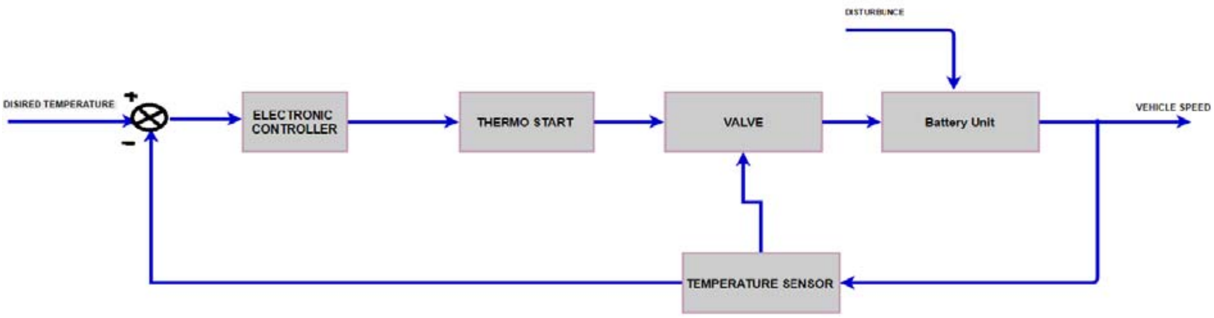


FIGURE 51 - BLOCK OF CLOSED LOOP CONTROL OF MOTOR COOLING SYSTEM

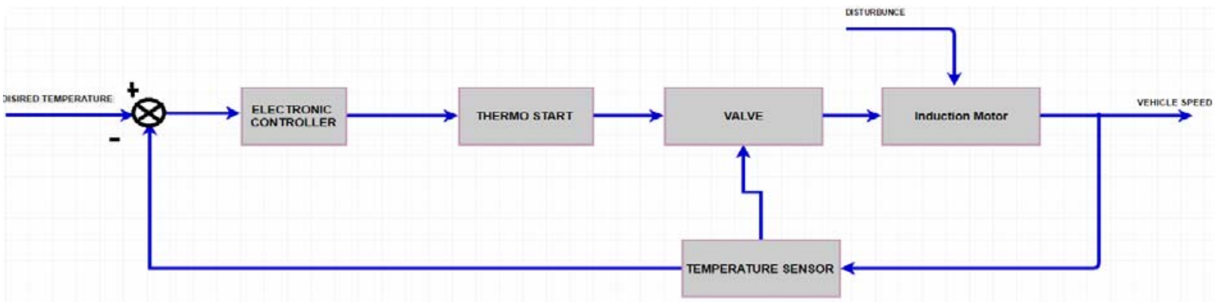


FIGURE 52 - BLOCK DIAGRAM OF CLOSED LOOP CONTROL OF BATTERY UNIT

The electric control module compares the sensed temperature information to the actual temperature to calculate the error. The electric control unit will then activate an actuator to compensate for the temperature difference. In our system, the electric control module triggers a cooling fan to go on when the coolant's temperature rises and deactivate the cooling fan when the coolant reaches the desired temperature value. A thermostat is triggered by the electric control module to close or open whenever the coolant goes below or above the rated temperature. The above mentioned is a methods which we proposed to use in this project. The closed loop method would help us to monitor and regulate the cooling process of the battery unit and motor. We however did not implement this method in our project because of the luck of needed resources.

21. TRANSMISSION

Our product will use an automatic transmission system with controlling closed loop of interface between hydraulic system, electronic system and pressure system. The closed loop system comprises of pressure regulators, pilot valves, pressure sensors and the clutch pressure control module. Our transmission closed loop system includes solenoid valves that provide hydraulic controlling signals to the hydraulic pressure controller which in turn activates the clutch actuators. The figure below shows the block diagram of the proposed closed loop control model of automatic transmission.

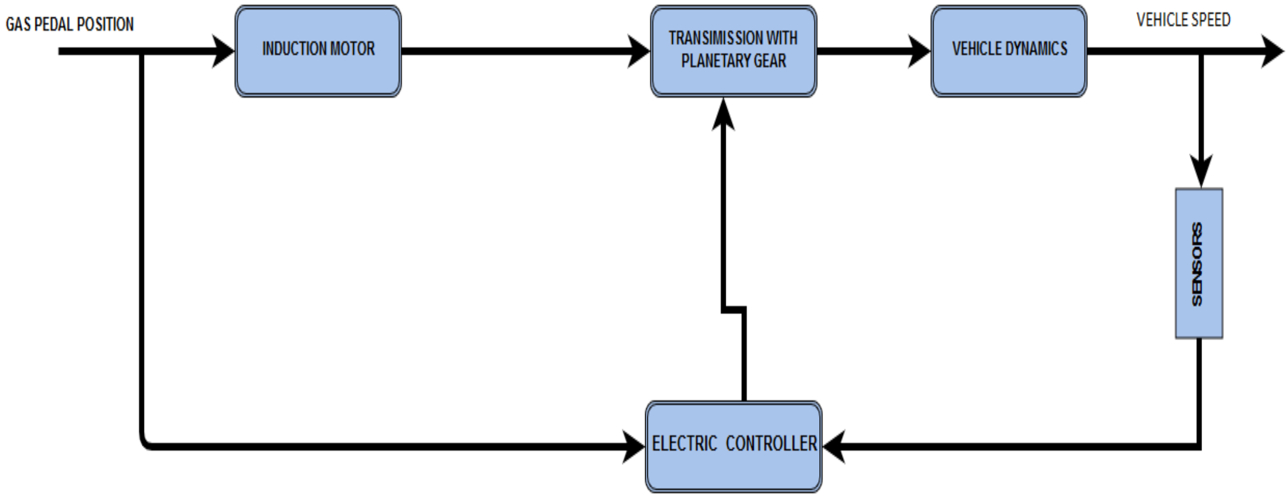


FIGURE 53 - PROPOSED CLOSED LOOP CONTROL MODEL OF AUTOMATIC TRANSMISSION

The transmission system is operated and controlled by pressure sensors and pressure valves. The pressure sensors are configured to transduce the amount of pressure in signal generated by the solenoid valve, which is an electromechanically operated valve. The pressure sensor then generates and send signal to the hydraulic- electric-pressure control module.

The hydraulic- electric-pressure control module activates the pressure regulating valves to compensate for the pressure in the clutch system. This electronic controlled automatic transmission requires to be controlled electronically via a closed loop with PID controller.

We modeled some Simulink models to simulate the automatic transition closed loop, but the model failed to simulate as planned.

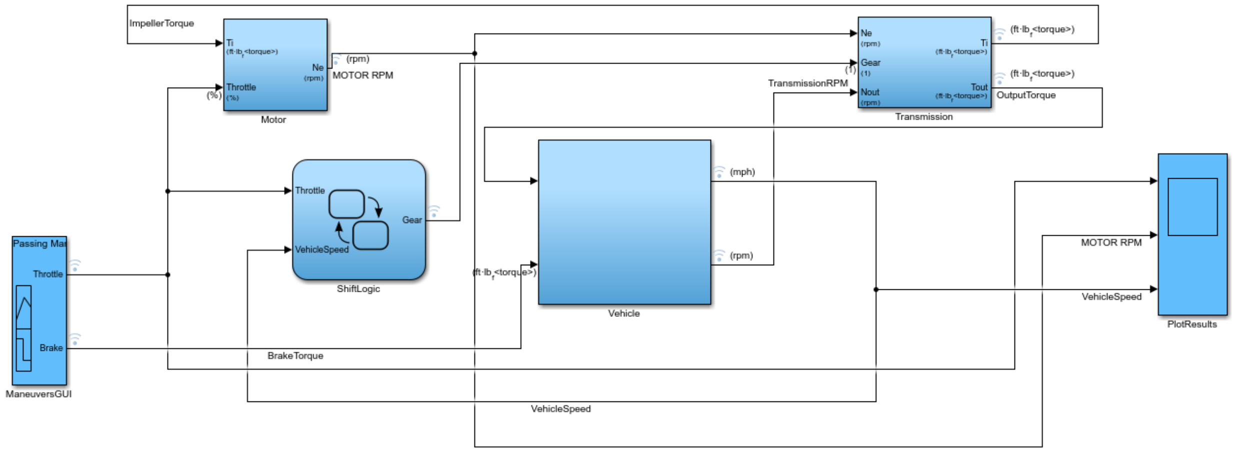


FIGURE 54 - CLOSED LOOP CONTROL OF AUTOMATIC TRANSMISSION

The model shows a suggested closed loop electronic controller for an automatic transmission with planetary gears created in Simulink/MATLAB. The main objective of this modeling is to study how our electronic automatic transmission controller selects the best gear ratio that is best for the vehicles driving situations.

The speed of our heavy-duty truck will depend on the gear ratio of the automatic transmission. This means that different gear ratio combinations will give different speed. The main purpose of our transmission is to transfer power from our induction motor to the wheels. And the main purpose of our closed loop automatic controller is to shift gear automatically depending on the driving road conditions. The main objective of this section of the

Automatic controller regulates the hydraulic system, which is the actuator that performs the gear shift. Our automatic controller Simulink model includes hydraulic system, an induction motor, PID regulator, torque converter and planetary gear.

The electronic controller performs the gear shifting by engaging and disengaging clutches through hydraulic system, which applies an amount of hydraulic pressure to the clutches depending on the driving vehicle driving conditions.

Hydraulic system is one of the important subsystem of our automatic transition using planetary gear. This sub system initiates the automatic gear shifting operation in our automatic transmission using planetary gear.

The hydraulic subsystem actuate the automatic gear shifting operation by supplying pressure on the clutch of the planetary gear where the torque from our induction motor is multiplied. The torque from our three-phase induction motor is transferred to the planetary gear.

Electronic control of hydraulic system involves regulating the pressure, controlling different valves, controlling different solenoid valve using closed loop system with controllers and regulating the clutch accumulator using closed loop systems with PID regulators. In our proposed automatic gear shift, the pressure is regulated by controlling duty cycle of the input voltage to the hydraulic system.

22. REFERENCES

[1] Tezpur University, "www.tezu.ernet.in," [Online]. Available: http://www.tezu.ernet.in/sae/Download/transmission.pdf. [Accessed 05 02 2017].

[2] C. Woodford, "http://www.explainthatstuff.com," 17 04 2017. [Online]. Available: http://www.explainthatstuff.com/gears.html. [Accessed 19 05 2017].

[3] H. Divedi, "www.hkdivedi.com," [Online]. Available: http://www.hkdivedi.com/2015/07/gear-terminology.html. [Accessed 25 02 2017].

[4] Kohara Gear Industry Co.,Ltd, "khkgears.net," Kohara Gear Industry Co.,Ltd, 2015. [Online]. Available: http://khkgears.net/gear-knowledge/abcs-gears-b/basic-gear-terminology-calculation/. [Accessed 12 04 2017].

[5] Mechanical Engineering, "mechanicalmania.blogspot.no," 2011. [Online]. Available: http://mechanicalmania.blogspot.no/2011/07/types-of-gear.html. [Accessed 19 05 2017].

[6] Transmission repair cost guide, "www.transmissionrepaircostguide.com," Transmission repair cost guide, [Online]. Available: https://www.transmissionrepaircostguide.com/types-of-transmissions/. [Accessed 12 02 2017].

[7] Slideshare, "www.slideshare.net," LinkedIn Corporation, 2017. [Online]. Available: https://www.slideshare.net/chaudhryshailja/manual-transmission-system-in-automobiles. [Accessed 12 02 2017].

[8] Fourwheeler Network, "www.fourwheeler.com," Fourwheeler Network, 2017. [Online]. Available: http://www.fourwheeler.com/how-to/0706or-automatic-transmission-tech/photo-20.html. [Accessed 12 02 2017].

[9] Gizmodo Media Group, "oppositelock.kinja.com," Gizmodo Media Group, 2017. [Online]. Available: http://oppositelock.kinja.com/why-more-cars-should-come-with-paddle-shifters-511478202. [Accessed 11 02 2017].

[10] D. Pratte, "www.superstreetonline.com," 2 04 2017. [Online]. Available: http://www.superstreetonline.com/how-to/transmission-drivetrain/1404-continuously-variable-transmissions/. [Accessed 12 04 2017].

[11] W. (. HARRIS, "auto.howstuffworks.com," Howstuffworks , [Online]. Available: http://auto.howstuffworks.com/cvt3.htm. [Accessed 3 02 2017].

[12] W. (. HARRIS, "auto.howstuffworks.com," Howstuffworks , [Online]. Available: http://auto.howstuffworks.com/cvt4.htm. [Accessed 3 02 2017].

[13] K. Nice, "howstuffworks.com," [Online]. Available: http://auto.howstuffworks.com/cooling-system.htm. [Accessed 13 03 2017].

[14] Classicindustries, "classicindustries.com," [Online]. Available: http://www.classicindustries.com/product/1969/truck/parts/al80901snd.html. [Accessed 05 03 2017].

[15] Gates, "gates.com," [Online]. Available: http://www.gates.com/products/automotive/fleet-and-heavy-duty/hd-cooling-system/hd-radiator-caps/heavy-duty-radiator-caps. [Accessed 05 03 2017].

[16] Truckstank, "truckstank.com," [Online]. Available: http://www.truckstank.com/ford-trucks-expansion-tanks.html#. [Accessed 08 03 2017].

[17] Ebay, "ebay.com," [Online]. Available: ebay.com/itm/Stant-14687-Engine-Coolant-Thermostat-/400482545961?hash=item5d3e9eb129:m:mxkYgtNpj-yEqx6TOSJ9CKg&vxp=mtr. [Accessed 10 03 2017].

[18] J. L. Z. Zhu, "Chalmers," Chalmers university of technology, Goteborg, 2014.

[19] Kharagpur, "nptel," [Online]. Available: http://nptel.ac.in/courses/108105066/PDF/L-33(DP)(PE)%20((EE)NPTEL).pdf. [Accessed 02 15 2017].

[20] G. Hatsidimitris, "University of New South Wales or of the School of Physics.," [Online]. Available: http://www.animations.physics.unsw.edu.au/jw/electricmotors.html. [Accessed 28 01 2017].

[21] R. W. De Doncker, "Modern Electrical Drives:," [Online]. Available: http://www.jee.ro/covers/art.php?issue=WO1175851273W4616110927c75. [Accessed 24 01 2017].

[22] R. Nave, "Magnetic Force," [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfor.html. [Accessed 03 02 2017].

[23] electrical4u, "Torque Equation of Three Phase Induction Motor," electrical4u, [Online]. Available: https://www.electrical4u.com/torque-equation-of-three-phase-induction-motor/. [Accessed 04 05 2017].

[24] Yunus A. Çengel & John M. Cimbala , "Fluid Mechanics," [Online]. Available: http://www.iu.hio.no/~ivarj/fluid%20mechanics/FM_2e_SM__Chap11.pdf. [Accessed 02 03 2017].

[25] Penton, "machinedesign," [Online]. Available: http://www.machinedesign.com/sensors/introduction-pid-control. [Accessed 14 05 2017].

[26] what-when-how, "The Ackermann Principle as Applied to Steering (Automobile)," [Online]. Available: http://what-when-how.com/automobile/the-ackermann-principle-as-applied-to-steering-automobile/. [Accessed 10 05 2017].

[27] Robotc, "Robotc.ne," [Online]. Available: http://www.robotc.net/wikiarchive/Tutorials/Arduino_Projects/Additional_Info/Turning_Calculations. [Accessed 05 05 2017].

[28] mogi.bme.hu, "Modelling Induction Motor," [Online]. Available: http://www.mogi.bme.hu/TAMOP/digitalis_szervo_hajtasok_angol/ch07.html. [Accessed 10 04 2017].

[29] M. Popescu, "Helsinki University of Technology," [Online]. Available: https://www.motor-design.com/cmsAdmin/uploads/induction_motor_modelling.pdf. [Accessed 05 04 2017].

[30] V. K. a. S. RAO, "induction-motor," National Institute of Technology, Warangal, A.P., India, [Online]. Available: https://www.omicsgroup.org/journals/space-vector-pulse-width-modulation-based-indirect-vector-control-of-induction-motor-drive-2332-0796-1000142.php?aid=54740&view=mobile.

[31] F. Korkmaz, "Department of Electric-Electronic Engineering," [Online]. Available: http://aircconline.com/ijics/V7N1/7117ijics02.pdf. [Accessed 11 05 2017].

[32] D. RAYMOND, "DTC: Theoretical etude and simulation," [Online]. Available: file:///C:/Users/134447/Downloads/AN_SimulationDTC_DamienRaymond.. [Accessed 17 05 2017].

[33] A.-R. Haitham. [Online]. Available: https://books.google.no/books?id=uquXDsFPveYC&pg=SA5-PA19&lpg=SA5-PA19&dq=dtc+simulation&source=bl&ots=RTVKJTAGOZ&sig=U0dXGkq-l6PyNdW-vdx83QreOPM&hl=no&sa=X&ved=0ahUKEwjMkYD27f7TAhVCZCwKHWB4ADY4FBDoAQgyMAI#v=onepage&q&f=false. [Accessed 2017 05 20].

[34] P. S. Jaroslav Lepka, "Freescale Semiconductor," [Online]. Available: http://cache.freescale.com/files/product/doc/AN1930.pdf. [Accessed 29 O4 2017].

[35] F. M.-M. M. M.-H. a. M. G.-V. Rafael Rodríguez-Ponce, "intechopen.com," IN TECH, [Online]. Available: https://www.intechopen.com/books/induction-motors-applications-control-and-fault-diagnostics/dtc-fpga-drive-for-induction-motors. [Accessed 05 05 2017].

[36] ushybrid, "ushybrid," ushybrid, [Online]. Available: http://www.ushybrid.com/documents/PD. [Accessed 2017 03 09].

[37] IEEE Globalspec, "http://www.globalspec.com," IEEE Globalspec, [Online]. Available: http://www.globalspec.com/learnmore/motion_controls/power_transmission/gears/spur_gears. [Accessed 19 05 2017].

[38] Pearltrees, "pearltrees.com," Pearltrees, [Online]. Available: http://www.pearltrees.com/smatt82/gearbox/id12647191/item127495321. [Accessed 19 05 2017].

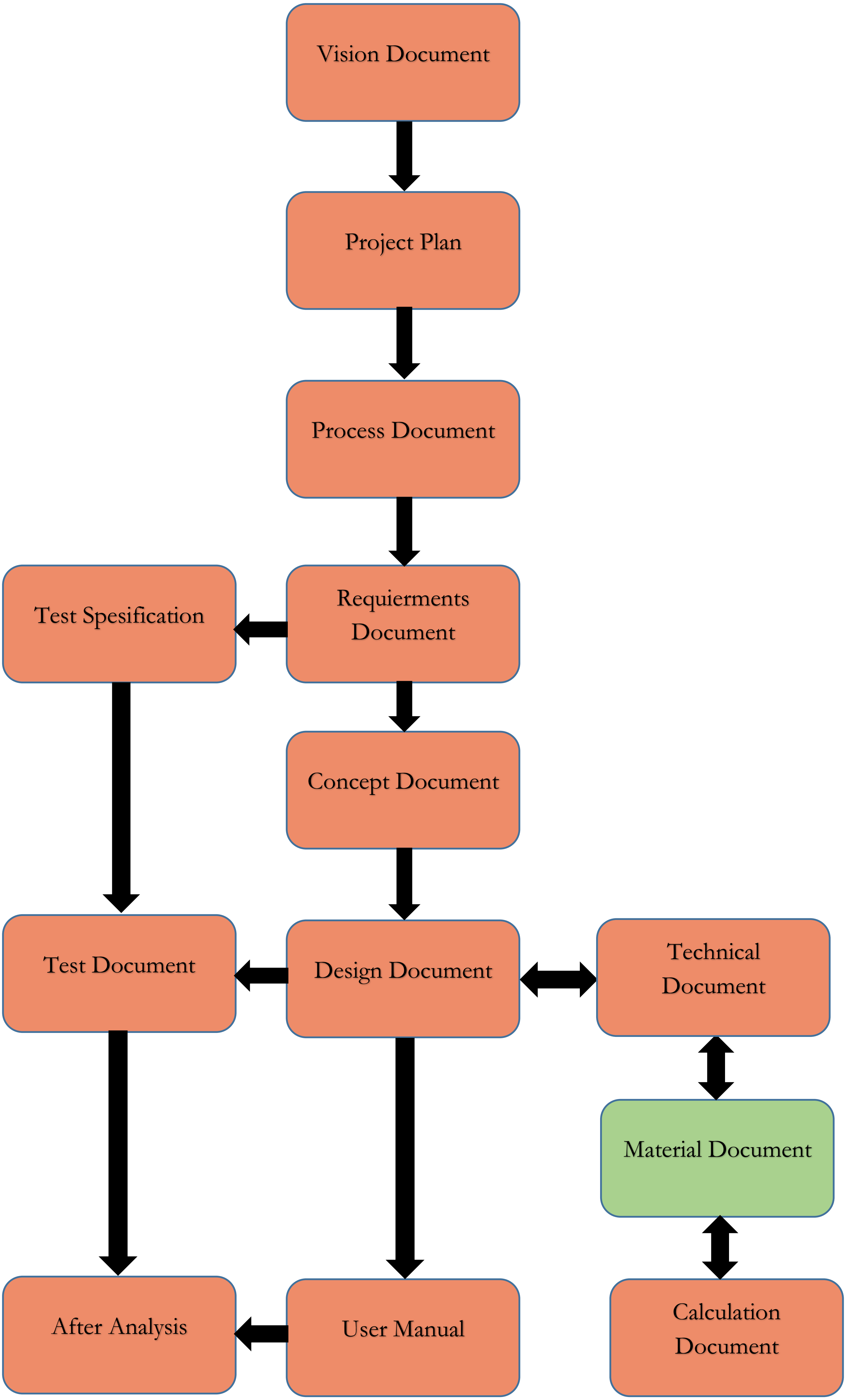
[39] M. S. El-Desoky, "Grabcad.com," 25 12 2013. [Online]. Available: https://grabcad.com/library/herringbone-gear-1. [Accessed 19 05 2017].

[40] Linn Gear Co., "www.linngear.com," Linn Gear Co., 2017. [Online]. Available: http://www.linngear.com/part-type/bevel/. [Accessed 19 05 2017].

[41] Tangient LLC, "iescjmechanisms.wikispaces.com," Tangient LLC, 2017. [Online]. Available: https://iescjmechanisms.wikispaces.com/RACK+AND+PINION+SYSTEM. [Accessed 19 05 2017].

[42] Shakti Engineers, "dir.indiamart.com," Shakti Engineers, [Online]. Available: https://dir.indiamart.com/ahmedabad/internal-gear.html. [Accessed 19 05 2017].

[43] Delroyd Worm Gear Altra Industrial Motion, "www.delroyd.com," Delroyd Worm Gear Altra Industrial Motion, 2017. [Online]. Available: http://www.delroyd.com/. [Accessed 19 05 2017].


Vision Document
Project Plan
Process Document
Test Spesification
Requierments Document
Concept Document
Test Document
Design Document
Technical Document
Material Document
After Analysis
User Manual
Calculation Document

MATERIAL DOCUMENT

Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive

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<tr><td>Employer</td><td colspan="4">Kongsberg Automotive</td></tr>
<tr><td rowspan="7">Group Members</td><td colspan="2">Name</td><td colspan="2">Initials</td></tr>
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<tr><td colspan="2">Ahat Turgun</td><td colspan="2">AT</td></tr>
<tr><td colspan="2">Anis Sadiq</td><td colspan="2">AS</td></tr>
<tr><td colspan="2">Egide Rubusa Bampo</td><td colspan="2">ERB</td></tr>
<tr><td colspan="2">Mustafa Moalim</td><td colspan="2">MM</td></tr>
<tr><td colspan="2">Pawan Bhatt</td><td colspan="2">PB</td></tr>
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21. februar 2017

MATERIAL DOCUMENT

Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive

TABLE OG CONTENT

LIST OF TABLES

LIST OF FIGURES

REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
11.04.17	0.1	Document created	MM
21.04.17	0.2	Added more information	MM
18.04.17	0.3	Language correction, more information	PB
19.05.17	0.4	Grammar and layout updates	AS
21.03.17	0.5	Minor changes and update	PB
23.05.17	0.6	Corrections and minor updates	AK
23.05.17	1.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
WS	Wheel suspension
ED	Electric drive
C	Carbon
Si	Silicon
Mn	Manganese
Cr	Chromium
P	Phosphorus
S	Sulfur
Cu	Copper
Ni	Nickel
Mo	Molybdenum
B	Boron
HSS	High Speed Steel
CC	Cemented Carbide
LPVC	Low Pressure Vacuum Carburizing
J	Joules
^{o}C	Celsius
MPa	Mega Pascal
UTS	Ultimate Tensile Strength

ABBREVIATIONS	DEFINITION
HAZ	Heat Affected Zone

TABLE 2 - DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

The aim of this document is to ensure that the materials used for our system accomplishes the requirements of the stakeholders.

Selecting materials for a vehicle is an important aspect for vehicle designing. There are different materials used for different parts of a vehicle. Here, we divide the WS with integrated ED into subsystems and select the suitable material for every part. The most significant criteria that a material should fulfill is; lightweight, safety, economic effectiveness, recyclability and regulations.

Selecting the type and characteristics of the material depends on the application of the system, which is intended for and the environment surrounding it.

1.1. Scope

The scope of this document is to:

- Describe some of the materials used for the subsystems we have designed
- Describe and explain the mechanical and chemical properties of these materials.
- Describe environmental impacts, which reduce the lifetime of the metal.
- Describe manufacturing process for some parts in our system.

2. SELECTED MATERIALS

2.1. A-arm Material

The material of the A-arm must be strong enough to withstand the different forces subjected to it. Therefore, it is of great importance to choose appropriate material. After some research we have decided to use steel. The type of steel we have selected for this application is called Strenx 700.

Strenx 700 is a steel alloy material used for applications such as load-bearing structures, where low weight and strength are the most important properties. It has a minimum yield strength of 650 MPa, which is high compared to several other steel alloys. The impact toughness of Strenx 700E is 69 J/-40°C, which means that this steel alloy can absorb 69 J of energy at -40°C. This is considered as a very high impact resistance compared to other similar high strength steel alloys.

The chemical composition is visible in the table down below.

C *) (max %)	Si *) (max %)	Mn *) (max %)	P (max %)	S (max %)	Cr *) (max %)	Cu *) (max %)	Ni *) (max %)	Mo *) (max %)	B *) (max %)
0.20	0.60	1.60	0.020	0.010	0.80	0.30	2.0	0.70	0.005

FIGURE 1 - CHEMICAL COMPOSITION OF STRENX 700 [1].

The table down below describes the physical properties of Strenx 700 steel.

Thickness (mm)	Yield strength1) $R_{p0.2}$ (min Mpa)	Tensile strength1) R_m (Mpa)	Elongation A_5 (min %)
4.0- 53.0	700	780- 930	14
53.1- 100.0	650	780- 930	14
100.1- 160.0	650	710- 900	14

FIGURE 2 - PHYSICAL PROPERTIES OF STRENX 700 [1]

The thickness of our A-arm is 120mm, therefore we are in the bottom row. There are some other Strenx steel alloys, which have yield strength up to 1100 MPa. These have a limitation. These alloys are produced as very thin sheet metals, no bigger than 100 mm.

2.2. Gear Materials

Gears are made from many different types of cast irons, steel alloys, non-ferrous alloys, and plastic. We know that all the power to the wheels must go through a transmission system and gears are the most important parts to transmit that power. These gears must withstand a huge amount of forces. Steel alloy are the most widely used materials to manufacture these gears and this is what we will be focusing upon in this document [2].

Figure down below shows us some of the most frequently used steel alloys in gear manufacturing, depending on the application. In addition, we can also see the type of gears used in each application.

Table 3 Recommended steels for various applications and gear types

Typical industrial application	Gear design type	Typical material choice
Differentials		
Automotive	Hypoid, spiral/straight bevel	4118, 4140, 4027, 4028, 4620, 8620, 8622, 8626
Heavy truck	Hypoid, spiral/straight bevel	4817, 4820, 8625, 8822
Drives		
Industrial	Helical, spur rack and pinion, worm	1045, 1050, 4140, 4142, 4150, 4320, 4340, 4620
Tractor-accessory	Crossed-axis helical, helical	1045, 1144, 4118, 4140
Engines		
Heavy truck	Crossed-axis helical, spur, worm	1020, 1117, 4140, 4145, 5140, 8620
Equipment		
Earth moving	Spiral/straight bevel, zerol	1045, 4140, 4150, 4340, 4620, 4820, 8620, 9310
Farming	Face, internal, spiral/straight bevel, spur	4118, 4320, 4817, 4820, 8620, 8822
Mining, paper/steel mill	Helical, herringbone, miter, spur, spur rack and pinion	1020, 1045, 4140, 4150, 4320, 4340, 4620, 9310
Starters		
Automotive	Spur	1045, 1050
Transmissions		
Automotive	Helical, spur	4027, 4028, 4118, 8620
Heavy Truck	Helical, spur	4027, 4028, 4620, 4817, 5120, 8620, 8622, 9310
Marine	Helical, helical conical, spiral bevel	8620, 8622
Off highway	Helical, internal, spiral/straight bevel, spur	1118, 5130, 5140, 5150, 8620, 8822, 9310
Tractor	Herringbone, internal, spur	4118, 4140, 8822

FIGURE 3 - RECOMMENDED STEEL ALLOYS [2]

After much discussion and research, we decided that there are two steel alloys, which can be used to produce gears suitable for our transmission system. Ferrium C61 and Ferrium C64, both of which are an upgrade from other high strength steel alloys such as 8620, 9310 and X53 [3]. In addition to gears, fermium will also be used to manufacture one of the planet carriers and sun gear output part. The reason being that these part also have groves, similar to gears.

2.2.1. Ferrium C61 – C64

Ferrium C61 and C64 are two new types of steel, which can be used for power applications. These steel types have much better mechanical properties compared to other similar alloys commonly used for power transmission. Ferrium C61 and C64 possess much higher core tensile strength, fracture toughness, fatigue strength and thermal stability [3].

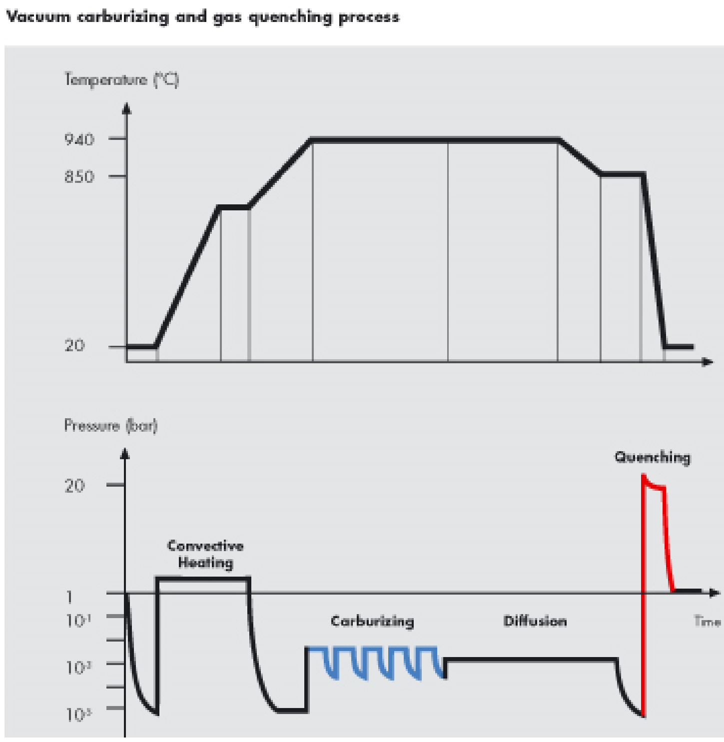


FIGURE 4 - LVPC TEMPERATURE AND PRESSURE VARIATION [4]

Ferrium C61 and C64 is produced by using low pressure vacuum carburizing method which is combined with solution heat treatment. In addition, sufficiently low quantity of gas with carbon content (Methane, propane or acetylene) is injected into the carburizing chamber and sucked out by an air pump. This carburizing and diffusion cycle is repeated many times to reach desired mechanical properties and case depth [5].

Next step is to quench the steel in gas (nitrogen, argon or helium) to below 66 °C. In the last step before tempering, the component is subjected to subzero temperatures using liquid nitrogen (cryotreatment). This leads to the formation of martensite from austenite structure throughout the component. Immediately after cold treatment the steel is tempered to prevent cracking and to allow the saturated carbon to form carbides. Figure below shows a rough gear manufacturing path, and where in the process vacuum carburizing is especially advantageous.

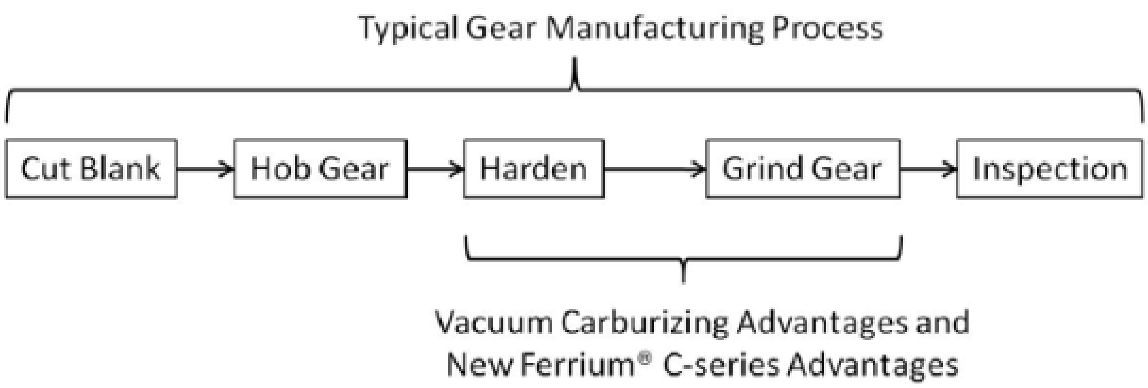


FIGURE 5 - TYPICAL GEAR MANUFACTURING PROCESS [5]

Figure below shows the normal atmospheric carburizing path, and comparing them to the vacuum carburizing method, where some of the steps have been eliminated. This leads to decreased process time, and lower costs.

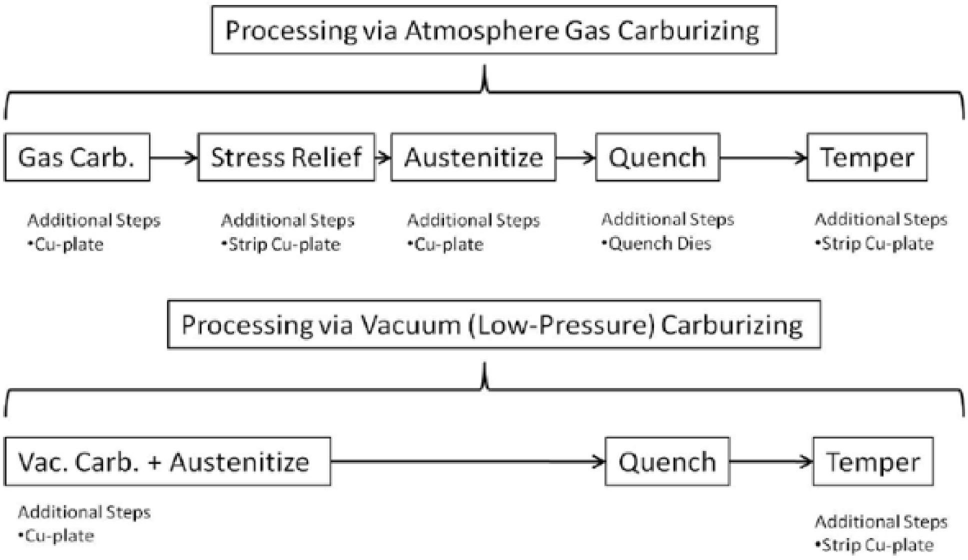


FIGURE 6 - METHOD COMPARISON [5]

2.2.2. Advantages of LPVM Method

LPVM method leads to a better quality of steel alloys, which have much higher UTS (up to 35%) compared to other steel alloys [6]. This allows the construction of parts with reduced size, making the overall construction weightless. In addition, Ferrium C61 and C64 can withstand service temperatures from 200 - 315 °C more than other steel alloys for similar constructions [3].

Ferrium C61 and C64 have much higher corrosion resistance compared to other steel types like 9310 or Pyrowear 53.

2.2.3. Applications

There are many applications for these steel alloys, where durability, corrosion resistance and fatigue resistance are of importance. All these characteristics are desirable for our transmission system. List below shows some areas where both C61 and C64 are applicable [3]:

- Transmission gearbox for conventional vehicles and helicopters
- Rotors
- Driveshaft

- Bearings
- Other power components

2.2.4. Chemical Composition

We can see the chemical composition of Ferrium C61 and C64 on figure 7 below. Ferrium C61 and C64 have similar chemical composition. Only difference is the percentage of each element and that C64 have 0,2 % tungsten which is not present in C61.

TYPICAL COMPOSITION

C	Cr	Ni	Co	Mo	V
0.15	3.5	9.5	18	1.1	0.08

FIGURE 7 - CHEMICAL COMPOSITION OF FERRIUM C61 [7]

TYPICAL COMPOSITION

C	Cr	Ni	Co	Mo	W	V
0.11	3.5	7.5	16.3	1.75	0.2	0.02

FIGURE 8 - CHEMICAL COMPOSITION OF FERRIUM C64 [8]

2.2.5. Mechanical Properties

The figure down below shows us the physical properties of Ferrium C61 and C64 and compares it with other similar steel alloys used in gear manufacturing. Ferrium C61 has the highest UTS, yield strength and fracture toughness compared to other alloys. C64 on the other hand can withstand higher temperatures and can achieve higher surface hardness.

Alloy Typical Properties	YS (ksi)	UTS (ksi)	Core Hardness (HRC)	Achievable Surface Hardness (HRC)	K_{Ic} Fracture Toughness (ksi-√in)	Elong (%)	RA (%)	Tempering Temp. (°F)
Ferrium C61	225	240	48-50	60-62	130	16	70	900
Ferrium C64	199	229	48-50	62-64	85	18	75	925
AISI 9310 (EN36)	155	175	34-42	58-62	85	16	53	300
Pyrowear 53	140	170	36-44	59-63	115	16	67	400
AISI 8620	121	168	41-48	61		14	53	450

FIGURE 9 - PHYSICAL PROPERTIES OF FERRIUM C61 AND C64 [3]

2.3. A-arm Connector

A-arm connector is a very important part for our wheel suspension. It is responsible for connecting A-arm to the frame. This part has to withstand a lot of forces together with the A-arm. Chosen material for the A-arm connector is Strenx 900. This steel alloy is a general and used for structural purposes.

It is typically used in load bearing structures where lightweight and strength is essential. Depending on the thickness, it can have a minimum yield strength of 900 MPa.

Other benefits include: [9]

- Superior bendability and surface quality.
- Weldability with excellent HAZ strength and toughness.
- High impact toughness, which provides increased resistance to fracture.

Mechanical Properties

Thickness (mm)	Yield strength $R_{p0.2}$ [1)] (min MPa)	Tensile strength R_m [1)] (MPa)	Elongation A_5 (min %)
4.0- 53.0	900	940- 1100	12
53.1- 100	830	880- 1100	12

[1)] For transverse test pieces according to EN 10 025.

FIGURE 10 - MECHANICAL PROPERTIES OF STRENX 900 [9]

2.4. Planet Carriers

Except for one, all the other planet carrier is made using steel alloy AISI 4340. This is a steel alloy, which is known for its strength and toughness. It is a nickel chromium molybdenum steel and is generally supplied hardened and tempered. AISI 4340 have good shock and impact resistance in hardened condition, as well as good wear and abrasion resistance. This steel is often applied where other steel alloys do not have the necessary hardenability to give the strength required [10].

AISI 4340 steel alloy have good machinability, but is best done in annealed or normalized state.

2.4.1. Mechanical Properties

Mechanical Properties			
Hardness, Brinell	321	321	
Hardness, Knoop	348	348	Converted from Brinell hardness.
Hardness, Rockwell B	99	99	Converted from Brinell hardness.
Hardness, Rockwell C	35	35	Converted from Brinell hardness.
Hardness, Vickers	339	339	Converted from Brinell hardness.
Tensile Strength, Ultimate	1110 MPa	161000 psi	
Tensile Strength, Yield	710 MPa	103000 psi	
Elongation at Break	13.2 %	13.2 %	
Reduction of Area	36 %	36 %	
Modulus of Elasticity	205 GPa	29700 ksi	Typical for steel
Bulk Modulus	140 GPa	20300 ksi	Typical for steel.
Poisson's Ratio	0.29	0.29	Calculated
Machinability	50 %	50 %	annealed and cold drawn. Based on 100% machinability for AISI 1212 steel.
Shear Modulus	80 GPa	11600 ksi	Typical for steel.

FIGURE 11 - MECHANICAL PROPERTIES OF AISI 4340 STEEL [11]

Figure 11 shows us the mechanical properties of AISI 4340 steel at normalized condition. The yield strength of this steel alloy is 710 MPa, which is on the higher end compared to other similar alloys.

2.4.2. Chemical composition

Component	Wt. %	Component	Wt. %	Component	Wt. %
C	0.37 - 0.43	Mn	0.7	P	Max 0.035
Cr	0.7 - 0.9	Mo	0.2 - 0.3	S	Max 0.04
Fe	96	Ni	1.83	Si	0.23

Physical Properties	Metric	English
Density	7.85 g/cc	0.284 lb/in^3

FIGURE 12 - CHEMICAL COMPOSITION OF AISI 4340 STEEL [11]

Figure 12 shows the chemical composition of AISI 4340 steel alloy. We can see that this steel alloy contains high amount of nickel, molybdenum and chromium, as mentioned previously.

3. CORROSION

One of the factors that reduces the lifetime of metals is corrosion. Therefore, engineers must take this into account during systems design. Corrosion is the destructive attack of a material, by chemicals or electrochemical substances. Both the type of metal and the environmental conditions, particularly gasses that are in contact with the metal, determine the form and rate of deterioration.

Types of corrosion, which can occur in our design are; galvanic corrosion, pitting corrosion, crevice corrosion and fretting corrosion.

3.1. Galvanic Corrosion

Galvanic corrosion is when two or more components/parts with different electric potential is in contact with each other. Metals, which are very active or have low electric potential, have a habit to form anode. While metals, which are not very active or have high electric potential tend to form cathode. This forms an electric current where ions move from anode to cathode. This means that metals with high electric potential corrode at a very slow pace and in some instances, can even stop corroding altogether [12].

There are some ways to prevent galvanic corrosion from occurring. One way is to use a sacrificial anode, which doesn't affect the performance of the parts/construction. Often used in metal hulled ships to prevent corrosion [12]. Another way to prevent this type of corrosion is to prevent direct metal to metal contact, by using non-conductive materials like paint, coatings or gaskets.

3.2. Pitting Corrosion

Pitting corrosion is an extremely localized form of corrosion, where metal corrode to develop small cavities or "pits". This is one of the most dangerous form of corrosion, because it is very difficult to detect, predict or design against this type of corrosion [13]. Cavities which are formed can progress very rapidly and can impair the part/construction. The driving force of pitting corrosion is depassivation of a small area, which leads to a localized anode, while another unknown area becomes cathode. This leads to a localized form of galvanic corrosion.

Steel alloys are very sensitive to this type of corrosion, predominantly stainless steel. Other metals, which can be affected by pitting corrosion, are chromium, cobalt, aluminum, copper and their alloys.

Pitting corrosion can be initiated by [14]:

- Chemical or mechanical damage to the oxide film
- Damage to, or poor application of coating
- Non-uniformity in the metal structure

To reduce risk of pitting corrosion we can use materials developed specifically to reduce this type of corrosion, and more appropriate for their environment [15].

3.3. Crevice Corrosion

Crevice corrosion occurs when stationary solutions are present in small crevices, like nuts and rivets. There are several factors, which can initiate crevice corrosion like [16]:

- Reduction of inhibitor in the crevice
- Reduction of oxygen in the crevice
- Acid conditions in the crevice
- Formation of ion species

To avoid or limit crevice corrosion we can use welds rather than bolts or rivets at the joint whenever possible, or hydrofuge joints, which cannot be welded [16].

3.4. Corrosion in Our System

The A-arm is exposed to the outside environment and can meet water, moisture, and salt on the streets during winter. All of these factors cause corrosion. In addition, several of our subsystems are made of steel alloys, which can corrode after a while.

In gearboxes, we can see pitting corrosion when the oil breaks down and chemicals in the oil start attacking gear material. The chemical present in the oil attacks grain boundaries, which leads to pitting corrosion. The fact that the material we have chosen, have high corrosion resistance makes it even better for this application [17].

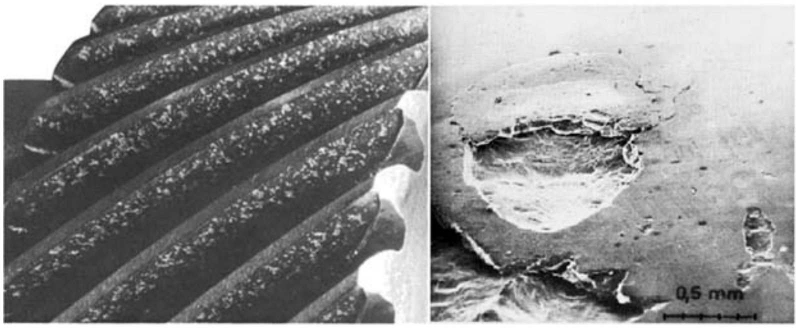


FIGURE 13 - PITTING CORROSION NORMAL & MICROSCOPIC VIEW [17]

4. FATIGUE

Some components of our system, such as gears, shafts and springs are subjected to both oscillating periodic loads and static loads. These fluctuating and static loads cause components to be subjected to fatigue.

Fatigue can develop into cracks that grow with every stress cycle and propagates through the material until a critical crack length is reached when the material fractures [2].

Under these circumstances, the system or the component fails at a stress level below yield strength of material.

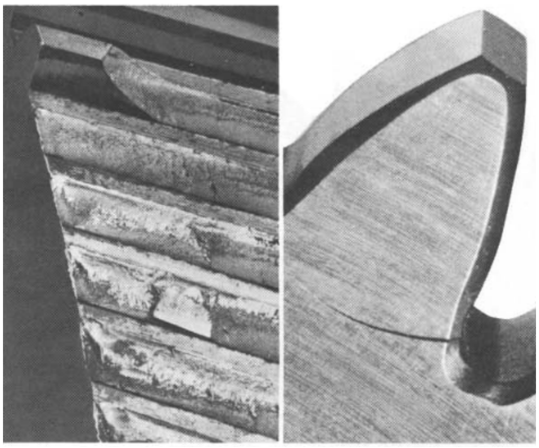


FIGURE 14 - TOOTH FRACTURE IN A GEAR [17]

There are many kinds of failures, which can occur in gears, but we want to focus on tooth fracture. Tooth breakage can occur due to high overload in static situations or due to impact (change in directions). Over a long period, these fractures propagate and lead to breakage of the gear tooth. This is one of the most dangerous failures, which can occur in a gear system, as it can damage other components like bearing, axle etc. [18].

5. MANUFACTURING PROCESS

Our system contains several subsystems. We need to manufacture the subsystems from different materials and use different techniques depending on the application.

Methods used of manufacturing for our subsystems:

- Turning
- Milling
- Cutting
- Drilling
- Welding

Strenx is a steel alloy that can be machined with HSS or CC tools.

	Hardness in Brinell (HBW)	Hardness in Rockwell (HRC)	Tensile strength, Rm (N/mm²)
Strenx 700	~260	~24	~860

FIGURE 15 - TYPICAL PROPERTIES OF STRENX STEEL [1]

5.1. Drilling

In order to connect (bolt together) the A-arm to the system, we need to drill holes. We only use HSS drills when we have unstable machine conditions. HSS drills are only suitable up to 500 Brinell hardness. If the machine conditions are good, we have several choices of solid cemented carbide drills with exchangeable heads or drills.

5.2. Milling

Milling includes several highly versatile machining operations taking place in a variety of configurations. It is one of the most common form of machining and is a material removal process, which can create parts that are not actually symmetrical.

Milling the A-arm is crucial to make large holes, where axles from transmission comes through. Milling is used to give different forms and get accurate tolerances.

5.3. Turning

Turning is used to produce straight, conical, curved, or grooved workpieces, such as shafts, spindles and pins. Turning can be used on the outside surface or inside (also called boring) in order to produce hollow components.

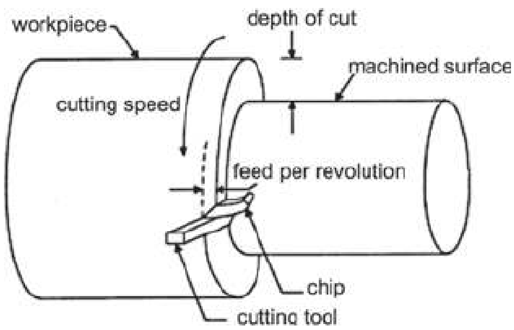


FIGURE 16 - TURNING PROCESS

Turning is one of the most basic form of machining and is widely used today. In our system, we manufacture the shaft from the transmission by turning.

5.4. Gear Hobbing

Gear hobbing is one of the most widely used gear manufacturing processes, and provides gear manufacturers with a fast and accurate method for cutting gear. Unlike gashing or milling, hobbing is not a form cutting process, where the cutter is a conjugate form of the gear tooth [21].

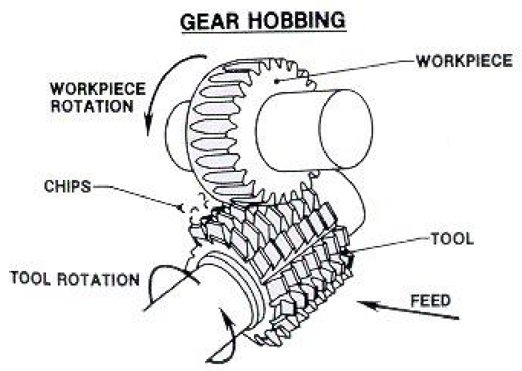


FIGURE 17 - GEAR HOBBING PROCESS [22]

The hob (Cutting tool) produces a tooth by cutting many facets of each gear tooth on the workpiece. For a single-thread hob, the machine synchronize each revolution of the cutting tool to one tooth of the work piece. This type of hob would rotate 30 times per revolution of a 30 tooth gear.

Hobbing can be used to make a wide variety of gears like; spur gears, helical, hearing bone, splines, etc. Despite all of the advantages, the main disadvantage is the manufacturing of internal gears, which is not possible with hobbing.

5.5. Gear Shaping

Gear shaping is another gear generating process which is used extensively in gear manufacturing industry. Gear shaping is done on a special machine called gear shaper, where the cutter is mounted on a spindle vertically. In addition the axis of the cutter and blank is parallel.

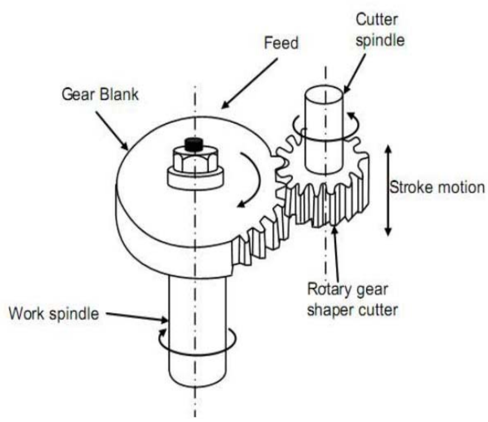


FIGURE 18 - GEAR SHAPING PROCESS [23]

The cutter and blank are synchronized and made to rotate together, like two gears in a mesh. The cutter moves in vertical direction along the width of the blank, but during the return stroke the cutter is withdrawn from the blank. This is done in order to avoid rubbing of the cutting edges and to prevent damage on gear tooth being generated.

Gear shaping method is used to make several different types of gears, with the exception of worm gears. Gear shaping can also produce internal gears, which is not possible with hobbing.

6. REFERENCES

[1] SSAB, "www.ssab.com," SSAB, [Online]. Available: https://www.ssab.com/products/brands/strenx/products/strenx-700#!accordion=downloads. [Accessed 24 4 2017].

[2] J. R. Davis, Gear Materials, Properties, and Manufacture, ASM International, 2005.

[3] QuesTek Innovations LLC (64), "www.questek.com," QuesTek Innovations LLC, 2017. [Online]. Available: http://www.questek.com/ferrium-c64.html. [Accessed 17 4 2017].

[4] ALD Vacuum Technologies, "AMG," ALD Vacuum Technologies, [Online]. Available: http://web.ald-vt.de/cms/vakuum-technologie/technologien/vacuum-heat-treatment/vacuum-case-hardening/vacuum-based-carburizing/. [Accessed 17 4 2017].

[5] QuesTek Innovations LLC [61, 64], "www.questek.com," [Online]. Available: http://www.questek.com/filebase/src/Articles/AGMATechPaper11FTM27Mfgand.pdf. [Accessed 17 4 2017].

[6] QuesTek Innovations LLC(61), "www.questek.com," QuesTek Innovations LLC, 2017. [Online]. Available: http://www.questek.com/ferrium-c61.html. [Accessed 17 4 2017].

[7] QuesTek Innovations LLC [61], "www.questek.com," [Online]. Available: http://www.questek.com/filebase/src/Material_Data_Sheets/FerriumC61CarpenterDataShe.pdf. [Accessed 17 4 2017].

[8] QuesTek Innovations LLC [64], "www.questek.com," [Online]. Available: http://www.questek.com/filebase/src/Material_Data_Sheets/FerriumC64CarpenterDataShe.pdf. [Accessed 17 4 2017].

[9] Ssab, Ssab, 20 04 2017. [Online]. Available: https://www.ssab.com/products/brands/strenx/products/strenx-900. [Accessed 12 05 2017].

[10] Otai Special Steel, "www.astmsteel.com," Otai Special Steel, [Online]. Available: http://www.astmsteel.com/product/4340-steel-aisi/. [Accessed 15 05 2017].

[11] ASM International, "asm.matweb.com," Asm International, [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=M434AE. [Accessed 17 05 2017].

[12] T. Bell, "The Balance," 17 3 2017. [Online]. Available: https://www.thebalance.com/galvanic-corrosion-2339698. [Accessed 19 4 2017].

[13] Nace International (C), "www.nace.org," [Online]. Available: https://www.nace.org/Corrosion-Central/Corrosion-101/Crevice-Corrosion/. [Accessed 19 4 2017].

[14] Nace International (P), "www.nace.org," Nace International, [Online]. Available: https://www.nace.org/Pitting-Corrosion/. [Accessed 18 4 2017].

[15] INSA Lyon (P), "The Multimedia Corrosion Guide," INSA Lyon, [Online]. Available: http://www.cdcorrosion.com/mode_corrosion/corrosion_pitting.htm. [Accessed 19 4 2017].

[16] INSA Lyon (C), "The Multimedia Corrosion Guide," INSA Lyon, [Online]. Available: http://www.cdcorrosion.com/mode_corrosion/corrosion_crevice.htm. [Accessed 18 4 2017].

[17] XTEC INC., "www.xtec.com," 7 12 1967. [Online]. Available: http://www.xtek.com/pdf/wp-gear-failures.pdf. [Accessed 23 3 2017].

[18] K. G. &. M. M. Mayuram, Indian Institute of Technology Madras, [Online]. Available: http://nptel.ac.in/courses/112106137/pdf/2_6.pdf. [Accessed 23 3 2017].

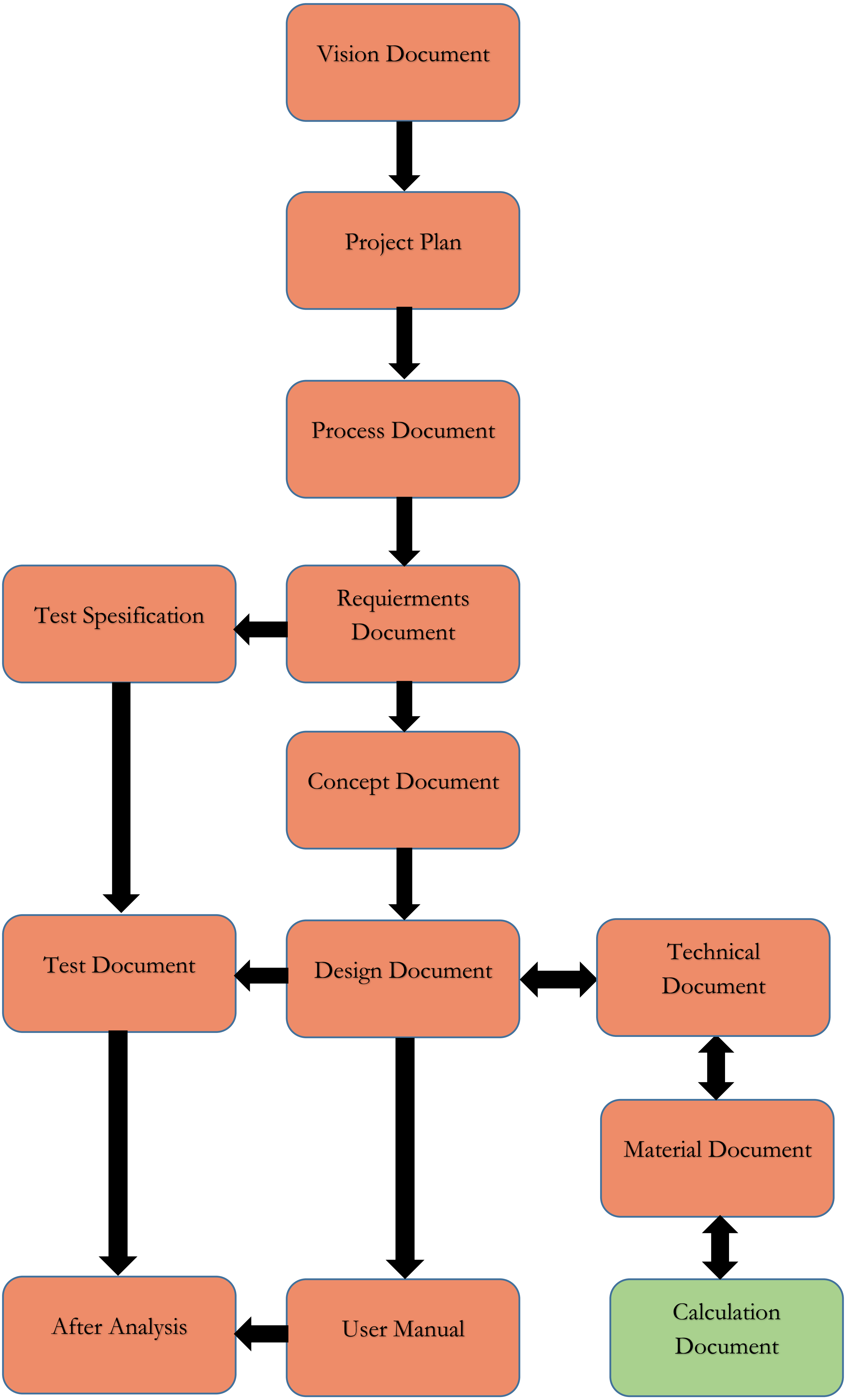
[19] M. S. Ray, The Technology and Application of Engineering Materials, 1987.

[20] S. Kalpakjian, Manufacturing Engineering and Technology, 2014.

[21] As the gear turns, 08 07 2014. [Online]. Available: http://asthegearturns.com/2014/07/08/the-hobbing-process-part-1/. [Accessed 12 5 2017].

[22] Maxwell tools, Maxwell tools, 2014. [Online]. Available: http://www.maxwelltools.com/gear-hobs.html. [Accessed 25 04 2017].

[23] Slideshare, 25 03 2015. [Online]. Available: https://www.slideshare.net/naanmech123/gear-ppt-46260640. [Accessed 25 04 2017].


Vision Document
Project Plan
Process Document
Test Spesification
Requierments Document
Concept Document
Test Document
Design Document
Technical Document
Material Document
After Analysis
User Manual
Calculation Document

CALCULATION DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

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Group Members	**Name**		**Initials**	
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Document Information	**Version**	**Date**	**Approved**	**Pages**
	1.0	23.05.17	AS	32

28. april 2017

CALCULATION DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

TABLE OF CONTENT

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LIST OF FIGURES

REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
28.04.17	0.1	Document created	MM
08.05.17	0.2	Added more calculations	MM
09.05.17	0.3	Added more calculations and transmission calculations	MM & PB
10.05.17	0.4	Minor changes	MM
16.05.17	0.5	Language correction	PB
17.05.17	0.6	Added electrical calculations	ERB
20.05.17	0.7	Grammar and reference revision	AS
23.05.17	0.8	Added some information	PB
23.05.17	1.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
WS	Wheel suspension
ED	Electric drive
IN	Inverter

TABLE 2 – DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

This document will explain all of the calculations we have done for our system. The document contains both mechanical and electrical calculations.

1.1. Scope

In this document, we focus on calculating only for critical subsystems of interest. Since the entire system is very large, a calculation of all subsystems require more time than we have planned for this project.

2. FORCES

2.1. Wheel and Axle Forces

We know that the carrying capacity per wheel is 6 tons [1].

M = 6000 kg

To find the normal force per wheel:

F = m*a a = g = gravitation Newton's second law [2]

F = mg g = 9,81 m/s^2

F = 6000kg * 9,81 m/s^2

F = 58860 N ≈ 60000 N

F = 58,9 kN ≈ 60 kN Normal force

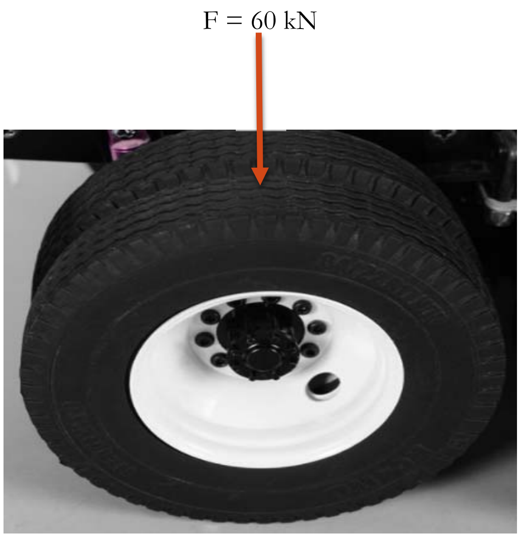


FIGURE 1 – FORCE ON WHEEL [3]

Force per axle becomes:

M = 12000 kg	Mass on the axle	[1]
F = mg = 12000 kg * 9,81 m/s²	Newton's second law	
F = 117720 N ≈ 120000 N		
F = 117,7 kN ≈ 120 kN	Normal force	

FIGURE 2 - FORCE DISTRIBUTION [4]

There are forces acting on the wheels in both X direction and Y direction [1]:

$F_x = 50$ kN $\qquad\qquad$ $F_y = 50$ kN

Forces acting on the wheels can reach maximum up to 100 kN.

2.2 A-arm

Different forces are applied to the A-arm. We will calculate the forces affecting the A-arm [5] :

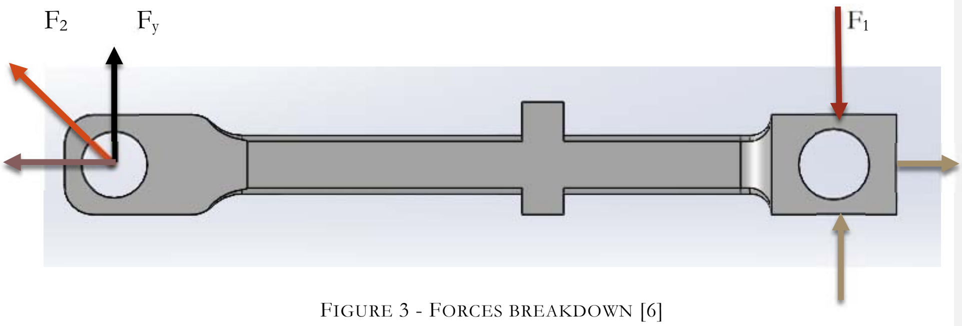


FIGURE 3 - FORCES BREAKDOWN [6]

$F_1 = 60000$ N

$\Sigma F_y = 0$

$\mathbf{F_y + F_{y2} - F_1 = 0}$

$F_{y2} = 60000 \text{ N} - F_y$ (equation 1)

$\Sigma F_x = 0$

$F_x - F_{x2} = 0$

$50000 \text{ N} - F_{x2} = 0$

$F_{x2} = 50000$ N

The angle between F_x and F_y is 45 degree, therefore:

$\mathbf{F_1 \cos 45^\circ = F_x}$

$\mathbf{F_1 sin45^\circ = F_y}$

So both F_x and F_y has the same value, therefore:

$F_y = 50000$ N (equation 2)

Solving equation 1 with equation 2, we find:

$F_{y2} = 10000$ N

To find the resultant force value of F_2 :

$$\mathbf{F_2 = \sqrt{(Fx)^2 + (Fy)^2}}$$

$$F_2 = \sqrt{(50000\ N)^2 + (50000)^2}$$

$F_2 = 70710{,}7$ N ≈ 71000 N

$F_2 = 71$ kN

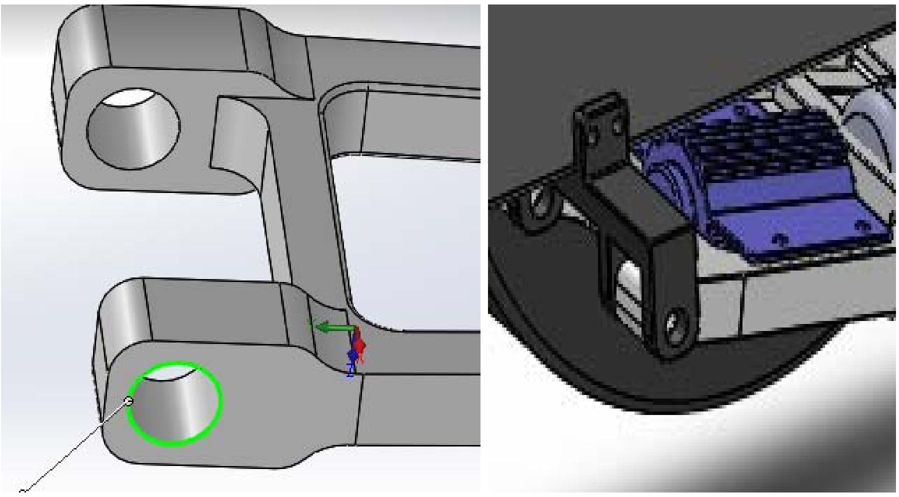


FIGURE 4 – A-ARM CONNECTION WITH FRAME [6]

The A-arm is connected to the frame by a supporting connection joint. (Fig. 4)The bolt going through is acting as shear stress. Thus, we might calculate the shear stress as follows:

Ó = 80 mm Hole diameter

σ_{max} = 650 MPa Max stress that the material can withstand

Kommentert [AAS1]: Hvor har du fått denne verdien fra? Er det for bolt eller A-armen?

F_2 = 71000 N Tension force acting on A-arm

The shear force is also:

$V = \frac{F2}{2}$ = 35500 N Shear force [5]

There is a rubber bushing inside the hole of the A-arm. The dimension of the rubber bushing is:

$Ó_y$: 80 mm Outer diameter of rubber bushing

$Ó_i$: 50 mm Inner diameter of rubber bushing

Before we calculate the shear stress, we must find the area of the bolt going through A-arm holes:

Ó = 50 mm Bolt diameter

$\mathbf{A = \pi * r^2}$ Area equation [2]

A = 1963,5 mm^2 Area of shear plane of the bolt

Thus, the shear stress becomes:

$\boldsymbol{\tau = \frac{V}{A}}$ = 18,1 MPa Shear stress of the bolt [7]

2.2. Factor of Safety

We have to determine a factor of safety for A-arm (Durability A-arm X- and Y-axis). Chosen factor of safety for the given material of A-arm is 2. Material in use is Strenx 700 and Yield strength is 700 MPa.

To get the factor of safety for each test, we are going to the factor of safety equation:

$$\textbf{Facotor of safety} = \frac{Yield\ stress\ of\ material}{working\ stress} \qquad [8]$$

3. TRANSMISSION CALCULATIONS

The electric motor we have decided to use in our system has following parameters:

- Induction motor
- Power : 200kW peak, 85kW continuously
- Torque : 815 Nm out of motor and 2215 Nm out of gear box
- Speed : 7200 out of motor and 2645 out of gear box
- Integrated gear reduction with gear ratio 2.72:1

Using these parameters we can calculate gear ratio needed to satisfy our requirements. We use following equation:

- **$P = T * \omega$** [5]

Where:

P = power

T = torque

ω = angular velocity, which can be calculated using equation:

- **$\omega = 2\pi * RPM/60$** [5]

To find the gear ratio we divide expected output torque with highest torque input from the electric motor.

In 1st gear expected output torque = 30000 Nm [1]

This is the total amount of torque which is needed to move our vehicle. We divide this by 2 since we have 2 electric drives in our system.

15000 Nm/2215 Nm = 6.772 = 9

This is the total reduction which must happen in our transmission system. We have chosen to round up to 9 to make it easier to work with.

In 2nd gear expected output torque = 10000 Nm [1]

5000 Nm/2215 Nm = 2.257 = 3

Again we have rounded up the reduction ratio up to 3 to make it easier.

3.1. Gear Ratio Selection

1st gear overall reduction ratio = 9

- Using factorization we get: 3*3 = 9

This means that we can divide this reduction into 2 steps where we get a reduction ratio of 3, two times in a row.

2nd gear overall reduction ratio = 3

We do not need to divide this into any more steps.

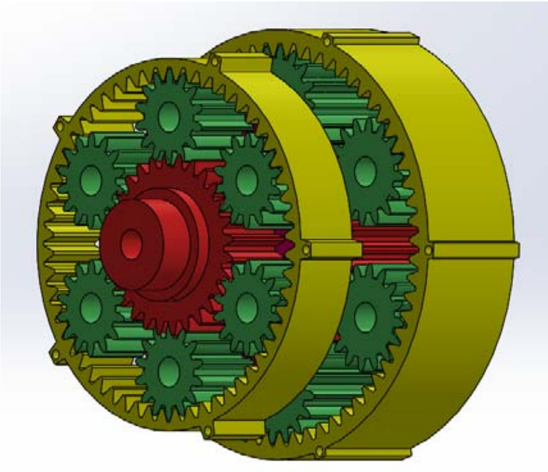


FIGURE 5 – TRANSMISSION CONCEPT [6]

Picture above shows a concept of our transmission system, and we can see that it is made up of two planetary gear sets.

3.2. Gear Teeth Calculation

Smallest sun gear teeth = 28

To calculate number of teeth on other gears in that set we use:

$$\mathbf{GR = 1 + \frac{Zr}{Zs}}$$ [9]

$$\mathbf{Zr = (Gr - 1) * Zs = (3 - 1) * 28 = 56}$$

$$\mathbf{Zr = Zs + 2\,Zp}$$ [10]

$$\mathbf{Zp = (Zr - Zs)/2 = (56 - 28)/2 = 14}$$

Where:

Zr = Number of teeth on ring gear

Zs = Number of teeth on sun gear

Zp = Number of teeth on planet gear

3.2.1. Conditions

We also have to meet some conditions regarding how many teeth there can be in a planetary gear set. There are in total three conditions [11].

- Condition 1 = $\mathbf{Zr = Zs + 2\,Zp}$
- Condition 2 = $\mathbf{\frac{Zs+Zr}{N} = Integer}$
- Condition 3 = $\mathbf{Zp + 2 < (Zs+Zp)\sin\frac{180}{N}}$

Where:

- N = number of planet gears in a set
- 180 degrees

Condition 1 is met since we use it to calculate number of teeth in our planetary gears.

Condition 2:

$\frac{28+56}{6} = 14$ (which is an integer)

Condition 3:

$14+2 = 16 < (28+14)\sin\frac{180}{6} = 21$

As we can see our gear set meet all of the conditions, which is also true for the other gear set we have.

In addition we have to calculate the tooth profile of the gears. These terminology is important to understand the basic gear technology (Figure 6).

For our sun gear we have chosen module (m) =4 [12], based on this we can calculate other values [13].

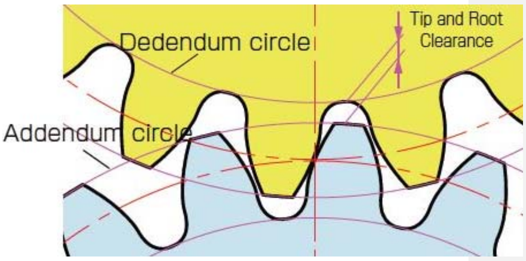


TABLE 3 - TIP AND ROOT CLEARANCE [13]

Circular pitch **(p) = π*m** = 12.56

Tooth height **(h) = 2.25*m** = 9mm

h = addendum + dedundum

Addendum **(ha) = 1*m** = 4mm

Dedendum **(hf) = 1,25*m** = 5mm

Tooth thickness **(s) = p/2 = πm/2** = 6,283mm

Reference diameter **(d) = Z*m** = 28*4 = 112mm

Tip diameter **(da) = d + (2*m) = d + 2*ha** = 112 + 2*4 = 120mm

Root diameter **(df) = d – (2,25*m) = d – 2*h**f = 122mm

Root and tip clearance (Figure 3) **(c) = 0.25*m** = 1mm

3.3. Bending Stress Analysis

To calculate bending stress in gears we need:

- Torque
- Tangential force
- Amount of teeth on a gear
- Pitch diameter of the gear
- Module
- Face width

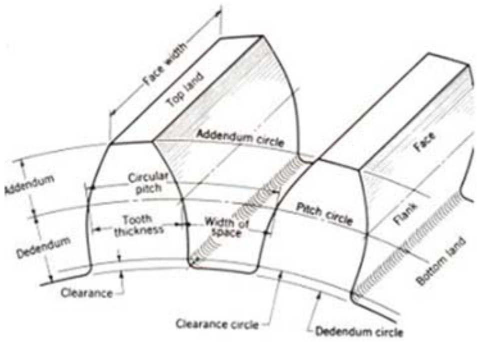


FIGURE 6 - GEAR TERMINOLOGY [20]

3.4. Bending Stress Calculations for Small Sun Gear:

- Teeth (Z) = 28
- Module (m) = 4
- Pitch diameter (D) = 112
- Face width = 48

We know the torque out of gear box, but we need to find the RPM of the shaft:

- $\mathbf{RPM} = \frac{\mathbf{P*60*1000}}{\mathbf{2\pi*Torque}} = \frac{240kW*60*1000}{2\pi*2215Nm}$ = 862.3 RPM [5]

Next we calculate tangential force on one gear tooth.

- $\mathbf{Ft = T/R = Ft = 2T/D}$ = (2000*2215)/112 = 39553.8 N

Using equation for maximum bending stress we finally get amount of stress our gear can withstand.

Lewis bending stress equation:

- $\boldsymbol{\sigma_b} = \frac{\mathbf{Wt} * \boldsymbol{\pi}}{\mathbf{m} * \mathbf{Y} * \mathbf{F}} = \frac{6592.3 * \pi}{4 * 0.352 * 48} = 306.4\ \mathrm{N/mm^2}$ [14]

Where:

Wt = Ft (for us this will be Ft/6 since we have 6 planetary gears around the sun gear and will divide the total force on 6 teeth which they are in contact with)

Y = Lewis factor (dependent on the amount of gear teeth's, Figure 3)

F = Face width

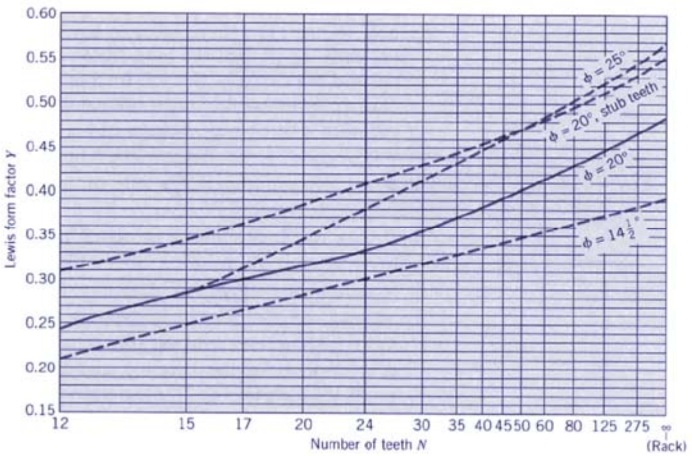


FIGURE 7 - LEWIS FORM FACTOR GRAPH [14]

3.5. Shear Stress Calculation:

Shear stress is defined as: $\boldsymbol{\sigma} = \frac{\mathbf{F}}{\mathbf{A}}$ [7]

We modify this equation to get:

- $\boldsymbol{\sigma} = \frac{\mathbf{Wt}}{\mathbf{F} * (\boldsymbol{\pi} * \mathbf{m})/2} = \frac{6592.3}{2 * (\pi * 4)/2} = \mathbf{21.86\ N/mm^2}$ [15]

We use similar methods on the other gears in our transmission system and made this table.

Name	Teeth (Z)	Module (m)	Facewidth	Diameter (D)	RPM	Power (kW)	Torque - Nm	Force - N	σb (N/mm^2)	σs (N/mm^2)	Lewis factor
SS	28	4	48	112	862,3	200	2215	6592,3	306,4	21,86	0,352
SP	14	4	48	56	-862,3	200	2215	13184,5	781,6	43,7	0,276
SR	56	4	48	224	0	200	4430	6592,3	259,9	21,86	0,415
BS	32	4	80	128	287,4	200	6645	17304,6	466,7	34,4	0,364
BP	16	4	118	64	-287,4	200	6645	34604,7	780,9	46,7	0,295
BR	64	4	80	256	0	200	13290	17304,7	399,7	34,4	0,425
CS					287,4	200	6645				
CB					95,8	200	19935,9				

FIGURE 8 – CALCULATION TABLE

3.6. Tabular Method

To find the torque of the carriers we had to find their rpm. To do this we use the tabular method which we can see below [16].

	SUN	PLANET	RING	CARRIER-S
1	-2	4	1	0
2				
3				
4				
5				

FIGURE 9 - TABULAR METHOD STEP 1

We want to find the speed of the small planet set carrier, when the sun gear is rotating at 862,3 rpm. We first assume that the carrier is fixed, and rotate the ring gear clockwise once.

We have to find how many revolutions the planet- and sun gear make for every time ring gear rotates.

For planet gear: Np = $\frac{Zr}{Zp} * 1$ rev = 4 rev

For sun gear: Ns = $-\frac{Zp}{Zs} * 4$ rev = -2 rev

Then we fix the entire gear set and rotate it counter clockwise once.

	SUN	PLANET	RING	CARRIER-S
1	-2	4	1	0
2	-1	-1	-1	-1
3				
4				
5				

FIGURE 10 - TABULAR METHOD STEP 2

After that we add the two sums together.

	SUN	PLANET	RING	CARRIER-S
1	-2	4	1	0
2	-1	-1	-1	-1
3	-3	3	0	-1
4				
5				

FIGURE 11 - TABULAR METHOD STEP 3

Now we want to multiply this value with another value which will give us a Sun speed of 862,3 rpm.

862,3/-3 = -287,4

	SUN	PLANET	RING	CARRIER-S
1	-2	4	1	0
2	-1	-1	-1	-1
3	-3	3	0	-1
4	X-287,4	X-287,4	X-287,4	X-287,4
5	862,3	-862,3	0	287,4

FIGURE 12 - TABULAR METHOD FINAL STEP

Similar methods are used to find the carrier speed of the second carrier.

3.7. Factor of Safety

It is important to design a component with fatigue and overload in mind. Factor of safety is a very important aspect of mechanical engineering.

We have to design our transmission system with a minimum factor of safety value of 2. Obtaining this value means that our system can withstand double the amount of maximum forces, before failure occurs.

Factor of safety **(n)** = $\frac{\sigma yield}{\sigma max}$ [7]

For our sun gear we have a factor of safety of:

n = $\frac{1531.32}{306,4}$ = 4,99 = 5

4. ELECTRIC DRIVE CALCULATIONS

4.1. Three Phase Induction Motor

Equation below is used to estimate the speed of the induction motor of our system.

$$\text{Ns} = \frac{\mathbf{120\ F}}{\boldsymbol{p}} \qquad [17]$$

Equation one is used to calculate the synchronous speed of the induction motor.

Ns stands for synchronous speed of the induction motor in RPM.

P stands for the number of poles

F denotes the frequency of the motor in Hertz

Using the parameters of our induction motor, which has four poles and a frequency of 60Hz we can calculate the rotational speed of our induction motor as follow.

$$\mathbf{Ns} = \frac{\mathbf{120*60}\boldsymbol{Hz}}{\mathbf{4}} = \mathbf{1800rpm}$$

To determine the full-load motor toque we use equation two. We need to know the full load motor torque before we can determine the required braking torque of the induction motor [18].

$$T_{im} = \frac{5252\text{HP}}{Sn}$$

Where:

$\mathbf{T_{im}}$ stands for full load motor torque

5252 is a standard constant

HP is the induction motor's horsepower

Sn is the speed of the induction motor

Our induction motor has a horsepower of 322hp, and a shaft speed of 1800 rpm.

$$T_{im} = \frac{5252 * 322hp}{1800rpm} = 940 \text{ lb-ft.}$$

To be able to model our induction motor in Simulink, we have to first define the mathematical sets describing the motor. [19] They are required in order to be able to model and simulate the induction motor and the control system of our integrated electric drive using DTC :

$$\Psi ds \frac{d}{dt} = R_s i_{ds} + Ws\Psi qs + Vas$$

$$\Psi qr \frac{d}{dt} = - R_s i_{qs} - Ws\Psi qs + Vqs$$

$$\Psi dr \frac{d}{dt} = - R_r i_{dr} (W_s - W_r \ \ )\Psi d$$

$$\Psi dr \frac{d}{dt} = - R_r i_{dr} + -(Ws - Wr)\Psi dr$$

We use circuit analysis of figure 13 to derive necessary equations.

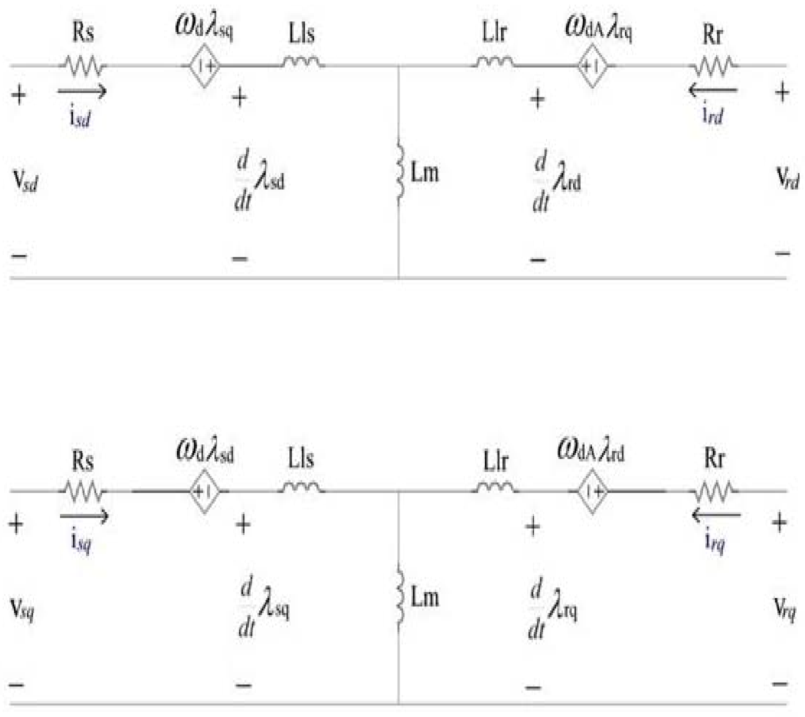


FIGURE 13 - EQUIVALENT CIRCUIT FOR AN INDUCTION MOTOR IN D AND Q AXIS [20]

We use the derived equations [19] below to estimate the flux and torque based on currents and the control voltage inputs:

$$\mathbf{\Psi ds = L_{is}\, i_{ds} + L_m\, (i_{ds} + i_{dr}) = L_{is}\, i_{ds} + L_m\, i_{dr}}$$

$$\mathbf{\Psi dr = L_{ir}\, i_{dr} + L_m\, (i_{ds} + i_{dr}) = L_{ir}\, i_{dr} + L_m\, i_{dr}}$$

$$\mathbf{\Psi dm = L_m\, (i_{dr+}\, i_{ds})}$$

$$\mathbf{\Psi qs = L_{is}\, i_{qr} + L_m\, (i_{qs} + i_{qr}) = L_{is}\, i_{qs} + L_m\, i_{qr}}$$

$$\mathbf{\Psi qr = L_{ir}\, i_{qr} + L_m\, (i_{qs} + i_{qr}) = L_{ir}\, i_{qr} + L_m\, i_{qr}}$$

$$\mathbf{\Psi qm = Lm\, (i_{qs\,+}\, i_{qr})}$$

$$\mathbf{T_e = \frac{d}{dt}\frac{3}{2} \quad (\Psi_{ds}\, i_{qs\,-}\, \Psi_{qs}\, i_{ds})}$$

Where:

- Ψ = stator flux
- $\mathbf{T_e}$ = motor torque
- i_{ds} and i_{dr} = stator currents in d and q axis
- Ψdr and Ψds are quadrature component of stator flux.
- Ψqs and Ψqr denotes direct and quadrature axis components of rotor flux.
- R_S = stator resistances.
- R_r = rotor resistances.
- L_m, L_{is} and L_{ir} stands for stator and rotor mutual inductances
- V_{ds} = stator voltage in d axis
- V_{qs} = voltage in q axis

- W_s = stator angular speed
- W_r = rotor angular speed. Normally the Ψds is fixed along the d axis. This makes the Ψqr equal to zero [19].

To determine the mathematical model needed to model the voltage inverter, we expand the formula below.

$\Psi ds \frac{d}{dt} = R_S i_{ds} + Ws\Psi qscVas$

$\Psi dr = L_{ir}\, i_{dr} + L_m\, (i_{ds} + i_{dr}) = L_{ir}\, i_{dr} + L_m\, i_{dr}$

Neglecting the rotor resistance, we can integrate the equation above to become

$\frac{d\Psi s}{dt} = V_s$

Neglecting the rotor resistance, we can integrate the equation above to become

$\frac{d\Psi s}{dt} = V_s \frac{d}{dt}$

$V_s = \frac{3}{2} V\mathbf{ds}\ (S_a\, \Psi e^{\frac{-2i\omega t}{3}} + S_b\, \Psi e^{\frac{-4i\omega t}{3}} + S_C\, \Psi e^{\frac{-8i\omega t}{3}})$

These equations are used to create a model of the inverter in Simulink.

4.2. Power Requirements

This section of our document shows the calculations done to determine the amount of power our electric drive unit need to deliver. Considering that the vehicle will drive in different road conditions, we have to choose an induction motor that will be able to provide the power required in different road conditions.

The max speed of our truck is a constant speed of 80km/h. For a big heavy truck to be able to move at this kind of speed, the driving motor have to provide enough power to overcome the motion resistive forces. This means that the sum of all the forces acting on the truck must be zero.

$$\sum \mathbf{F} = 0 \qquad [2]$$

We assumed that the four main motion resistive forces acting on the truck will be:

- Drag force
- Rolling resistance
- Aerodynamic force
- Forward drive force, which is provided by the motors.

The forward force must be greater than the motion resistive forces in order for the vehicle to move forward. Assuming that the rolling resistance force for the truck on fine concrete road will be nearly 1.1% of the vehicle's weight and the drag coefficient is 0.84, we calculate the required power $\mathbf{P_p}$ as follows:

Table 3 below shows the parameters related to power requirement calculations.

DESCRIPTION	VALUE
The coefficient of rolling friction $\mathbf{C_{rr}}$	0.03
The ambient air density **p** at 0° C	1.225 kg/m3
Acceleration due to gravity **g**	9.81 m/s^2
Mass factor $\mathbf{f_m}$	1.05
The vehicles frontal area (A)	3000mm
The total weight of the vehicle W_{eig}	30 * 10^3 kg
Wind speed indoors $\mathbf{V_W}$	Negligible
Road slope angle (**θ**) is estimated to be	20.00°
The Desired top speed	80 Km/h
Acceleration time from 0 to 80 km/h is estimated to be	10 seconds.
Aerodynamic drag coefficient C_d	0.89

TABLE 4 PARAMETERS OF OUR SYSTEM

First we convert desired speed in km/h to m/s. S_{top} stands for the desired top speed [2]:

$$S_{top} = \frac{(80*10^3)}{3600} = 23 \text{ m/s}$$

We then use this equation to estimate the acceleration at the desired speed.

$V = V0 + at$

Which results in acceleration   a = 2.3m/s^2

To estimate the aerodynamic force of our system, we use following equation

$F_{aero} = \frac{1}{2} C_d AV^2$ [21]

$F_{aero} = 0.5*0.89*3*7*1.225*(\frac{80*10^3}{3600})^2$

$F_{aero} = 57N$

To estimate the total motion resistive forces we use [15]:

$F_{tot} = F_m Ma + MgCrr \cos\theta + \frac{1}{2} pAC_d (V - V_w)^2 + Mg \sin\theta$

$F_{tot} = F_m Ma + Mg\ Crr \cos(0) + \frac{1}{2} pAC_d (V - V_w)^2 + \sin(0)$

$F_{tot} = F_m Ma + Mg\ Crr * \frac{1}{2} pAC_d (V - V_w)^2$

$F_{tot} = F_m Ma + MgCrr + \frac{1}{2} pAC_d (V - V_w)^2$

$F_{tot} = F_m Ma + MgCrr + \frac{1}{2} pAC_d (V - V_w)^2$

$F_{tot} = F_m Ma + MgCrr + \frac{1}{2} pAC_d (V - 0)^2$

$F_{tot} = F_m Ma + MgCrr + \frac{1}{2} pAC_d V^2$

$\sum \mathbf{F} = 0$

In order for the vehicle to move forward the equation underneath has to balanced

$F_{drag} + F_{roll} + F_{aero} = F_F$

Where

F_{drag} = the drag force

F_{roll} = the rolling force

F_{aero} = aerodynamic

F_F = the forward force.

We used equation underneath to estimate the power needed to drive the heavy-duty vehicle forward.

$P_p = (F_{drag} + F_{aero} + F_{roll})V$ [18]

$P_p = \frac{1}{2} C_d \, pV^2 A + F_{aero} + F_{drag} * W_{eig}) \, V$

$$P_p = (\frac{1}{2} *0.79*1.225*(\frac{80*10^3}{3600})^2 *2.7*7+ 57+0.011*30000*9.81)*\frac{80*10^3}{3600}$$

$\mathbf{P_p}$ = 200 Kilo watts

The estimated power needed is nearly 200 kilo watts.

This means that the estimated power need of our vehicle is approximately 200 kilowatts. Since our system is driven directly by two induction motors, one of the two motors will have to deliver a minimum power of 100 kilo watts.

The motor type we chose to use deliver 200 Kilo watts peak power and 85 kilo watts continuously. This means that two induction motors of this type will deliver 400 kilo watts peak power and 170 kilo watts continuously. The motor are perfect for our system, but a motor type delivering 150 kilo watts continuously would do perform much better.

4.3. Battery Calculations

One of the requirements from KA states that we should create as much as possible place for battery unit. We need to know the number of batteries needed to drive our electric drive unit.

Assuming that 200 kilo watts I s the maximum power needed to drive our vehicle and the battery unit delivers 800 volts DC, we used the equation below to estimate the current needed to generate a constant power of 200*10^3 Watts.

P= IV

$$\mathbf{I} = \frac{\mathbf{P}}{\mathbf{V}} = \frac{\mathbf{200*10^3 Watts}}{\mathbf{800}\boldsymbol{Volts}} = \mathbf{250\ Amps}$$ [2]

This means that our battery unit needs to deliver a consistent current of 313 Amps to generate the power of 200 Kilowatts. We want to run 200 Kilowatts with 750 V_{AC} from an inverter for 10 hours.

Watts-Hour = Watts* Hours = 200 kilo watts *10 hours = 2000 Kilowatts per 10 hours.

Assuming the efficiency of 90%

Watt-hours = watts * hours / efficiency = 200 Kilowatts *1 hour /0.90 = 222 Kilo watts per hour.

313 Amps* 10 hours = 3130 Amps hour.

In order to satisfy the requirement about more place for the battery unit we need to at least create a place big enough to accommodate 5 LiFePO4 144V 100AH battery packet.

The battery type chosen for our system is

5. REFERENCES

[1] S. Bjørkgård, *Product Requirement Targets,* Kongsberg: Kongsberg Automotive, 2016.

[2] J. Haugan, Formeler og Tabeller, Vigmostad og Bjørke AS, 2016.

[3] L. Deal, "Truckpartsandservice.com," 10 02 2011. [Online]. Available: http://www.truckpartsandservice.com/volvo-trucks-and-fontaine-create-new-fifth-wheel-system/. [Accessed 08 05 2017].

[4] Press Kogyo co ltd., "Presskogyo.com," [Online]. Available: http://www.presskogyo.co.jp/en/products/parts.html. [Accessed 05 05 2017].

[5] R. C. Hibbeler, Mechanics of materials, Ninth Edition, 2014.

[6] E-Axle, "Design Document," E-Axle, Kongsberg, 2017.

[7] S. C. a. G. Strømsnes, Konstruksjons elementer, Oslo: Gyldendal Norsk Forlag, 1991.

[8] Oregon State University, "oregonstate.edu," [Online]. Available: http://classes.engr.oregonstate.edu/mime/winter2013/me383-001/Factor%20of%20Safety.pdf. [Accessed 15 04 2017].

[9] K. Nice, "science.hostuffworks.com," How stuff works, [Online]. Available: http://science.howstuffworks.com/transport/engines-equipment/gear7.htm. [Accessed 10 04 2017].

[10] woodgears, "woodgears.ca," [Online]. Available: https://woodgears.ca/gear/planetary.html. [Accessed 12 4 2017].

[11] Qtc Metric Gears, "qtcgears.com," [Online]. Available: http://qtcgears.com/tools/catalogs/PDF_Q420/Section%203.pdf. [Accessed 12 04 2017].

[12] E-Axle, "Technical Document," E-Axle, Kongsberg, 2017.

[13] Kohara Gear Industry Co.,Ltd., "khkgears.net," Kohara Gear Industry Co.,Ltd., [Online]. Available: http://khkgears.net/gear-knowledge/abcs-gears-b/basic-gear-terminology-calculation/. [Accessed 12 04 2017].

[14] Engineers Edge, "engineersedge.com," [Online]. Available: http://www.engineersedge.com/gears/lewis-factor.htm. [Accessed 12 04 2017].

[15] V. K. Yogesh C. Hamand, "http://www.scirp.org/," 5 11 2011. [Online]. Available: http://file.scirp.org/pdf/MME20110200005_90260471.pdf. [Accessed 2 05 2017].

[16] Eric Constans and Rowan University, "benctophybrid.com," [Online]. Available: http://benchtophybrid.com/PG_Analysis_Intro.html. [Accessed 29 04 2017].

[17] Electrical 4u, "Electrical4u.com," [Online]. Available: https://www.electrical4u.com/speed-control-of-three-phase-induction-motor/. [Accessed 05 05 2017].

[18] L&S electric inc., "lselectric.com," [Online]. Available: http://www.lselectric.com/the-abcs-of-large-induction-motors-part-1/. [Accessed 10 05 2017].

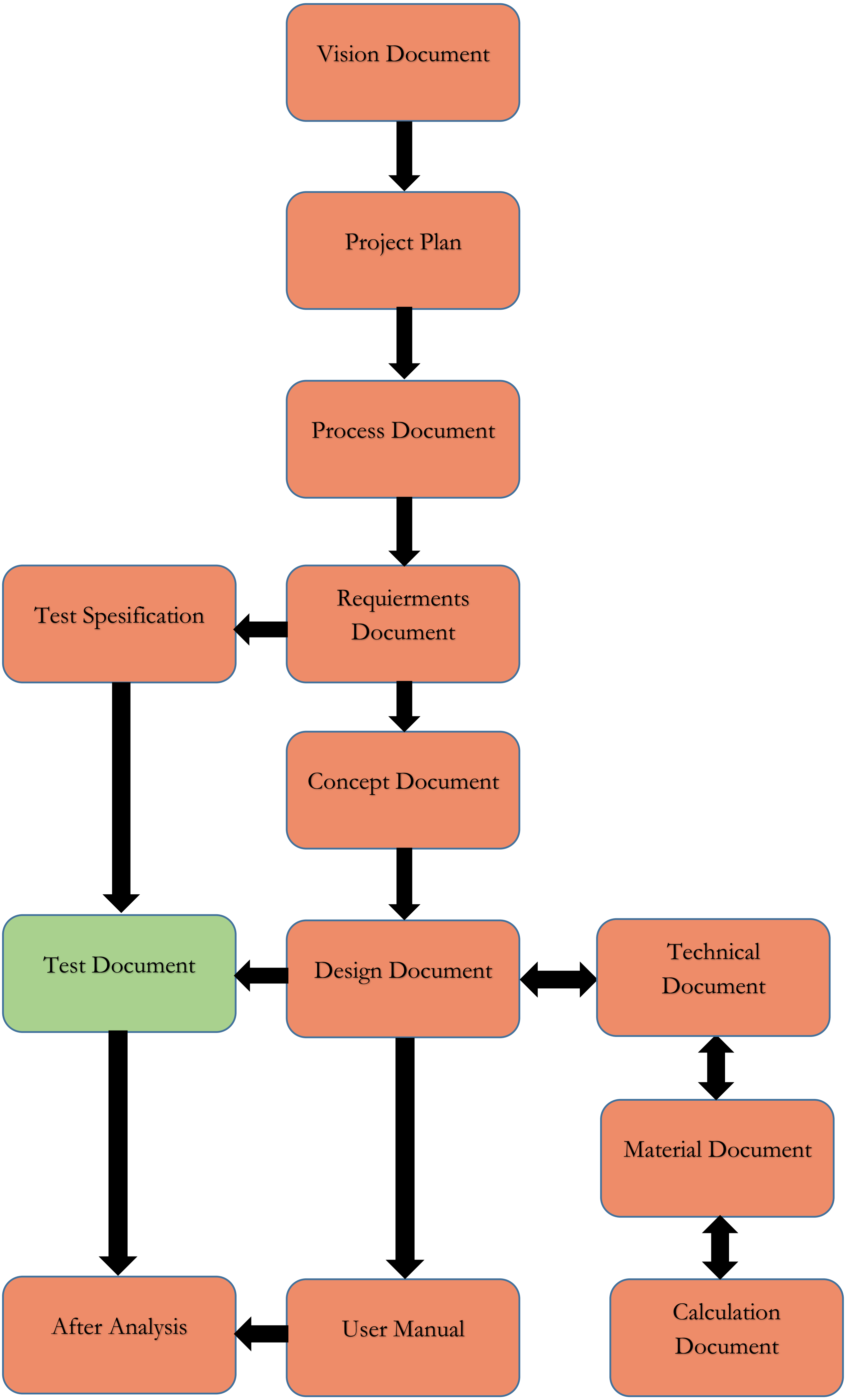
[19] M. Popescu, "motor-designs.com," 2000. [Online]. Available: https://www.motor-

design.com/cmsAdmin/uploads/induction_motor_modelling.pdf. [Accessed 14 05 2017].

[20] H. Ø. Røstøen, "Rostoen.com," 17 06 2002. [Online]. Available: http://rostoen.com/Elkraft/DIPLOMOPPGAVE%20WEB/Wind%20Turbines%20NTNU%20Diplom%20oppgave.htm. [Accessed 15 05 2017].

[21] Y. A. Ç. &. J. M. Cimbala, "iu.hio.no," McGraw-Hill , 2010. [Online]. Available: http://www.iu.hio.no/~ivarj/fluid%20mechanics/FM_2e_SM__Chap11.pdf . [Accessed 10 May 2017].

[22] Scholar Express, "Scholarexpress.com," [Online]. Available: http://scholarexpress.com/gear-terminology/. [Accessed 29 04 2017].


Vision Document
Project Plan
Process Document
Test Spesification
Requierments Document
Concept Document
Test Document
Design Document
Technical Document
Material Document
After Analysis
User Manual
Calculation Document

TEST DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

Employer	Kongsberg Automotive			
Group Members	**Name**		**Initials**	
	Abubakar Khan		AK	
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	Pawan Bhatt		PB	
Document Information	**Version**	**Date**	**Approved**	**Pages**
	2.0	23.05.17	AS	91

21. mai 2017

TEST DOCUMENT

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

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LIST OF TABLES

LIST OF FIGURES

REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
17.04.17	0.1	Document created	AK
20.04.17	0.2	Test 1.5 added	AK
21.04.17	0.3	Minor updates and changes	AK
27.04.17	0.4	Update and changes	AK
01.05.17	0.5	Minor changes	AK
02.05.17	0.6	Changes to the test and minor updates	AK
03.05.17	1.0	Another test added	AK
04.05.17	1.1	Added transmission test	AS
08.05.17	1.2	Updated transmission test	AS
10.05.17	1.3	Added electric drive	ERB
12.05.17	1.4	Layout corrections	AS
15.05.17	1.5	Updated durability test	AK
16.05.17	1.6	Max force test added	AK
18.05.17	1.7	Electric tests added	AK & ERB
18.05.17	1.8	Grammar and reference revision	AS
18.05.17	1.9	A-arm tests changed and updated	AK
19.05.17	1.10	Test 1.9 added	AS
23.05.17	1.11	Updated the document	PB
23.05.17	2.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
KA	Kongsberg Automotive
FEM	Finite Element Method
FEA	Finite Element Analysis
kN	Kilo Newton
MPa	Mega Pascal
CAD	Computer-Aided Design
3D	Three Dimensional
KW	Kilo Watts
RPM	Revolution Per Minute
HP	Horsepower
DTC	Direct Torque Control
V_{DC}	Volt direct current
GVW	Gross Vehicle Weight

TABLE 2 - DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

The purpose of this test document is to validate all system requirements that have been given to us by KA [1]. We must make sure that all the requirements are met through testing and validating.

Test will be done mostly in 3D CAD modeling. Because we are making a conceptual design and not a physical construction of our model, most of the tests are done with non-physical products. This document will give an overview of how we test our system and to discover if there are any defects within our system. We use Solidworks to do the Finite Element Analysis of different parts. In addition we have done simulations in Simulink, and programming in Arduino. Each test will be referred to its respective requirement- and test tables [2] [3].

1.1. Scope

The scope of this document is the following:

- Requirements validation
- FEM tests
- Arduino programming test
- Simulation in Simulink

2. DURABILITY A-ARM X- AND Y-AXIS

In this finite element analysis we will prove that the A-arm is able to handle the working forces. We will show that it is able to handle 50 kN from both x- and y-axis. The load and weight of the vehicle will also be taken into consideration in this test. The load from the vehicle working on the wheel is 60 kN.

ID	REQ1.16	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.5
DESCRIPTION Durability is 50 kN in both of x- and y-axis on each wheel			**PRIORITY**
WHY	To withstand forces from different directions under driving in curve roads		A
COMMENTS			

TABLE 3 - REQUIREMENT 1.16

TEST ID	TES 1.5	**REQ ID**	1.16 - 1.17 - 1.18
DESCRIPTION	These requirements will be tested using SolidWorks simulations.		**STATUS** Verified

TABLE 4 - TEST 1.5 DURABILITY A-ARM X AND Y AXIS

2.1. Test Procedure

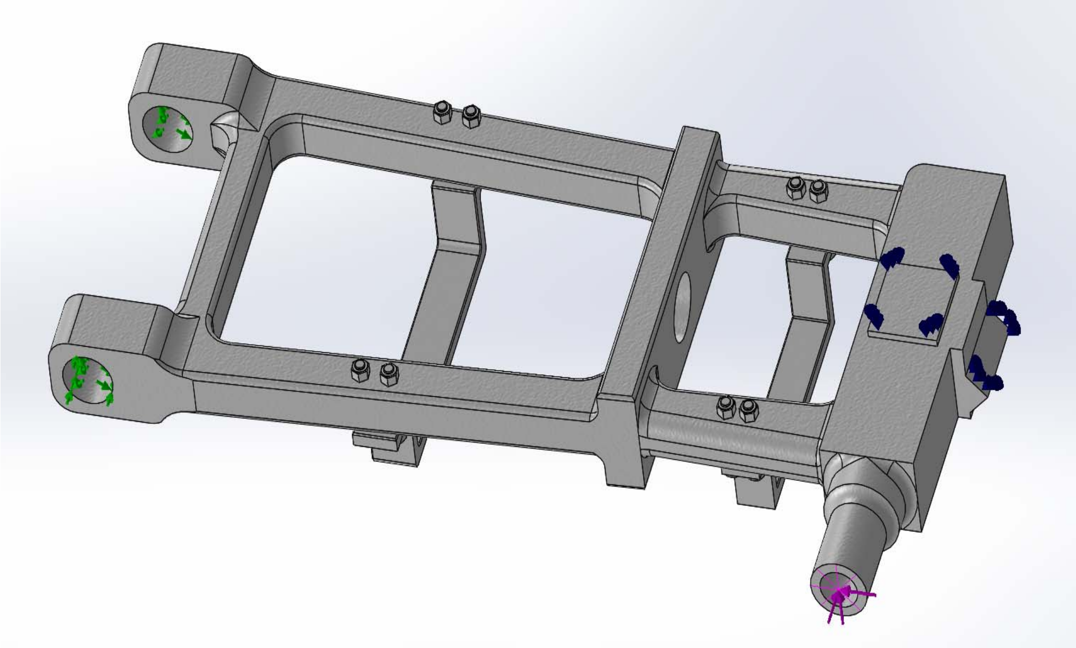


FIGURE 1 - FORCES AND FIXTURES

2.1.1. Simplifications and Assumptions

During A-arm testing, some simplifications and assumptions have to be made. To place the working forces, we have to apply forces coming from all directions of x, y and z on the midpoint of the wheel holder (fig. 2). This simplification allows us to apply the force properly, making it as close to reality as possible.

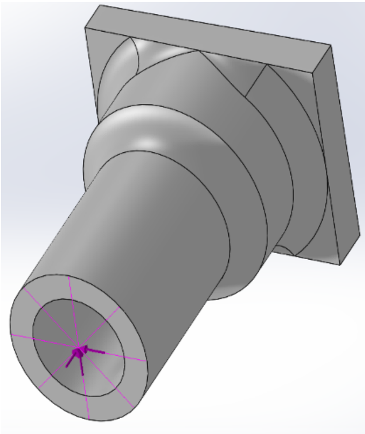


FIGURE 2 - SECTION VIEW OF WHEEL HOLDER (ANALYSIS)

The actual wheel holder in green is an independent part that is mounted to the wheel hub holder (fig. 3). The reason we make a simplifying illustration of the wheel holder in our analysis (fig. 2), is because it takes less time to run the analysis.

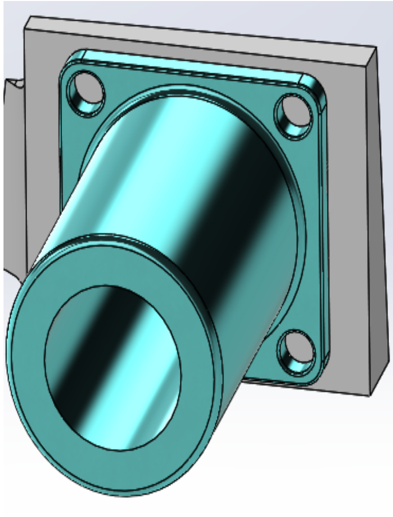


FIGURE 3 - SECTION VIEW OF WHEEL HOLDER (ACTUAL PART)

Another simplification we make is the air bellow and shock absorber, which is part of the wheel suspension system. From figure 4 we can see that the fixture on the top face illustrates the air bellow and the right face illustrates the shock absorber.

If we don't make the necessary simplifications and assumptions, it will become more time consuming. A test can take up to several hours if it is too big. Hence, the necessary simplifications.

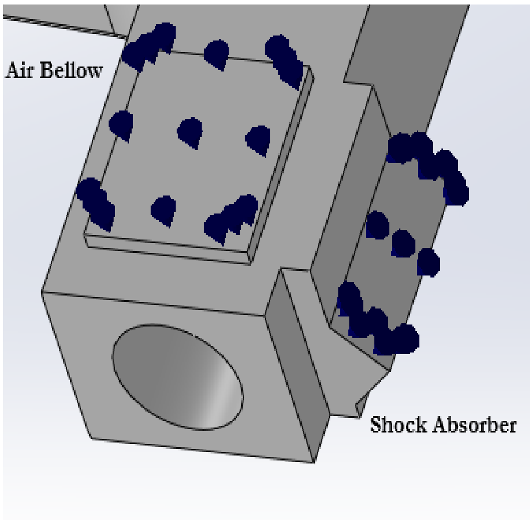


FIGURE 4 - AIR BELLOW AND SHOCK ABSORBER ILLUSTRATION

2.1.2. Fixtures

Applied fixtures are in two big holes that connect the arm to the frame of the vehicle (fig. 5). However, the fixtures have been applied differently in the two holes.

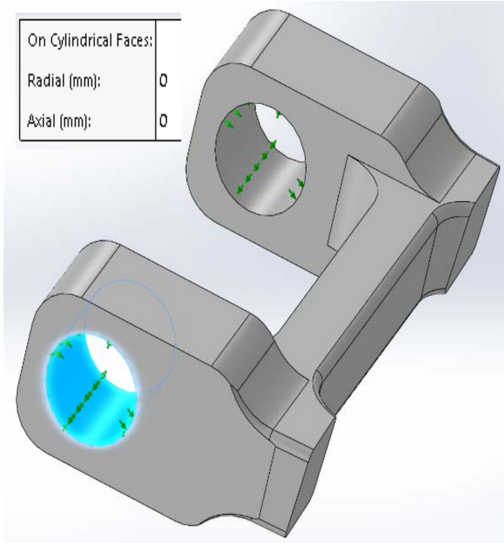


FIGURE 5 - FIXTURES, LEFT HOLE

From figure 5 we can observe that the fixtures have been made on the cylindrical face of the holes. The fixture has been applied in such a way so that radial and axial directions has been locked, and the circumferential direction is free to move.

To get a better understanding of the directions, we can take a look at figure 6. It explains what the different directions mean.

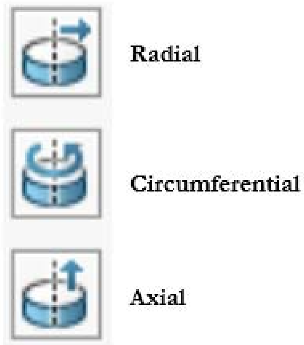


FIGURE 6 - DIRECTIONS OVERVIEW

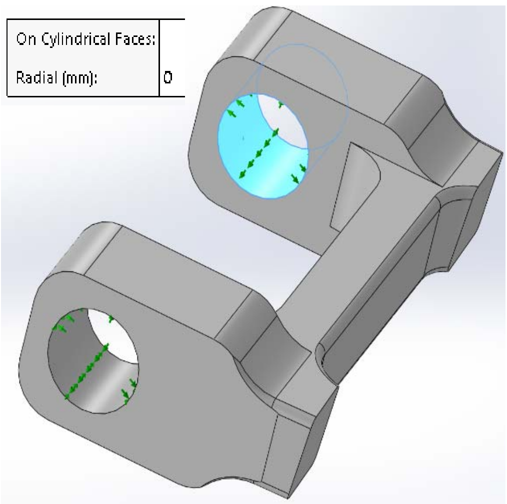


FIGURE 7 - FIXTURES, RIGHT HOLE

Marked hole (fig. 7) has a fixture that's been applied on the cylindrical face. However, the fixture has been made in such a way that the circumferential and axial direction is locked, but the radial direction is free to move.

Another fixture we have made is on the air bellow and shock absorber. Black dots on the top face represent air bellow fixture, and right face represents shock absorber.

This is an elastic support fixture. We have added a value for the stiffness for both the air bellow and shock absorber. We assume that the arm will move 5 mm when exposed to the applied forces. To find the stiffness value we divide 60 kN (working load on wheel) by 5 mm, and the answer we get from this is 12 million in stiffness. This value of 12 million is than divided between the air bellow and shock absorber. Thus, giving us stiffness of 6 million on each part.

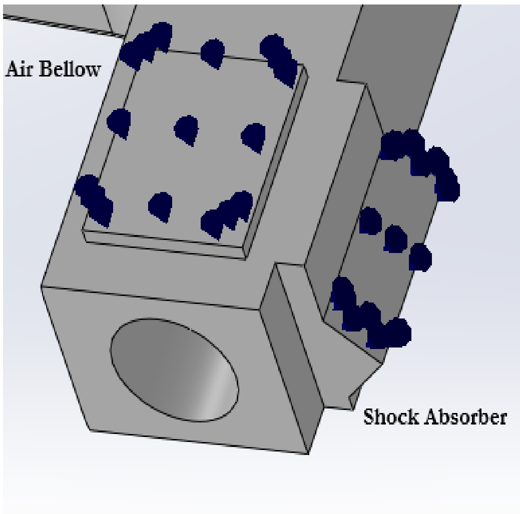


FIGURE 8 - FIXTURES, AIR BELLOW AND SHOCK ABSORBER ILLUSTRATION

2.1.3. Forces

Applied forces on the A-arm are the weight of the vehicle working on the wheel. Z -axis is 60 kN. The x- and y- axis forces are both 50 kN.

As we can observe from figure 9, the applied forces work in z-, x- and y direction of the midpoint on the wheel holder.

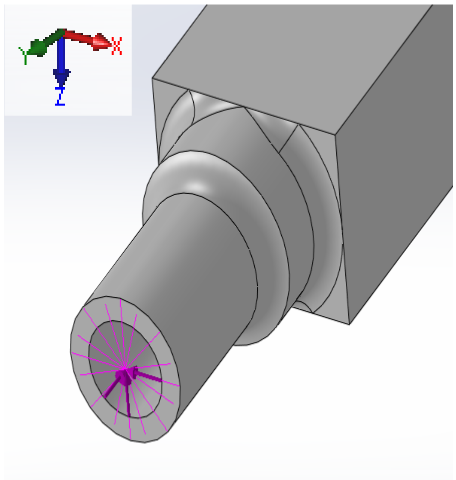
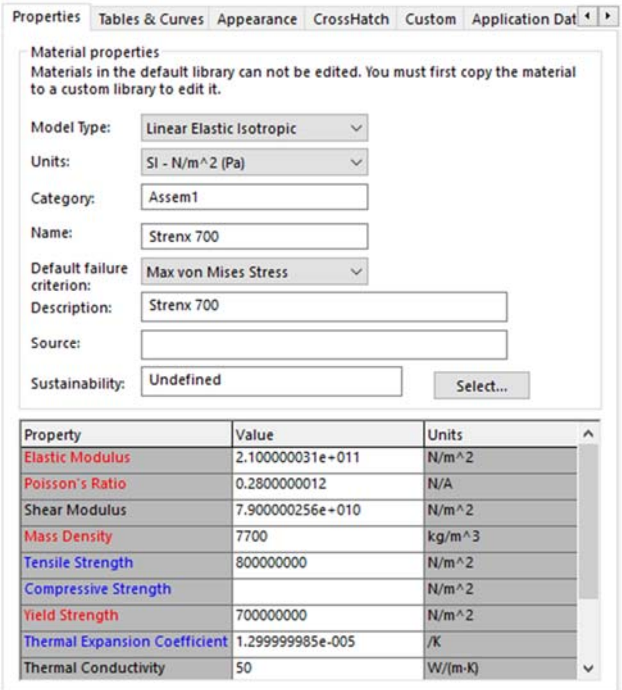


FIGURE 9 - APPLIED FORCES ON WHEEL HOLDER

2.1.4. Material

Same material has been applied on the whole arm. We have chosen Strenx 700 [4]. Mechanical properties for Strenx 700 is shown in figure 10.


Properties | Tables & Curves | Appearance | CrossHatch | Custom | Application Dat

Material properties

Materials in the default library can not be edited. You must first copy the material to a custom library to edit it.

Model Type: Linear Elastic Isotropic

Units: SI - N/m^2 (Pa)

Category: Assem1

Name: Strenx 700

Default failure criterion: Max von Mises Stress

Description: Strenx 700

Source:

Sustainability: Undefined

Select...

Property	Value	Units
Elastic Modulus	2.100000031e+011	N/m^2
Poisson's Ratio	0.2800000012	N/A
Shear Modulus	7.900000256e+010	N/m^2
Mass Density	7700	kg/m^3
Tensile Strength	800000000	N/m^2
Compressive Strength		N/m^2
Yield Strength	700000000	N/m^2
Thermal Expansion Coefficient	1.299999985e-005	/K
Thermal Conductivity	50	W/(m·K)

FIGURE 10 - STRENX 700 PROPERTIES

2.1.5. Result

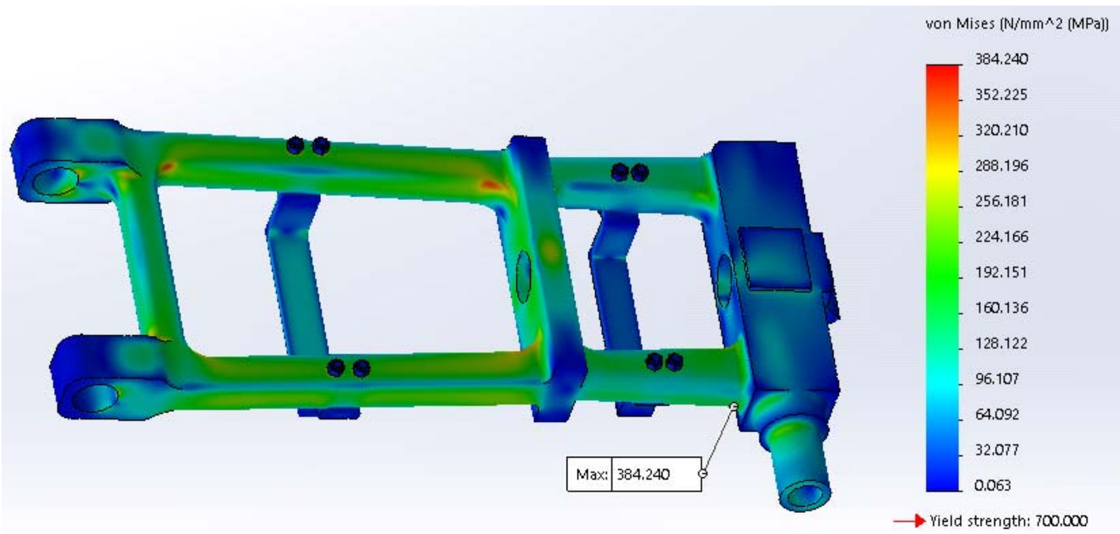


FIGURE 11 - STRESS DISTRIBUTION, ISOMETRIC VIEW

Results show that the highest stress when the forces is applied is 384, 2 MPa. The stress can be seen mostly on the length of the arm and the wheel holder. We calculated the factor of safety too be around 1, 82 [5] which means that the arm can handle up to 1, 82 times the applied forces, but we assume that this only applies to the local max stress area.

Max stress is under the yield strength, but is below the factor of safety.

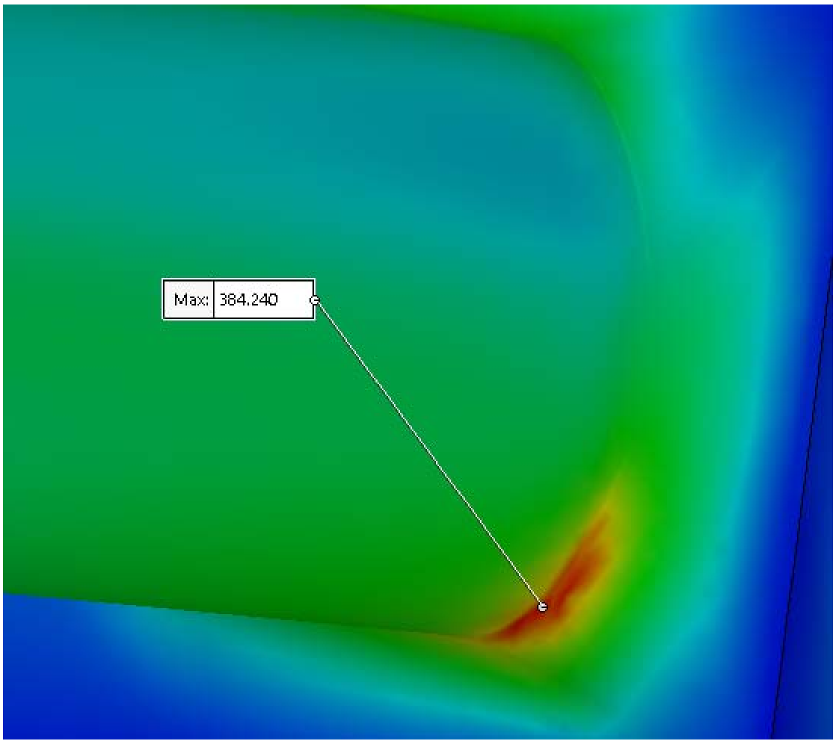


FIGURE 12 - MAX STRESS

From figure 12 we observe that the max stress (384, 4 MPa) is working under the corner of arm close to the wheel holder.

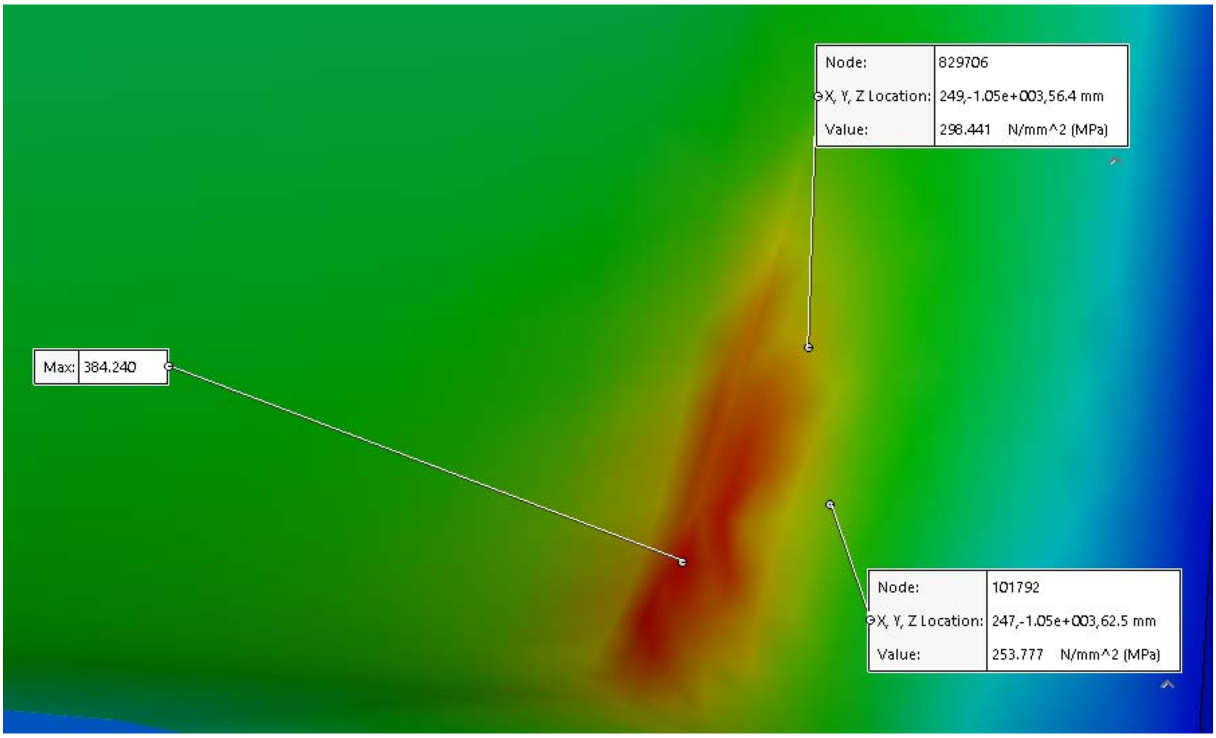


FIGURE 13 - LOCAL MAX STRESS & NODE POINTS

Figure 13 illustrates the max stress working on the corner of the arm edge. We have additionally added 2 node points. These 2 points are close to the local max stress, it is added to demonstrate that the max stress is only local, and we can assume that it has no physical value. This is because the color of max stress changes drastically when it moves out from the corner.

On the 2 added nodes the max stress on those particular areas are 298, 44 MPa and 253, 77 MPa. These results are more realistic.

2.1.6. Deformation

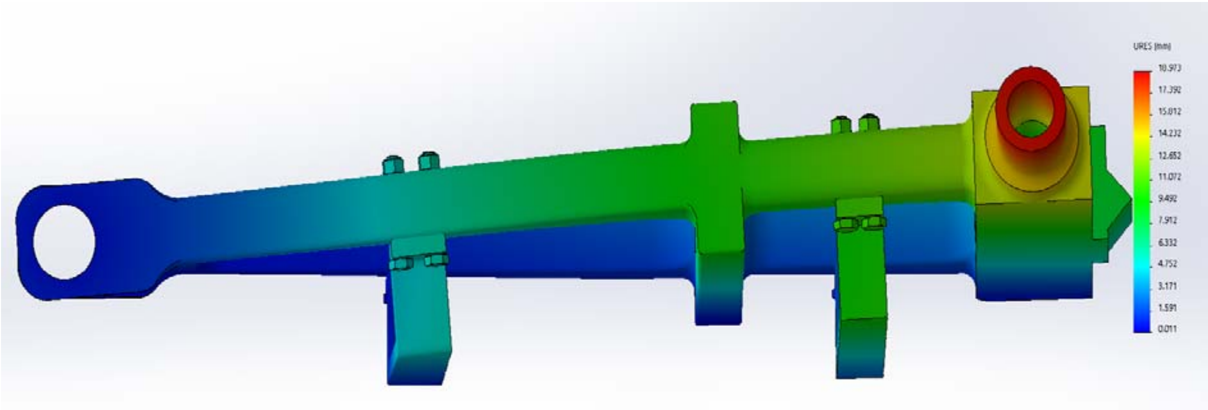


FIGURE 14 - DEFORMATION LEFT SIDE VIEW

From figure 14 we see the deformation of the arm. The displacement is moving up by 19 mm. In reality this is very low and will cause no damage or defect on the system. The illustration is highly exaggerated.

2.1.7. Conclusion

We can conclude that the arm will be able to withstand all the necessary applied forces. This means that the stress working on the arm will not cause any damage. The local max stress is only working on particular areas mostly corners only, we can assume that it has no physical value. The rest of the stress working on the arm is above the factor of safety which is 2.

3. MAX FORCES A-ARM X- AND Y-AXIS

In this test, we will verify that the system can handle applied max forces working on the system. Now instead of the durability force which is 50 kN, we will increase them too 100 kN in both x- and y- axis. We will also take into consideration the load weight of 60 kN working on the wheel.

The only difference in this test from the previous one is that the applied forces from x- and y- axis will be increased to 100 kN.

ID	REQ1.18	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.5
DESCRIPTION Max force should be 100 KN in both of x- and y-axis on each wheel			**PRIORITY**
WHY	To withstand max forces from different directions under driving in curve roads		A
COMMENTS			

TABLE 5 - REQUIREMENT 1.18

TEST ID	TES 1.5	**REQ ID**	1.16 - 1.17 - 1.18
DESCRIPTION	These requirements will be tested using SolidWorks simulations.		**STATUS** Verified

TABLE 6 - TEST 1.5 MAX FORCES A-ARM X AND Y AXIS

3.1. Test Procedure

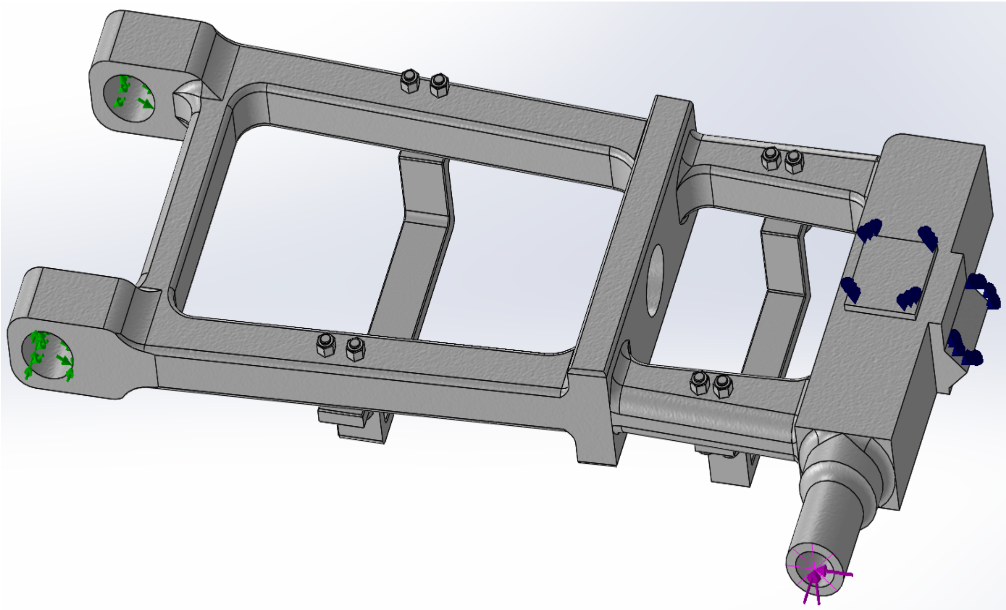


FIGURE 15 - FORCES AND FIXTURES

3.1.1. Simplifications and Assumptions

Same simplifications and assumptions has been done in this test as well (fig. 2 - 4). The only difference is the increased amount of forces applied from x- and y- axis.

3.1.2. Fixtures

We will apply the same fixtures as the previous test (fig. 5 - 8).

3.1.3. Forces

We are going to test the max forces working on the system. Meaning that the only difference is the forces applied in x- and y- axis (fig. 9) which we have increased from 50 kN to 100 kN.

3.1.4. Result

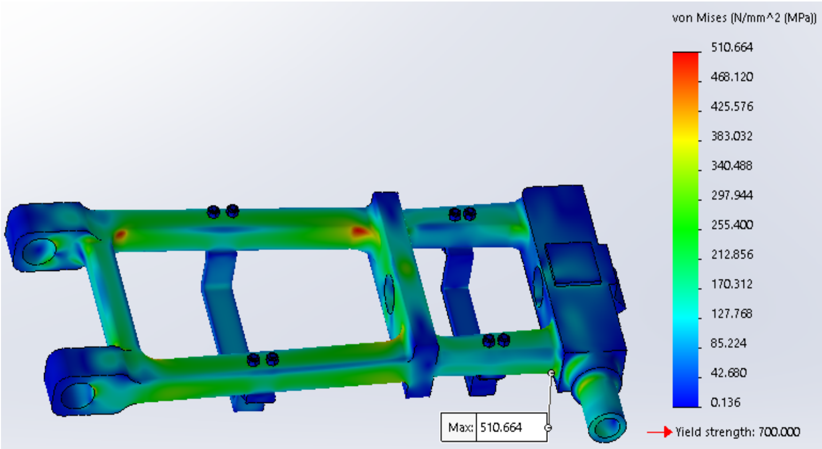


FIGURE 16 - STRESS DISTRIBUTION, ISOMETRIC VIEW

Here the result shows that the highest stress working on the arm when max forces are applied is 510, 6 MPa. As the previous test we can observe most of the stresses working on the length of the arm and on the wheel holder.

However now the stresses working on the arm have increased, because the forces coming from x- and y- axis have been increased to 100 kN.

The factor of safety in this test is calculated to be 1, 37 [5] but this is only on the applied local max stress. The max stress working is under the yield strength of the material.

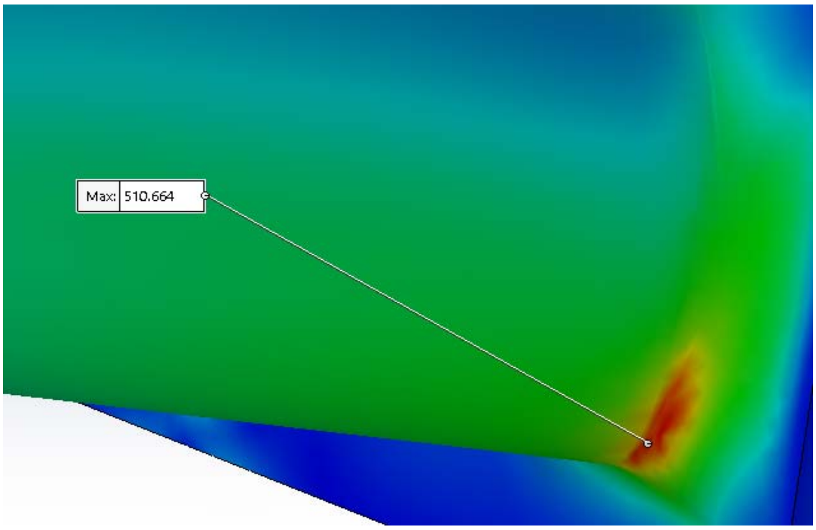


FIGURE 17 - MAX STRESS

Figure 15 shows us the max stress working on the arm. The point of the max stress is same as the previous test, however the stress is higher. As we can see (fig. 17) it is 510, 6 MPa.

3.1.5. Deformation

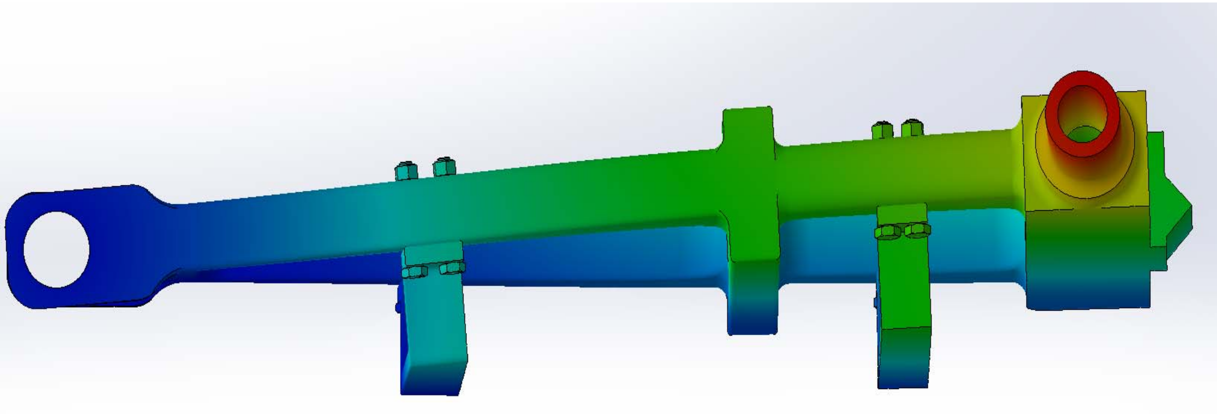


FIGURE 18 - DEFORMATION LEFT SIDE VIEW

The displacement on this test is almost equal to the previous one. It has moved up by around 19 mm. In reality this is very small, and the illustration of figure 16 is highly exaggerated.

3.1.6. Conclusion

We can conclude that the max force working is below the yield strength of the material. It will not cause any damage to the arm. It is like the previous test where the max stress concentration is only working on the corner, so we can assume it will have no physical value. The rest of the stress distribution is above the factor of safety which is 2.

4. TRANSMISSION

Underneath following requirement says that the transmission should have a torque of 30 000 Nm. Requirement 1.10 says it must have a torque of 10 000 Nm. By testing the highest torque value, we will simultaneously verify requirement 1.10. Requirement 1.11 has been verified during initial design of the transmission by having set design criteria to have a gear ratio of 30:1 & 10:1 [6]

This test will provide us with the necessary data to verify if the designed transmission can tolerate the forces acting on it.

The transmission has mainly one force acting upon it. Torsion forces from the motor, to the shaft, then the gears before distributing it to the wheel.

ID	REQ1.09	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION Gear one should have a torque of 30000 NM			**PRIORITY**
WHY	To give more torque to move the vehicle under low speed		A
COMMENTS			

TABLE 7 - REQUIREMENT 1.09

TEST ID	TES 1.4	REQ ID	1.09 - 1.10 - ~~1.11~~ - 1.12 - 1.13 - 1.14- 1.15
DESCRIPTION	These requirements will be tested by using calculations and FEA Method.		STATUS
			Verified
COMMENT	The requirement 1.11 is canceled, therefore we do not need to test it		

TABLE 8 - TEST 1.4 TRANSMISSION

4.1. Test Procedure

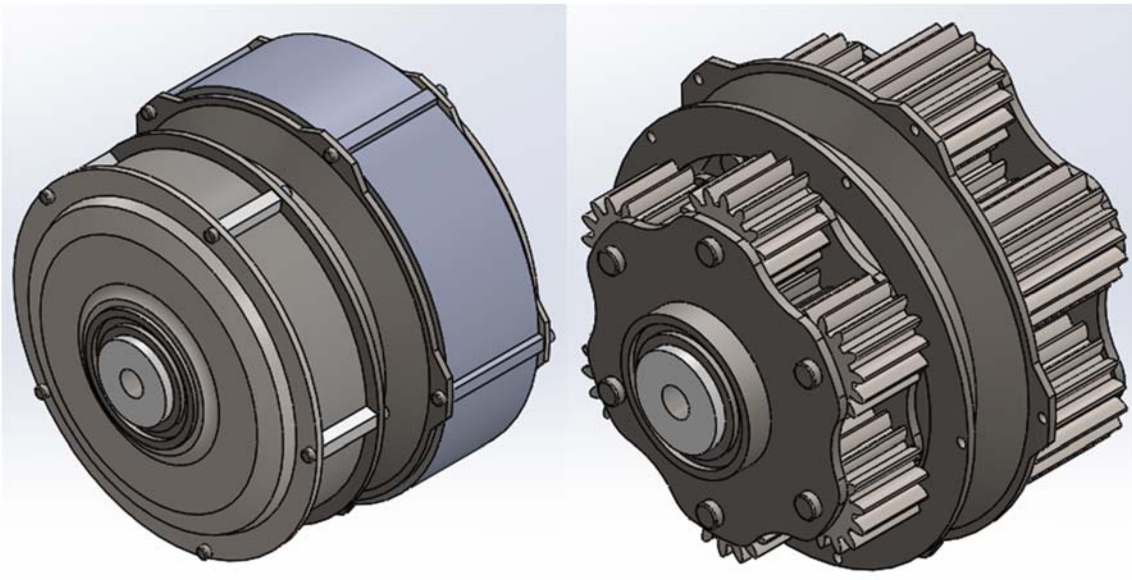


FIGURE 19 – EXTERIOR AND INTERIOR OF TRANSMISSION

In the picture above we can see the assembly we are going to analyze. To the left the transmission exterior and to the right the interior.

4.1.1. Simplifications and Assumptions

To make the testing manageable, some simplifications have been made. Transmission as an assembly is too complex to analyze. Many small parts and gear contacts makes it much more complex to cope with, considering we have only acquired basic analysis knowledge during our FEM course. We have simplified the testing by focusing on one part at a time.

4.1.2. Fixtures

Parts have one main fixture. We use fixed geometry since we don't want the transmission to rotate freely without transferring power. The reason for having this fixture is the purpose of the analysis; which is to verify if the transmission will be able to transfer torque to the wheels, without being deformed. Fixtures have either been placed inside holes or grooves of parts.

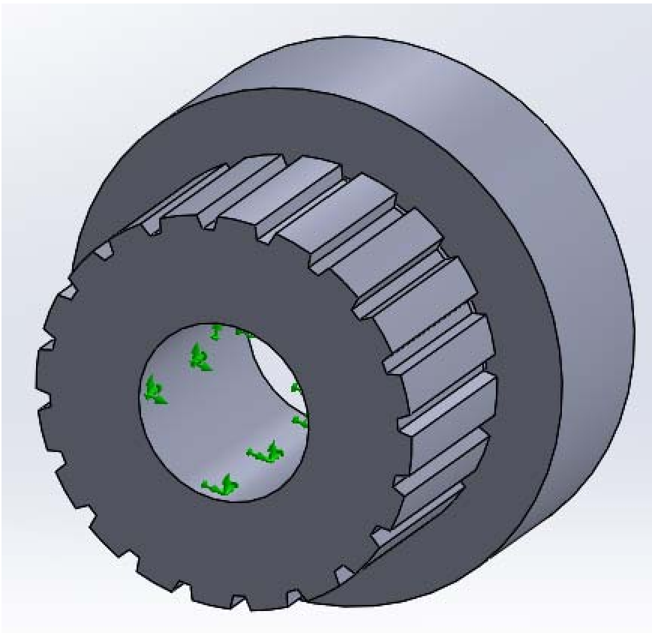


FIGURE 20 – FIXTURES

4.1.3. Forces

Applied force working on these component is the torque force from the motor. We have calculated a torque for each part based on the rpm. These calculations can be reviewed in detail in the Calculations document [5]. Acting force on each part will be mentioned during testing.

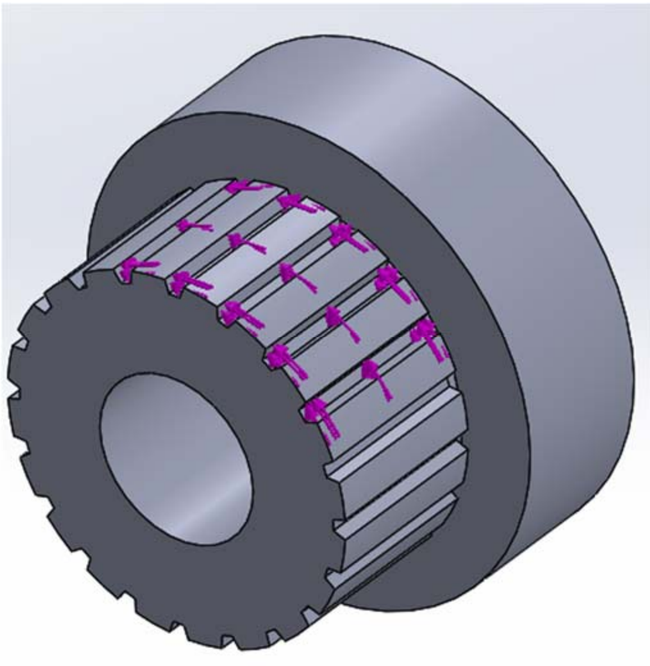


FIGURE 21 – FORCES

4.1.4. Material

We have chosen to use two materials. Applied material on the parts is either AISI 4340 normalized Steel or C61 Ferrium. Ferrium suits gear applications since gear teeth are small and must withstand high forces. Ferrium is only applied where necessary, and bigger parts have been applied with AISI 4340 Steel to save costs where possible [4].

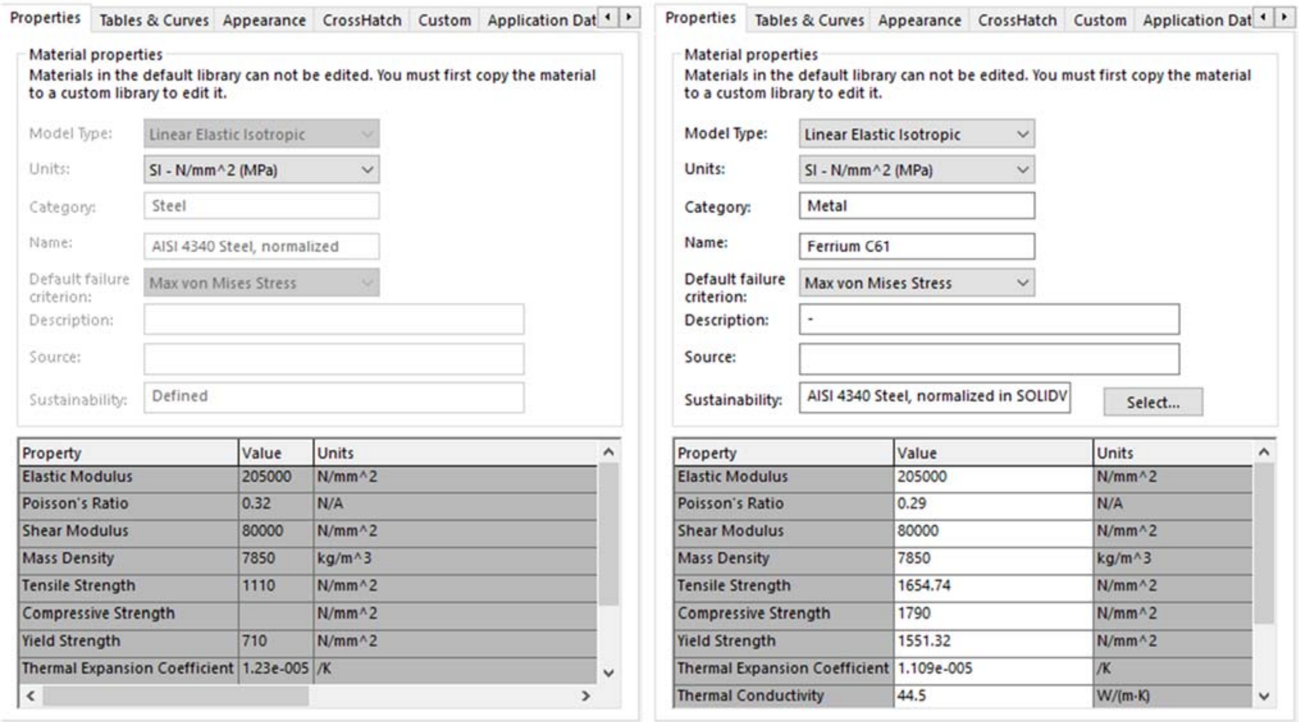


FIGURE 22 – AISI 4340 STEEL & FERRIUM C61 PROPERTIES

4.2. Small Sun Gear

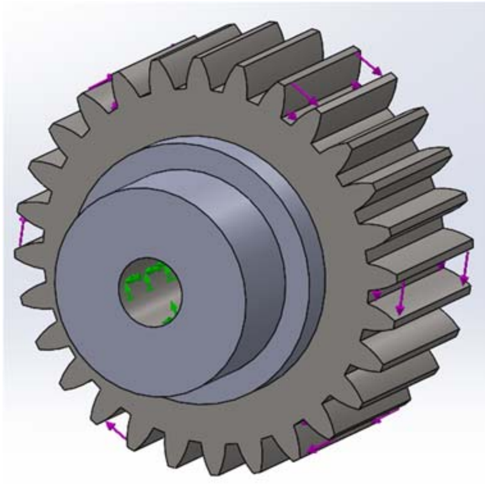


FIGURE 23 - SMALL SUN GEAR

This small sun gear is one of the parts we have tested from the transmission assembly. Fixed geometry is applied inside the hole and torque on gear teeth. Acting force is set to 2215/6 Nm since we have 6 planetary gears that share the torque. Material type is Ferrium C61.

4.2.1. Result

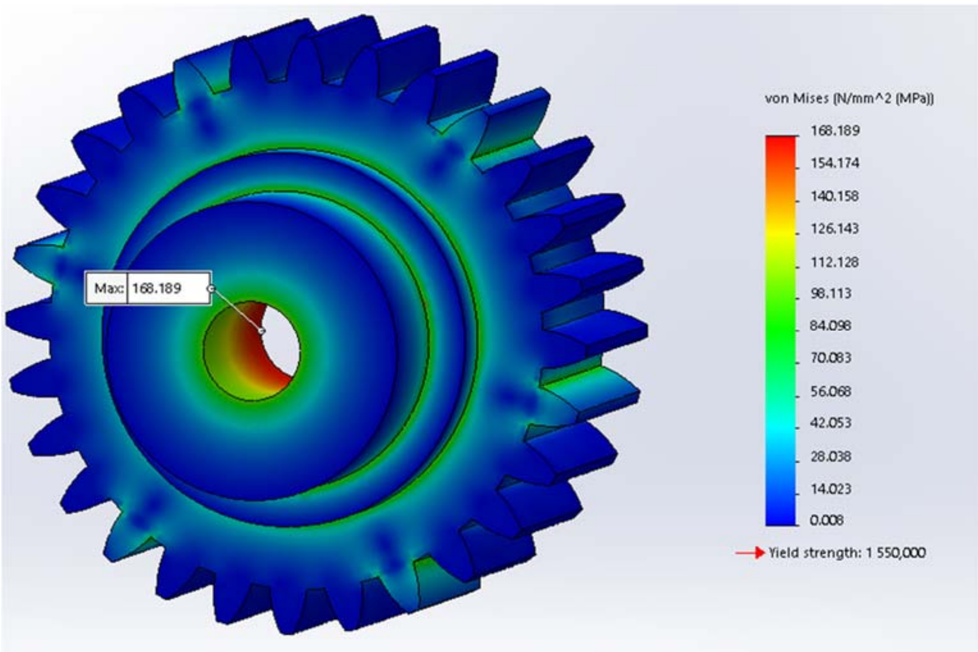


FIGURE 24 –SMALL SUN GEAR RESULT

Results indicate that max stress on the part is 168 MPa. Acting stress is very low compared to the yield strength of 1550 MPa. This stress can be found inside the sun gear, mostly at the back. Since max stress is low, deformation is also small.

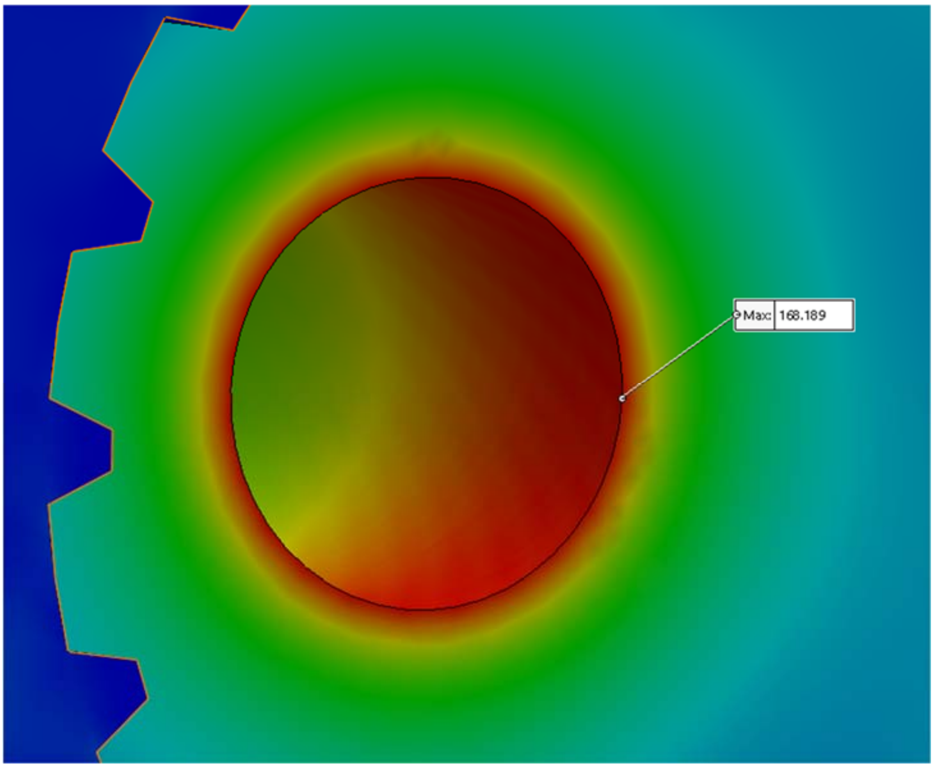


FIGURE 25 - MAX STRESS LOCATION OF SMALL SUN GEAR

As we can observe on the picture above, the sharp edge of the hole is most exposed to max stress.

4.2.2. Deformation

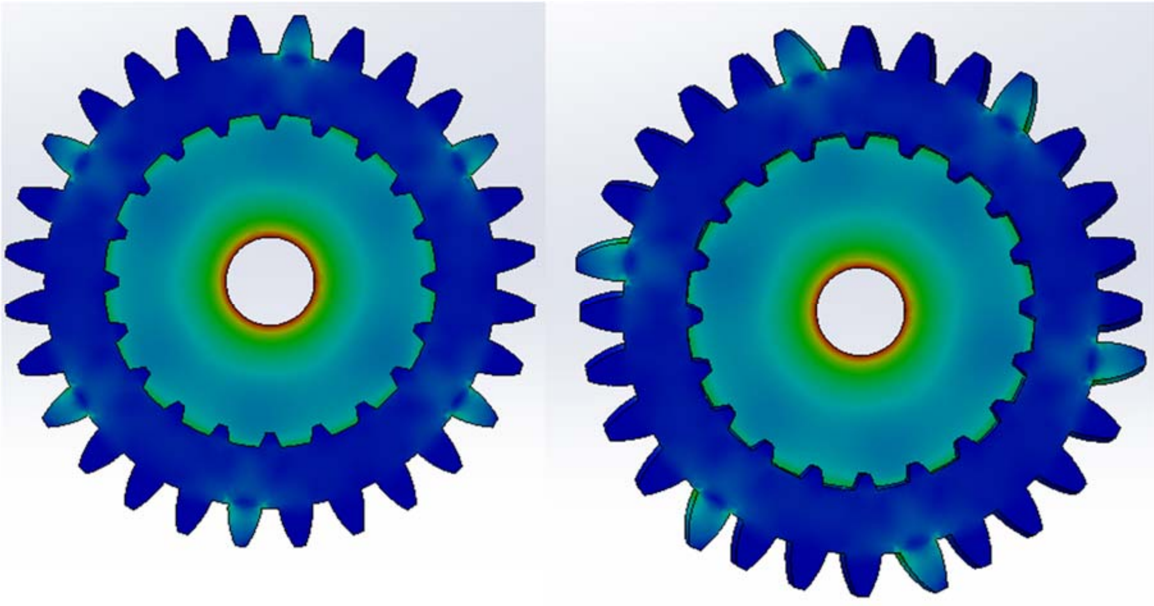


FIGURE 26 - SMALL SUN NORMAL VS DEFORMATION

As mentioned earlier, the deformation will be very small. Because of the small deformation, it's very difficult to observe the change. If we amplify deformation by 500 times we can observe that the teeth which are affected by the force tend to have a slight bending.

4.2.3. Conclusion

Since the acting stress is so low, no re-design will be necessary on this part. FEA verifies that this part can withstand the acting forces and no damage will be done during use.

4.3. Small Carrier

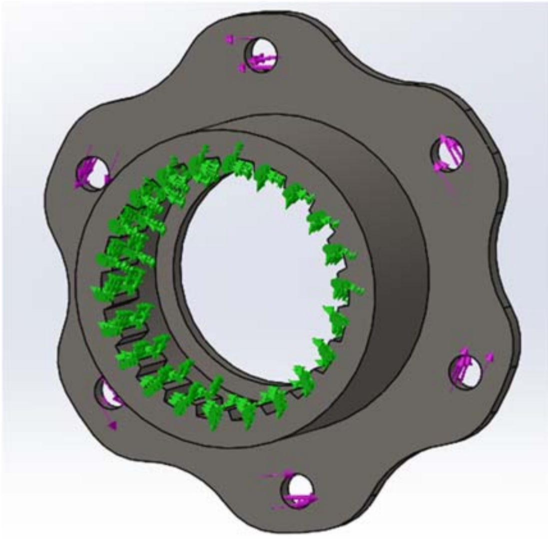


FIGURE 27 – SMALL CARRIER

Small carrier for gear will transfer torque to shaft. Fixed geometry is applied inside the big hole. Applied torque force is 6645 Nm. Material in use is AISI 4340 Steel, normalized.

4.3.1. Result

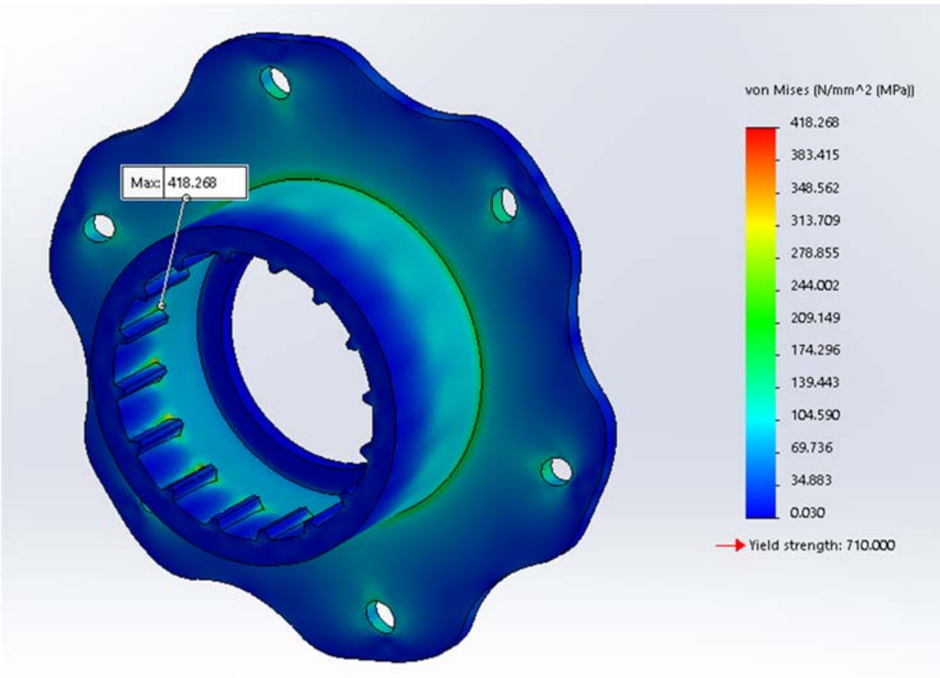


FIGURE 28 - RESULT OF SMALL CARRIER

Results display stress that is above the desired limits. A yield strength of 710 MPa will require the part to be redesigned to have a lower yield strength than 418 MPa. Maximum stress is mostly located at the edges of the grooves.

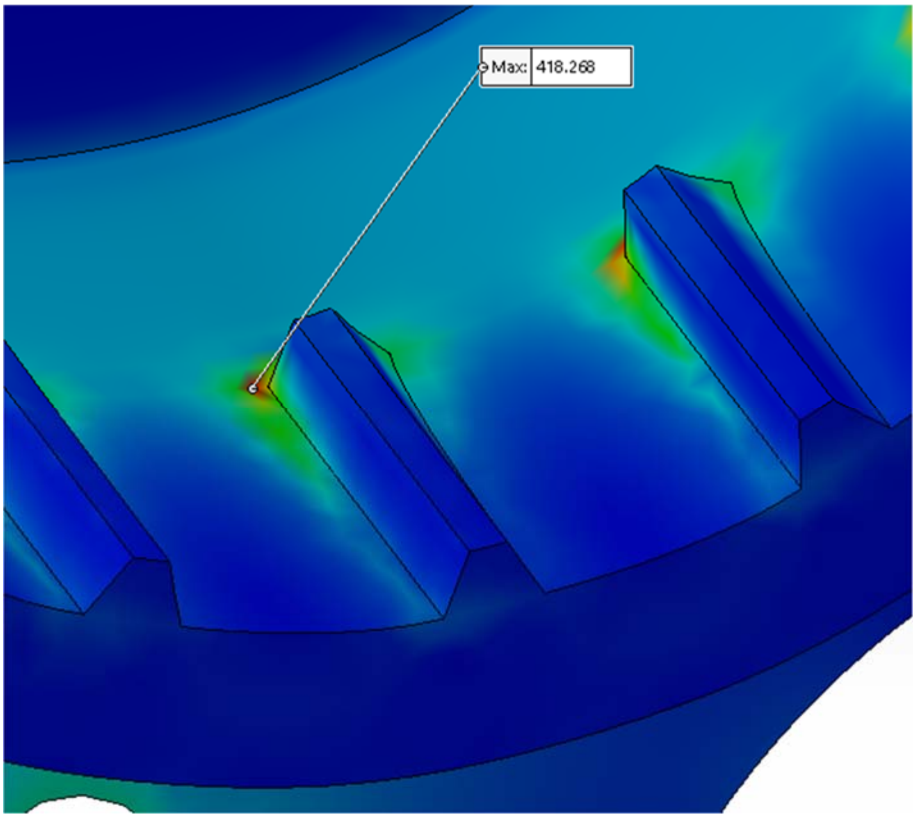


FIGURE 29 - LOCATION OF MAX STRESS ON CARRIER

As we can observe on the picture above, the maximum stress acting is at the edge of the grooves with sharp edges. Since this max stress is local, it is manageable and can be solved with further redesign.

4.3.2. Deformation

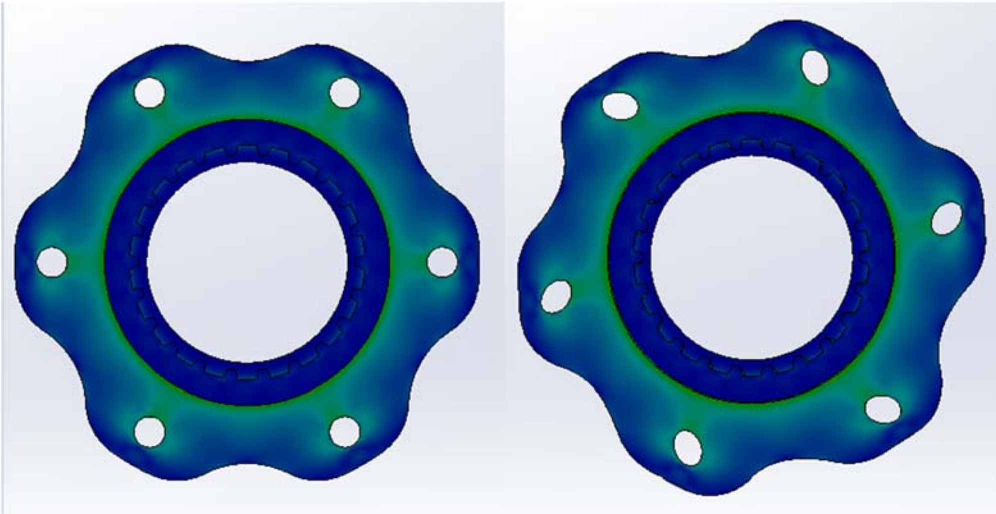


FIGURE 30 – NORMAL VS DEFORMED RESULT

Picture above illustrates a worst-case scenario if the part gets deformed. As we can observe, deformation will influence the back plate of the part, resulting in a deformed holes.

4.3.3. Conclusion

FEA tests conclude that the part is not strong enough to handle the max stress. Factor of safety value was found to be 1.7. This is below the recommended value of 2. As mentioned earlier, max stress acts locally, so it can be worked around. Suggested redesign would be increasing the diameter of the boss/base where the grooves are located.

4.4. Small Planet Gear

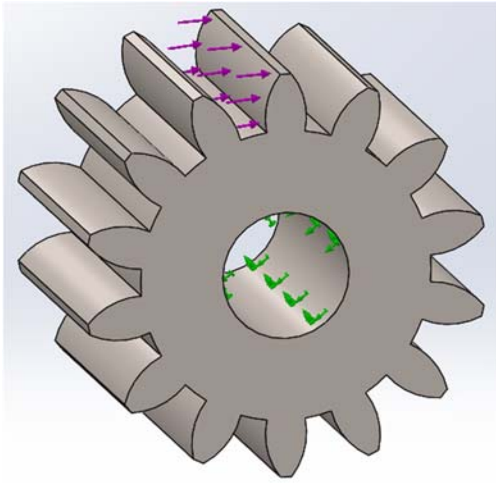


FIGURE 31 – SMALL PLANET GEAR

Torque force is set to 2215/6 Nm since we have 6 planetary gears that share the torque. Acting force is put on face of the teeth and the part is fixed in the central. Material applied is Ferrium C61.

4.4.1. Result

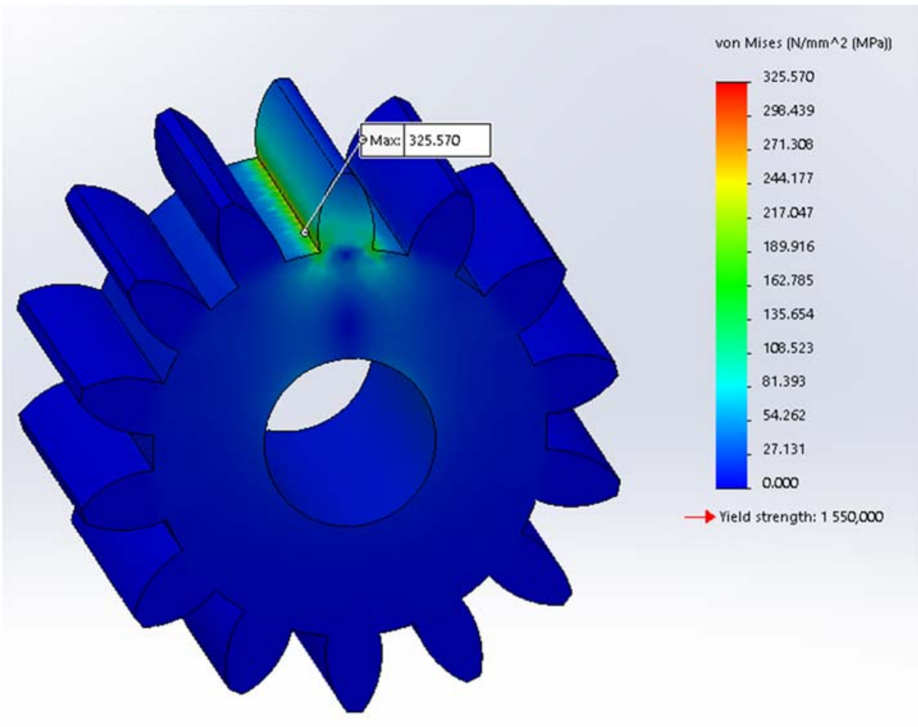


FIGURE 32 – RESULT SMALL PLANET GEAR

Results indicate that the small planet gear is more than strong enough to withstand the acting forces. When the acting force is applied on the gear, the maximum stress value is 325 MPa which is low compared to the yield strength of the material.

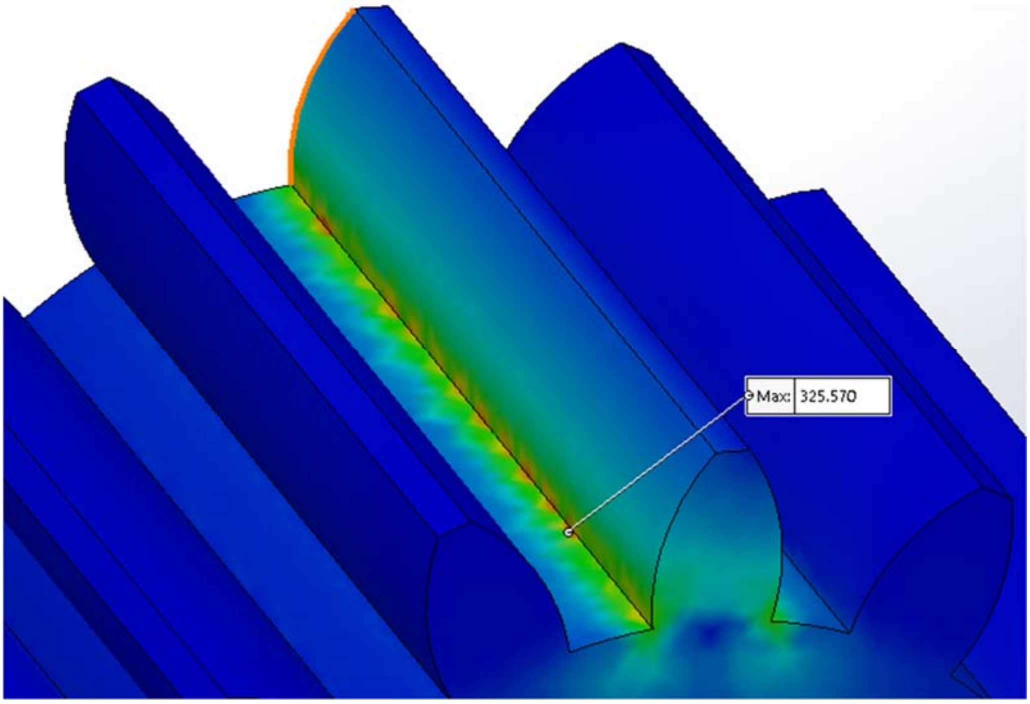


FIGURE 33 - GEAR STRESS LOCATION

As we can observe on the picture above, the maximum stress is located all along the bottom edge of the gear teeth. Like the other parts, sharp edges are most exposed to the max stress.

4.4.2. Deformation

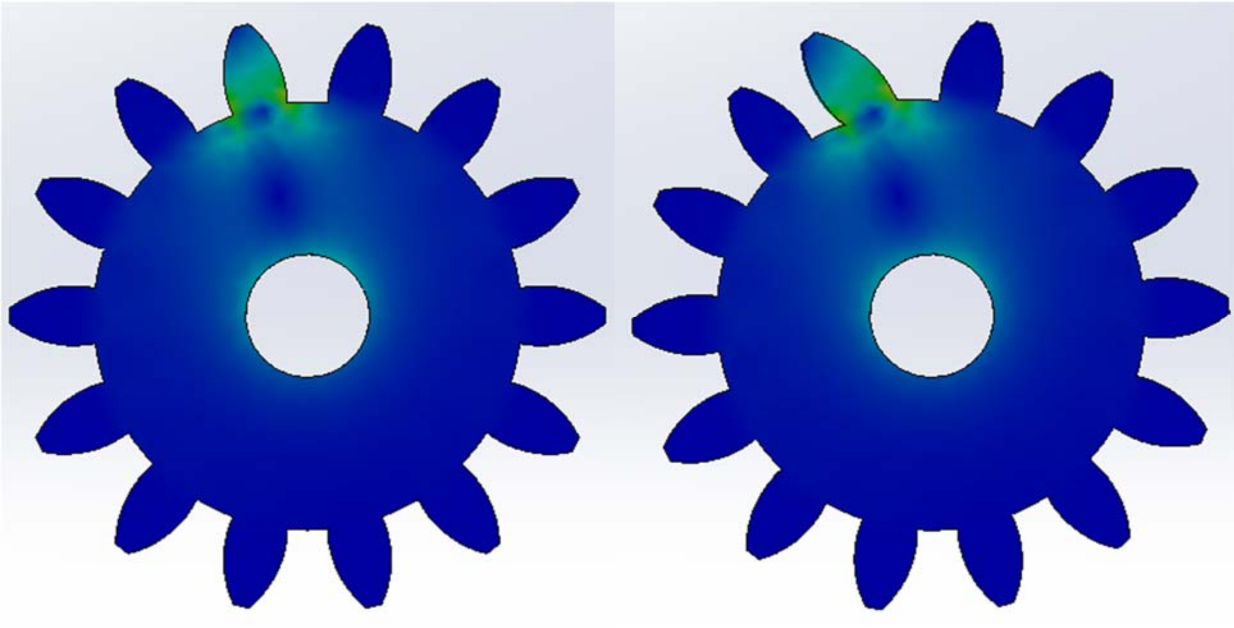


FIGURE 34 - NORMAL VS DEFORMED SMALL PLANET GEAR

Deformation will cause the teeth to bend excessively. Since the force was applied on one tooth to simplify the test, only one tooth is deformed in the picture above.

4.4.3. Conclusion

Acting stress is so low compared to the yield strength of the material, so no further action is necessary. Gear is strong enough to handle the torque which is transmitted from the motor. Part is verified to be good enough according to the FEA. If necessary, the sharp edges can be designed with more curvature to lower the max stress.

4.5. Small Ring Gear

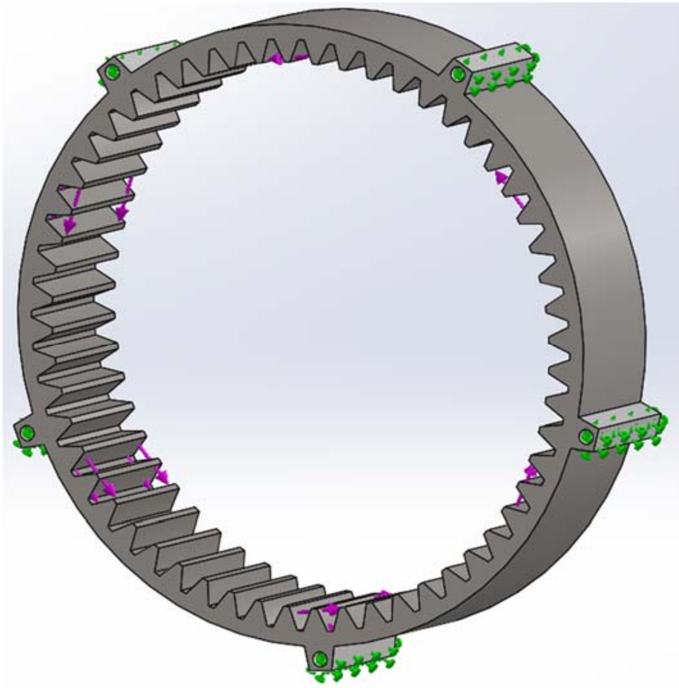


FIGURE 35 - SMALL RING GEAR

Small ring gear has a torque of 4430/6 Nm. Total force is divided by six since this is the number of planetary gears inside the ring. Torque is applied with an equal space of nine teeth because of the connection point of the planetary gear teeth. Fixture is applied inside mounting holes to ensure no movement, and material is Ferrium C61.

4.5.1. Result

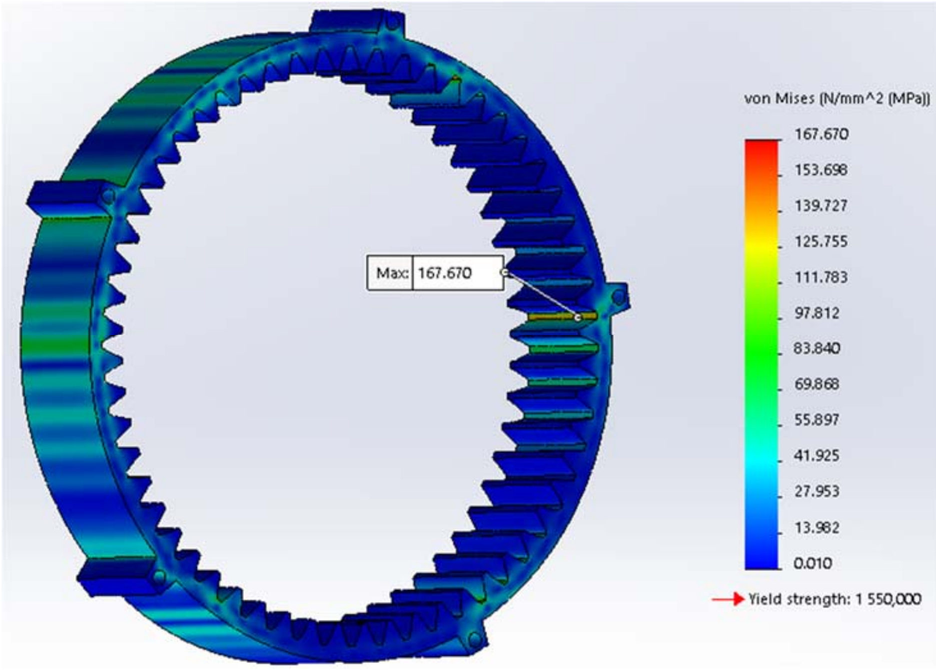


FIGURE 36 - SMALL RING GEAR RESULT

Results show a maximum stress of 167 MPa. Compared to the yield strength of the material this is considered very, very low. We can observe that max stress is located inside the ring, on the surface between the gear teeth.

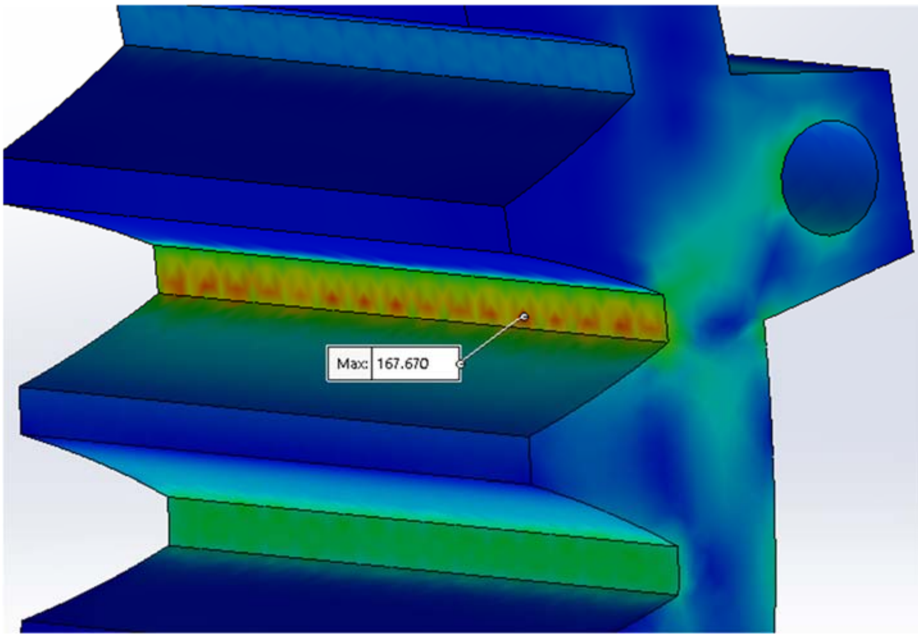


FIGURE 37 - LOCATION OF MAX STRESS SMALL RING GEAR

If we zoom in on the part, we can clearly see the distribution of the max stress along the surface between teeth of the ring.

4.5.2. Deformation

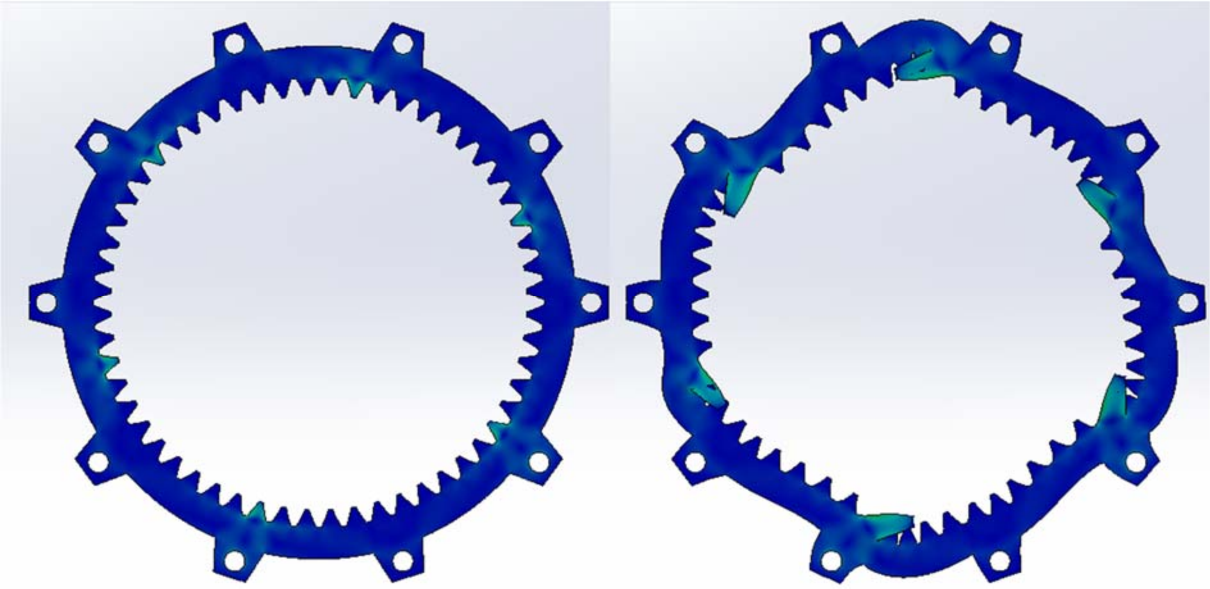


FIGURE 38 - NORMAL VS DEFORMED SMALL RING GEAR

Considering the very low stress that acts on the part, this deformation scale is amplified by 300 to show the results of any deformation that might occur.

4.5.3. Conclusion

Test verify that this part is more than sufficient to handle the distributed force. This part has so far showed us the lowest max forces of all the parts we have tested.

4.6. Big Sun Gear

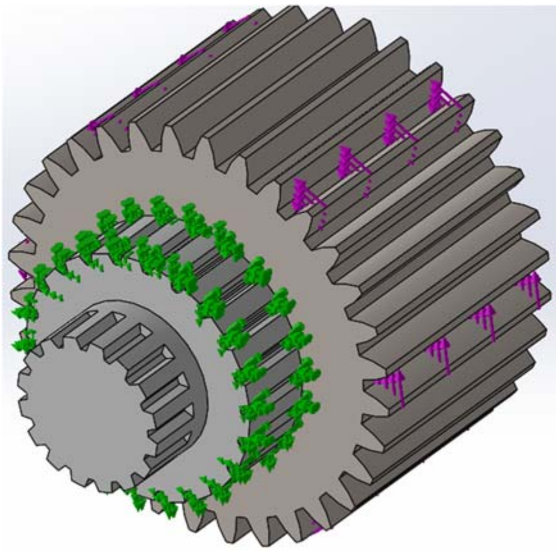


Figure 39 - Big sun gear

This big sun gear has fixtures placed on the surface of the grooves. Torque is set to 6645/6 Nm since the entire torque is shared with five teeth and has five planetary gears. For more information view calculations document [5].

4.6.1. Result

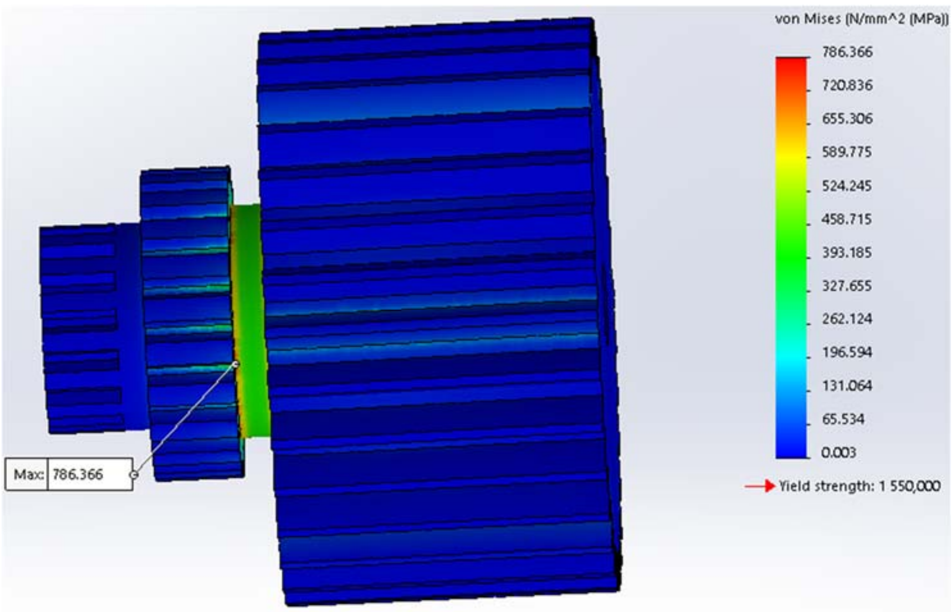


Figure 40 - Result big sun gear

Results show max stress of 786 MPa with a yield strength of 1550 MPa. This part has been redesigned a couple of times since the max stress was way beyond the desired results. Diameter of parts has been increased were possible, which ultimately gave us a safety factor value of 2.0 that we have set as a minimum.

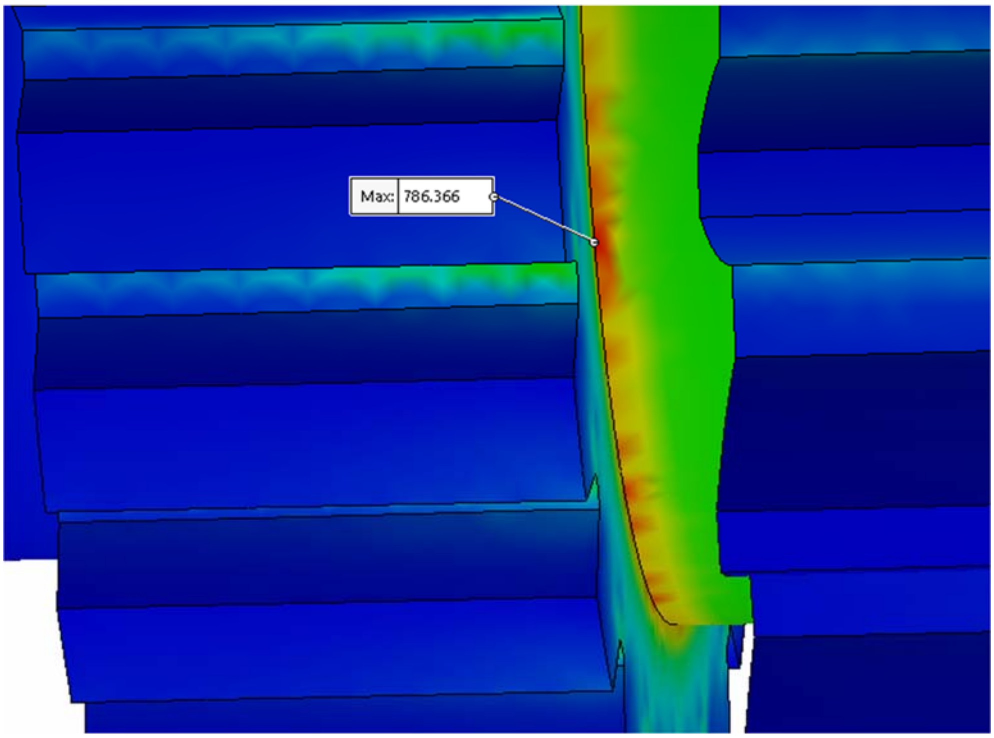


FIGURE 41 - LOCATION OF MAX STRESS ON BIG SUN GEAR

If we zoom on the location of the max stress, we can see that it is found in the space between the back and middle gear boss/base. Max stress works all along the circumference.

4.6.2. Deformation

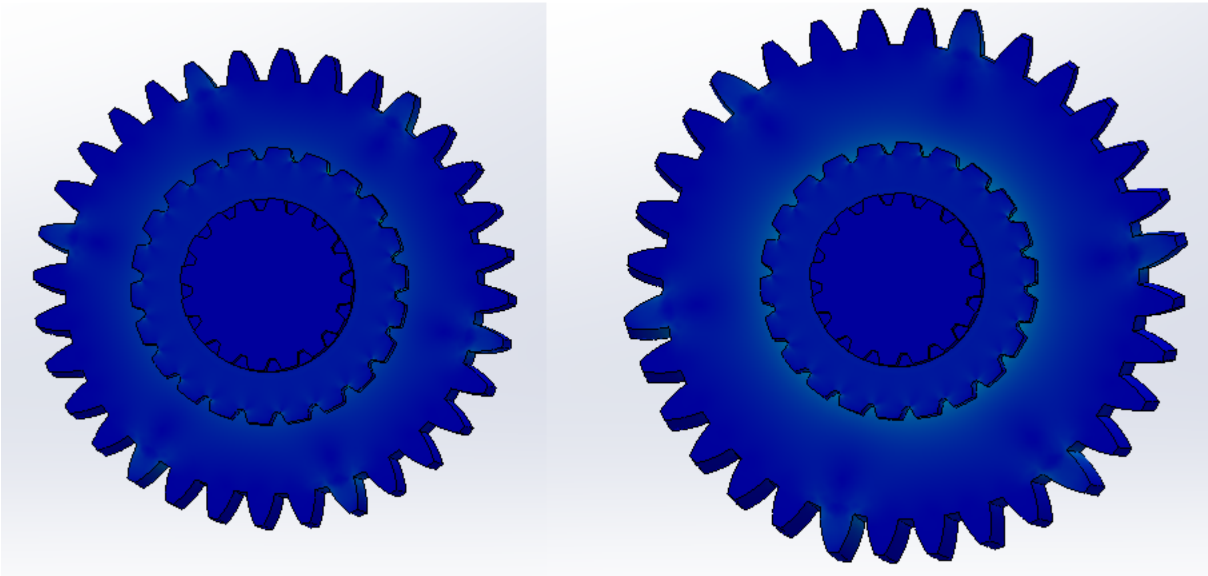


FIGURE 42- NORMAL VS DEFORMED BIG SUN GEAR

Amplified deformation shows us that the part will expand in size due to the maximum stress. The biggest expansion will happen on the big gear on the back.

4.6.3. Conclusion

Redesigning the part has for now given us the minimum required factor of safety that we have chosen. To increase this factor additional redesign can be done. This will result in increasing the diameter of the part. It will lead to a major redesign of the transmission assembly. And also the wheel suspension, which we have customized to the specific size of this transmission.

4.7. Big Carrier

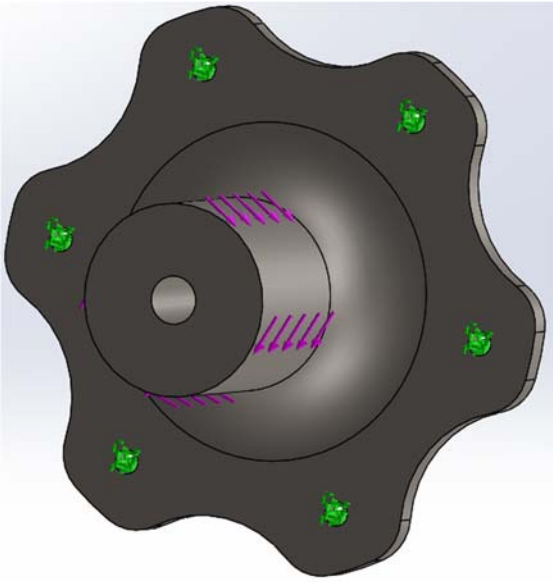


FIGURE 43 - BIG CARRIER

Fixture is applied on the same spots as we did on the small carrier. A total force of 19935/6 Nm is applied. Material in use is 4340 Steel. A noticeable difference between the big and small carrier is the fillet between the back plate and the extruded boss/base to give it a smoother design. This is done to solve high stresses that we got on earlier tests due to sharp edges.

4.7.1. Result

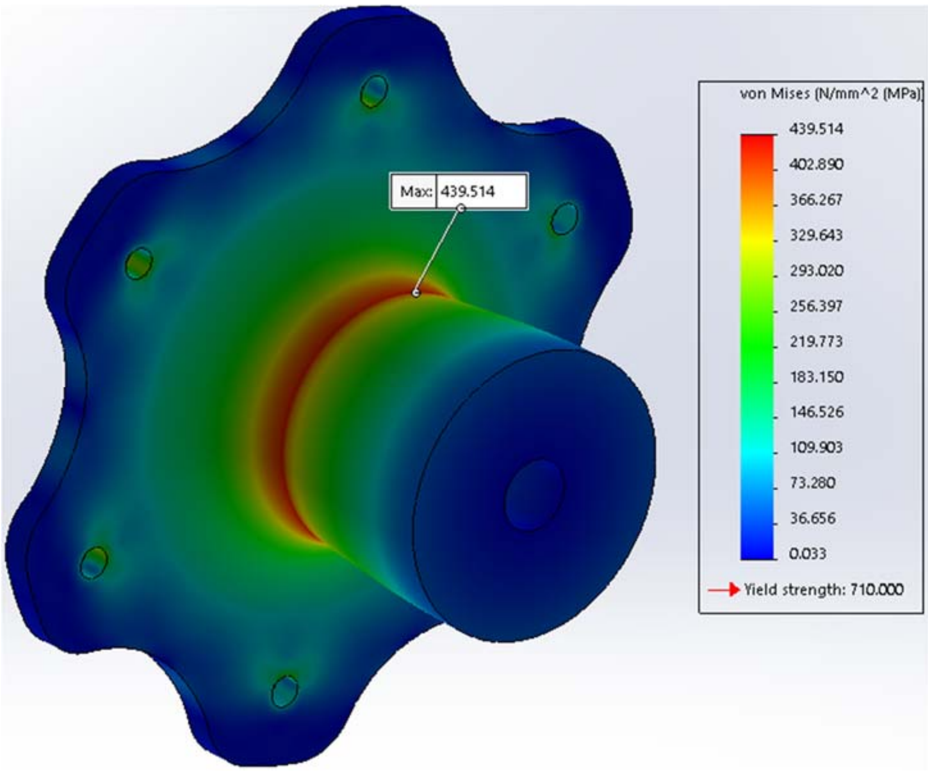


FIGURE 44 - RESULT BIG CARRIER

This part has given us the biggest challenges during the testing. In the initial test the max stress was double the yield strength. To solve this we did a redesign to smooth out sharp edges. We have managed to get the max stress down to 439 MPa with a yield strength of 710 MPa.

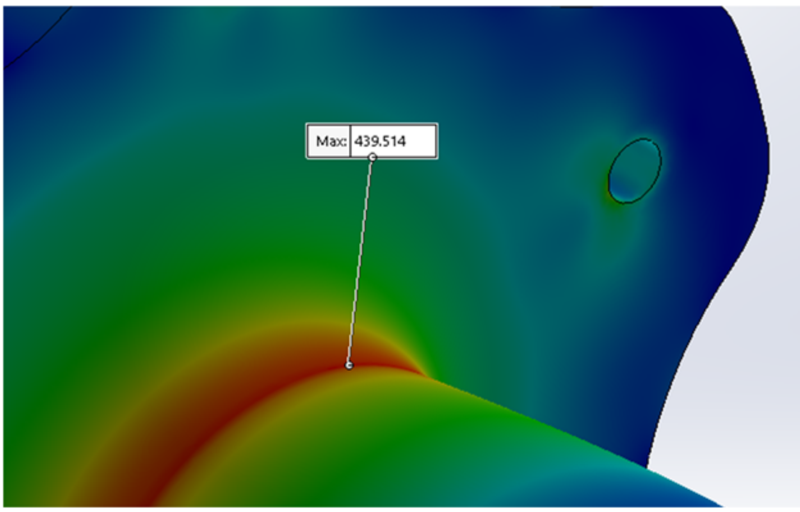


FIGURE 45 - LOCATION OF MAX STRESS ON BIG CARRIER

Max stress on the big carrier can be found mostly at the fillet of the boss/base. A suggestion to make the max stress lower would be to increase the diameter of the boss/base.

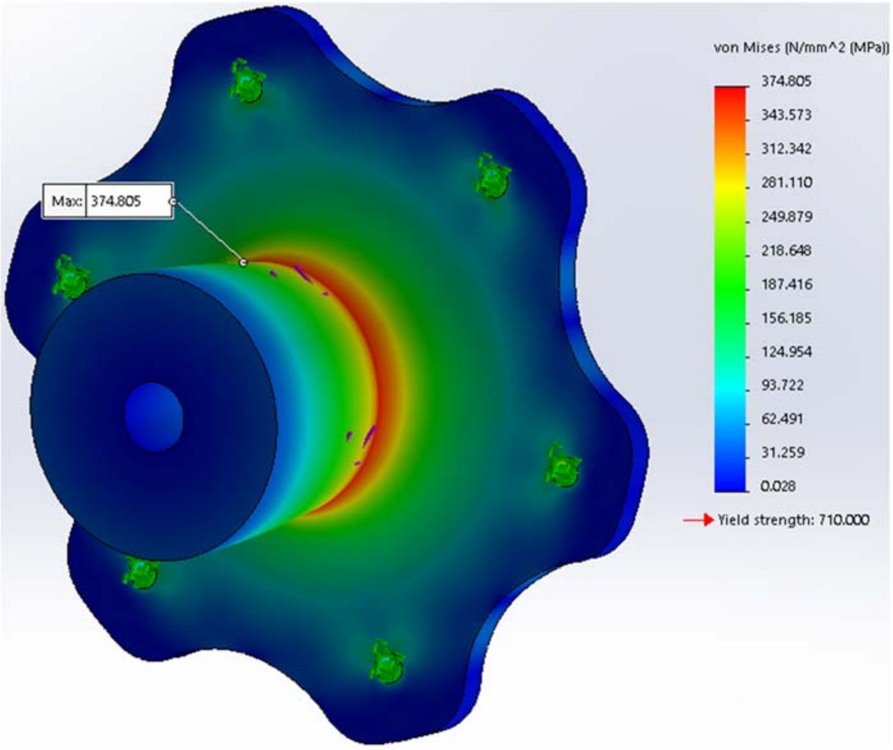


FIGURE 46 - RESULT BIG OUTPUT WITH LOSS

Since transmission systems aren't 100% efficient, a loss will occur. This loss results in a torque force of 17000 MPa that is much more realistic. We decided to run tests using this force to compare with the previous result. As we can observe, with a realistic torque, we get a value that is better, but still need some work.

4.7.2. Deformation

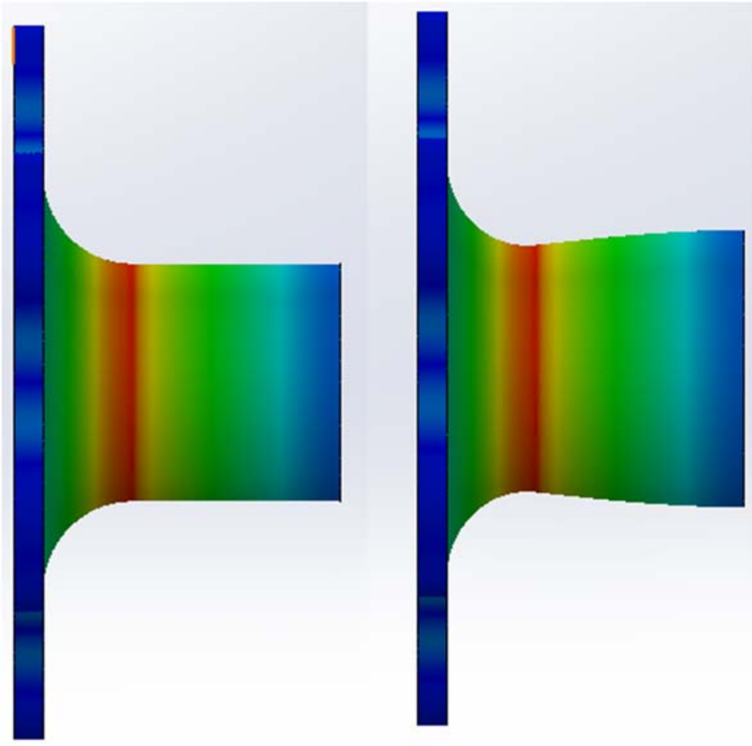


FIGURE 47 - BIG CARRIER NORMAL VS DEFORMATION

Deformation of the part shows that the front of the boss/base increases in diameter due to rotation. Deformation is amplified by 200.

4.7.3. Conclusion

For now, the test results look sufficient. We would recommend additional redesign of the part to lower the maximum stress. A possible solution could be to increase the diameter of the carrier. The reasoning to not increase the part right now is that the entire transmission would need redesign if the size increases. Timeframe does not allow for such a huge redesign so this is considered sufficient as for now.

4.8. Big Ring Gear

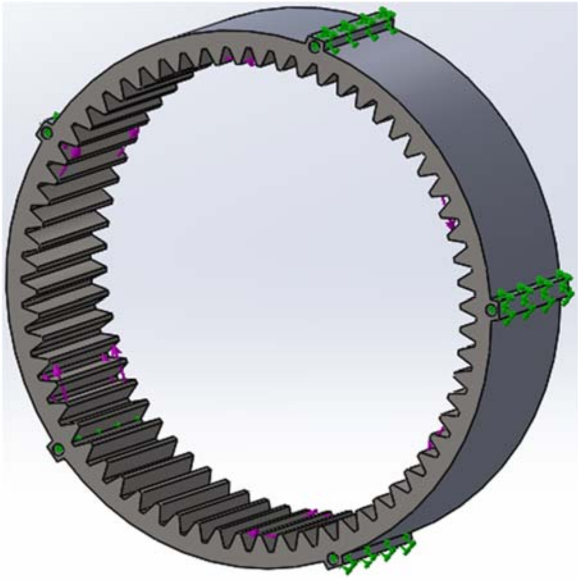


FIGURE 48 - BIG RING GEAR

Applied force is 13290/6 Nm which gives us 2215 Nm per teeth. Applied material is Ferrium C61 and the fixtures are applied in the mounting holes.

4.8.1. Result

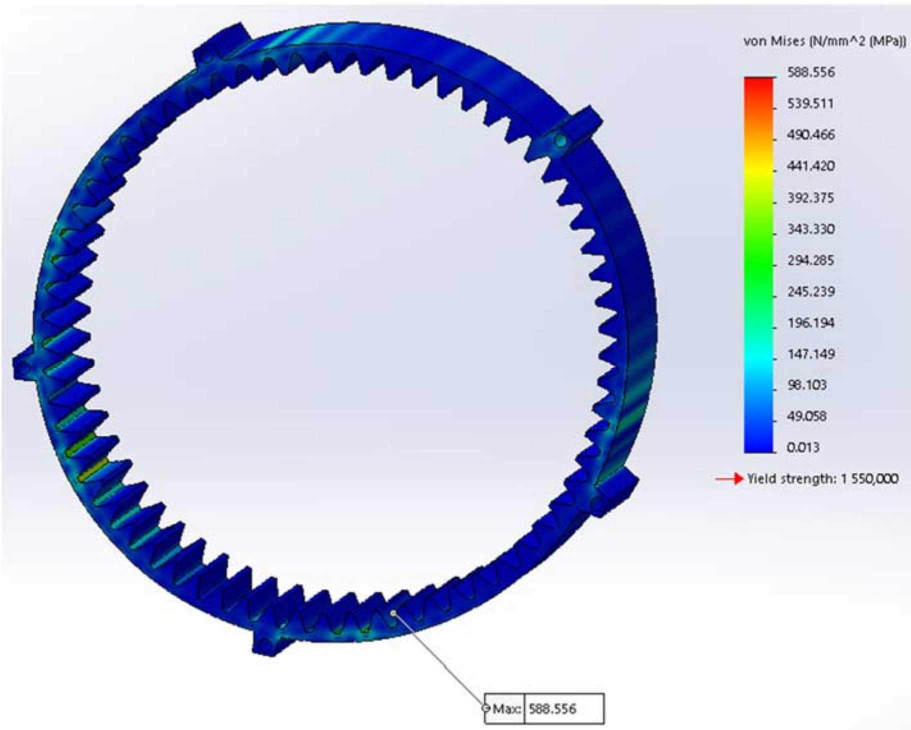


FIGURE 49 - BIG RING GEAR RESULT

Results of the FEA give us a maximum stress of 588 MPa with a yield strength of 1550 MPa. This gives a factor of safety value of 2.6 which is very good.

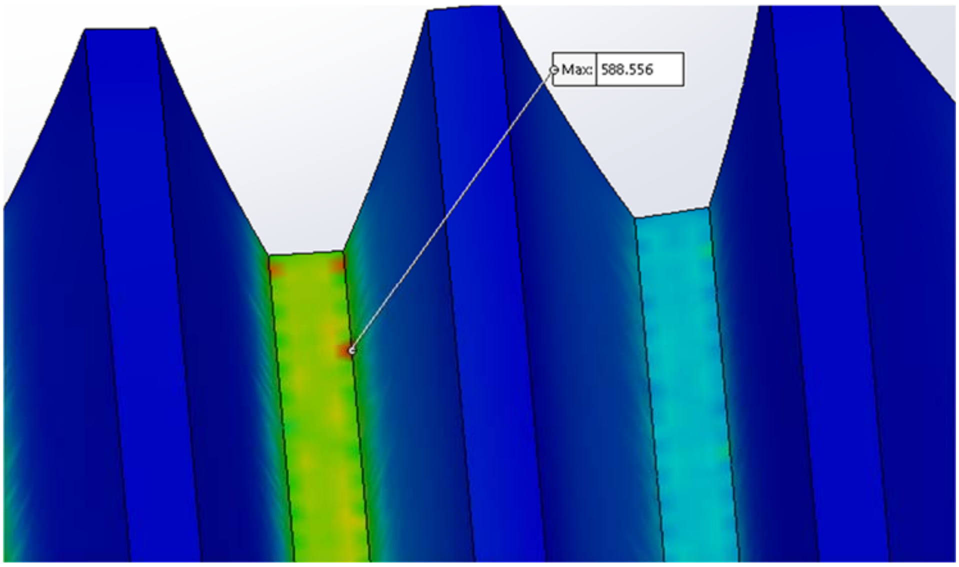


FIGURE 50 – LOCATION OF MAX STRESS

Location of maximum stress is on the surface between gear teeth. These are small and local.

4.8.2. Deformation

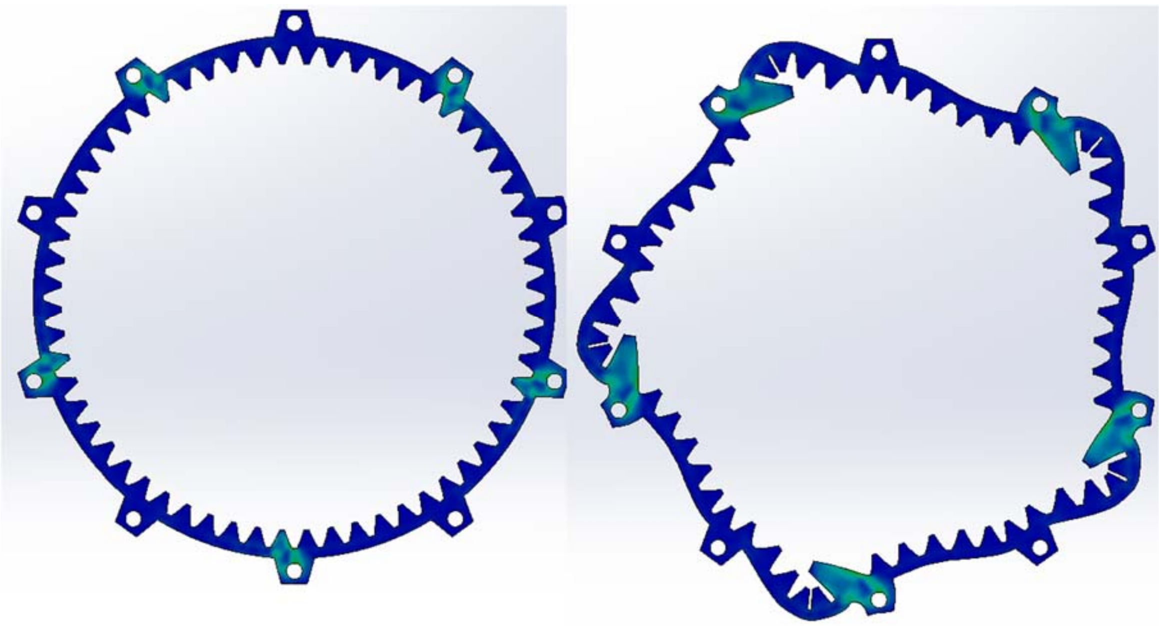


FIGURE 51 - NORMAL VS DEFORMED RESULTS

To be able to observe the worst-case scenario the deformation has been amplified. As we can see, the ring would crunch up mostly where the fixture is applied and torque is working.

4.8.3. Conclusion

FEA verifies the part to be within the desired limits. Acting max stress is within the boundaries, and a 2.6 factor of safety value ensures that no further action will be necessary for this part.

5. ELECTRIC MOTOR POWER

ID	REQ1.05	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.1
DESCRIPTION Electric motor should have a power of 150 kW per wheel			**PRIORITY**
WHY	To supply enough power to the system to work		A
COMMENTS			

TABLE 9 - REQUIREMENT 1.05

TEST ID	TES 1.1	**REQ ID**	1.05 - 1.06 - 1.07 - 2.02 - ~~2.03~~ - 2.04 - 2.05 - ~~3.02~~ - 3.03 - ~~3.04~~ - 3.05 - 3.06
DESCRIPTION	All the requirements above are those we do not have to test because these are specifications we will get when we buy these materials or components. It is not necessary to test these requirements.		**STATUS**
			Verified 1.05, 1.06, 1.07, 2.02 & 2,04
COMMENT	We cancelled requirements 2.03, 3.02, 3.04 and do not need to be tested. We adjusted requirements 2.05, 3.03, but testing will be the same.		

TABLE 10 - TEST 1.1 ELECTRIC MOTOR POWER

To verify and validate these requirements, we will compare information given in the datasheets for components in use and verify the requirements [2].

To verify and validate requirement 1.05, which states that the motor we use shall have 150 KW per wheel, we compare the information given in the datasheet to our motor and we can verify that the motor delivers 200 KW (322hp), at 1800 rpm and 120 KW continuously.

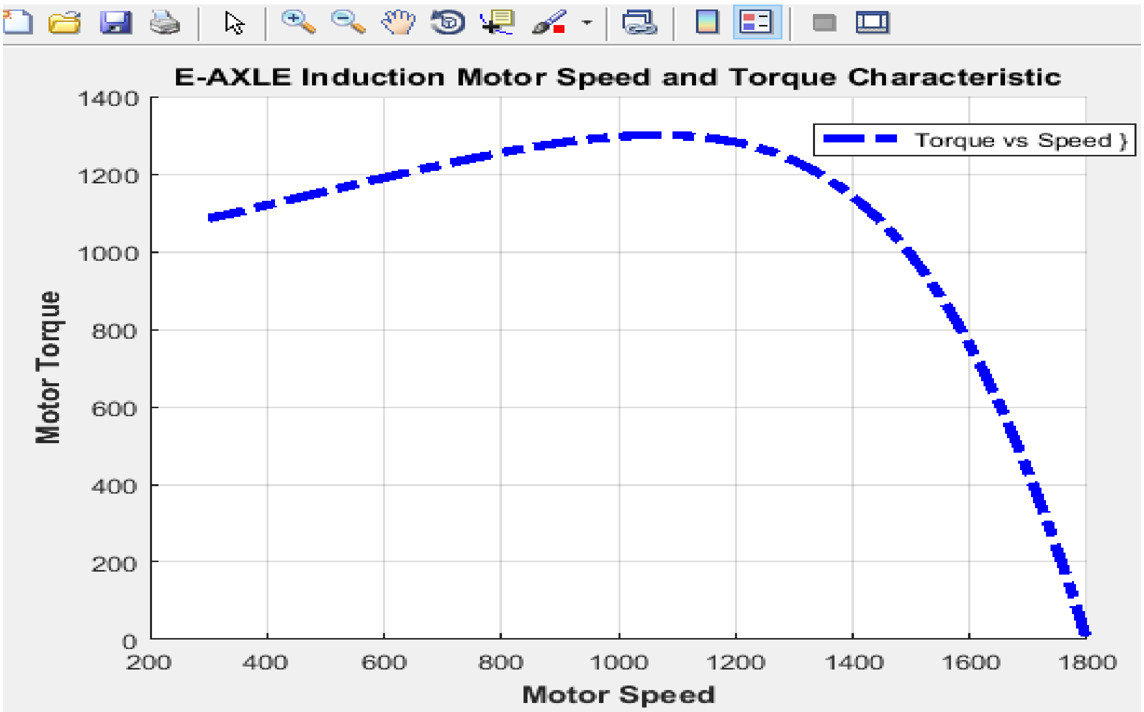


FIGURE 52 - SPEED TORQUE CURVE OF E-AXLE INDUCTION MOTOR

Additionally, we have simulated the speed/torque graph of our motor to verify that the motor is able to provide required torque at rated speed. The resulting graph of the simulation is shown in figure 50, and verifies that our motor will be able to provide both the required power and torque at rated speed.

6. ELECTRIC MOTOR VOLTAGE

ID	REQ1.06	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.1
DESCRIPTION The electric motor should operate at 750V			**PRIORITY**
WHY	In order the motor to produce the desired power		A
COMMENTS			

TABLE 11 - REQUIREMENT 1.06

TEST ID	TES 1.1	**REQ ID**	1.05 - 1.06 - 1.07 - 2.02 - ~~2.03~~ - 2.04 - 2.05 - ~~3.02~~ - 3.03 - ~~3.04~~ - 3.05 - 3.06
DESCRIPTION	All the requirements above are those we do not have to test because these are specifications we will get when we buy these materials or components. It is not necessary to test these requirements.		**STATUS**
			Verified 1.05, 1.06, 1.07, 2.02 & 2,04
COMMENT	We cancelled requirements 2.03, 3.02, 3.04 and do not need to be tested. We adjusted requirements 2.05, 3.03, but testing will be the same.		

TABLE 12 - TEST 1.1 ELECTRIC MOTOR VOLTAGE

Requirement 1.06 states that AC motor should operate at 750V. We can't find a motor that exactly satisfies this requirement. However, the chosen motor which operates at 700V, produces more than enough power and torque to satisfy this requirement indirectly [7].

Motor Type	Induction Motor
Torque (Motor Shaft) Torque (Gear Box Shaft)	815 Nm 2215 Nm
Power	200kW peak, 85kW continuous
Speed (Motor Shaft) Speed (Gear Box Out)	7200 RPM (FWD or REV) 2645 RPM (FWD or REV)
Weight	176 kg
Input Voltage (See CEU160)	MV: 250-450 V_{DC} HV: 450-700 V_{DC}
Cooling	-40 °C to 65°C (50/50 WEG, 1" fitting)
Shaft Flange	DANA 4-1-3101 or Rockford 02067368
Efficiency	93%
Isolation resistance	**> 1** MΩ at 700V_{DC}
Parking Brake	ZEMARC (Optional)
Environment	IP65 rated (IP-67 optional)
Mounting	Integrated Flange
Gears	2.72:1, planetary type
Installation	±3.5° Vertical plane, ±10° Horizontal

FIGURE 53 - INDUCTION MOTOR SPECIFICATION.

7. ELECTRIC MOTOR RPM

ID	REQ1.07	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.1
DESCRIPTION The electric motor should operate between 0-2000 RPM			**PRIORITY**
WHY	Because the motor should have maximum and minimum rotational speed		A
COMMENTS			

TABLE 13 - REQUIREMENT 1.07

TEST ID	TES 1.1	**REQ ID**	1.05 - 1.06 - 1.07 - 2.02 - ~~2.03~~ - 2.04 - 2.05 - ~~3.02~~ - 3.03 - ~~3.04~~ - 3.05 - 3.06	
DESCRIPTION	All the requirements above are those we do not have to test because these are specifications we will get when we buy these materials or components. It is not necessary to test these requirements.			**STATUS**
				Verified 1.05, 1.06, 1.07, 2.02 & 2,04
COMMENT	We cancelled requirements 2.03, 3.02, 3.04 and do not need to be tested. We adjusted requirements 2.05, 3.03, but testing will be the same.			

TABLE 14 - TEST 1.1 MOTOR RPM

This requirement states that the motor shall operate between zero and 1800 rpm. The datasheet [7] of the motor type we use in this project specifies that the motor gives a torque of 1300 Nm up to speed of 1800 rpm, while the rated peak speed of the motor is 7,000 (Bi-direction).

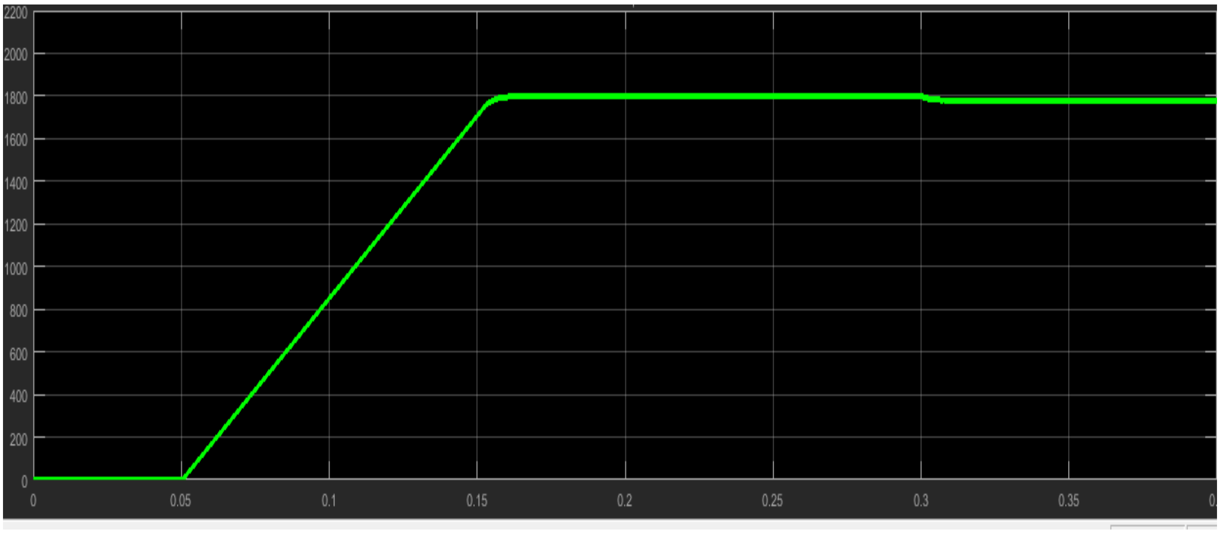


FIGURE 54 - SPEED TIME CHARACTERISTIC OF E-AXLE INDUCTION MOTOR

To verify this requirement electronically we simulate our induction motor in Simulink. The simulation results are shown in figure 54, and the result verifies that the induction motor will have a speed between 0 and 1800 rpm. The speed of our motor will vary between zero and 2000 rpm depending on the load size.

8. INVERTER

ID	REQ3.04	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.1
DESCRIPTION Integrated inverter, size flexible depending on packaging space			**PRIORITY**
WHY	To save design space		C

TABLE 15 - REQUIREMENT 3.04

TEST ID	TES 1.1	**REQ ID**	1.05 - 1.06 - 1.07 - 2.02 - ~~2.03~~ - 2.04 - 2.05 - ~~3.02~~ - 3.03 - ~~3.04~~ - 3.05 - 3.06
DESCRIPTION	All the requirements above are those we do not have to test because these are specifications we will get when we buy these materials or components. It is not necessary to test these requirements.	**STATUS**	Verified 1.05, 1.06, 1.07, 2.02 & 2,04
COMMENT	We cancelled requirements 2.03, 3.02, 3.04 and do not need to be tested. We adjusted requirements 2.05, 3.03, but testing will be the same.		

TABLE 16 - TEST 1.1 INVERTER

The motor we use in this project has an electric drive unit. We can therefore conclude that this requirement will be satisfied by using this type of motor together with its driving unit.

The requirements in this test are intended to be validated by comparing them to the information specified in the datasheet of the components in use. These requirements are therefore tested by comparing them against technical specifications in the data sheets.

9. GEAR FUNCTIONALITY

ID	REQ1.20	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.3
DESCRIPTION Inverter should have differential gear functionality			**PRIORITY**
WHY	To control the AC electric motor		A
COMMENTS			

TABLE 17 - REQUIREMENT 1.20

TEST ID	TES 1.3	**REQ ID**	~~1.20~~ - 1.24 - 3.01
DESCRIPTION	The requirements above will be fulfilled by reading the datasheet of each of the components related to a given requirement. We will find information from datasheets to verify and validate that the technical specifications in the data sheet satisfies the requirement as specified by requirement specification.	**STATUS**	Verified

TABLE 18 - TEST 1.3 GEAR FUNCTIONALITY

We haven't been able to find a suitable inverter with integrated differential gear. To satisfy this requirement, we use direct torque control to compare the speed of the two electric drives. This will compensate and increase the stability of the vehicle during cornering.

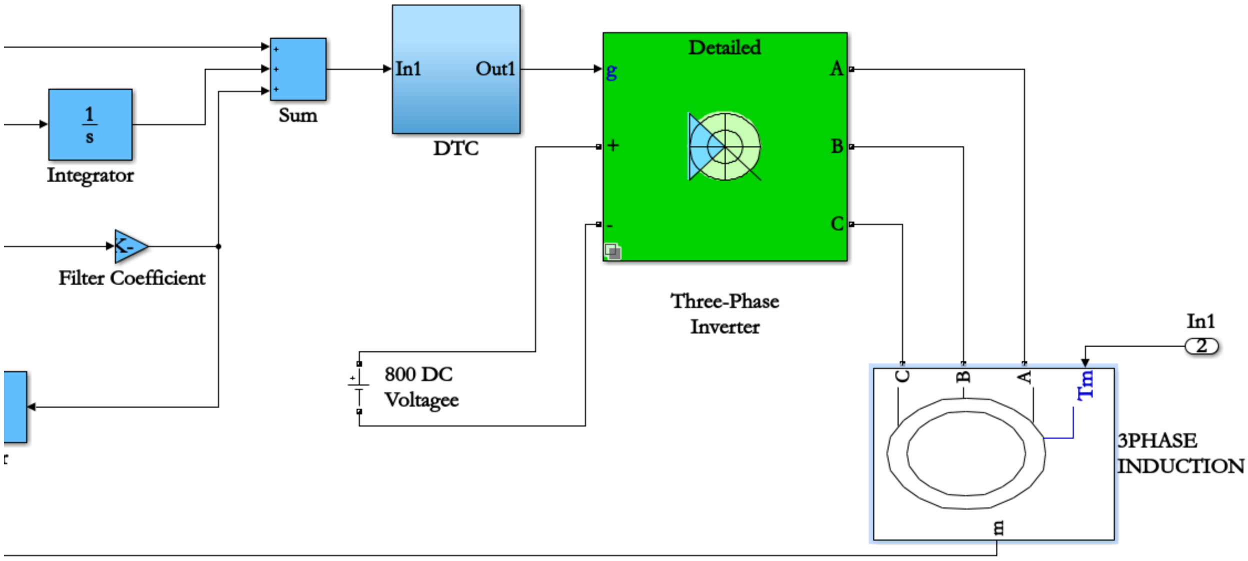


FIGURE 55 - INVERTER CONTROLLED BY DTC

The driving unit chosen for this project has an integrated motor control connector. This connector makes it possible for us to use the direct torque controller to perform the function of an electronic differential. Figure 55 shows how our inverter is controlled through DTC. We can therefore conclude that this requirement is partially satisfied by using the DTC to function as differential gear.

10. CONTROL AC MOTOR VIA INVERTER

ID	REQ1.19	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.6
DESCRIPTION The AC electric motor should be controlled via an inverter			**PRIORITY**
WHY	Inverter can limit the power input to the motor and thus regulating the motor.		A
COMMENTS			

TABLE 19 - REQUIREMENT 1.19

TEST ID	TES 1.6	**REQ ID**	1.19
DESCRIPTION	This requirement will be tested by calculating some values of a closed controlling loop and verify that the system is both controllable, observable and stable. Furthermore, some Simulink Matlab simulations will be performed to test and verify that AC motors are adapted to variations in the load, as specified by the requirement specification. To verify and validate that the dynamics of the motors respond to the applied loads as required the Matlab Simulations will be analyzed and commented.		**STATUS** Verified

COMMENT	This requirement were tested by simulating the motor in Simulink, but we did not calculate to analyses the dynamic behavior of the closed loop system. This is because the motor we use has a suitable electric drive unit consisting of inverter and other necessary power electronics. The requirement is therefore satisfied without further testing.	

TABLE 20 - TEST 1.6 CONTROL AC MOTOR VIA INVERTER

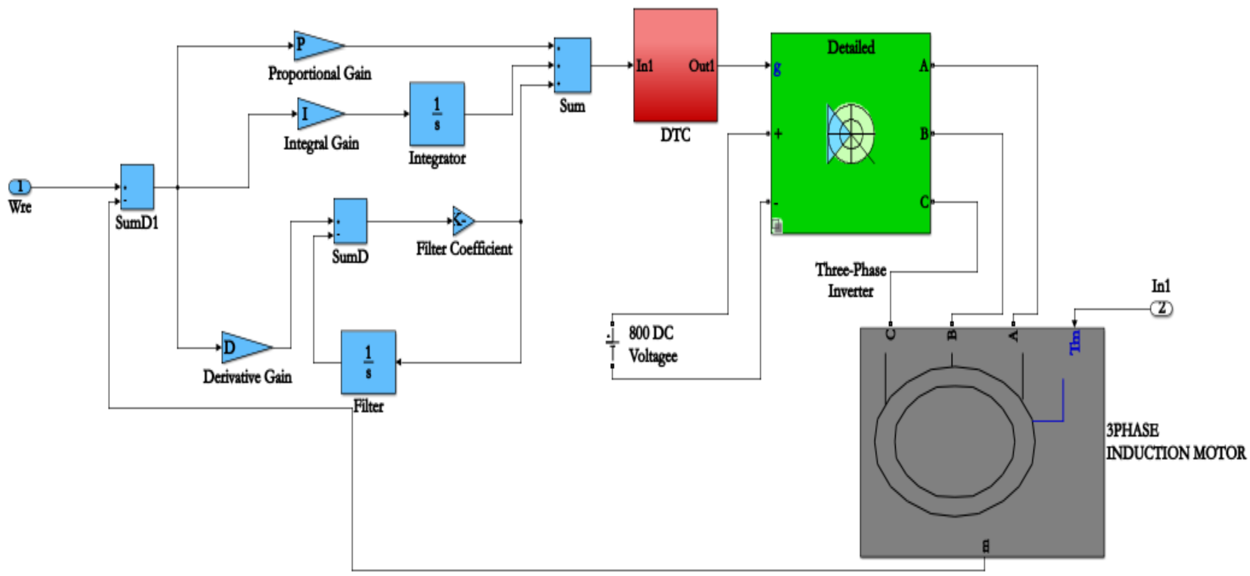


FIGURE 56 – MOTOR CONTROLLED VIA INVERTER

On figure 56 we can observe that our closed loop control module consists of an inverter which is controlled via DTC, and an induction motor controlled via a three phase inverter.

This module verifies that we are controlling the speed of the motor via an inverter.

11. BATTERY OUTPUT VOLTAGE

ID	REQ2.06	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.11
DESCRIPTION The BU should give 800 V DC current through two wire connectors			**PRIORITY**
WHY	To make it possible to connect the BU and inverter and to supply required power to the ED		A
COMMENTS			

TABLE 21 - REQUIREMENT 2.06

TEST ID	TES 1.11	**REQ ID**	2.06
DESCRIPTION	This requirement can be tested using a Voltmeter and verify and validate that there is connection between the battery unit and the inverter through a two-wire connector.		**STATUS** Verified

TABLE 22 - TEST 1.11 BATTERY OUTPUT VOLTAGE

This requirement cannot be tested physically, since we have no physical model to test with a voltmeter.

In order to verify and validate this requirement electronically, a three phase voltage source inverter has been modeled in Simulink. This is done to analyze and verify the connectivity. The Simulink model of the three phase inverter is connected to a battery source of 800 V_{DC}. We then analyze the behavior of the inverter when it is connected to 800 V_{DC} source. Additionally we vary the voltage to see how our inverter behaves. The figure below shows the simulation results.

12. BATTERY EFFECT

ID	REQ1.01	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.17
DESCRIPTION The BU should be able to drive E-Axle for at least 10 hours.			**PRIORITY**
WHY	Because this is a standard driving time for a truck		A
COMMENTS			

TABLE 23 - REQUIREMENT 1.01

TEST ID	TES 1.17	**REQ ID**	1.01
DESCRIPTION	This requirement can be verified by calculating the average amount of energy we use while driving for 10 hours, and how much battery space we need for that amount of energy.		**STATUS**
			Verified
COMMENT			

TABLE 24 - TEST 1.17 BATTERY EFFECT

We have calculated the amount of motion-resistive forces acting on our heavy duty vehicle and determined the number of batteries needed to supply required voltage. We have made calculations and chosen a battery type that will provide power to the vehicle. Using these calculations we can verify that the chosen battery will be able to provide the power needed to our vehicle for at least 10 hours, while driving in different road conditions [5].

13. WHEEL SUSPENSION CAPACITY

ID	REQ1.14	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION WS carrying capacity should be at least 6 tons per wheel			**PRIORITY**
WHY	To be able to withstand heavy load per wheel		B
COMMENTS			

TABLE 25 - REQUIREMENT 1.14

ID	REQ1.15	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION WS carrying capacity should be at least 12 tons per axle			**PRIORITY**
WHY	To be able to withstand a heavy load per axle		B
COMMENTS			

TABLE 26 - REQUIREMENT 1.15

TEST ID	TES 1.4	REQ ID	1.09 - 1.10 - ~~1.11~~ - 1.12 - 1.13 - 1.14- 1.15
DESCRIPTION	These requirements will be tested by using calculations and FEA Method.		STATUS
			Verified
COMMENT	The requirement 1.11 is canceled, therefore we do not need to test it.		

TABLE 27 - TEST 1.4 WHEEL SUSPENSION CAPACITY

These are very important requirement, as load capacity is a very important topic in transportation industry. According to our requirements, the wheel suspension should be able to withstand up to 12 tons of load per axle (6 tons per wheel). These are the parameters we use to calculate all the forces acting our wheel suspension [5].

These requirements were tested together with requirements REQ1.16 and REQ1.18 [2]. As we mentioned during TES 1.5 the weight of the vehicle was always included during FEA/FEM analysis. This means that we have achieved this requirement since the A-arm was able to withstand all of the forces.

14. OPTIONAL TORQUE VECTORING

ID	REQ1.23	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.9
DESCRIPTION The system should have optional torque vectoring.			**PRIORITY**
WHY	To have better handling and control of the vehicle.		B
COMMENTS			

TABLE 28 - REQUIREMENT 1.23

TEST ID	TES 1.9	**REQ ID**	1.23
DESCRIPTION	This requirement will be tested by demonstrating this feature with an RC car.		**STATUS** Verified

TABLE 29 - TEST 1.9 OPTIONAL TORQUE VECTORING

To demonstrate how our design looks, we have developed a simple prototype using LEGO technic. The main purpose of the prototype is to display our wheel suspension design and optional torque vectoring. The prototype consists of two separate motors controlling each wheel. Each wheel has an independent A-arm type suspension system. The two motors make it possible for E-Axle to demonstrate that each wheel has different speed if the vehicle is turning either left or right. To make the construction as light as possible we only use a dummy wheel in front. This is done because the motors aren't strong enough to drive the prototype with 2 wheels in front and the excessive Lego required. Excess Lego makes the prototype bulkier and heavier.

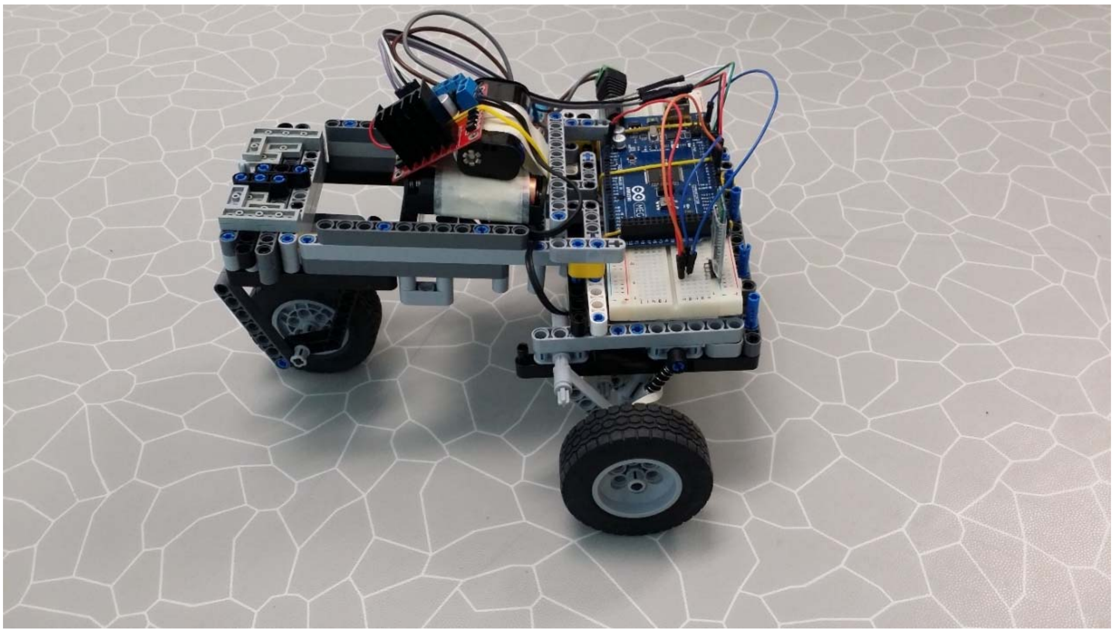


FIGURE 57 - PROTOTYPE

This prototype has been made using:

- Arduino Mega 2560
- Two 9V Lego motors
- 6 AA batteries
- Breadboard
- HC-06 Bluetooth module
- Male and Female jumper wires
- On/Off button
- L298N dual H-bridge motor controller module

A breadboard Schematic follows to explain how the electronic is wired together.

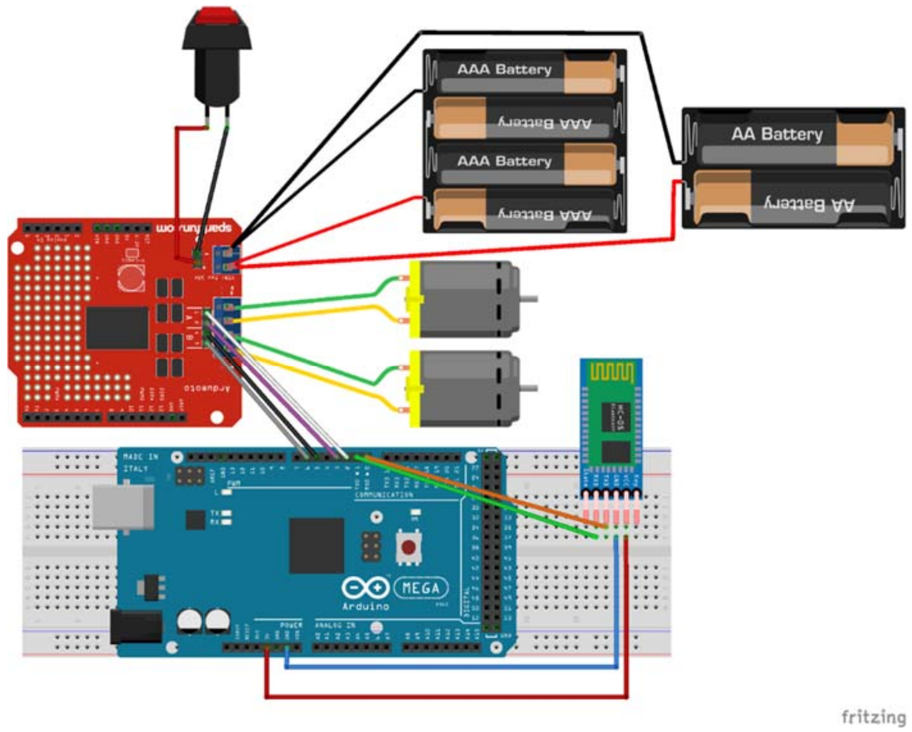


FIGURE 58 - BREADBOARD SCHEMATIC

Note that this could also be done by using a potentiometer to be more accurate. But this method would require us to physically turn the potentiometer each time. To make it more elegant we choose the remote-controlled solution, even though it isn't as accurate as the method mentioned above. The chosen solution is sufficient for our requirement and test.

The code for this prototype can be studied further in the attachment (Att: A).

15. WHEEL SUSPENSION TRAVEL

Wheel suspension and wheelbase is an important part of suspension system. We have acquired some requirements from KA, about suspension drop and lift. This is to ensure that our suspension system have enough moving space.

ID	REQ1.12	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION WS travel Lift should be100 mm.			**PRIORITY**
WHY	To make it easier to connect truck trailer and adapt to different road conditions.		A
COMMENTS			

TABLE 1 - REQUIREMENT 1.12

ID	REQ1.13	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.4
DESCRIPTION WS travel Drop should be 60 mm.			**PRIORITY**
WHY	To make it easier to connect truck trailer and adapt to different road conditions.		A
COMMENTS			

TABLE 2 - REQUIREMENT 1.13

TEST ID	TES 1.4	REQ ID	1.09 - 1.10 - ~~1.11~~ - 1.12 - 1.13 - 1.14- 1.15
DESCRIPTION	These requirements will be tested by using calculations and FEA Method.	STATUS	
		Verified	
COMMENT	The requirement 1.11 is canceled, therefore we do not need to test it.		

TABLE 30 - TEST 1.4

As the tables shows us the requirements about wheel suspension travel. Chassis lift is 100 mm and chassis drop is 60 mm. First of all, we should understand what wheel suspension travel means. Wheel suspension travel is the distance for the wheels to have motion between chassis and road. To have smooth driving comfort in different road conditions, the wheels should always keep the contact with the road.

Figure 59 shows 3D model of our independent suspension system in front view. And from that we have illustrated how the wheel suspension travel for our design in figure 60. This helps us visualize how the wheel suspension lift and drop happens in our system.

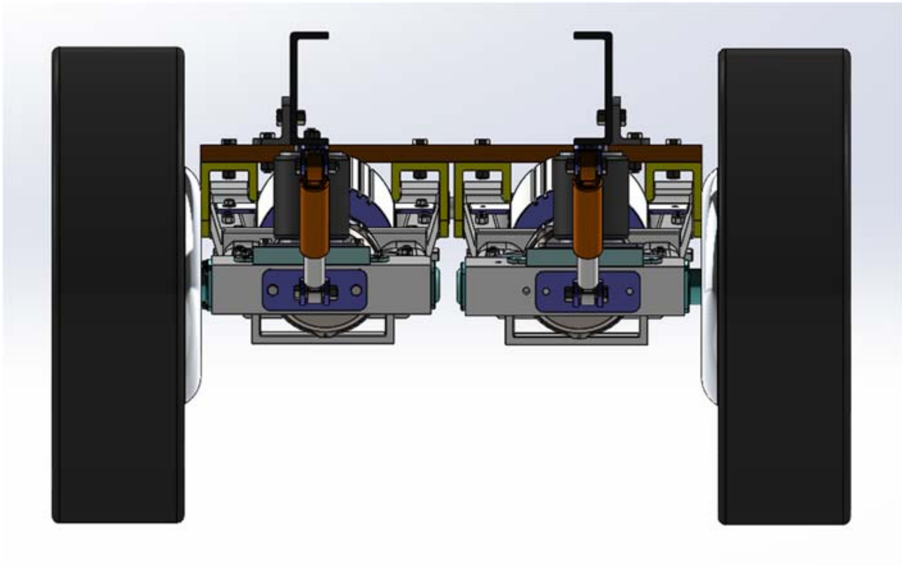


FIGURE 59 - FRONT VIEW OF OUR SUSPENSION SYSTEM

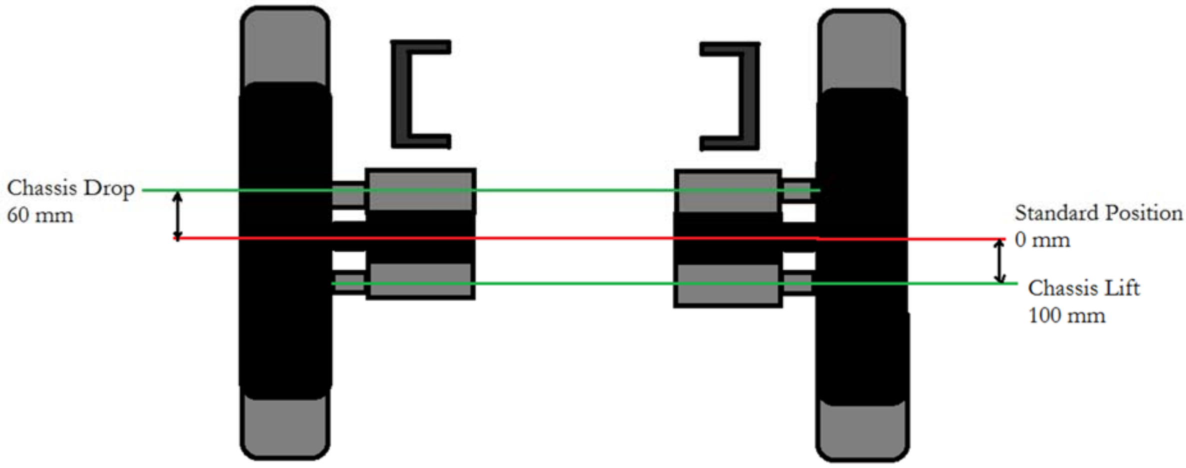


FIGURE 60 - SIMPLIFICATION OF SUSPENSION SYSTEM AND WHEEL SUSPENSION TRAVEL

From figure 60 can we see standard position, chassis lift and chassis drop of the suspension system. Standard position is when vehicle has no load or the vehicle drives in smooth road. Chassis lift will be 100 mm when the distance between chassis and suspension axle is at maximum. The chassis drop distance will be 60 mm when the distance between chassis and suspension axle is closer than in idle position. The sum will be 160 mm from chassis lift to chassis drop [8].

16. WHEELBASE

The motion of wheel suspension is created by different driving conditions. That means suspension system have a motion when it absorb shocks and stabilize the vehicle. And this motion of the suspension system will change the wheelbase of the vehicles. Wheelbase is distance between the center of front axle and rear axle. Figure 61 shows an illustration of wheelbase when we have a rear axle group.

When the A-arm, which we have designed moves up and down, it changes the wheelbase.

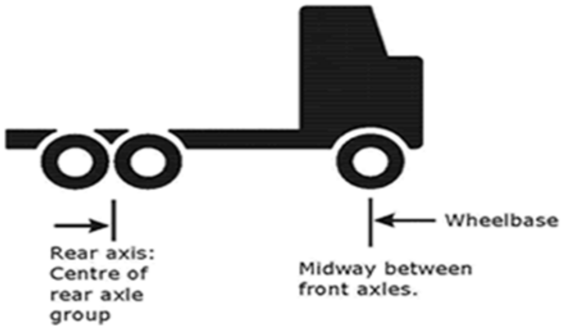


FIGURE 61 - WHEELBASE DESCRIPTION

ID	REQ1.21	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.7
DESCRIPTION Varying wheelbase shall be taken into account.			**PRIORITY**
WHY	To control and adjust varying distances between the wheelbase.		C
COMMENTS			

TABLE 31 - REQUIREMENT 1.21

TEST ID	TES 1.7	REQ ID	1.21
DESCRIPTION	To test this requirement we will calculate variations in the wheelbase. After that we can further test how this effect our systems driving characteristic.	STATUS	
		Verified	
COMMENT			

TABLE 32 - TEST 1.7 WHEELBASE

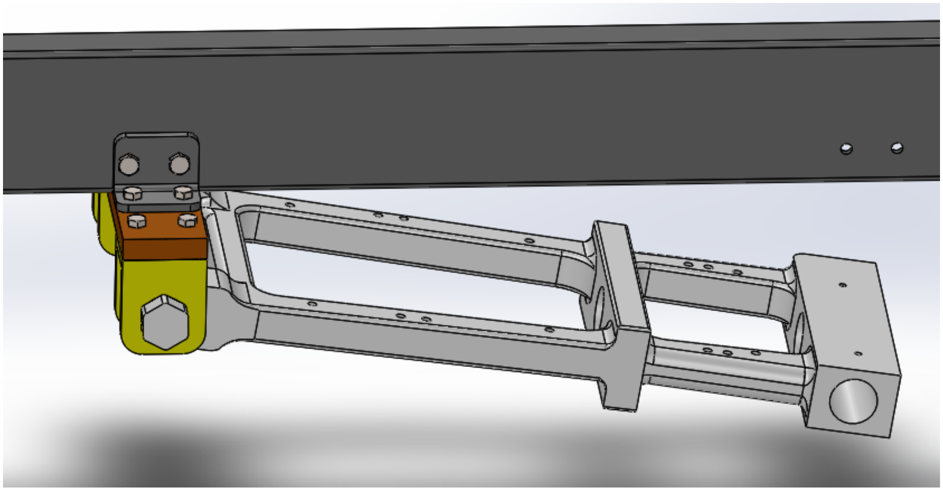


FIGURE 62 - ISOMETRIC VIEW OF A-ARM

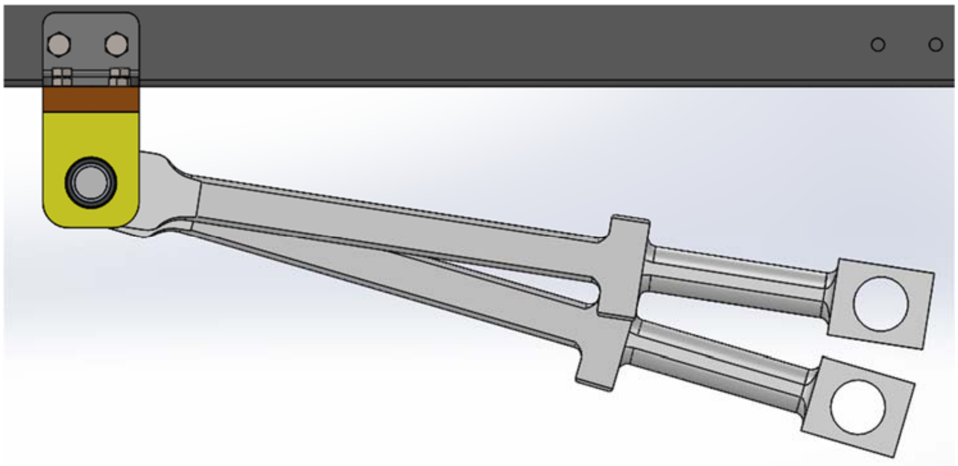


FIGURE 63 - SIDE VIEW OF A-ARM

Figure 64 is the 2D drawing of A-arm and we can easily see how the wheelbase changes when the A-arm have vertical movement. As the figure shows us the one side of the A-arm fixed to frame and we call that point as hinge point. Drive axle is fixed opposite to the hinge point. Circle center of the A-arm is hinge point and A-arm is acting like the radius of a circle. Therefore, A-arm rotates around the hinge point and it results variation in wheelbases.

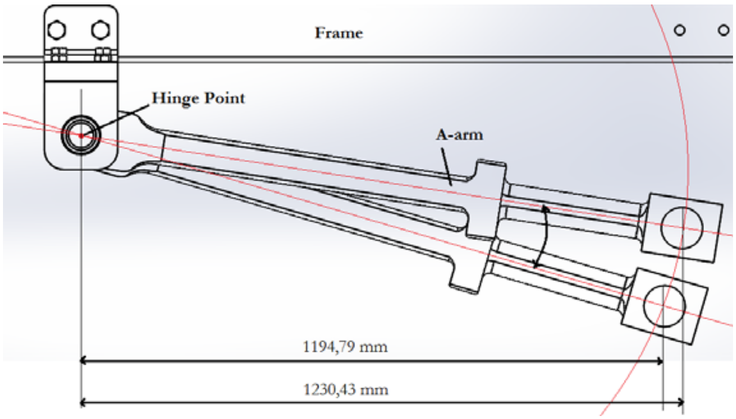


FIGURE 64 - 2D DRAWING OF A-ARM AND WHEELBASE VARIATION

Figure 65 illustrates the wheelbase variation. We see that the change in wheelbase is about 35,64 mm or 3,5 cm which is not a very high number. According to our own assumptions this change in wheelbase doesn't affect the performance of our system in any significant way. Further testing is required to verify this.

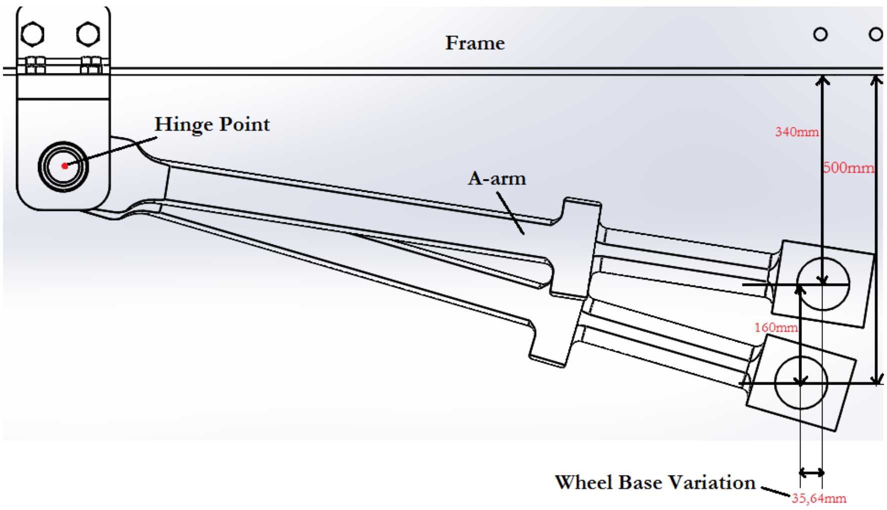


FIGURE 65 - WHEELBASE VARIATION AND SUSPENSION TRAVEL

17. LIFT AXLE

ID	REQ1.22	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.8
DESCRIPTION Should be able to have a lift axle in front or behind the driven axle.			**PRIORITY**
WHY	To distribute the weight among several wheels under heavy load and to reduce friction under light load.		C
COMMENTS			

TABLE 33 - REQUIREMENT 1.22

TEST ID	TES 1.8	**REQ ID**	1.22	
DESCRIPTION	This requirement will be tested in two different ways. First, we will test the mechanism for the dead axle, then we will test if the hydraulics of this system is working as intended or not.			**STATUS**
COMMENT				Pending

TABLE 34 - TEST 1.8 LIFT AXLE

One of the requirements we have is that our system should have a lift axle either at the front or behind the driven axle. This is a crucial requirement, because lift axle are almost standard feature in modern heavy duty vehicle. It allows for better weight distribution, and increase in gross weight.

Testing method for this requirement (table 33) is described in table 34.

This requirement has not been fulfilled. The reason being that we simply did not have enough time to develop lift axle concepts [9]. According to our own opinion we felt that it would be much better to continue developing the WS.

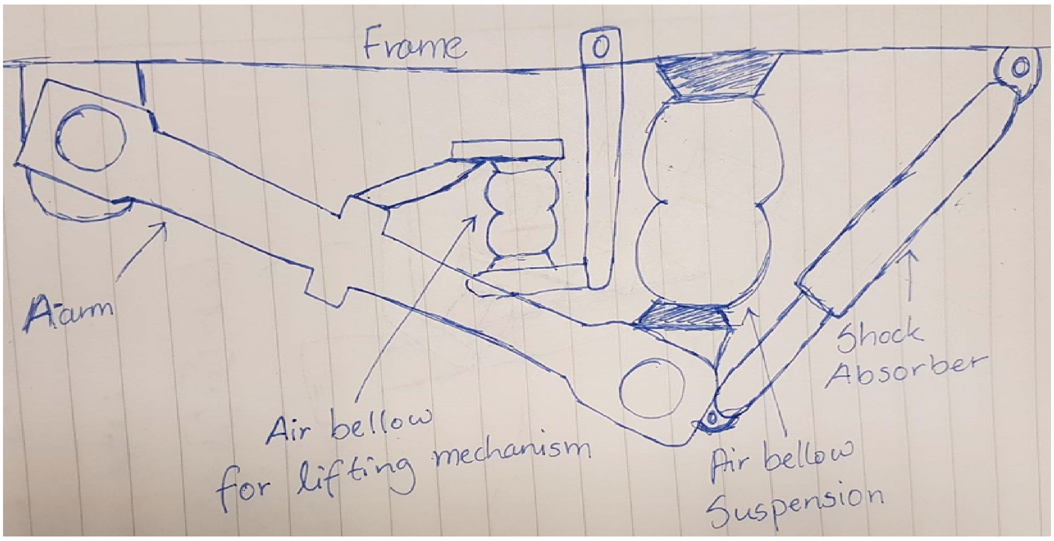


FIGURE 66 - CONCEPT 1 LIFT AXLE [9]

18. ELECTRIC DRIVE FOR EACH WHEEL

ID	REQ1.26	**SOURCE**	KA
DATE CREATED	11.01.2017	**TEST ID**	TES 1.2
DESCRIPTION The system should have one ED per wheel.			**PRIORITY**
WHY	To give room for more concepts and designs.		A
COMMENTS			

TABLE 35 - REQUIREMENT 1.26

TEST ID	TES 1.2	**REQ ID**	1.08 - 1.26 - 1.27 - 1.28 - 1.29 - 3.07	
DESCRIPTION	To test these requirements, we will make a 3d model which can show these different components to us as well as their functions in relation to each other. We will also use a 3D animation to show the functionality of these components.			**STATUS**
				Verified 1.08, 1.26, 1.28 & 1.29
COMMENT				

TABLE 36 - TEST 1.2 ELECTRIC DRIVE FOR EACH WHEEL

Test specification for this requirement says that this requirement can be tested by making a 3D model of our system to show that our system indeed have one electric drive per wheel.

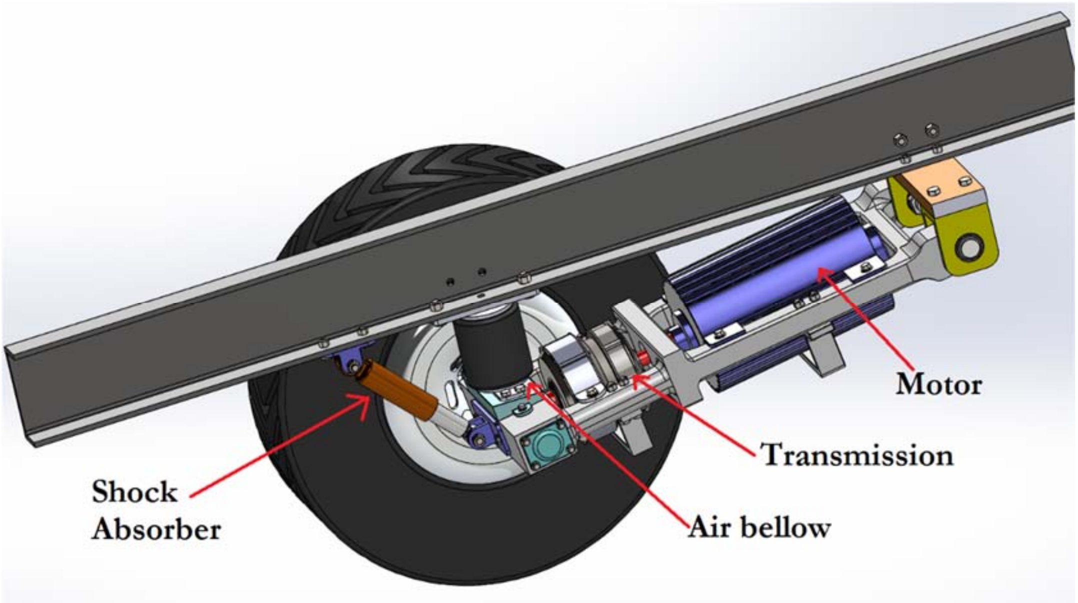


FIGURE 67 - 3D MODEL OF OUR SYSTEM

Figure 66 shows a 3D model of our system, and we can see that it includes both the electric motor, a transmission system, air bellow and shock absorber. This means that we have also satisfied REQ1.28 and REQ1.29 [2].

19. STANDARD TRUCK FRAME

ID	REQ2.01	**SOURCE**	KA
DATE CREATED	11.01.2017	**TEST ID**	TES 1.10
DESCRIPTION The system shall be placed in standard truck frame.			**PRIORITY**
WHY	To fit all types of trucks.		B
COMMENTS			

TABLE 37 - REQUIREMENT 2.01

TEST ID	TES 1.10	**REQ ID**	2.01	
DESCRIPTION	This requirement can be tested by making a 3D model of our system.			**STATUS**
				Verified
COMMENT				

TABLE 38 - TEST 1.10 STANDARD TRUCK FRAME

This requirement is important to us because we are designing a wheel suspension, which will be integrated into existing truck frames sizes, and whom are standardized.

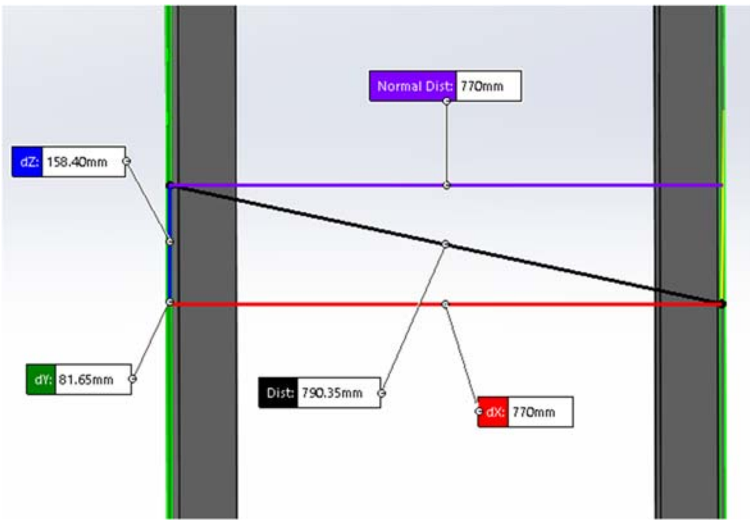


FIGURE 68 - SECTION OF FRAME

Figure 68 shows us a 3D model of frame, and we can see that the distance between these is 770mm, which is correct according to Scania blue print. We have designed our truck frame according to these blueprints, which means that our system can be placed in a standard truck frame.

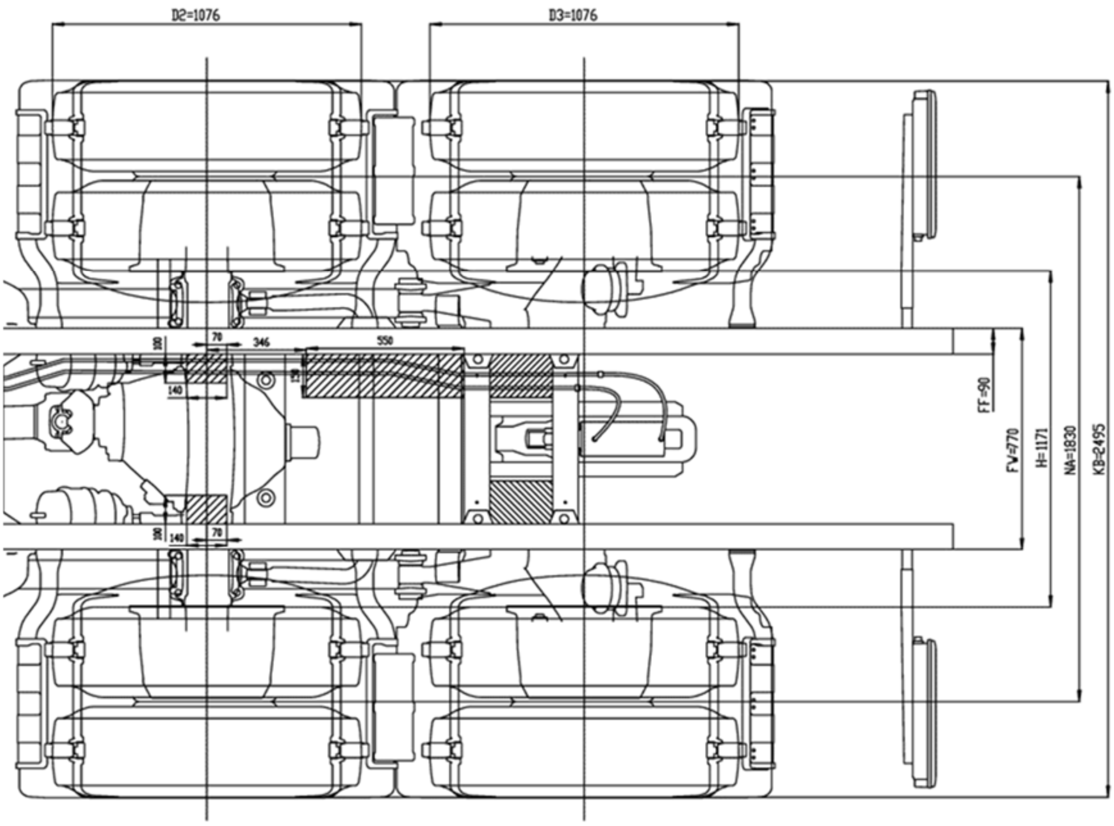


FIGURE 69 - BLUEPRINT OF SCANIA CB 6X2 TRUCK

20. STANDARD WHEEL SIZES

ID	REQ2.02	**SOURCE**	KA
DATE CREATED	09.01.2017	**TEST ID**	TES 1.1
DESCRIPTION Wheel size should be (315/80R22,5 twin assembly).			**PRIORITY**
WHY	To fit the standard truck.		C
COMMENTS			

TABLE 39 - REQUIREMENT 2.02

TEST ID	TES 1.1	**REQ ID**	1.05 - 1.06 - 1.07 - 2.02 - ~~2.03~~ - 2.04 - 2.05 - ~~3.02~~ - 3.03 - ~~3.04~~ - 3.05 - 3.06
DESCRIPTION	All the requirements above are those we do not have to test because these are specifications we will get when we buy these materials or components. It is not necessary to test these requirements.	**STATUS**	
		Verified 1.05, 1.06, 1.07, 2.02 & 2.04	
COMMENT	We cancelled requirements 2.03, 3.02, 3.04 and do not need to be tested. We adjusted requirements 2.05, 3.03, but testing will be the same.		

TABLE 40 - TEST 1.1 STANDARD WHEEL SIZES

According to our test specification we don't need to test this requirement, but we can verify this requirement by looking at our 3D model.

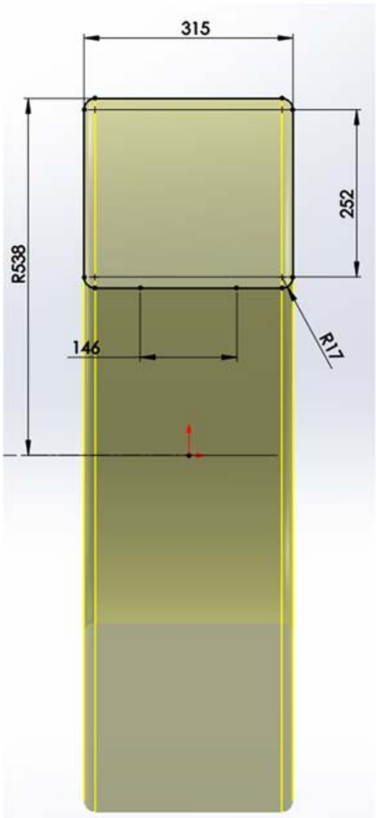


FIGURE 70 - DIMENSIONS OF WHEEL

Figure shows us the 2D drawing of our wheel. We can see that the section width of the wheel is 315mm and the radius is 538mm. The section height is 252, which is 80% of section width.

This means that the wheel we have designed for our system is of size 315/80R22,5.

21. FATIGUE TEST

We have a requirement which says that our wheel suspension should be able to withstand 200000 cycle of load. To verify this requirements we use Solidworks simulation fatigue test.

ID	REQ1.17	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.5
DESCRIPTION The wheel could make 200 000 cycles.			**PRIORITY**
WHY	Number of cycles before fatigue occurs.		A
COMMENTS			

TABLE 41 - REQUIREMENT 1.17

TEST ID	TES 1.5	**REQ ID**	1.16 - 1.17 - 1.18
DESCRIPTION	These requirements will be tested using Solidworks simulations.		**STATUS**
COMMENT			Verified

TABLE 42 - TEST 1.5 FATIGUE TEST

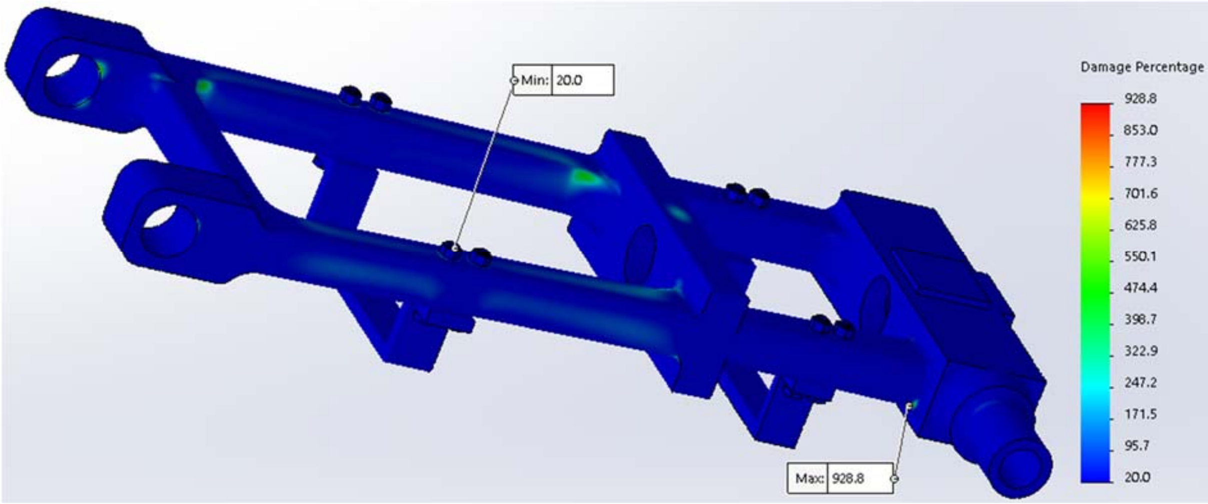


FIGURE 71 - FATIGUE DAMAGE

Figure 71 shows fatigue damage of on A-arm, when subjected to 200000 cycles. As we can see almost all of the A-arm is blue colored, which means that these area have fatigue damage of about 20 percent. Some areas on the A-arm has a damage percentage of 928.8, which is very high. According to Solidworks study advisor, 100% or above means that the part will not withstand as many load cycles as we have specified.

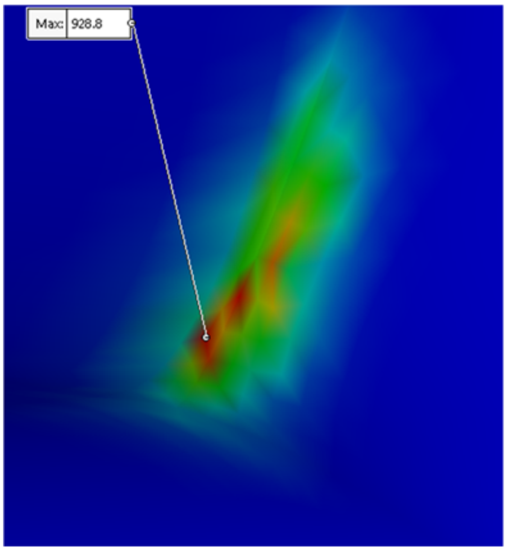


FIGURE 72 - HIGHEST FATIGUE DAMAGE AREA

Here is a close view of the affected area, with max damage. Notice that this is the same area where the highest amount of stress is working. This confirms that the tests we did were indeed correct.

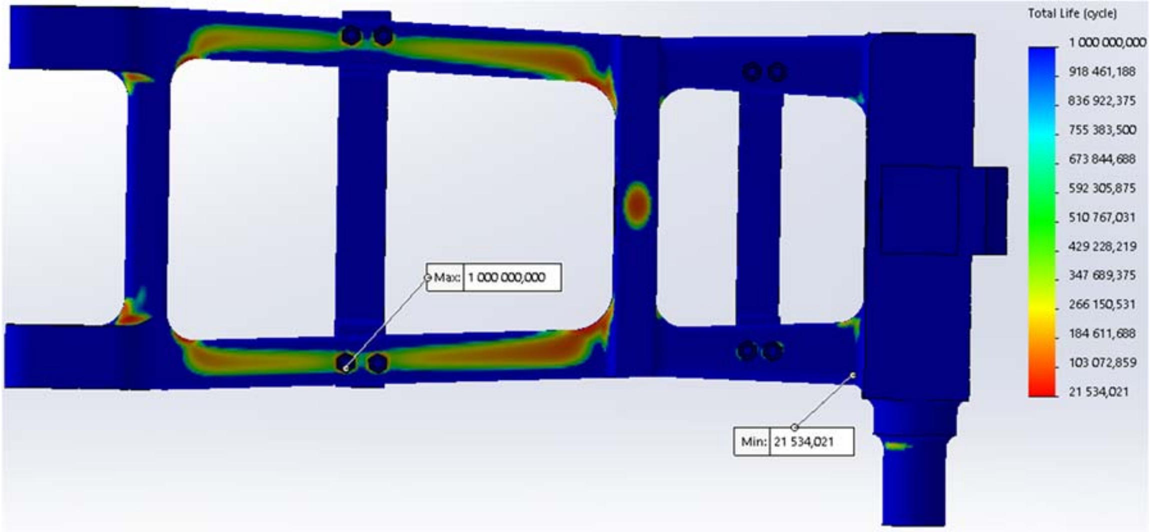


FIGURE 73 - FATIGUE LIFE CYCLE

Figure above shows the expected life of our A-arm, and the distribution. The highest life cycle is at the bolts, and the lowest life cycle is at the area with most fatigue damage.

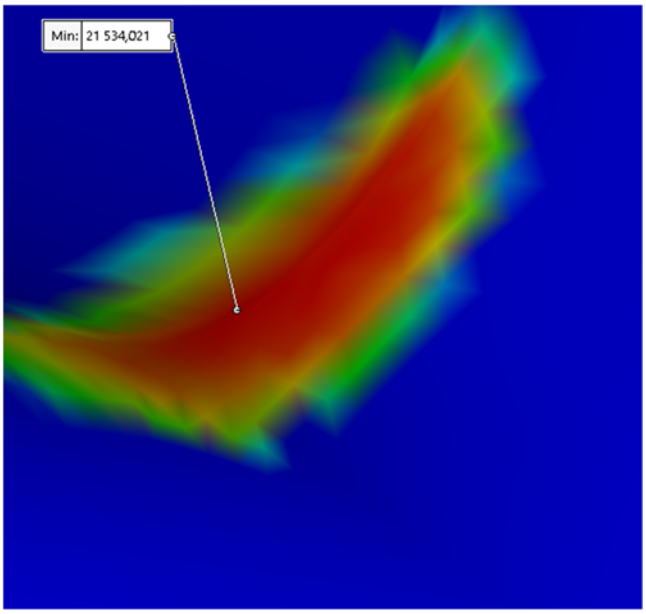


FIGURE 74 - LOWEST LIFE CYCLE AREA.

Here we have a close view of the area with lowest life expectancy, which is at 21534 load cycles.

With this test we can conclude that the A-arm as it is now will not withstand 200000 load cycles. Currently it can only withstand 1:10 of the expected load cycle.

We can see that the most affected area is at the point with highest stress concentration, and which is a curve. If we can somehow resolve this problem it is possible that the A-arm can withstand much more than the expected load cycles.

22. REDUCE WEIGHT

One of our requirements were to reduce the total weight of the truck as much as possible. This is a very important requirement, because reduced weight means less fuel consumption and increased GVW.

ID	REQ1.04	**SOURCE**	KA
DATE CREATED	06.01.2017	**TEST ID**	TES 1.19
DESCRIPTION Reduce overall weight.			**PRIORITY**
WHY	To reduce energy consumption.		C
COMMENTS			

TABLE 43 - REQUIREMENTS 1.04

TEST ID	TES 1.19	**REQ ID**	1.04
DESCRIPTION	This requirement can be verified by using SolidWorks program, and calculate how much existing system weighs.		**STATUS** Verified
COMMENT			

TABLE 44 - TEST 1.19 REDUCE WEIGHT

This requirement is tested and verified by using Solidworks to estimate the weight of our system. We also use various data sheets where Solidworks program is lacking (Motor and other electrical components). We use this information to make a weight budget diagram (Att: M) and compared it to components found in a regular combustion engine heavy duty truck [10].

We can verify that the overall weight is reduced significantly.

23. UNTESTED REQUIREMENTS

There are some requirements which were not tested by the group. The reason for this is that these requirements were either changed or removed entirely. Another reason for why some of the requirements were not tested was time limit. Some of the other requirements were very time consuming. The opinion of the group was that these other requirements were not as important, but will be tested if we are done testing other more important requirements.

Requirement we were not able to test were REQ1.02, 1.22, 2.07 and 2.08, and the reason was limited time.

Requirement REQ1.27, 2.03, 3.05, 3.06 and 3.07 are requirements we did not test. Requirements related to torsion beam were not tested because we decided not to use torsion beam in our wheel suspension. This was done, because it is very difficult to simulate torsion beam in Solidworks. That’s why it was decided that we will not use torsion beam.

24. REFERENCES

[1] S. Bjørkgård, *Product Requirement Targets,* Kongsberg: Kongsberg Automotive, 2016.

[2] E-Axle, "Requirements Document," E-Axle, Kongsberg, 2017.

[3] E-Axle, "Test Specification," E-Axle, Kongsberg, 2017.

[4] E-Axle, "Material Document," E-Axle, Kongsberg, 2017.

[5] E-Axle, "Calculations Document," E-Axle, Kongsberg, 2017.

[6] E-Axle, "Design Document," E-Axle, Kongsberg, 2017.

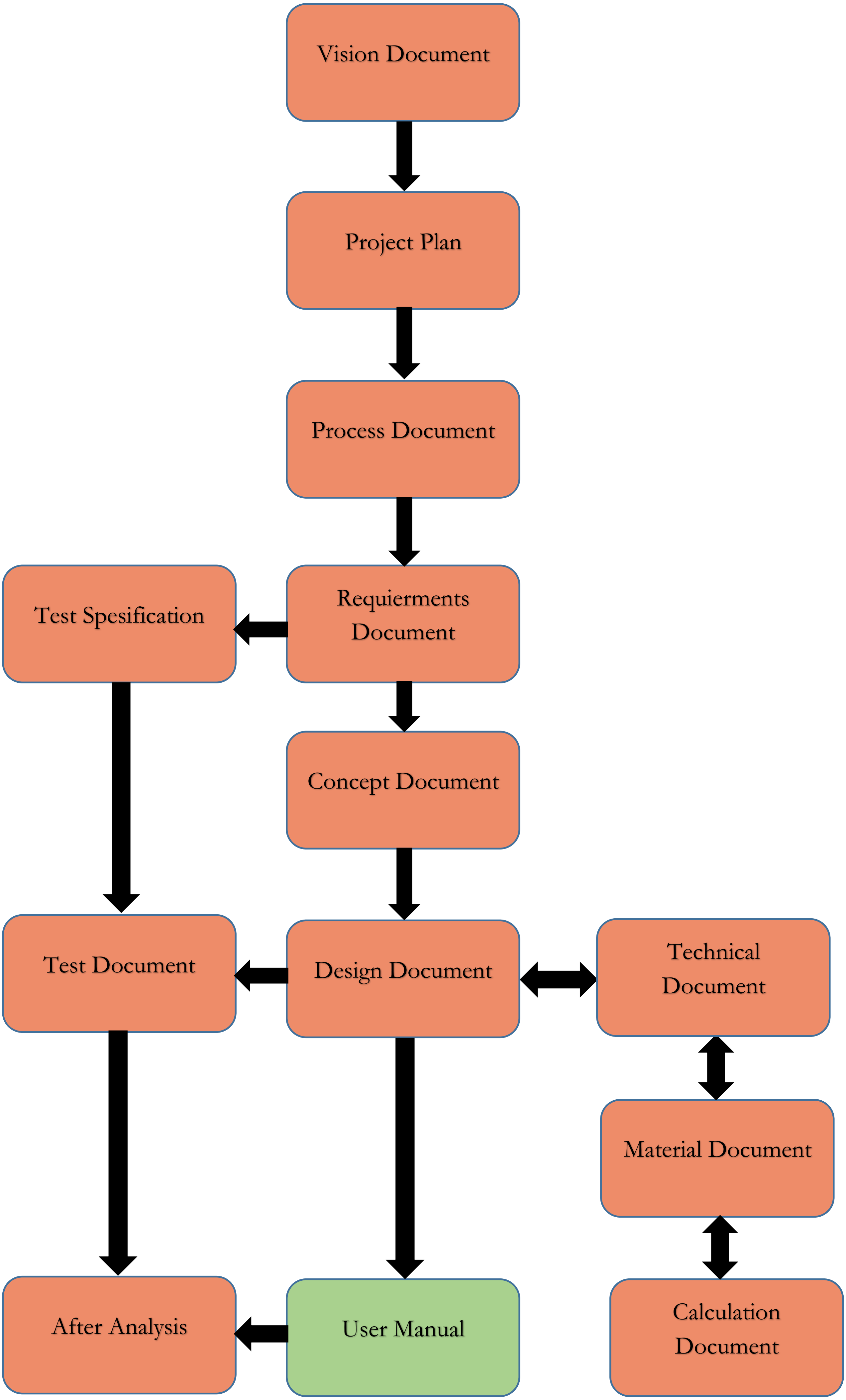
[7] "ushybrid," [Online]. Available: http://www.ushybrid.com/documents/PDF/EDU240.pdf. [Accessed 10.05.2017 May 2017].

[8] V. Vaidya, "www.quora.com," Quora, 16 02 2017. [Online]. Available: https://www.quora.com/What-is-wheel-travel. [Accessed 13 05 2017].

[9] E-Axle, "Concept Document," E-Axle, Kongsberg, 2017.

[10] Mack Trucks, "www.macktrucks.com," Mack Trucks, [Online]. Available: https://www.macktrucks.com/powertrain-and-suspensions/engines/mp7/. [Accessed 19 05 2017].

[11] Shenzhen Cone Technology CO. LTD., "alibaba.com," SHENZHEN CONE TECHNOLOGY CO.,LTD., [Online]. Available: https://www.alibaba.com/product-detail/144V100AH-96V50AH-48V60AH-120V100AH-300V100AH-72V50AH_111488325.html. [Accessed 14 05 2017].


Vision Document
Project Plan
Process Document
Requierments Document
Test Spesification
Concept Document
Test Document
Design Document
Technical Document
Material Document
After Analysis
User Manual
Calculation Document

USER MANUAL

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

Employer	Kongsberg Automotive			
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	Pawan Bhatt		PB	
Document Information	**Version**	**Date**	**Approved**	**Pages**
	1.0	23.05.17	AS	18

21. februar 2017

USER MANUAL

Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive

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LIST OF FIGURES

REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
09.05.17	0.1	Document created	AT
09.05.17	0.2	Added pictures	AT
22.05.17	0.3	Added text	AS
23.05.17	1.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
BOS	Bill Of Materials
WS	Wheel Suspension

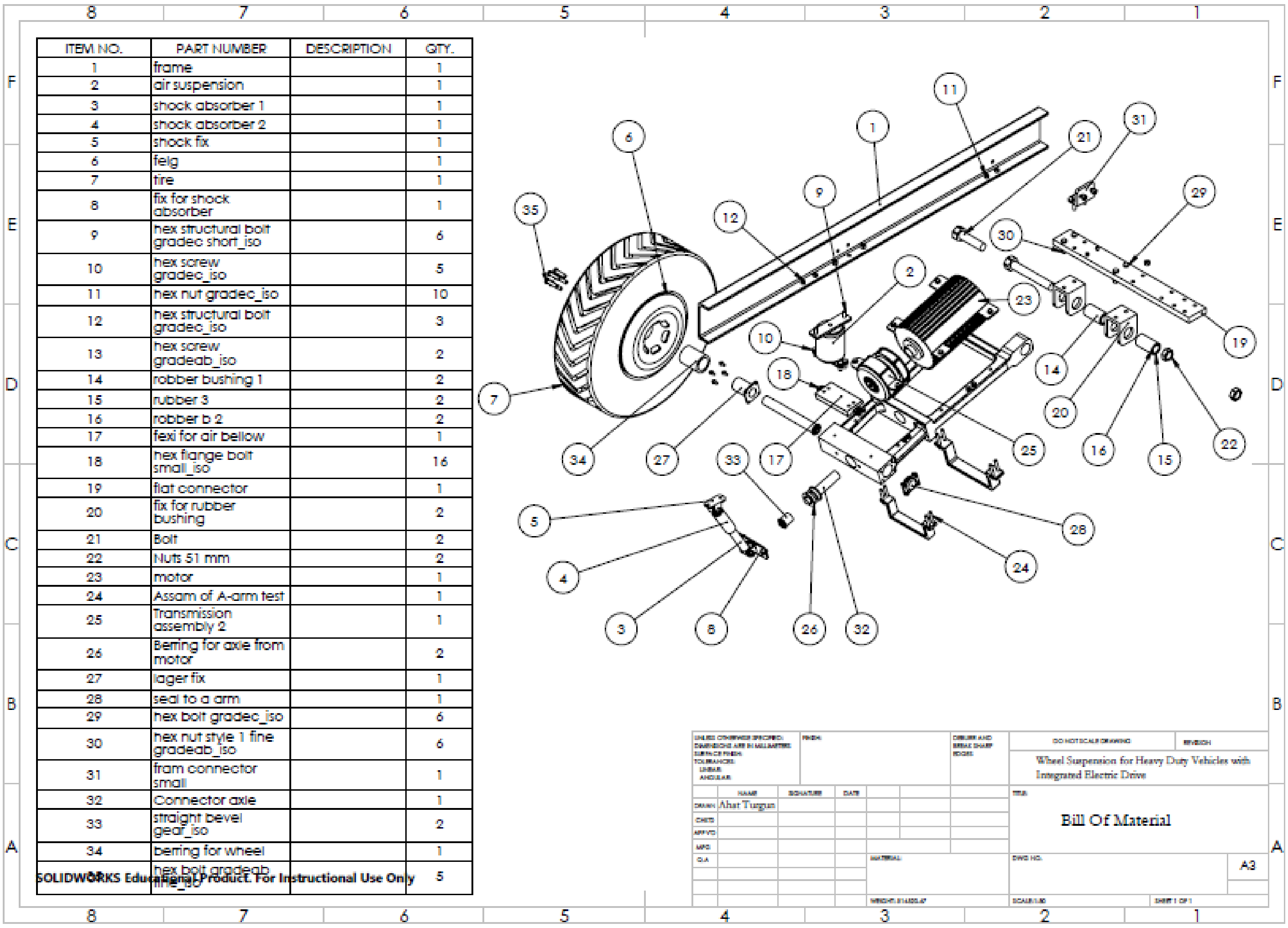
TABLE 2 – DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

User manual is an essential document to make final products usability as good as possible. An assembly of different parts is very often complex. To make it more manageable, a user manual breaks down how to assemble each part systematically to end up with the final product. In this document we give a systematical guide in how each part is going to be put together in a time efficient manner. In our user manual some simplifications are made to be able to show the functionality of the final product. E.g. bevel gear, bearings and axle shaft between motor and transmission.

2. BILL OF MATERIALS

Bill of materials contains all necessary parts to build the wheel suspension assembly.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	frame		1
2	air suspension		1
3	shock absorber 1		1
4	shock absorber 2		1
5	shock fix		1
6	feig		1
7	tire		1
8	fix for shock absorber		1
9	hex structural bolt gradec short_iso		6
10	hex screw gradec_iso		5
11	hex nut gradec_iso		10
12	hex structural bolt gradec_iso		3
13	hex screw gradeab_iso		2
14	robber bushing 1		2
15	rubber 3		2
16	robber b 2		2
17	fexi for air bellow		1
18	hex flange bolt small_iso		16
19	flat connector		1
20	fix for rubber bushing		2
21	Bolt		2
22	Nuts 51 mm		2
23	motor		1
24	Assam of A-arm test		1
25	Transmission assembly 2		1
26	Berring for axle from motor		2
27	lager fix		1
28	seal to a arm		1
29	hex bolt gradec_iso		6
30	hex nut style 1 fine gradeab_iso		6
31	fram connector small		1
32	Connector axle		1
33	straight bevel gear_iso		2
34	berring for wheel		1
35	hex bolt gradeab fine_iso		5

FIGURE 1 - BOS OF WS SYSTEM

3. ASSEMBLY SEQUENCE

Under follows the recommended assembly sequence. Left side of the frame is illustrated down below. The assembly shows only one side since both sides are identical. Same procedure is recommended on the right side.

I. Locate left side of truck frame

FIGURE 2 - STEP 1 LEFT SIDE

II. Screw the mounting bracket to frame

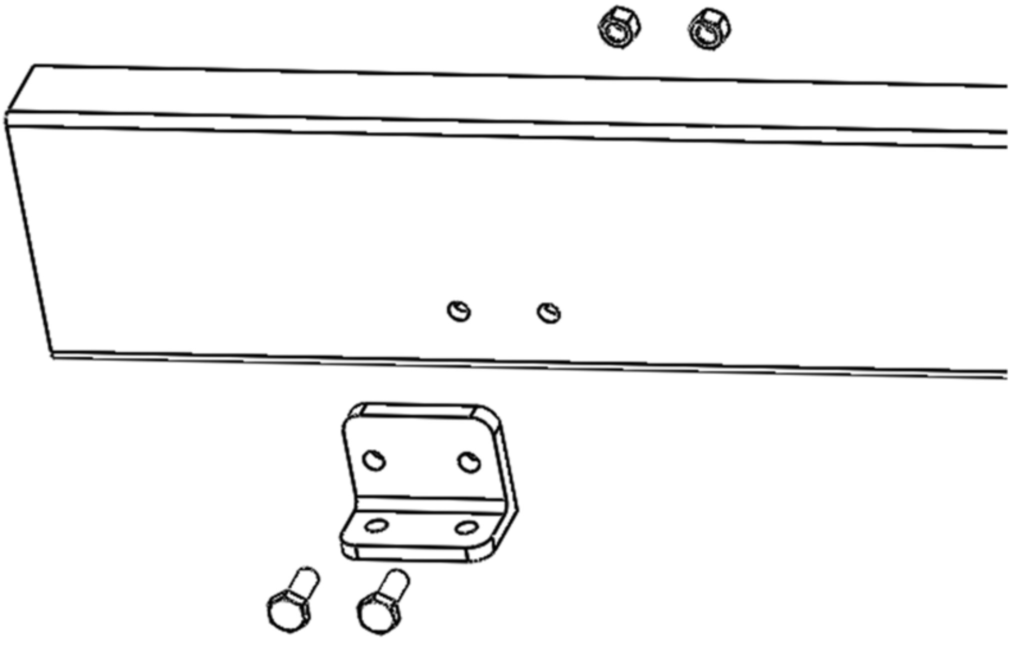


FIGURE 3 - MOUNTING BRACKET

II.1. Result

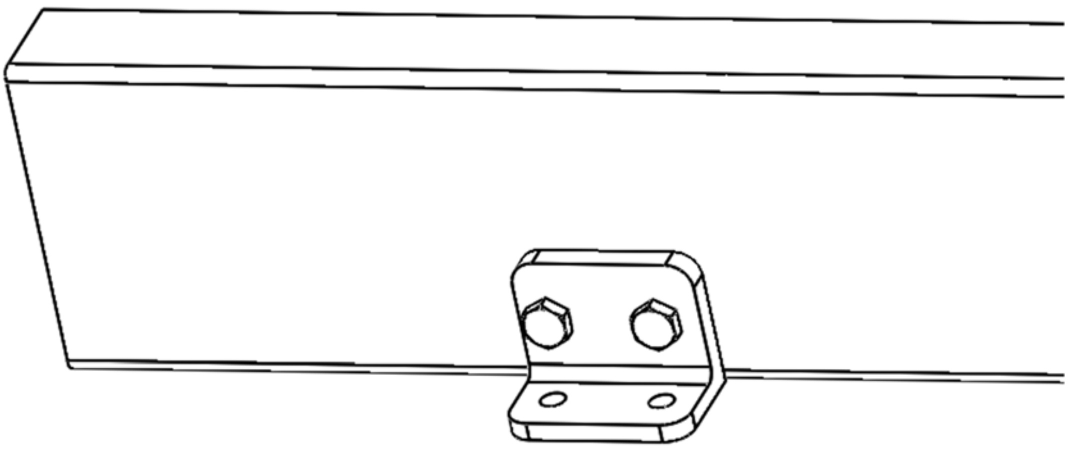


Figure 4 - Result step 2

III. Mount connection plate to frame and A-arm brackets at bottom

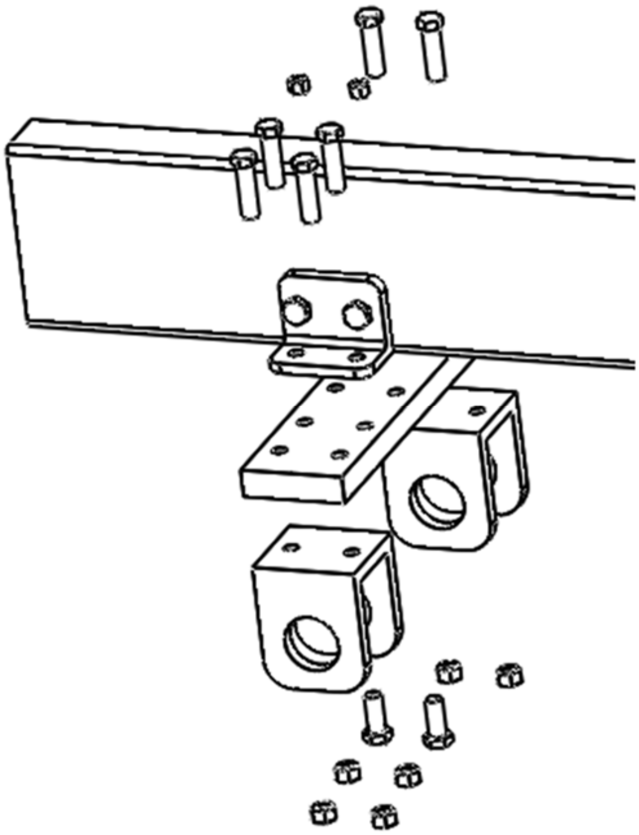


Figure 5 - Connection plate & A-arm brackets

III.1. Result

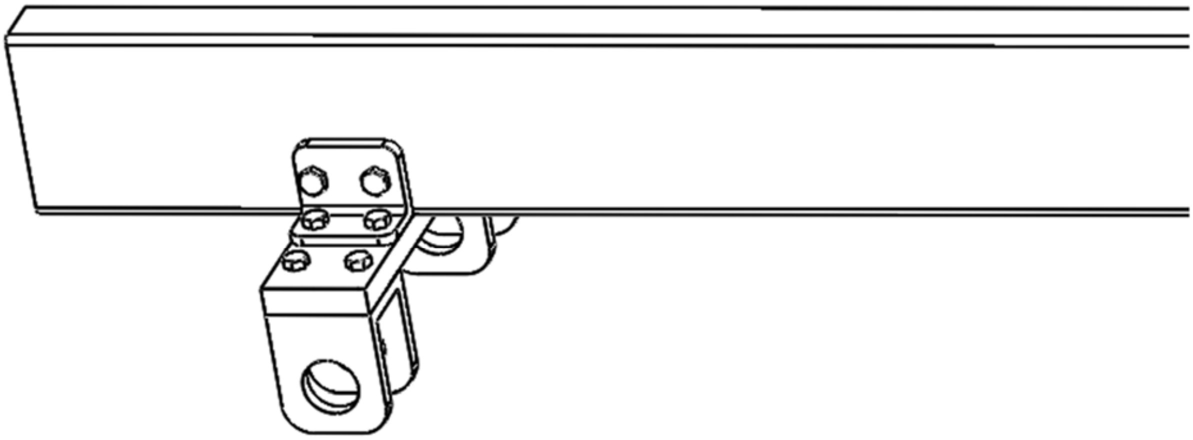


FIGURE 6 - RESULT CONNECTION PLATE & A-ARM BRACKET

IV. Locate A-arm part

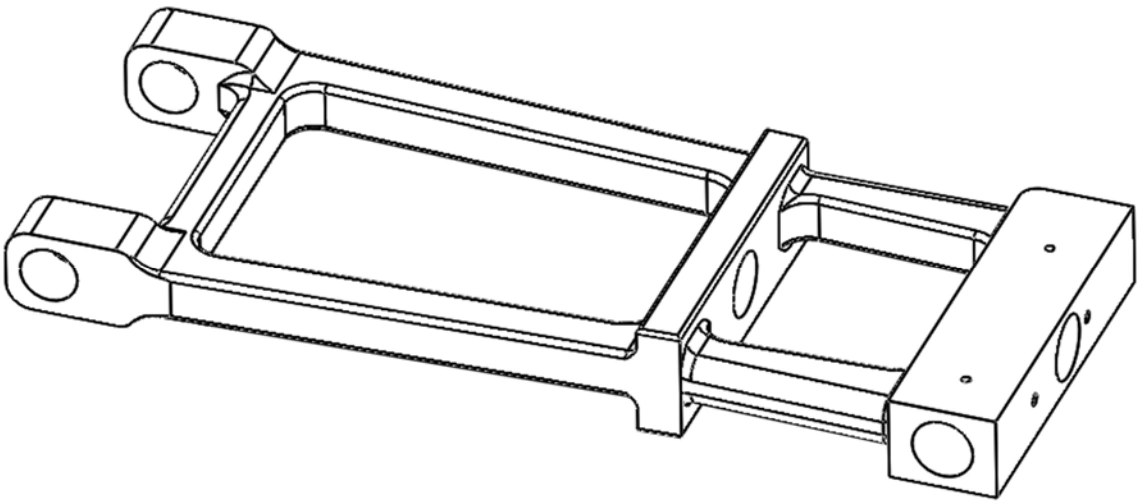


FIGURE 7 - A-ARM

V. Mount brackets to A-arm

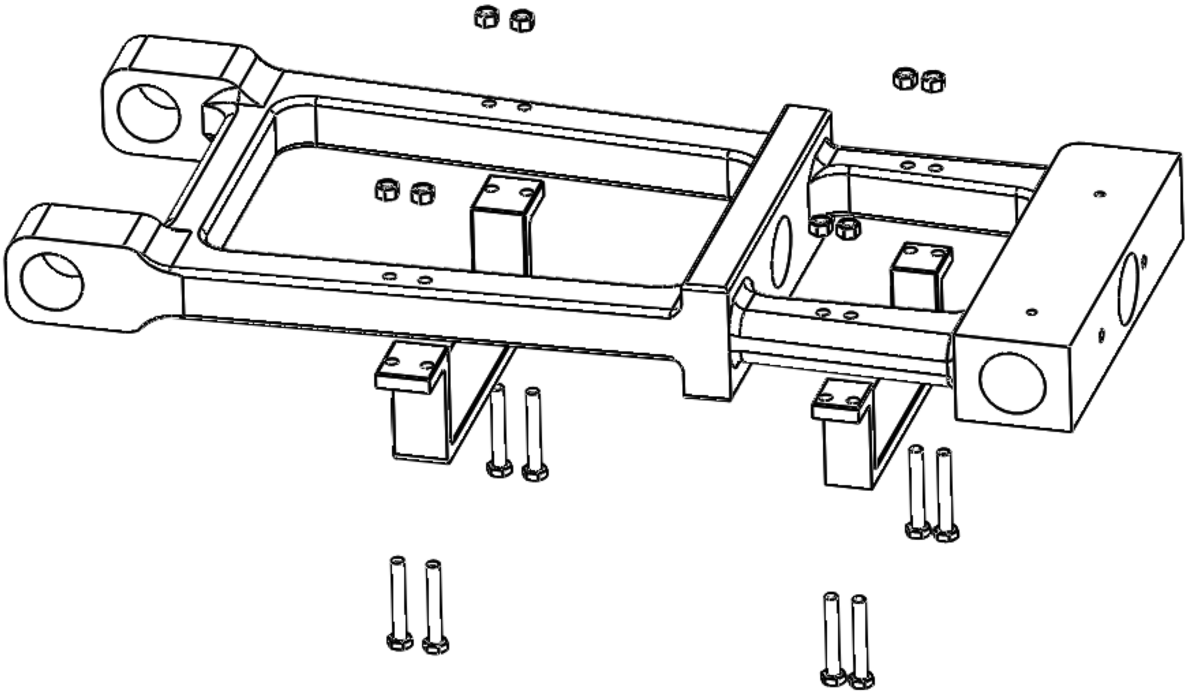


FIGURE 8 - BRACKETS TO A-ARM

VI. Result

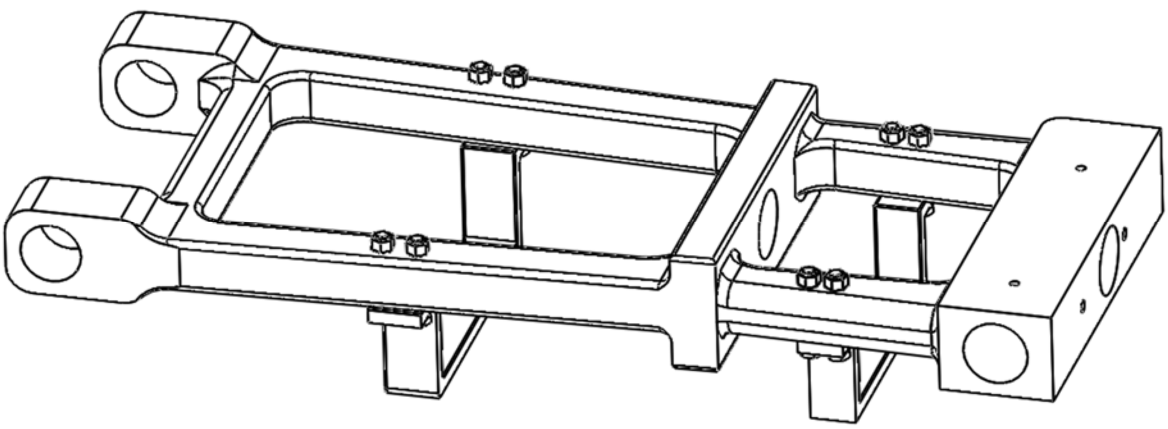
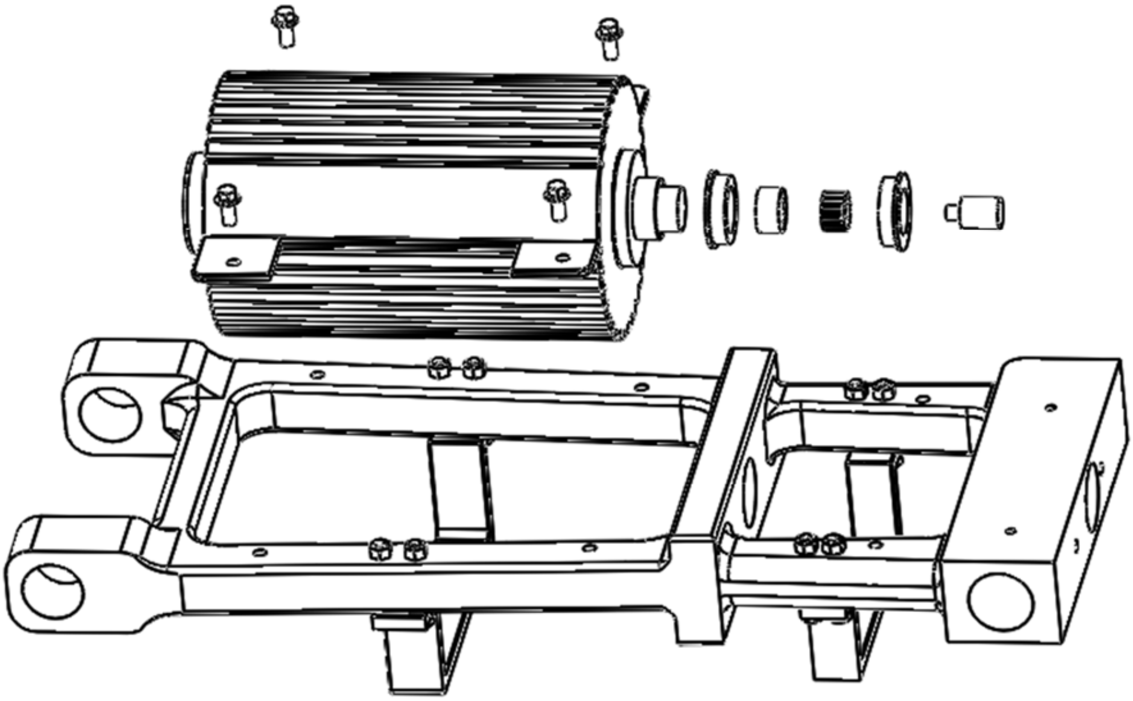


FIGURE 9 - RESULT OF A-ARM WITH BRACKETS

VII. **Place three-phase induction motor inside A-arm. Apply bearing, internal gear, external gear, another bearing and shaft.**



VIII. **Results**

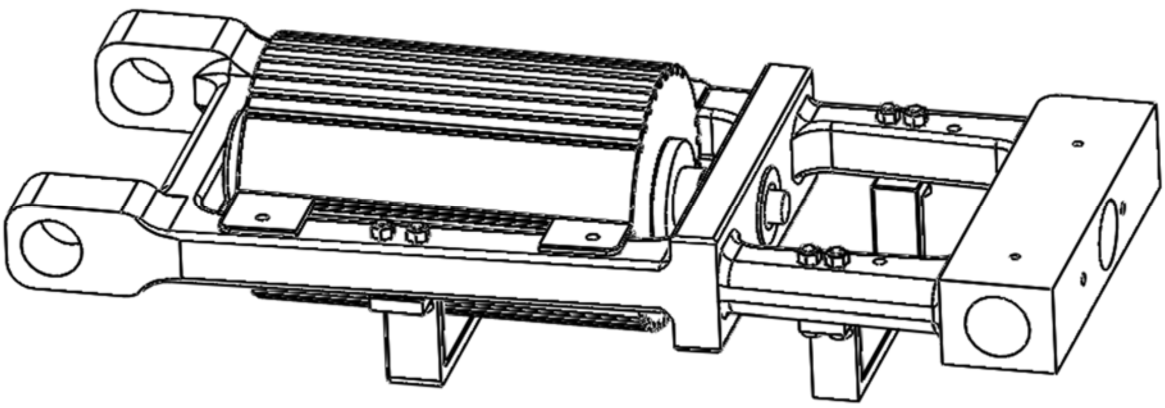


FIGURE 10 - RESULT A-ARM WITH MOTOR

IX. Insert transmission in front of motor and secure tightly.

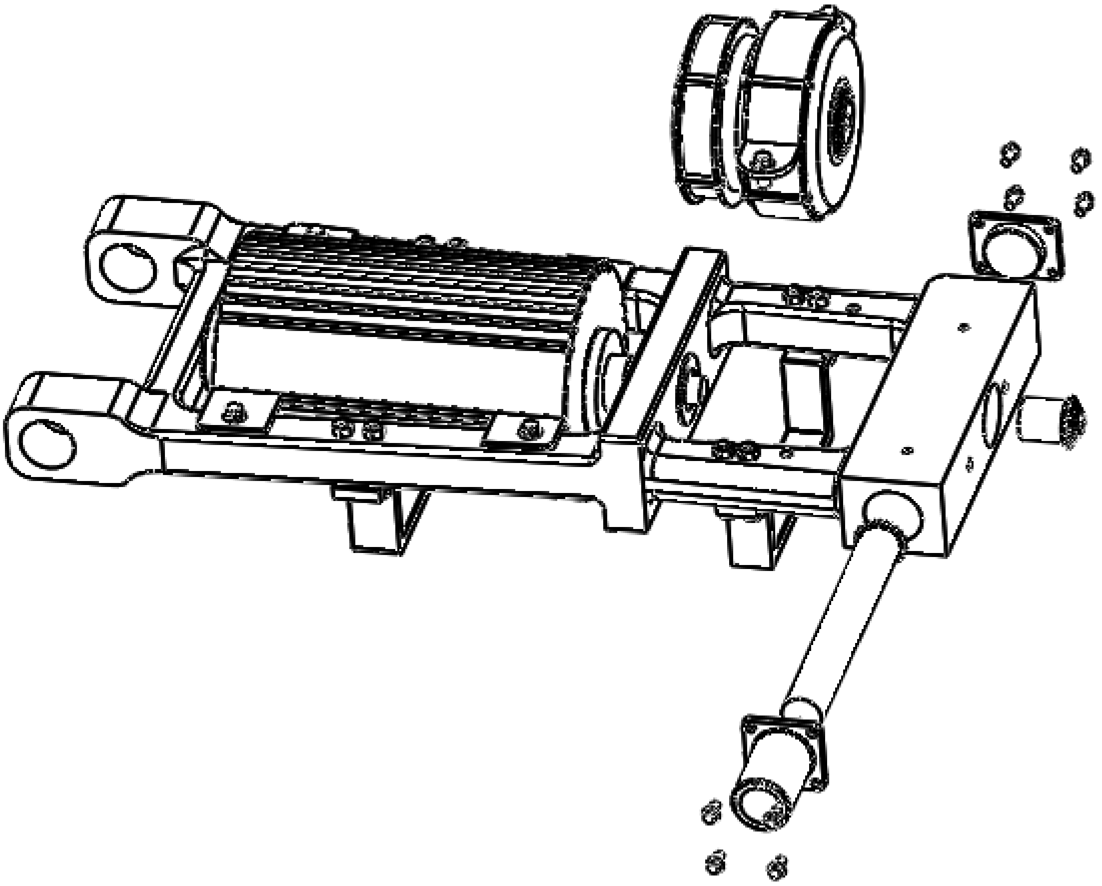


FIGURE 11 - TRANSMISSION PLACEMENT

IX.1. Result

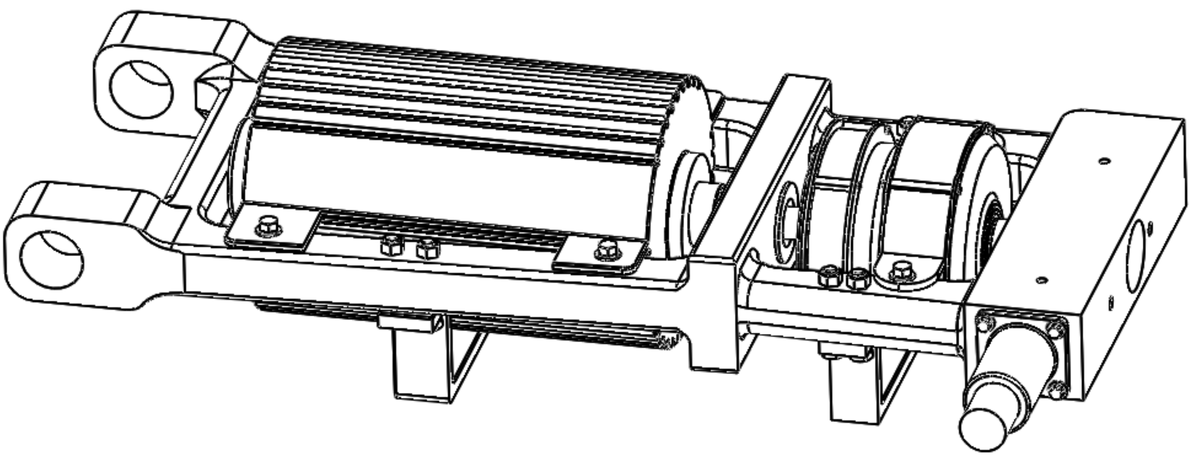


FIGURE 12 - RESULT WITH TRANSMISSION

X. Mount A-arm assembly to frame

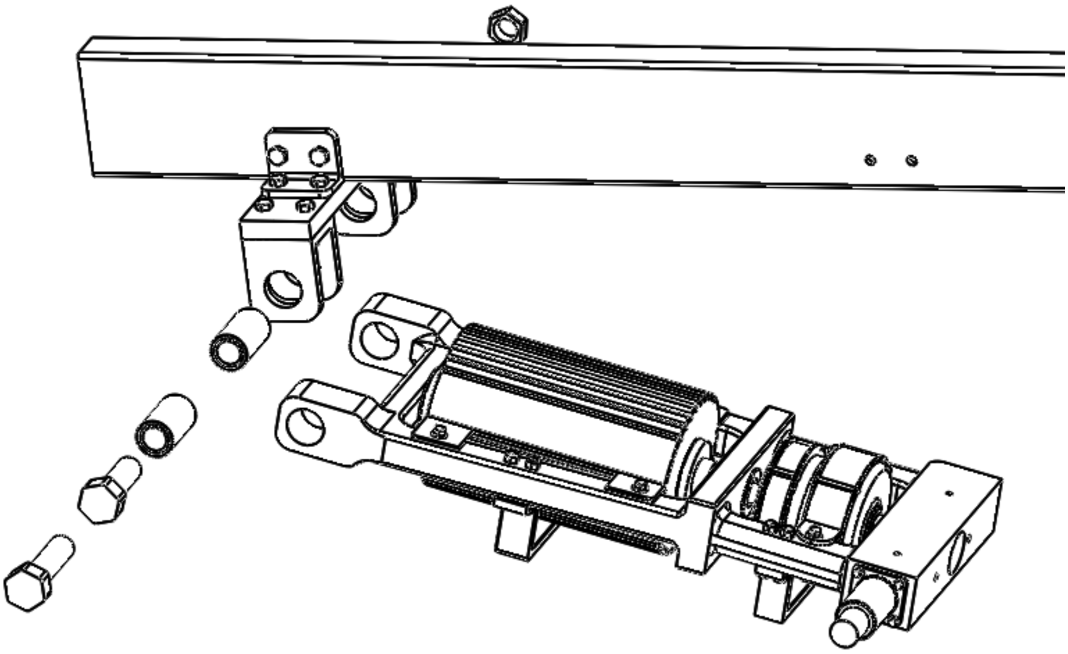


FIGURE 13 - A-ARM ASSEMBLY TO FRAME

X.1. Result

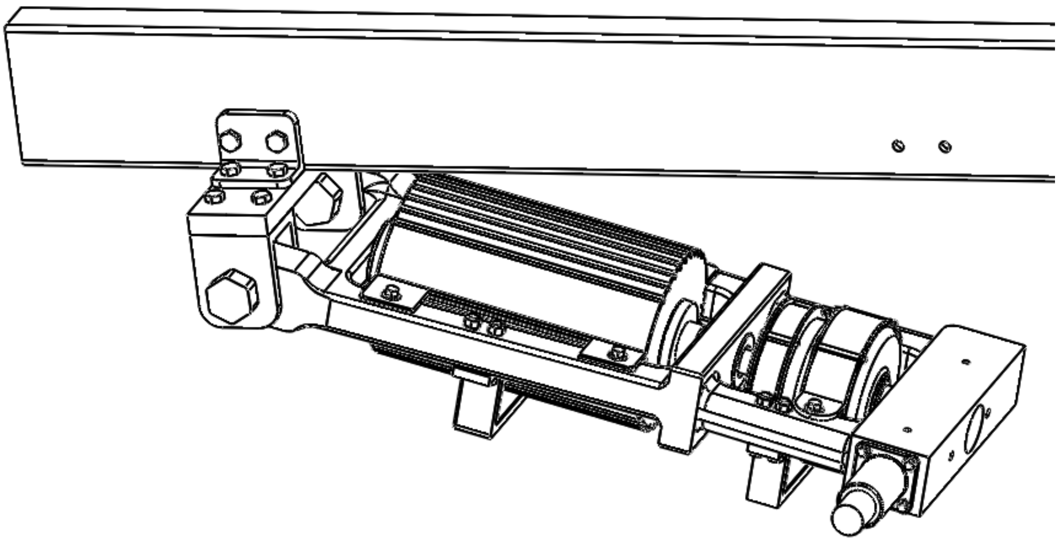


FIGURE 14 - RESULT A-ARM TO FRAME

XI. Place and screw plate to A-arm

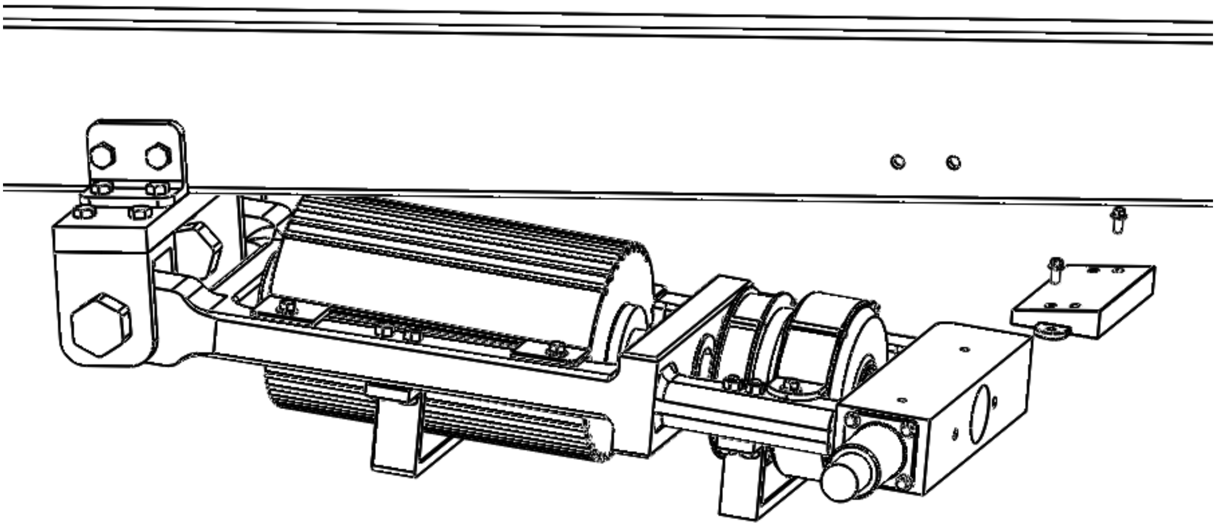


FIGURE 15 - PLATE ON A-ARM

XII. Mount air-bellow and shock absorber to frame

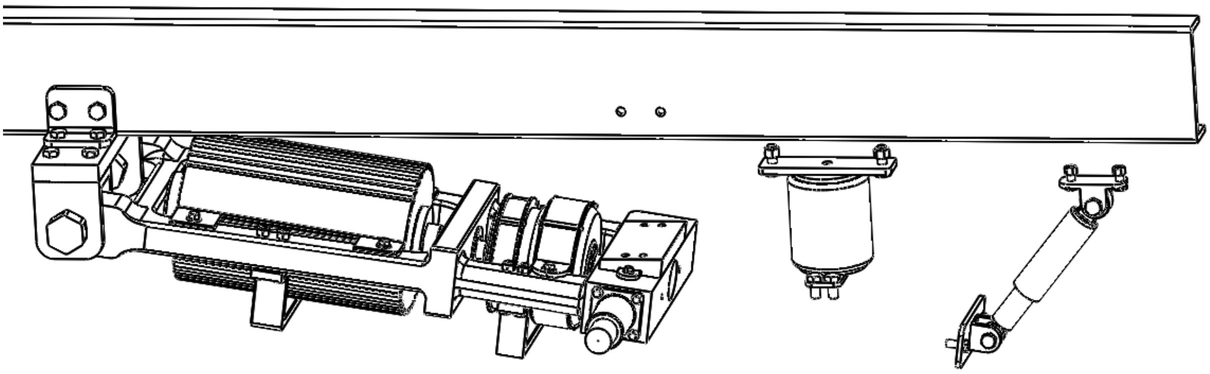


FIGURE 16 - AIR-BELLOW & SHOCK ABSORBER

XII.1. Result

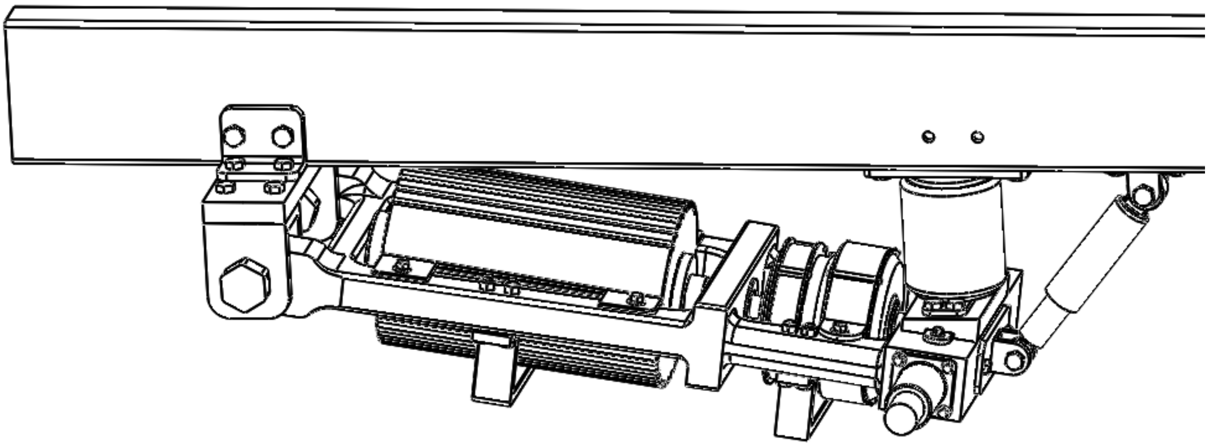


FIGURE 17 - RESULT WITH AIR-BELLOW & SHOCK ABSORBER

XIII. Fasten wheel to axle shaft. Secure with bolts.

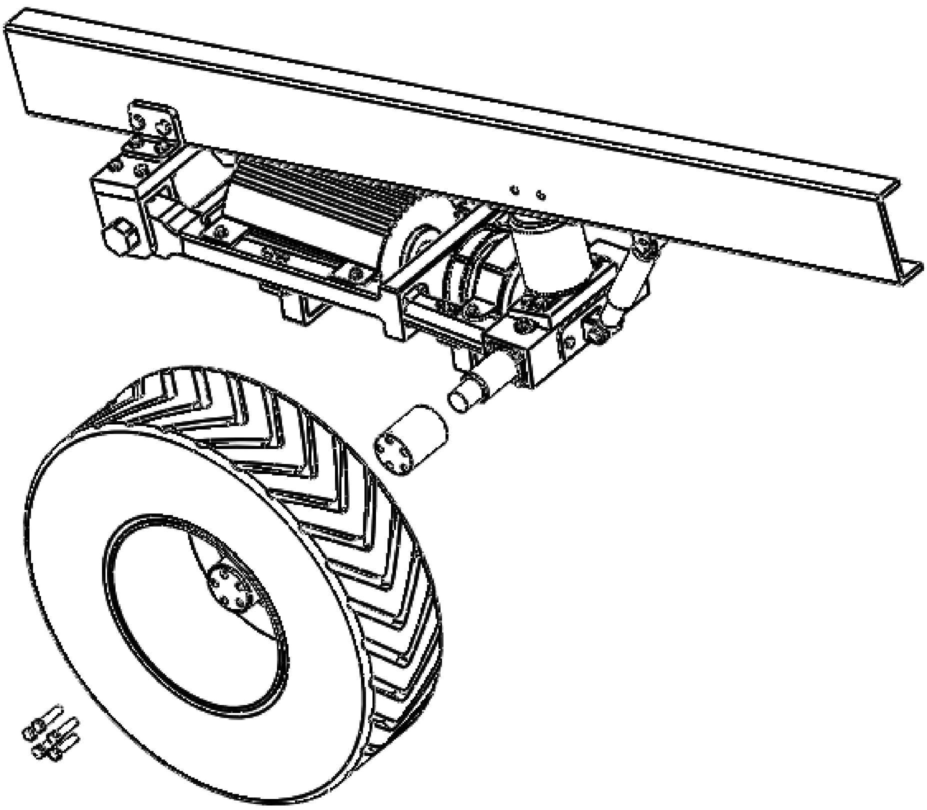


FIGURE 18 - WHEEL TO A-ARM

XIII.1. Result – External view

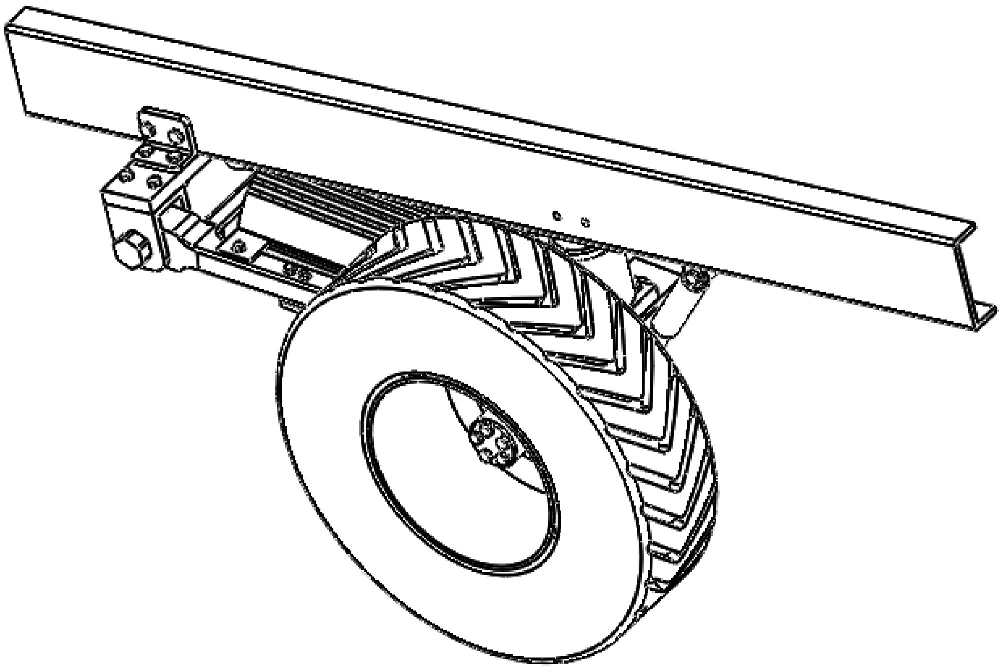


FIGURE 19 - RESULT EXTERNAL VIEW

XIII.2. Result – Internal view

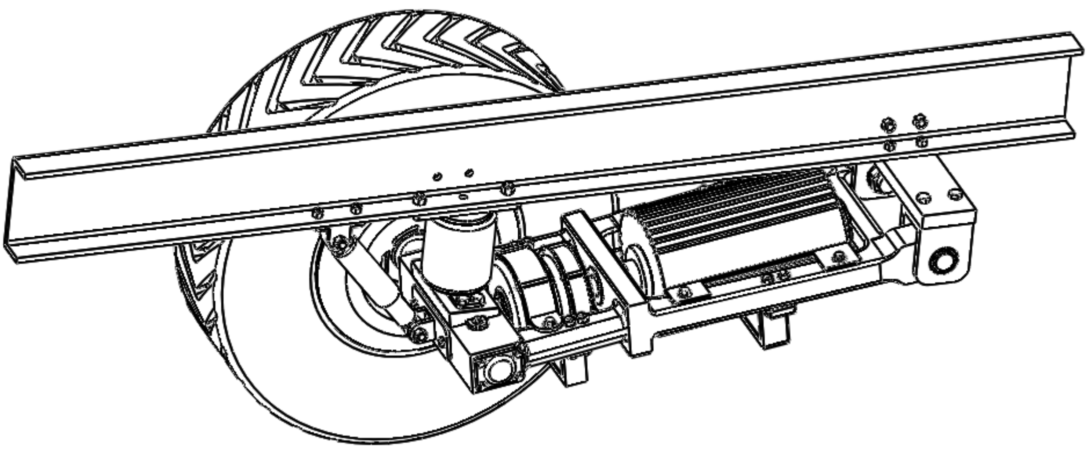


FIGURE 20 - RESULT INTERNAL VIEW

XIV. Final result – Isometric view

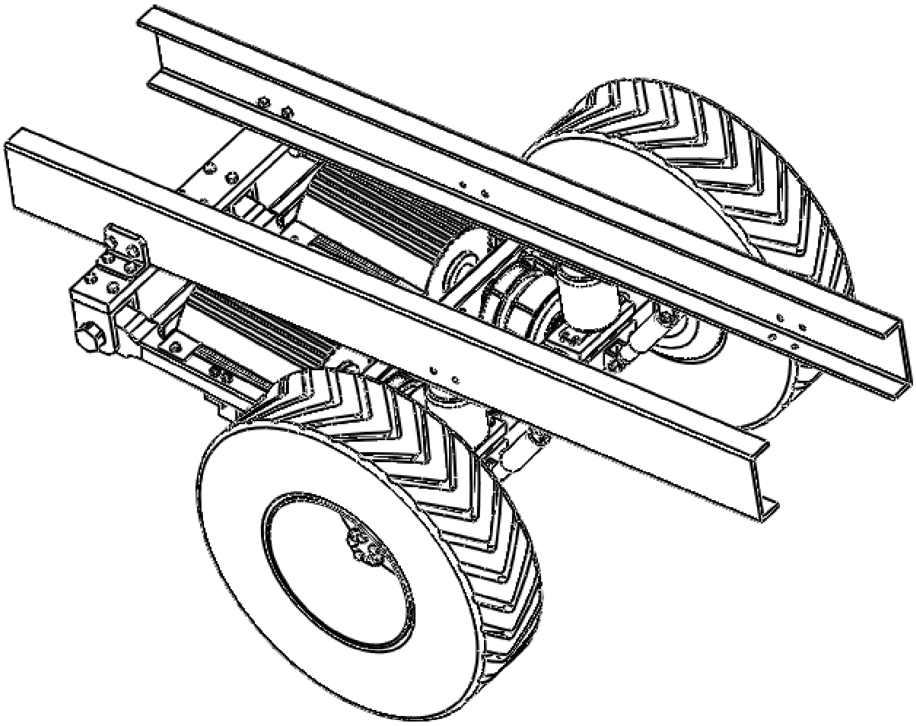


FIGURE 21 - FINAL RESULT ISOMETRIC VIEW

XV. Final result – Back view

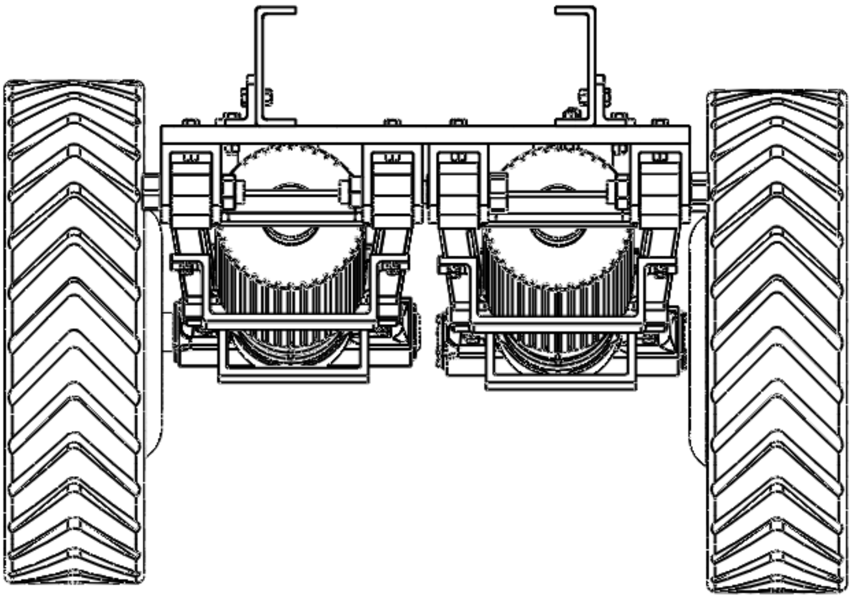


FIGURE 22 - FINAL RESULT BACK VIEW

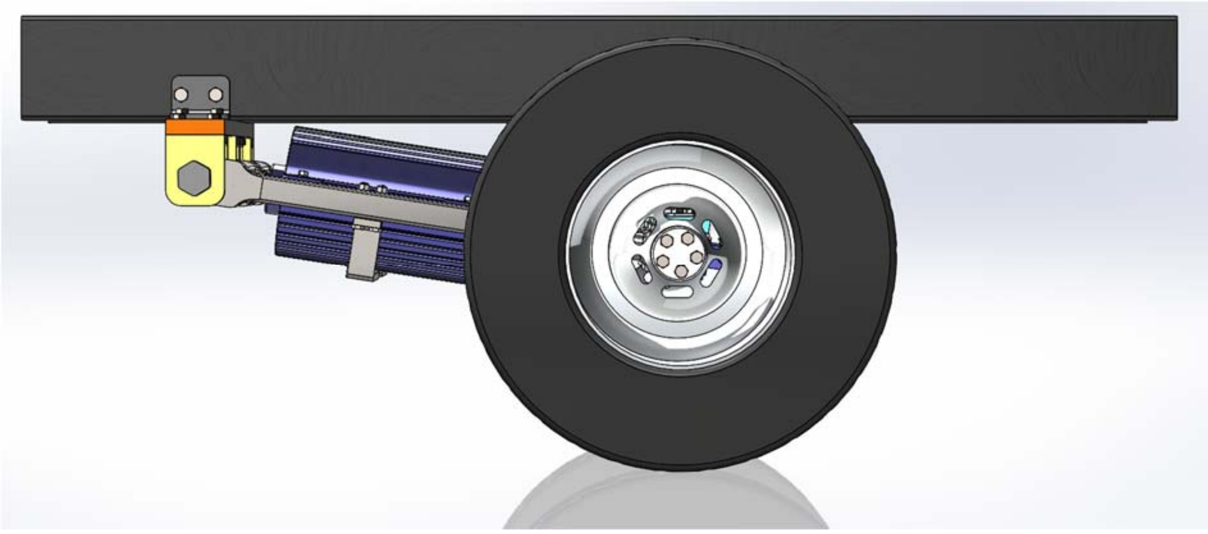


Figure 23 - Wheel suspension with electric drive 1

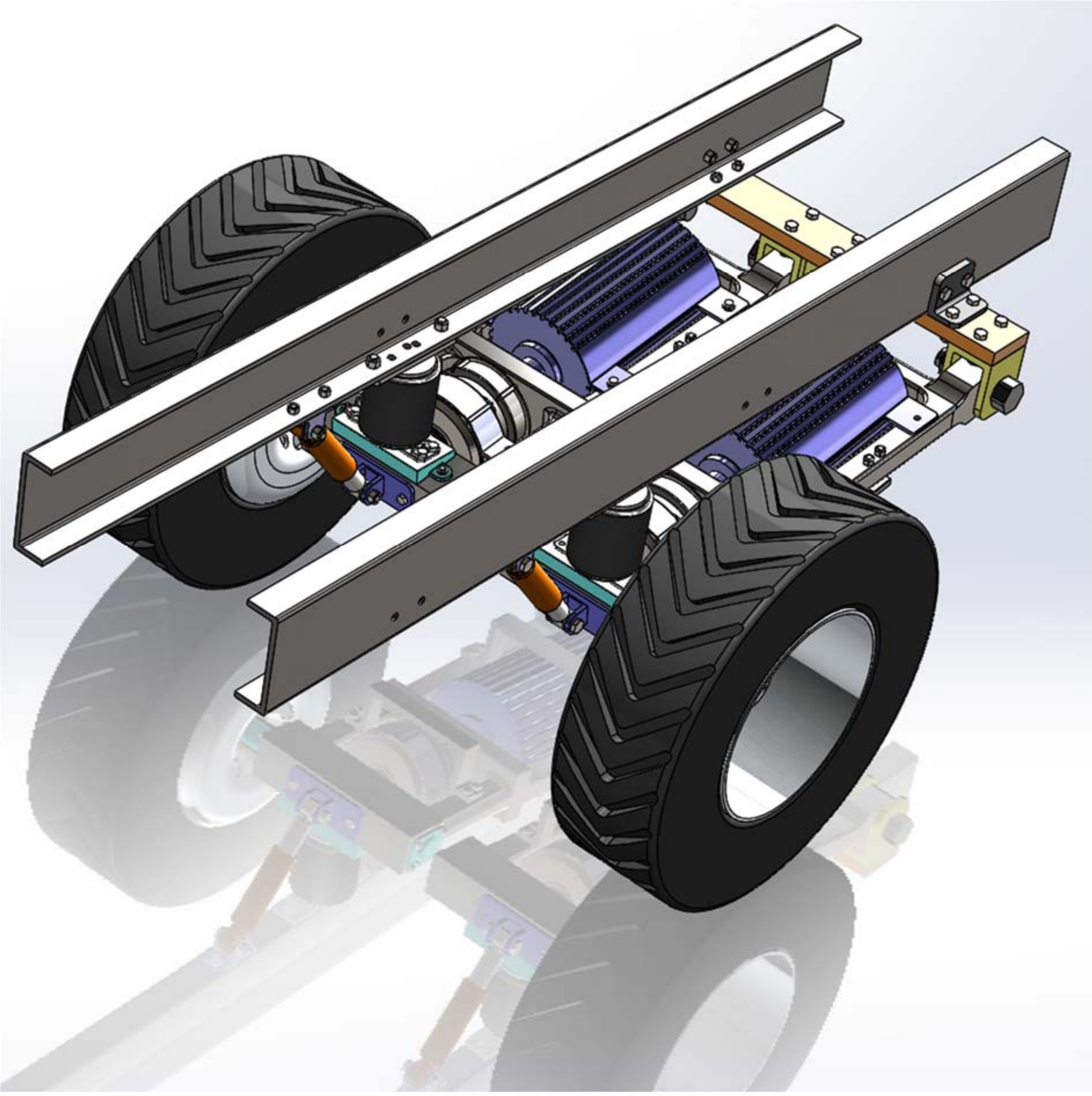


FIGURE 24 - WHEEL SUSPENSION WITH ELECTRIC DRIVE 2

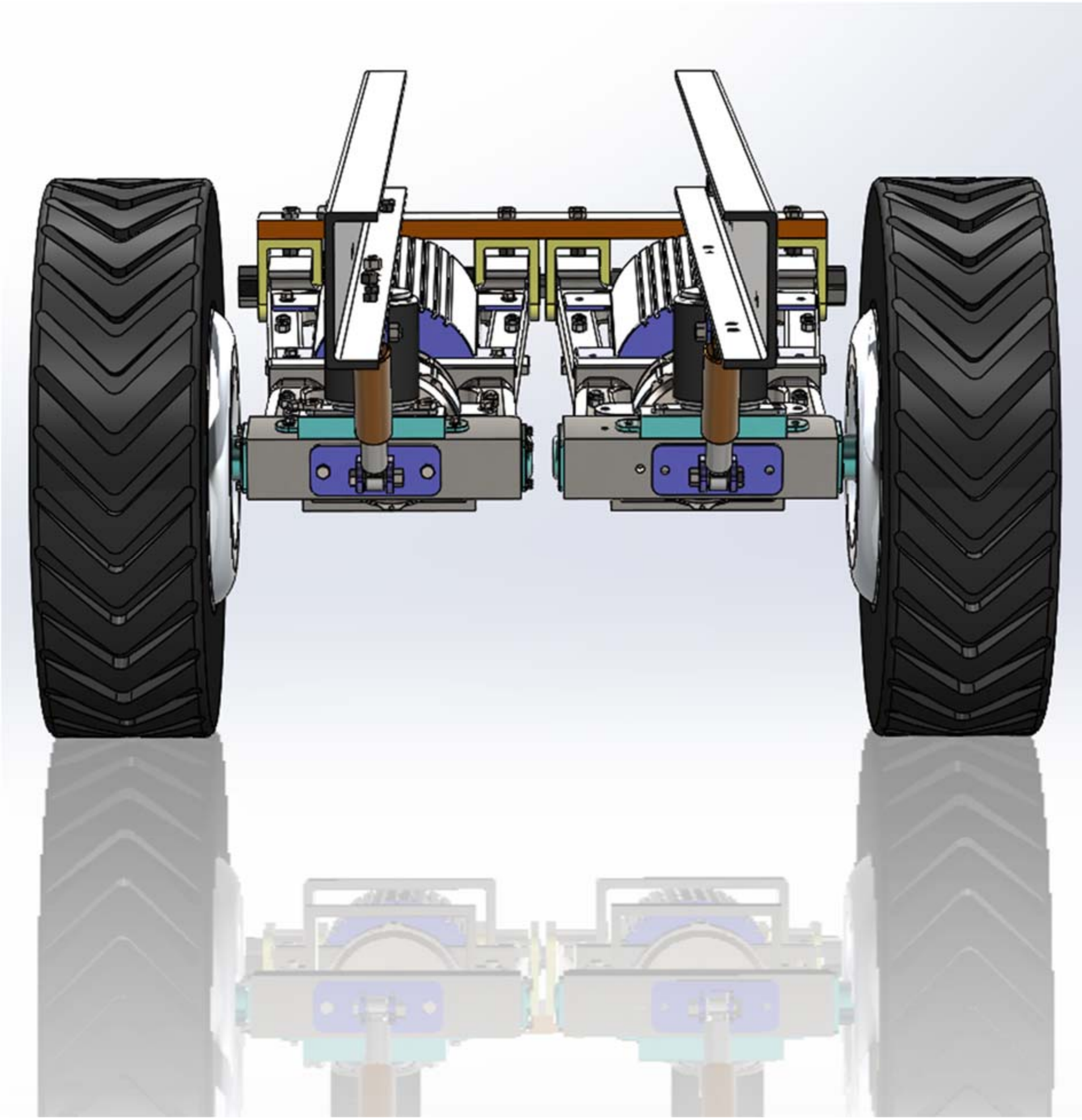
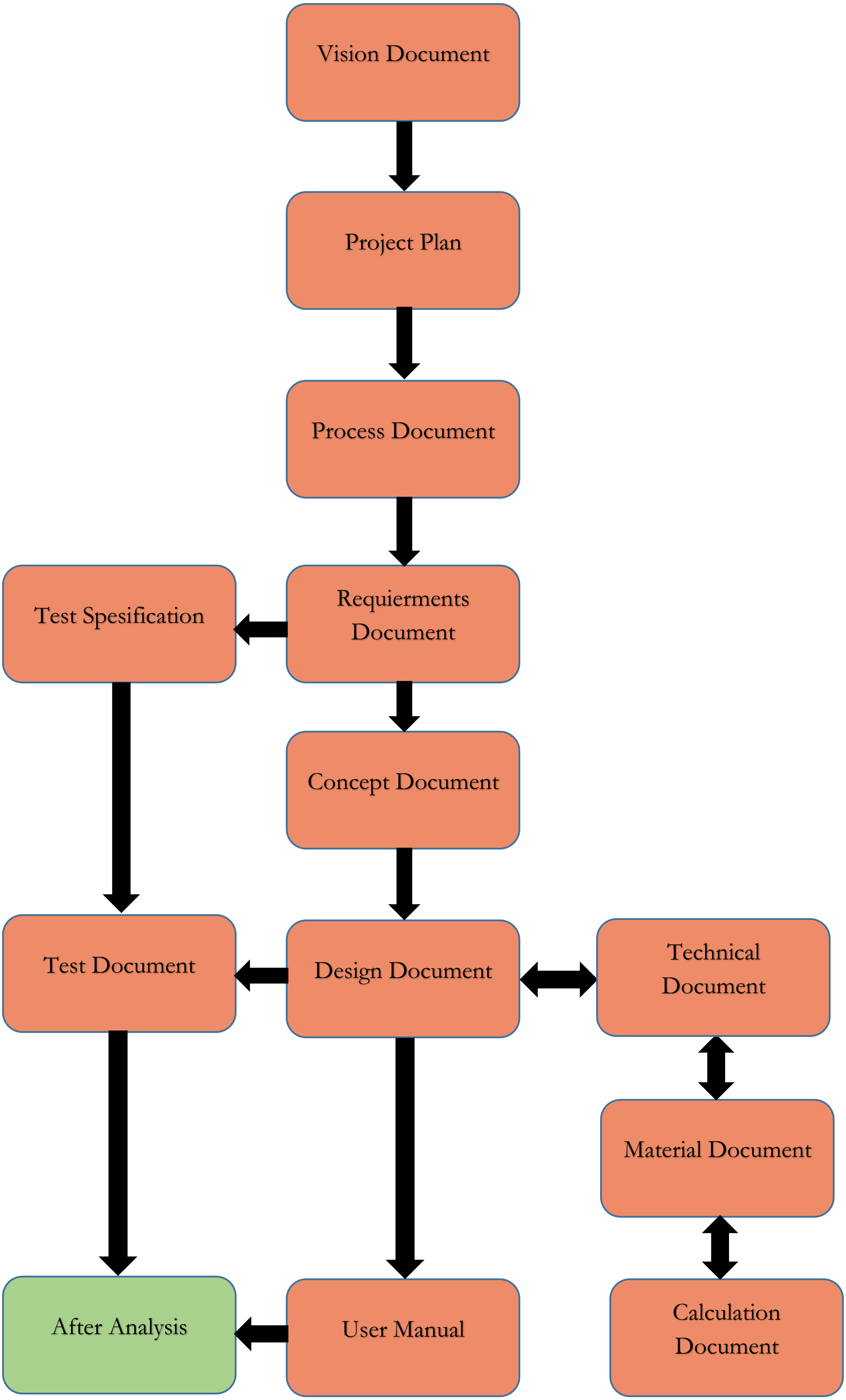


Figure 25 - Wheel suspension with electric drive 3


Vision Document
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User Manual
Calculation Document

AFTER ANALYSIS

Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive

Employer	Kongsberg Automotive			
Group Members	**Name**		**Initials**	
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	Ahat Turgun		AT	
	Anis Sadiq		AS	
	Egide Rubusa Bampo		ERB	
	Mustafa Moalim		MM	
	Pawan Bhatt		PB	
Document Information	**Version**	**Date**	**Approved**	**Pages**
	1.0	23.05.17	AS	15

21. februar 2017

AFTER ANALYSIS

Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive

REVISION HISTORY

DATE	VERSION	DESCRIPTION	AUTHOR
23.05.17	0.1	Document created	AS
23.05.17	0.2	Added after analysis	AS
23.05.17	1.0	Finalized	AK

TABLE 1 - REVISION HISTORY

DEFINITION OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
KA	Kongsberg Automotive
WS	Wheel Suspension
ED	Electric Drive
FEM	Finite Element Method

TABLE 2 – DEFINITIONS OF ABBREVIATIONS

1. INTRODUCTION

The purpose of this document is to give the reader a general and individual evaluation of work performed during the bachelor project. General part of this document is a brief summary of test results linked to the test plan. It describes successful and failed tests. To get more detailed description of each tests, view test document [1]. Explanation of deviations during the project follows. Individual part is an evaluation of members concerning the entire project and their thoughts about it.

2. REVIEW OF VISION- AND PROJECT PLAN

Looking back at both the vision document and project plan, there are some key visions and goals set by the group, which were both somewhat ambiguous and very ambitious. Our visions of *why* KA wanted us to deliver a WS with ED changed during initial phase of the project. The team had several rounds with external- and internal supervisor to get the grasp of *what* the actual problem was. Instead of jumping to our own conclusions of why they wanted us to do the project to begin with, an early mapping of relevant questions concerning their needs would result in more efficient time usage. In the project plan, we have a major milestone; to produce a prototype of some sort. This is in relation to what Kongsberg Automotive expects from us. A better understanding of what a prototype is would benefit us in deciding a more realistic goal and less stressing method of approach. Instead of focusing on understanding the complexity of the system and challenges regarding them, we started thinking of how to design a possible prototype in 3D because the task was so big. The team was reeled back to the right track with guidance from experienced engineers at KA. Instead of product, we now focused more on the *process* to get to the result. Project plan also states that each team member would work at least 48.2 hours total per day. This proved to be wrong. At a majority of time, we were under this calculated total.

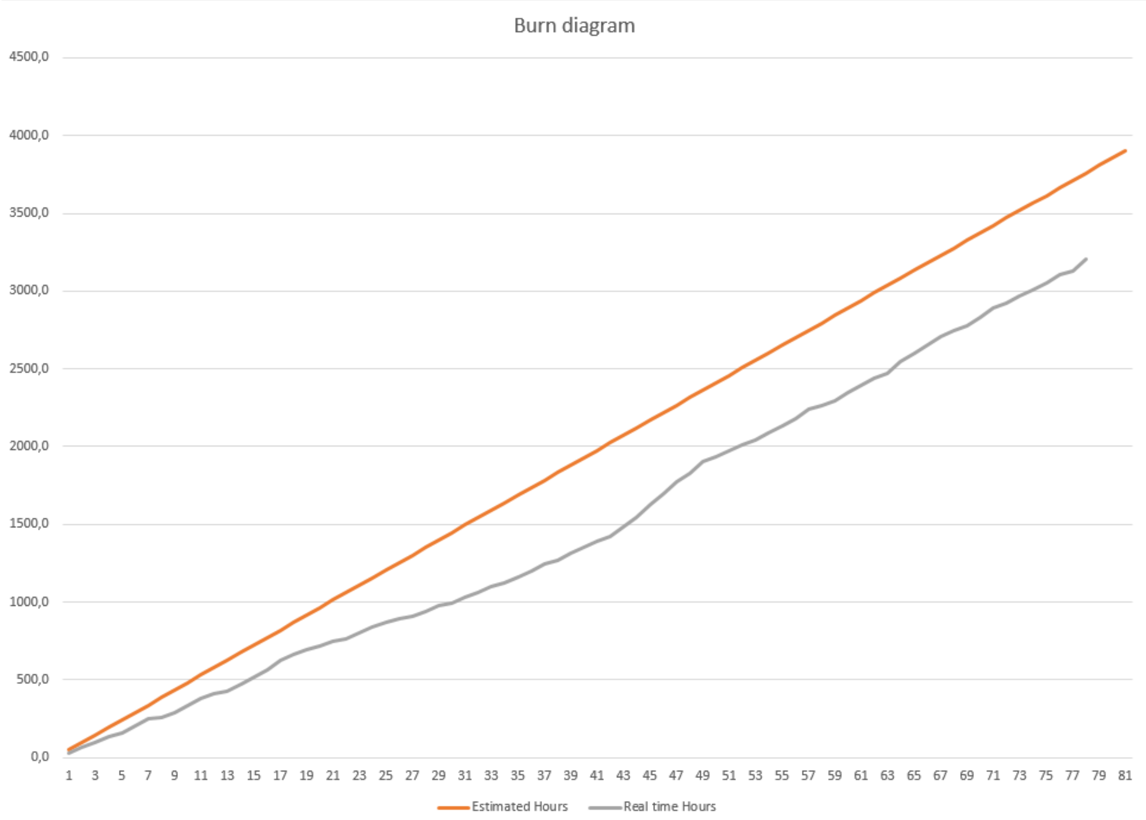


FIGURE 1 - BURN DIAGRAM

Burn diagram above compares the estimated hours with real time hours. Estimated hours calculated gave us 3711 hours. Real time hours at the end of the project calculates to 3202 hours. This gives a difference of 509 hours total. A difference of 80 hours per student who have no experience with such a large project is tolerable.

Activity list made in the project plan made it easier to track what members had worked on at a daily basis. A much more detailed breakdown would however serve as a better management tool to compare and track work in detail. Some of the activity ID's were at bit vague and were not as easy to track in detail at a later stage in the project. E.g., *"Iteration E1"* was planned to represent work done in this iteration. However, this would then mean that every task done would have the same ID for 4 weeks. This is a poor decision when having traceability in mind.

3. REQUIREMENT MANAGMENT

Breakdown of requirements made the process easier. Chosen structure of breaking down requirements to system- and user level showed to be efficient in getting a grasp of what had to be solved for the project to be successful. In addition, it made traceability and documentation easier. Requirements specification was initially classified in a separate document. But, for the group it was of great importance to make a requirements breakdown hierarchy to make them more accessible. Table format in a separate document does not necessarily guarantee a good overview of them. This decision of a simple hierarchy structure was definitely a good and efficient strategy.

Regarding the requirements status. Some were met, others were not while some were cancelled. The ones we did manage to meet where the ones which we classified as critical for the project. If these requirements were not met, other ones would be impossible to meet as well. Time constraint in relation to the size of the project made it almost impossible to cover all requirements. Requirements, which we did not finish, are described in the test document.

One major issue with the requirements given by the stakeholder KA was that some of them were ambiguous. This was very confusing and time consuming. E.g., Requirement 1.05 states; *"electric motor should have power of 150 kW per wheel"*. Because we were not able to find a motor with 150 kW, we had to choose 200 kW .This led to challenges regarding requirement 1.11 which states "*gear ratio should be 30:1 and 10:1 respectively*". Since we chose a stronger motor, we did not need as much reduction as specified in the requirements to generate enough torque. This lead to us not being able to fulfill this requirement. Instead of a 30:1 ratio, we only got 25:1 & instead of 10:1, we would get 8:1. KA were not able to give a clear enough answer on if requirements were a minimum or maximum. When asked about these and other requirements, KA could not assist us in a satisfying way. Author of the assignment was not available to give answers, and supervisor was not always sure what the specific intention of the author was when making the questioned requirement. The team moved forward and made choices as fit, which resulted in requirements not being met. Supervisor at KA supported any change or decision, and we could design as we see fit.

4. DESIGN PROCESS REVIEW

The design process turned out to be the most fun part of the entire project. At first, the team was locked to CAD drawings. However, this was quickly scrapped since it was a bad idea. Instead, we focused a lot on concept drawings. Each member got complete freedom to draw concepts of suggested design. There were no limitations to what one could produce. Every idea would be considered. Mentality throughout the design process was "there are no bad ideas". This sort of concept process with no limits proved to bring a lot of positive motivation to the group. Many crazy ideas led to a lot of laughter amongst the team and sessions with a lot of passion and heated discussion. Every concept was logged and kept for reviewing. These concept idea sessions led to ideas that gave a feeling of moving forward towards a clearer goal. Further on, when an idea was chosen, the 3D modelling of the chosen concept could start. The most challenging part about this process was the time management. Designing in 3D is time consuming, and every change and challenge we had not thought of initially led to redesigns. If it had not been for the specific interest of modelling in 3D, some of the major changes in design could potentially have been demotivating. These challenges could have been avoided if we were more consistent in analyzing issues with each design, at the early concept stages.

5. TEST MANAGMENT

Tests help us to verify design of a product under development. Specification of tests is a major part of the verification process. To map test routines, test specifications were made in the early phase of the project. This is directly connected to the requirements specification and gives a clear-cut picture of what needs to be done in order for the project to be considered successful. During the project, we realized that a physical design was nowhere near possible for us to make. Validation would therefore be out of the picture, and our focus would be on verifying if conceptual designs were feasible or not. The verification process consisted of following test plan and how each test would be executed. This strategy made the entire process more systematical. Each requirement was addressed and gave us a "pathway" on how we would attack each problem.

Even though the tables were efficient, in retrospect they could have been more simplified. The thought behind the test plan was that if many requirements needed the same test, it would be unfavorable to repeat same test repeatedly. Later on in the process, we discovered this setup was not such a good idea after all. A smarter way would be to have a unique test without a whole group of requirements in test spec as we did. This was a bit confusing during the documentation and verification process.

The biggest challenge during the test process was to verify the chosen concept of design. Finite Element Analysis had to be done on the biggest components. Some of the testing procedures required knowledge beyond what we had acquired during our course with Solidworks. A lot of resources and time was spent on figuring out solutions. HSN usually has a teacher assigned as responsible for question regarding FEM. This was not the case this semester, so we stood on our own for a long period without any sort of guidance. Luckily, KA managed to contribute with some desperately needed resources to help us out of this stagnant period.

6. GENERAL REVIEW

The overall opinion regarding the project is that it was a major learning experience. We strengthened our technical aspect of engineering and the entire process of how a project of such a magnitude is dealt with. Even though we have not been able to deliver a working product, we have solved the project with the knowledge we possess.

Key lessons learnt during the entire project:

- Understand the problem sufficiently before trying to solve it. Ask each other questions if you do not understand. Even more important, ask stakeholders what the need is and demand answers. In our case, this caused many issues. Instead of waiting for answers, we should have demanded them from our stakeholders.
- Have a mutual understanding of how you want to solve the problem and what resources each team member possesses.
- Apply use of the project model the team decides on. Following the project model makes the process more structured and more manageable.
- Continuously keep documents up to date. Do not wait to document. Do it immediately. This way everything is trackable and addressed.
- For the teams part, there were no conflicts. However, illness or other family matters would occur. This would affect the work so a more effective way of work distribution is of great importance.
- Team composition should also be, with the task in mind. Our project was of such a complexity, that every member had to learn almost everything about vehicles from scratch. In hindsight, this project would probably have served much more by having a composition of both practical and theoretically strong members. The latter being the case throughout this project.

7. INDIVIDUAL REFLECTION

7.1. Anis Sadiq

This project has given me a major experience in how to manage a project of this magnitude. In the beginning, I had some doubts regarding the given task and my own knowledge. At first glance, it seemed too complex. The lack of experience with vehicles also made me think very long before I decided to say yes to join the rest of the group. I am very happy I made this decision. I feel I have gained much more knowledge about vehicles in general. Being the project leader also thought me how to manage five different individuals with each their own strengths and weaknesses. I learned to utilize their strengths for the benefit of our project. I had to be conscious about how to motivate the group, and be disciplined enough so that work would be done. I feel that I have increased my stamina greatly during this semester. The project has taught me that good communication is key, how to be efficient, structured and deliver quality work while dealing with professional stakeholders. I would also like to use this opportunity to thank Jamal Safi for being a great supervisor and guiding us with his knowledge.

7.2. Mustafa Moalim

Before our bachelor thesis, I had prejudices that a bachelor thesis is only an assignment to fulfill, but what I realized was that there is a hidden knowledge to discover. A knowledge whereby you cannot receive under lectures taking place in the classes.

This bachelor thesis was a wonderful lesson and experience, which improved my personality. I have full confidence now about that I can be an engineer who can adapt to work with other engineers.

What I discovered is that cleverness alone is not enough to be a successful engineer. Communication among the team and stakeholders is very critical, to find that you are doing the right thing.

At the beginning of our project, we began to solve our project believing that we understood everything. However, after we met with our internal supervisor he asked us several questions. Have you thought about this and that? Have you met with KA and discussed whether you are in the same position? No... No..., Then we knew that communication is critical.

Another lesson was documenting every single part you have researched, understood and solved. Otherwise, it is in your mind and no one knows until you document it. I remember that we worked several hours and discussed. However, during the regular weekly meeting with the internal supervisor we told him that we discussed and solved this part of the problem. He simply asked us have you documented. No...

Our assignment, which we got from Kongsberg Automotive, involved making wheel suspension with integrated electric drive. The assignment was big enough; therefore, we divided the system in to subsystems and dived in every subsystem. At the beginning of the assignment, I had no idea about trucks and heavy-duty vehicles. Now I am familiar with trucks and, how their subsystems function.

System engineering was important tool that helped me when dealing with our assignment. A T-shaped structure we used always helped me to understand what others had done.

What I was surprised about was that during our bachelor thesis; I used all subjects I had during the 3 years bachelor study.

At the end, I want to thank my internal supervisor Jamal Safi who motivated us and required more during our project and at the same time guiding us philosophically. He followed us to KA to ensure that we were communicating correctly with KA. I also want to thank our external supervisor Kent Häll who helped us to understand the assignment and gave us tips and showed us around the company and how they test etc.

I want to thank our mechanical supervisor Lars, a technical teacher who helped me to understand subsystems of trucks.

7.3. Bampo Egide Rubusa

This self-reflection essay is written to reflect the experiences and lessons learned during our bachelor thesis project. The group consisted of five students from mechanical engineering and one electrical engineering.

As an electro engineering student, I gained many beneficial things by participating in this bachelor thesis. The project increased my knowledge both academically, socially and disciplinary.

Through research, I managed to acquire more information about vehicles, electronic control, solidworks, simulink and other helpful academic tools.

Socially, the project increased my communication ability and my time managing ability. The project required working together; sharing information with a spirit of achieving a common goal and this helped me to improve my communication ability.

Participating in this project as a sole electric engineering student was at the beginning challenging, but the group developed a communication method, which made it easier for us to communicate and understand each other effectively. The methods facilitated our work, information conveying and working together.

Conclusively, the project was challenging and require ring, but the group took some measures, which created a better working environment and made it easier for every group member to apply the knowledge acquired from HSN, in order to find a solution to the problem.

7.4. Pawan Bhatt

This bachelor project has been a very good learning experience for me. I have learned that to be a good engineer and to develop a good system we have to work as a team, and support each other. However, it is important to remember that nobody is here to do another person's work. The group has to share responsibility and meet the expectation of other group members. It is never too late to ask for help if needed. My own opinion is that our team worked quiet well. There were some issues related to communication sometimes, but it worked out fine in the end. There were many things we could have done differently, and I am sure that if we did this project again, nothing would be the same.

As mentioned above this bachelor project period has been a learning experience for me. At the start of the project, I did not know much about vehicles and certainly nothing about heavy-duty vehicles. Now as I have finished this project, I am quite confident in my knowledge about heavy-duty vehicles.

Lastly, it is important to have a good project plan, when starting a project. Even more important is to follow that plan as tightly as possible. Change is a part of system engineering, and similarly a project plan can be changed if necessary. Nevertheless, it is always a good idea to finish all the planning at the start, so that we can focus on development during the design process.

7.5. Abubakar Khan

This bachelor thesis has been one of the biggest academically challenges in my entire life. From the moment, I started my bachelor degree I was always looking forward to the bachelor thesis.

We got our task from KA (Kongsberg Automotive). When I first saw the task, I thought it would not be so difficult. However this task has proven to be the most challenging task for me ever, and for this I am very grateful. The bachelor thesis have given me knowledge and experience that I would not have gained otherwise. I am sure the knowledge I now possess after this project will benefit me greatly in the future.

My expectations to the task did not play out as I thought it would. On the contrary, the outcome was a big learning experience. I have gained a lot knowledge and skills as how an engineer's working process is. With this task, I have learned how to combine theoretical skills with practical skills.

Everything I have learned for the past 2,5 years as an engineer student was a big assessment to this task. I experienced the importance of my knowledge in this project. All my knowledge came to good use in this project.

The key to this project was communication. When working with other team members you will realize that communication is everything. I played very well along with my team members. If we came across a problem, we would have a discussion and solve it peacefully.

I learned that everyone has different types of strength and weaknesses, nobody is perfect. In our project, each member was assigned tasks according to their ability and strength. I believe that my team members are satisfied with my contribution to the project. I believe we solved the task in the best way possible according to our skills and knowledge. Obviously, many things could have been done differently, but this was our first project, so we cannot expect it to be perfect. You can overcome any obstacles in a project if the team is in an agreement with each other.

I have learned a lot about the mechanism in a vehicle as our task was to design wheel suspension for heavy-duty vehicle with integrated electric drive. My knowledge of mechatronics which is a combination of electronics and mechanics has increased significantly after this project.

I have learned that not everything plays out the way you would want it to. It is not about how many times you fail, but rather how you stand up to your failures and keep moving forward. I now feel ready to work as an engineer. Lastly, I would like to thank our internal supervisor Jamal Safi, and all the other supervisors who provided us with great resources.

7.6. Ahat Turgun

This bachelor project was given to us by Kongsberg Automotive. The idea behind this project was to replace the combustion engine with electric drive in heavy duty vehicles. KA expected that we could come up with new design or ideas, which may be somewhat useable.

Through the project I have learned how important it is to understand the functions of a system. Because the project is huge, we used much more time to understand how the individual sub-system works and what other kind of solution we can find. To understand the function of a system it is important because it can affect your design in a positive or negative way, based on what we may know.

In this project my role was to design and make a 3D model of our system. At the start of design process I always drew our concepts by hand or on CAD to illustrate the ideas we designed. When we had some misunderstanding, we discussed this in group. I tried to express my thought and ideas with my drawings to communicate with my teammates. But I always had discussions with others and gave my opinions about challenges we have met during the process.

We had a great team in this project and all teammates have different skills and experiences. Therefore we collaborated good to solve this project and I think our team worked very well.

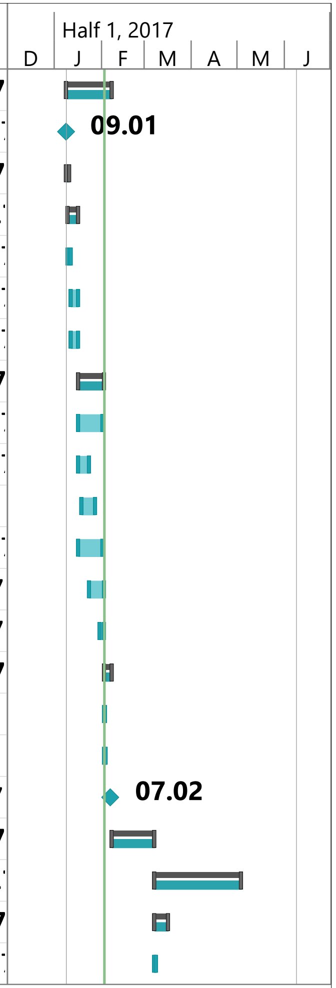
During this 6 month long journey I recognized my strengths and weaknesses, and I'm always improving myself to be the best. It has been a long and hard working process in this project time, but I think learning the process should be like this. Because there is no short way to the success.

I would like to thank all of our advisors who have contributed and helped us during this process.

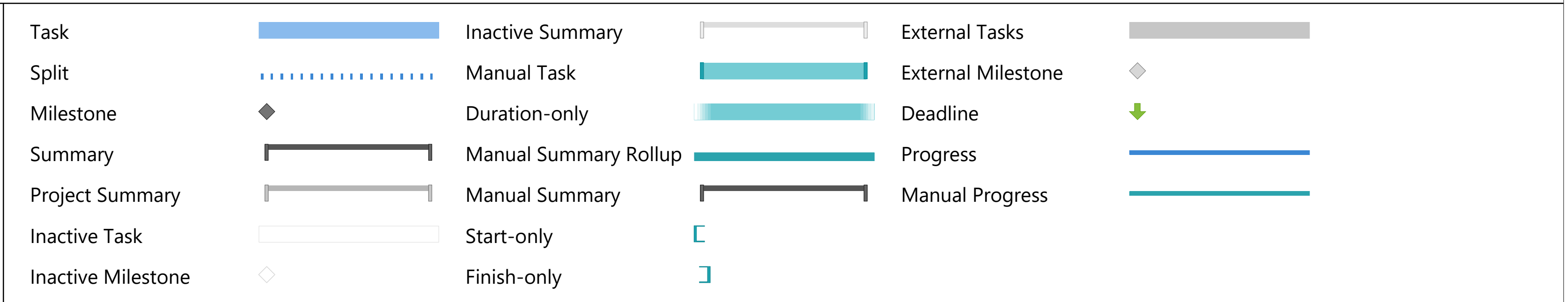
8. REFERENCES

[1] E-Axle, "Test Document," E-Axle, Kongsberg, 2017.

ID		Task Mode	Task Name	Duration	Start	Finish
1			**INCEPTION**	**18 days**	**Mon 09.01.17**	**Tue 07.02.17**
2			Startup of project	0 days	Mon 09.01.17	Mon 09.01.1
3			**Planning**	**2 days**	**Mon 09.01.17**	**Tue 10.01.17**
8			**Research**	**5 days**	**Tue 10.01.17**	**Mon 16.01.1**
9			Truck and Wheel suspension systems	2 days	Tue 10.01.17	Wed 11.01.1
10			Test specifications	3 days	Thu 12.01.17	Mon 16.01.1
11			Requirement specifications	3 days	Thu 12.01.17	Mon 16.01.1
12			**Documentation**	**11 days**	**Tue 17.01.17**	**Thu 02.02.17**
13			Requirement Specification	10 days	Tue 17.01.17	Wed 01.02.1
14			Vision Document	5 days	Tue 17.01.17	Mon 23.01.1
15			Design of existing system	6 days	Thu 19.01.17	Fri 27.01.17
16			Test Spec	10 days	Tue 17.01.17	Wed 01.02.1
17			Project Plan	7 days	Tue 24.01.17	Thu 02.02.17
18			Webpage creation	3 days	Tue 31.01.17	Thu 02.02.17
19			**Presentation 1**	**2 days**	**Fri 03.02.17**	**Tue 07.02.17**
20			Produce presentation slides	5 hrs	Fri 03.02.17	Fri 03.02.17
21			Drill Presentation	1 day	Fri 03.02.17	Fri 03.02.17
22			Presentation	0 days	Tue 07.02.17	Tue 07.02.17
23			**ELABORATION**	**16 days**	**Wed 08.02.17**	**Tue 07.03.17**
38			**ARCHITECTURAL DESIGN**	**33 days**	**Wed 08.03.17**	**Wed 03.05.1**
39			**Iteration A1**	**6 days**	**Wed 08.03.17**	**Thu 16.03.17**
40			Plan Iteration	1 day	Wed 08.03.17	Wed 08.03.1



Project: Prosjektplan versjon 0.1
Date: Fri 03.02.17



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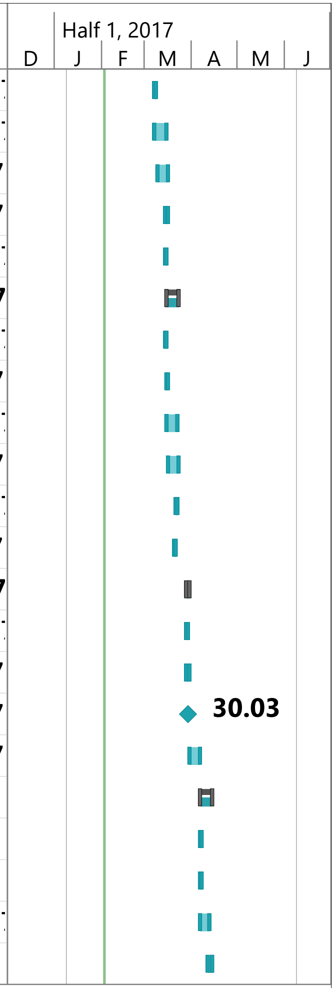
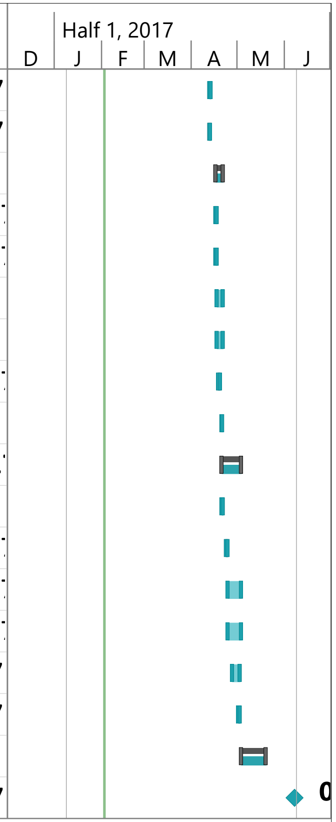
41			Describe remaining requirements	1 day	Wed 08.03.17	Wed 08.03.17
42			High level designing and analysis	5 days	Wed 08.03.17	Wed 15.03.17
43			Verification and testing	4 days	Fri 10.03.17	Thu 16.03.17
44			Evaluate	2 days	Wed 15.03.17	Thu 16.03.17
45			Iteration report A1	1 day	Wed 15.03.17	Wed 15.03.17
46			**Iteration A2**	**5 days**	**Thu 16.03.17**	**Thu 23.03.17**
47			Plan iteration	1 day	Wed 15.03.17	Wed 15.03.17
48			Requirements	1 day	Thu 16.03.17	Thu 16.03.17
49			Design and analysis	4 days	Thu 16.03.17	Wed 22.03.17
50			Test and Validation	4 days	Fri 17.03.17	Thu 23.03.17
51			Evaluate	1 day	Wed 22.03.17	Wed 22.03.17
52			Iteration report A2	1 day	Tue 21.03.17	Tue 21.03.17
53			**Presentation 2**	**2 days**	**Wed 29.03.17**	**Thu 30.03.17**
54			Make Powerpoint Slides	1 day	Wed 29.03.17	Wed 29.03.17
55			Presentation drills	2 days	Wed 29.03.17	Thu 30.03.17
56			Presentation	0 days	Thu 30.03.17	Thu 30.03.17
57			Exam period	4 days	Fri 31.03.17	Thu 06.04.17
58			**Iteration A3**	**5 days**	**Fri 07.04.17**	**Fri 14.04.17**
59			Iteration Plan	1 day	Fri 07.04.17	Fri 07.04.17
60			Requirements spec	1 day	Fri 07.04.17	Fri 07.04.17
61			Analysis and design	3 days	Fri 07.04.17	Wed 12.04.17
62			Verification and testing	3 days	Wed 12.04.17	Fri 14.04.17



Project: Prosjektplan versjon 0.1
Date: Fri 03.02.17

Task	Inactive Summary	External Tasks
Split	Manual Task	External Milestone
Milestone	Duration-only	Deadline
Summary	Manual Summary Rollup	Progress
Project Summary	Manual Summary	Manual Progress
Inactive Task	Start-only	
Inactive Milestone	Finish-only	

ID		Task Mode	Task Name	Duration	Start	Finish
63			Evaluate	1 day	Thu 13.04.17	Thu 13.04.17
64			Report Iteration A3	5 hrs	Thu 13.04.17	Thu 13.04.17
65			**Iteration A4**	**5 days**	**Mon 17.04.17**	**Fri 21.04.17**
66			Iteration planning	1 day	Mon 17.04.17	Mon 17.04.1
67			Requirements spec	1 day	Mon 17.04.17	Mon 17.04.1
68			Analysis and design	4 days	Tue 18.04.17	Fri 21.04.17
69			Verification and testing	4 days	Tue 18.04.17	Fri 21.04.17
70			Evaluate	1 day	Wed 19.04.17	Wed 19.04.1
71			Iteration report A4	5 hrs	Fri 21.04.17	Fri 21.04.17
72			**Iteration A5**	**7 days**	**Fri 21.04.17**	**Wed 03.05.1**
73			Iteration plan	1 day	Fri 21.04.17	Fri 21.04.17
74			Requirements spec	1 day	Mon 24.04.17	Mon 24.04.1
75			Analysis and design	6 days	Tue 25.04.17	Wed 03.05.1
76			Verification and testing	6 days	Tue 25.04.17	Wed 03.05.1
77			Evaluate	2 days	Fri 28.04.17	Tue 02.05.17
78			Report Iteration A5	1 day	Tue 02.05.17	Tue 02.05.17
79			**TRANSITION**	**10 days**	**Thu 04.05.17**	**Fri 19.05.17**
83			**Final Presentation**	0 days	Thu 08.06.17	Thu 08.06.17

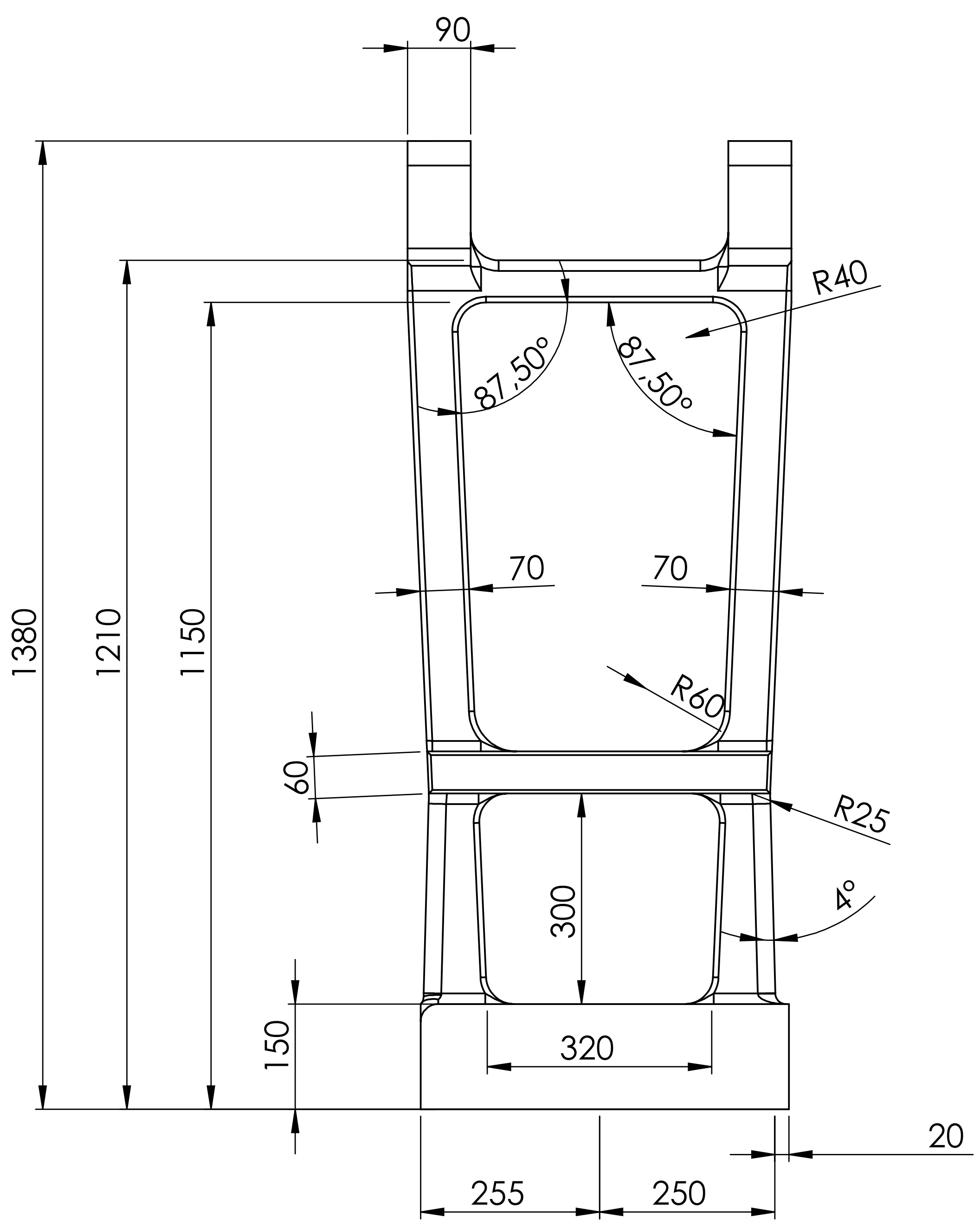


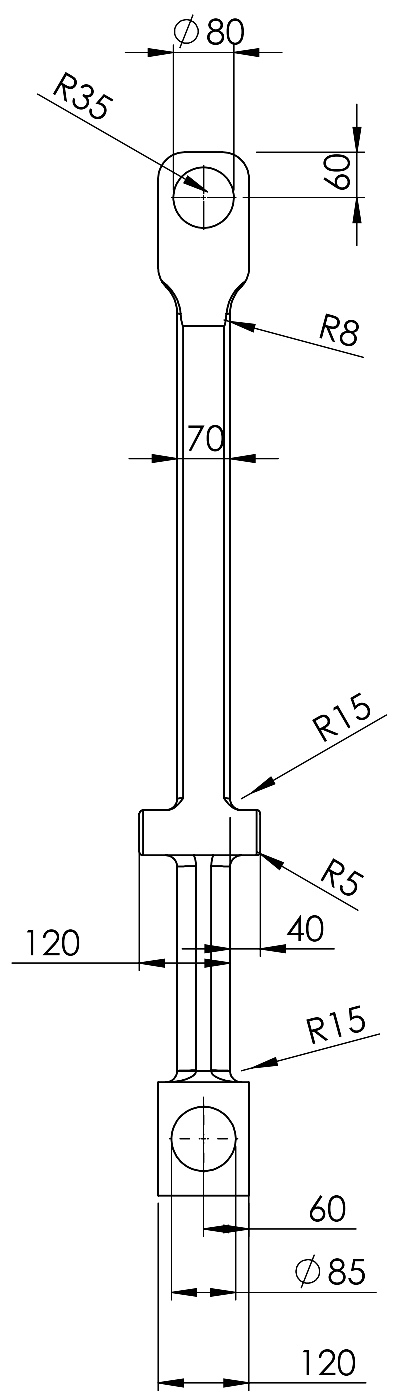
Project: Prosjektplan versjon 0.1
Date: Fri 03.02.17

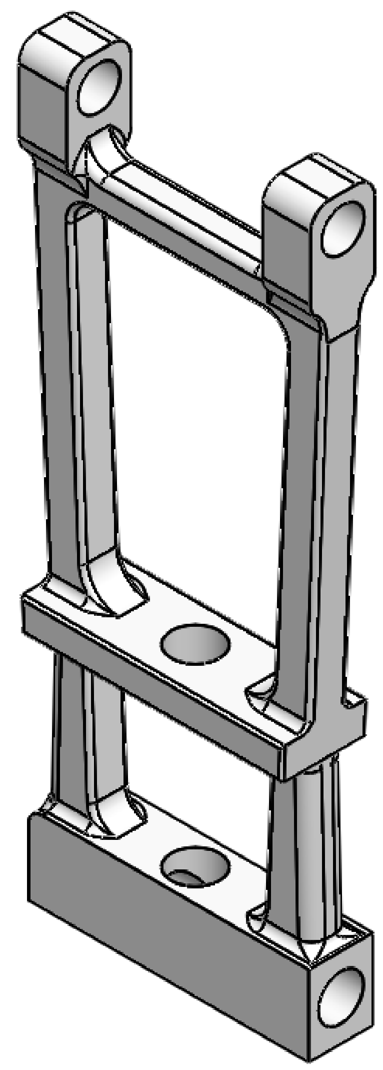
Task	Inactive Summary	External Tasks
Split	Manual Task	External Milestone
Milestone	Duration-only	Deadline
Summary	Manual Summary Rollup	Progress
Project Summary	Manual Summary	Manual Progress
Inactive Task	Start-only	
Inactive Milestone	Finish-only	

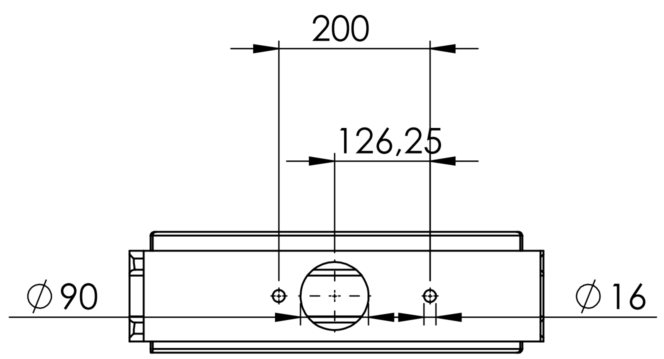
ATTACHMENT B – RISK ASSESMENT

Type of Risk	Consequences	Probability	Sev.	Strategy	Measures/Mitigation
Bad communication between team members	Conflicts between group members and lack of productivity	4	4	Share or avoid	Discussion among members, discussion with supervisor
Low motivation among group members	Lack of productivity or lagging behind the schedule	3	4	Avoid	Positive remarks, discussion with group members
Loss of digital files	Increased work to recover the lost data.	1	3	Avoid	Secure backup
Sickness among group members	Increased work for other group members.	4	2	Accept and share	Accept the risk, and share the workload among team members
Fail to meet the deadline	Low grades	2	5	Avoid	Reliable communication, accept help when in need
Fail to validate the system	Fail to satisfy the customer needs.	3	4	Avoid/mitigate	Understand the problem statement and customer need
Fail to verify the system	A system, which does not work as intended	3	5	Avoid/mitigate	Work on requirements and test specifications early on
Learning curves	Leads to delays Of the product	4	3	Share/mitigate /accept	Accept the risk, share the workload and ask for help from instructors and supervisor





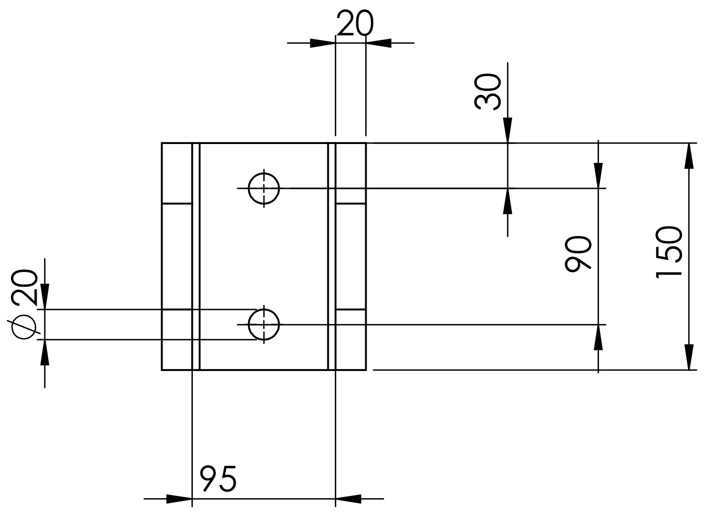


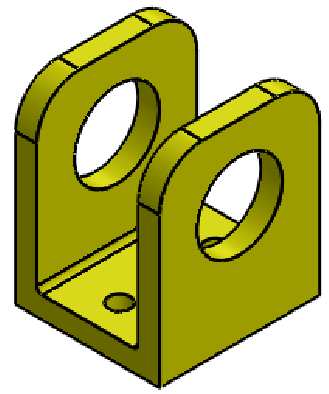


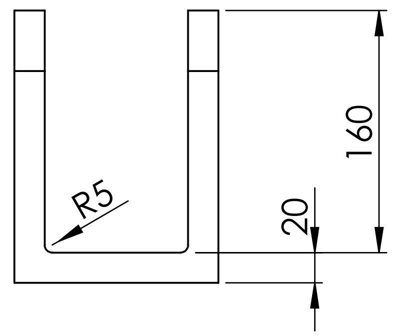
SOLIDWORKS Educational Product. For Instructional Use Only

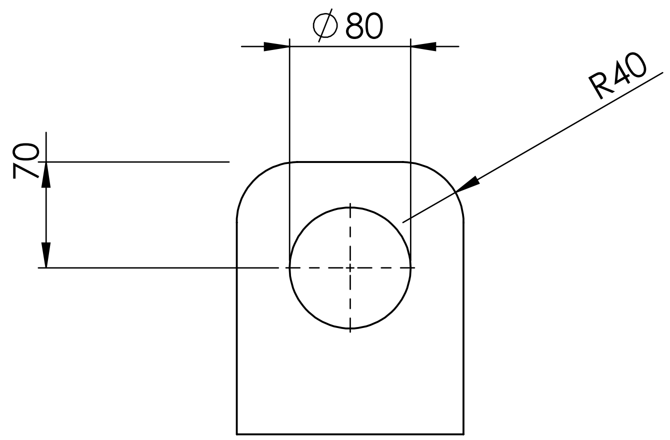
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
			Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive	

	NAME	DATE				
DRAWN	Ahat Turgun	20.05.2017			TITLE:	A-arm 2D
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL:	Strenx 700	DWG NO.	A3
			WEIGHT: 192728.52		SCALE:1:10	SHEET 1 OF 1









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				Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive	
	NAME	SIGNATURE	DATE	TITLE: A-arm bracket	
DRAWN	Ahat Turgun	22.05.2017			
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: Strenx 700	DWG NO.	A3
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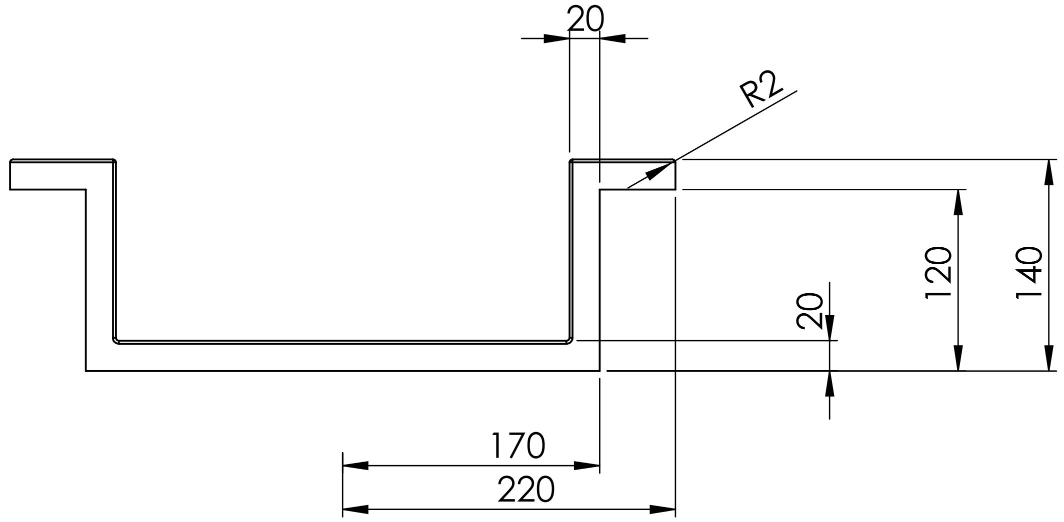

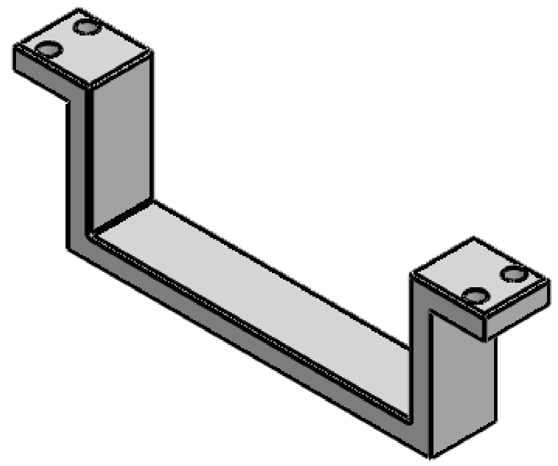

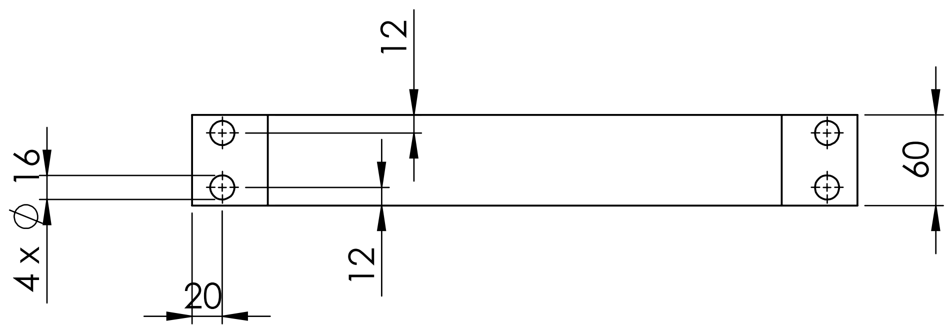

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
			Wheel Suspension for Heavy Duty Vehicles with Integrated Electric Drive	

	NAME	SIGNATURE	DATE
DRAWN	Ahat Turgun		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

omega arm 2

MATERIAL: Strenx 700

DWG NO.

A3

WEIGHT: 6149.65

SCALE:1:5

SHEET 1 OF 1

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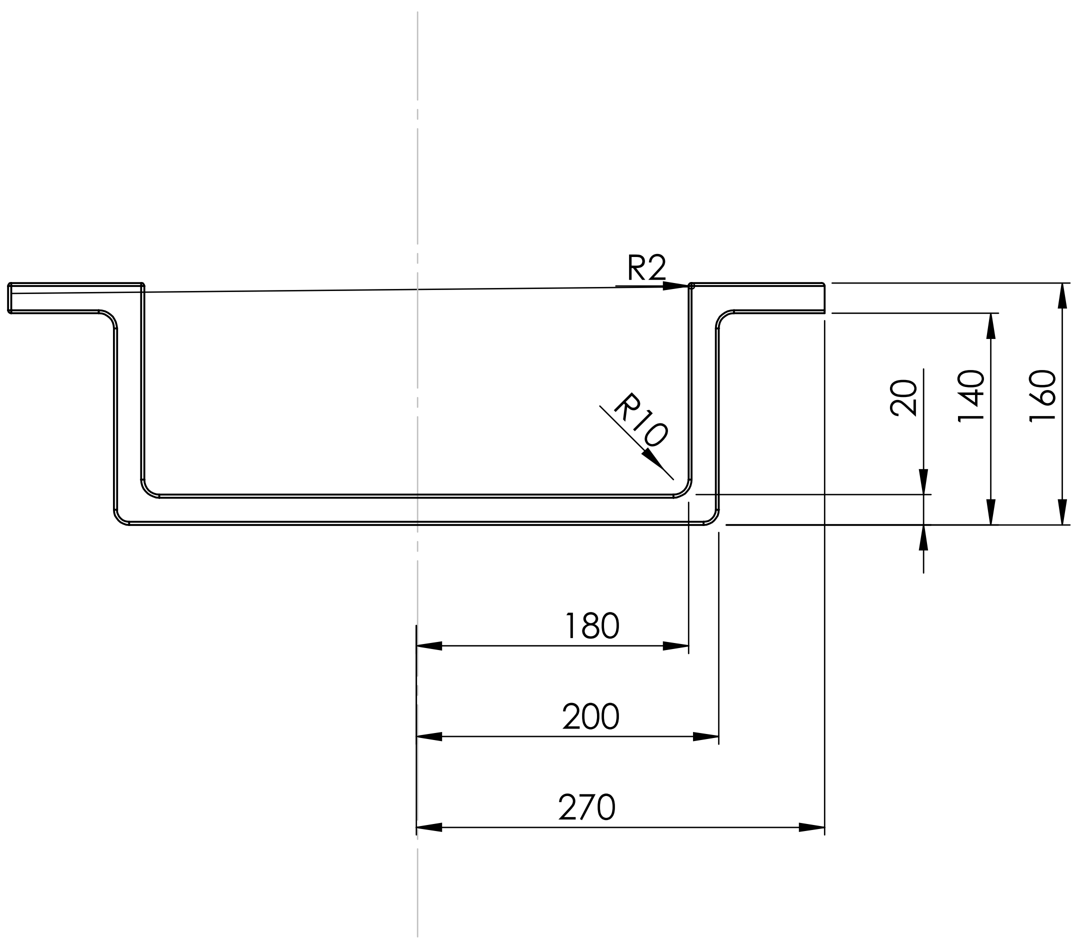

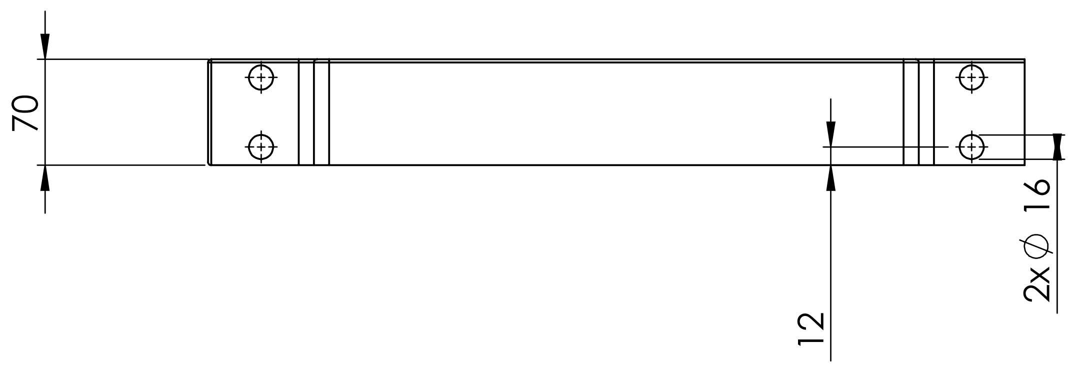

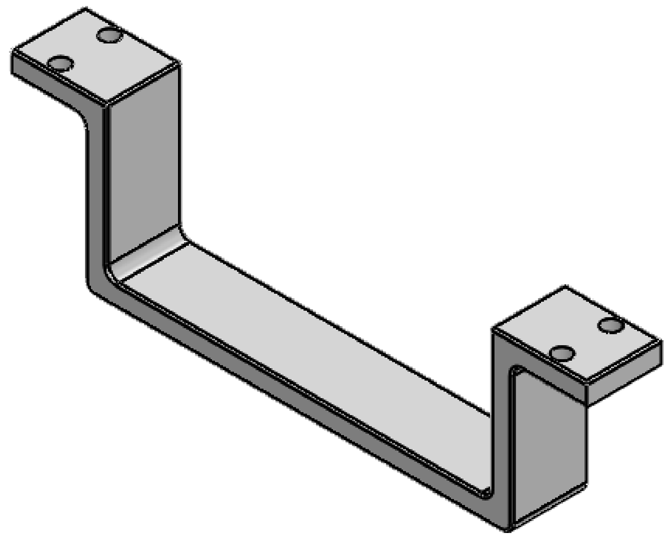

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UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
			Wheel Suspension for Heavy-Duty Vehicles with Integrated Electric Drive	
	NAME	DATE	TITLE:	
DRAWN	Ahat Turgun	22.05.2017	Omega arm	
CHK'D				
APPV'D				
MFG				
Q.A		MATERIAL: Strenx 700	DWG NO.	A3
		WEIGHT: 8720.34	SCALE:1:5	SHEET 1 OF 1

ATTACHMENT H – MATLAB PLOTTING

Motortorquespeedplotcode.m

```
% First, initialize the values needed in this program.
R = 0.641;                  % Stator resistance
Ls = 1.106;                  % Stator reactance
r2 = 0.332;                  % Rotor resistance
x2 = 0.464;                  % Rotor reactance
xm = 26.3;                   % Magnetization branch reactance
v_phase = 460 / sqrt(3);     % Phase voltage
n_sync = 1800;               % Synchronous speed (r/min)
w_sync = 188.5;              % Synchronous speed (rad/s)

% Calculate the Thevenin voltage and impedance from Equations
% 7-41a and 7-43.
v_th = v_phase * ( xm / sqrt(R^2 + (Ls + xm)^2) );
z_th = ((j*xm) * (R + j*x1)) / (R + j*(Ls + xm));
r_th = real(z_th);
x_th = imag(z_th);

% Now calculate the torque-speed characteristic for many
% slips between 0 and 1.  Note that the first slip value
% is set to 0.001 instead of exactly 0 to avoid divide-
% by-zero problems.
s = (0:1:50) / 50;            % Slip
s(1) = 0.001;
nm = (1 - s) * n_sync;        % Mechanical speed

% Calculate torque for original rotor resistance
for ii = 1:51
   t_ind1(ii) = (3 * v_th^2 * r2 / s(ii)) / ...
            (w_sync * ((r_th + r2/s(ii))^2 + (x_th + x2)^2) );
end

% Calculate torque for doubled rotor resistance
for ii = 1:51
   t_ind2(ii) = (3 * v_th^2 * (2*r2) / s(ii)) / ...
            (w_sync * ((r_th + (2*r2)/s(ii))^2 + (x_th + x2)^2) );
end

% Plot the torque-speed curve
plot(nm,t_ind1,'Color','k','LineWidth',2.0);
hold on;
plot(nm,t_ind2,'Color','k','LineWidth',2.0,'LineStyle','-.');
xlabel('\itn_{m}','Fontweight','Bold');
ylabel('\tau_{ind}','Fontweight','Bold');
title ('Induction Motor Torque-Speed Characteristic','Fontweight','Bold');
legend ('Original R_{2}','Doubled R_{2}');
grid on;
hold off;
```

ATACHMENT I- PUGH MATRIX FOR INVERTER

#	EVALUION CRITERIA	RATING (1-5)	ONE PHASE	THREE PHASE	PEMANENT MAGNET
1	Simplicity	3	-	+	-
2	Reliability	3	S	+	S
3	Maintenance cost	4	S	+	S
5	Noise and Vibration	1	S	+	S
6	Robustness	2	-	+	+
7	Speed controllability	3	+	+	+
8	Starting Current draw	4	+	-	+
9	Self-Starting	2	+	+	
10	Efficiency	5	+	+	-
11	Complexity	1	+	+	S
12	Power rating range	5	+	+	-
13	High starting torque	5	+	-	+
14	Components wear	3	-	+	+
Sum of Positives			7	11	5
Sum of Negatives			3	2	3
Sum of S			3	0	4
Weighted Sum of Positives			25	32	16
Weighted Sum of Negatives			8	9	13
SCORE SUM			**17**	**23**	**3**

ATACHMENT J - PUGH MATRIX FOR INVERTER

	EVALUATION CRITERIA	RATING (1-5)	3 PHASES VOLTAGE INVERTER	3 PHASES CURRENT INVERTER	5 PHASES VOLTAGE INVETER
1	Reliability	**2**	+	+	-
2	Maintenance cost	**5**	-	S	S
3	Harmonic distortion	**4**	+	+	+
4	Power losses	**5**	+	-	-
5	Efficiencies	**5**	+	-	+
6	Minimizing install time	**4**	+	+	+
7	High power factor	**4**	+	-	S
8	Fast dynamic response	**2**	-	-	-
9	Wide range of applications	**5**	+	+	-
9	Capable of running motors without de-rating	**3**	+	+	+
Sum of Positives			8	6	4
Sum of Negatives			2	4	4
Sum of Sames			0	1	2
Weighed Sum of Positives			32	18	16
Weighted Sum of Negatives			7	15	14
SCORE SUM			**25**	**3**	**2**

ATACHMENT K - PUGH MATRIX FOR CONTROL METHOD

#	CRITERIA	RATING (1-5)	VHC	DSC	DFOC	DTC
1	Simplicity	3	-	+	-	+
2	Reliability	4	S	S	S	+
3	Maintenance cost	4	-	+	S	+
4	Production cost	1	S	-	S	+
5	Wide range motors	2	-	+	+	-
6	tolerance	1	S	+	+	+
7	Robustness	4	+	-	+	-
8	Suitable torque	2	S	S		+
9	Efficiency	4	+	+	-	+
10	Complexity	1	+	+		-
11	Power rating range	5	+	S	-	+
12	Sensitivity to load	5	+	-	S	+
Sum of Positives			5	7	12	10
Sum of Negatives			4	3	3	3
Sum of S			4	3	4	0
Weighed Sum of Positives			20	21	12	29
Weighted Sum of Negatives			12	10	13	7
SCORE SUM			**8**	**11**	**0**	**22**

ATTACHMENT L – ARDUINO CODE

Red is the main code

Declare constants for motor so that I don't have to remember pin 2,4,5,6

```
const int motor_left_forward = 2;

const int motor_right_forward = 3;

const int motor_left_backward = 5;

const int motor_right_backward = 6;
```

Using the variable long to let the program store bigger quantities of positive/negative values. Int or unsigned int wouldn't be sufficient in this case. Long is a datatype, and is assigned to "lastTimeR". If one needs big number, an integer is the best choice to save space. It will store the last time the button was updated.

```
long lastTimeR;

char data = 0;          Variable to store received data

void setup()

{

 Serial.begin(9600);

}
```

Main function that will run continuously

```
void loop()

{

 if (Serial.available() > 0)
```
Send data only when data is received

```
 {

data = Serial.read();
```
Read and store incoming data and print value

```
Serial.print(data);

Serial.print("\n");
```

The motor will start running in the speed desired speed. Both motors are set to max and will drive the car forward if "F" is pressed.

```
if (data == 'F') {

lastTimeR = millis();

int motor_left_forward_speed = 255;

int motor_right_forward_speed = 255;

analogWrite(motor_left_forward, motor_left_forward_speed);

analogWrite(motor_right_forward, motor_right_forward_speed);
```

Analog function is used to drive. A test was done using digital and analog signals. The digital signal didn't seem to work as desired. Both motors were running on max, without responding to other buttons. Analog however gave med the results I wanted. Both the desired speed, and change of speed if new signal was sent/received.

```
} else if (data == 'V') {
  lastTimeR = millis();
  int motor_left_forward_speed = 0;
  int motor_right_forward_speed = 255;
  analogWrite(motor_left_forward, motor_left_forward_speed);
  analogWrite(motor_right_forward, motor_right_forward_speed);
```

Same principal as forward, but this time it will turn left. The speed is set to max on right wheel and left wheel has zero to make it turn left.

```
} else if (data == 'H') {
  lastTimeR = millis();
  int motor_left_forward_speed = 255;
  int motor_right_forward_speed = 0;
  analogWrite(motor_left_forward, motor_left_forward_speed);
  analogWrite(motor_right_forward, motor_right_forward_speed);
```

Car will turn to right since the speed is set to max on the left wheel.

```
} else if (data == 'B') {
  lastTimeR = millis();
  int motor_left_backward_speed = 255;
  int motor_right_backward_speed = 255;
  analogWrite(motor_left_backward, motor_left_backward_speed);
  analogWrite(motor_right_backward, motor_right_backward_speed);
```

The car will be put in reverse. This was done by sending a signal to reverse the motors so that the wheels rotate the opposite way. The speed is set to max.

```
} else {
 lastTimeR = millis();
 int motor_left_forward_speed = 0;
 int motor_right_forward_speed = 0;
 int motor_left_backward_speed = 0;
 int motor_right_backward_speed = 0;
 analogWrite(motor_left_forward, motor_left_forward_speed);
 analogWrite(motor_right_forward, motor_right_forward_speed);
 analogWrite(motor_left_backward, motor_left_backward_speed);
 analogWrite(motor_right_backward, motor_right_backward_speed);
}
```

If no buttons are pressed, the wheels will not move.

```
if ((millis() - lastTimeR) > 300) {
 int motor_left_forward_speed = 0;
 int motor_right_forward_speed = 0;
 int motor_left_backward_speed = 0;
 int motor_right_backward_speed = 0;
 analogWrite(motor_left_forward, motor_left_forward_speed);
 analogWrite(motor_right_forward, motor_right_forward_speed);
 analogWrite(motor_left_backward, motor_left_backward_speed);
```

```
analogWrite(motor_right_backward, motor_right_backward_speed);
```

I want the car to drive 300ms after the button is released to prevent it from freezing. The millis function will give me the number of milliseconds since the microcontroller was switched on. The if test will check if the time now minus last time is less than 300ms. This creates a pause between the actions and lets the microcontroller do other actions in the meanwhile, which a delay wouldn't.

```
    }
  }
}
```

ATTACHMENT M – WEIGHT BUDGETING