Bachelor's Degree Final Project

by

Mohamed Boutanaach

Design of a suspension system for a Formula Student electrical race car

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Supervisor:

Peter Menger, Responsible lecturer

Richard Mens, lecturer

Coordinators Learning Lab 'Sustainable Mobility', The Hague University of Applied Sciences

Examiner:

Dr. *David Tiemens*, Assessor

Professor of Mechanical engineering, The Hague University of Applied Sciences

Dr. *Yuste Pérez Pedro*, Mentor

Department of Computer Engineering, School of Design Engineering, Polytechnic University of Valencia

Abstract.

The Formula Cruisers is a student project started by The Hague University of Applied Sciences (Delft, The Netherlands). The purpose of the team is to gain work experience by creating an electric race car.

Our team consists of students from multiple studies, nationalities and disciplines. The project is challenging and educational, but enjoyable at the same time.

Currently, the team has students on the team who study Mechanical engineering, Electrical engineering, Applied physics, Industrial design and Aeronautical engineering.

The aim of our team will be build the HU-2, our first full-electric formula race car. The car will participate in the Formula Student event in Silverstone (United Kingdom). Formula student, Europe's most established educational motor sport competition, was the ultimate goal for The Formula Cruisers to take part in. Not only the competition between teams is exciting, but the thrill also comes from designing and building our own electric race car.
The HU-2 has to pass all the technical tests.

Figure 1. HU-2 Race Car. The Hague University of Applied Sciences.

Contents

1 CHAPTER 1. *INTRODUCTION*.

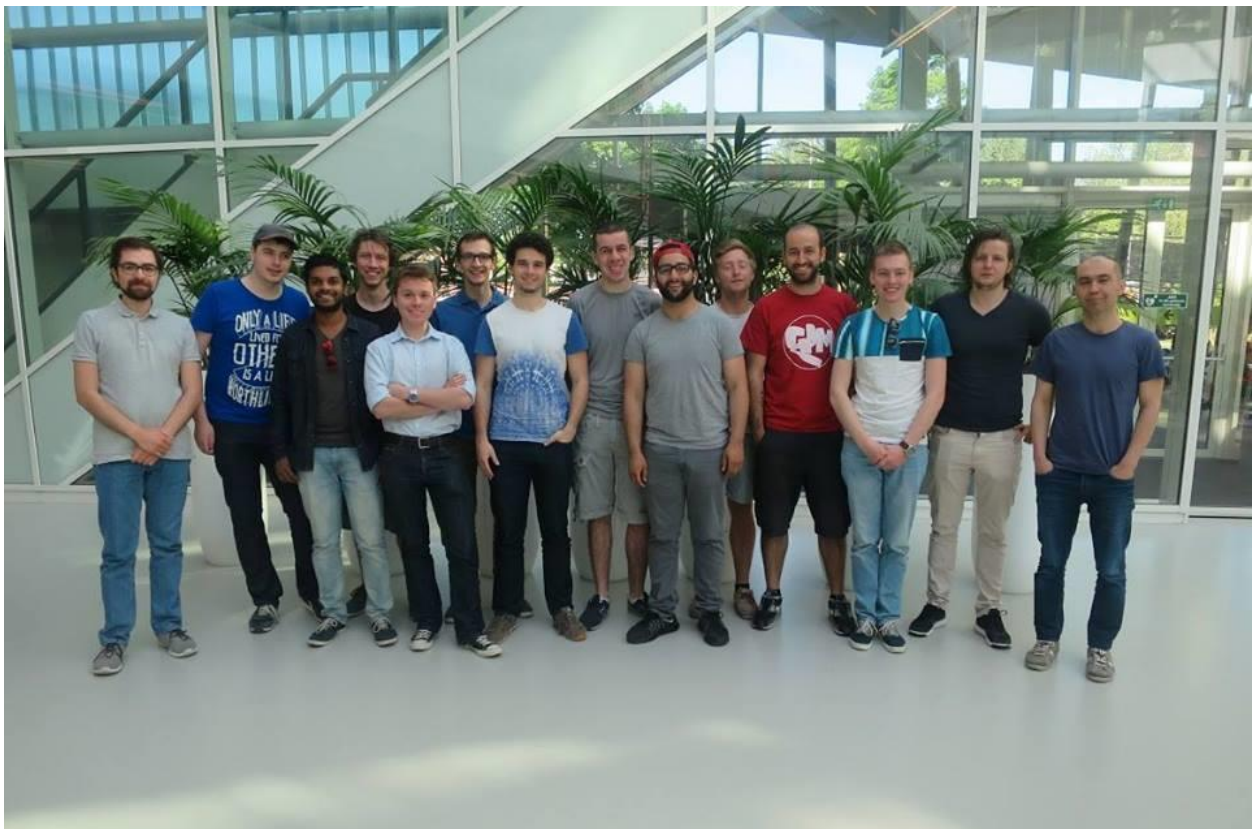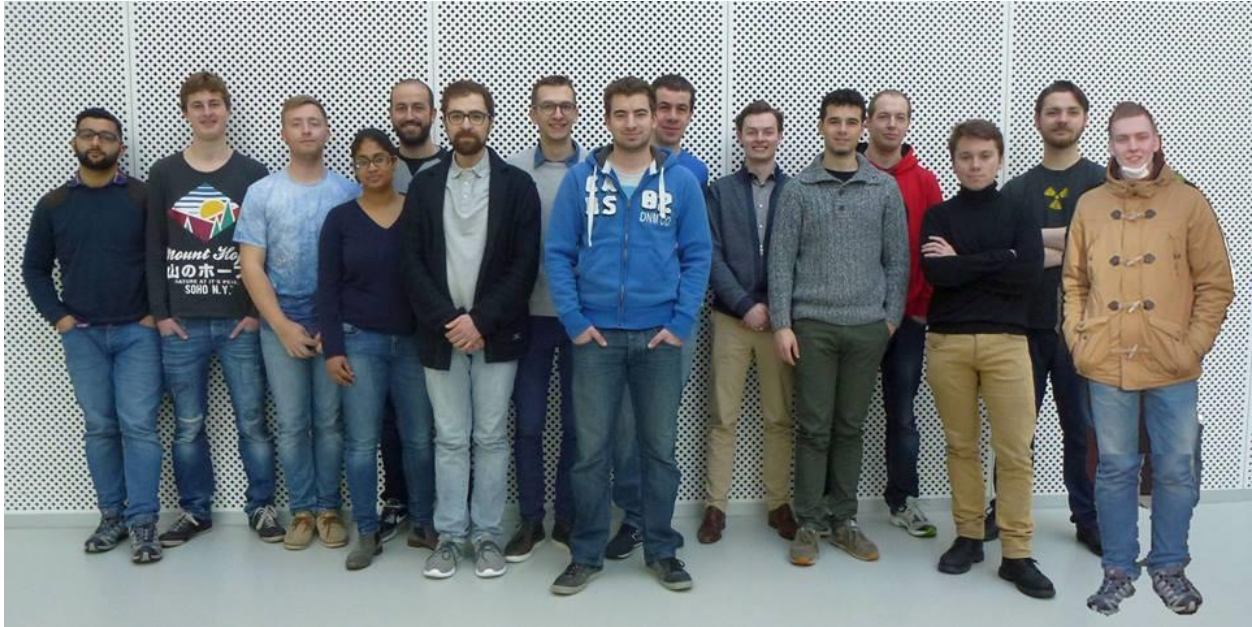Formula Cruisers Team 2015/16 (Beta factory. THUAS, Delft).

Figure 2. The Formula Cruisers Team. Delft (The Netherlands).

Study guide focusses on the projects in the Learning Lab 'Sustainable Mobility'.

Project

The minor is to be performed in the context of one of the multidisciplinary, multinational, multilevel engineering projects as carried out in the Learning Labs of the Beta factory of The Hague University of Applied Sciences in Delft.

Learning goals

After the course the participant is expected to be able to:

1. Technical
    1.1. **analyse** technical problems in a **systems view**,
    1.2. handle technical problems which are **incompletely stated** and subject to multiple, contradictory and technical and non-technical constraints,
    1.3. develop strategies for **systematic choice and use of available engineering methods, tools and resources**,
    1.4. **make estimations** and appreciate their value and limitations,
    1.5. **communicate engineering** – orally, in writing and graphically.
2. Project Management
    2.1. **Make decisions** based on acquired knowledge,
    2.2. **pursue** own ideas and realize them practically,
    2.3. **assess quality** of own work and work by others,
    2.4. **understand and explain** the mechanisms behind progress and difficulties in such a setting and **act** accordingly,
    2.5. **secure** knowledge and information.
3. Personal development
    3.1. **reflect** on own performance based on own experiences.

Processes in the Learning Labs

In the Learning Labs projects two main processes are distinguished, i.e. technical processes and learning processes respectively. All technical processes are directed to specify, design and realise a technical product. Learning processes concern the individual student.

Technical Processes

Engineering Process

The projects involved are engineering projects. In most of the times a technical result is obtained. This implies that the most important delivery process is the engineering process. The engineering process is supported by the Support Process. These two processes are controlled by the management process. These three main processes are visualized in the figure below.
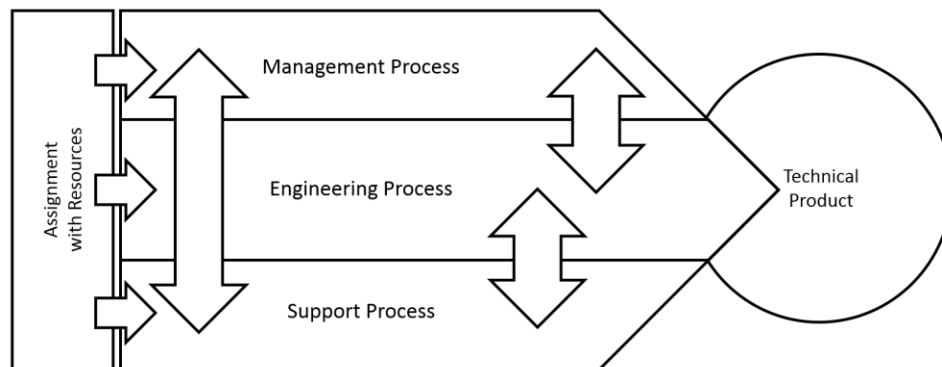
Figura3. Engineering Process.

So, a client grants an assignment to the student team and takes care of the resources (unless stated otherwise). The students take care of the three main processes mentioned above, which deliver in a technical product (deliverable).

The **Engineering Process** according to the adopted method of systems engineering has about ten phases, not mentioned here.

Support Process

The Support Process consists out of a number of sub-processes. The most important are

1. Finance Management
2. Procurement & Delivery
3. Marketing & Fundraising
4. Public Relations, Social Media & Event Management
5. Human Resources (Recruitment)

Management Process

The Management Process consists of the management of all processes. It can be split up in the following sub-processes

1. General Management
   a. Planning
   b. Finance
   c. Knowledge, Information
   d. Quality
   e. Organization
2. Engineering Management
3. Support Management
4. Systems Engineering

Learning Process

The Technical Processes and their environment are the vehicle with which the learning processes take place.

Main learning process: experienced based learning

Working and learning in the Learning Lab is, just like an internship, a full time job, i.e. eight hours a day, 40 hours a week. The learning process is embedded in the execution of the project. It is called 'experience based learning'. The actions undertaken for the project and their outcome are input for the lessons on project management, personal development and portfolio building. The most important micro-process for learning is the feedback process as shown below.

Figure 4. Main learning process.

This implies the following. In order for students to learn they should generate output for others, i.e. fellow team members (peers), lecturers and stakeholders, for them to give feedback on. This feedback is incorporated in the result obtained so far. Output and feedback are stored in the portfolio for evidence of the learning process which is used in the assessment.
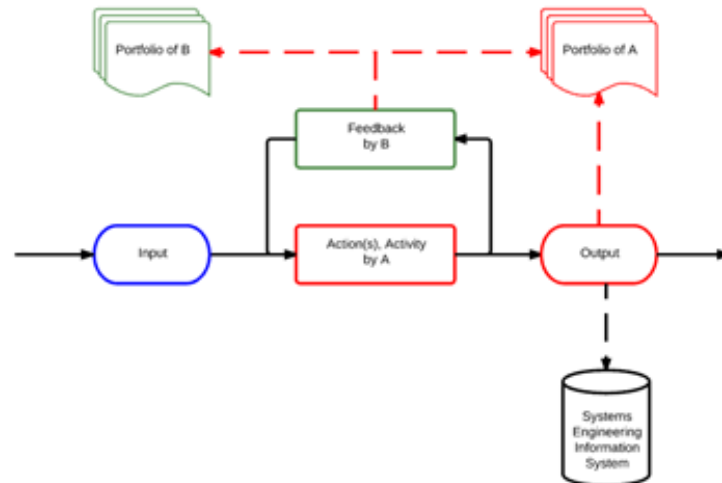
Figure 5. Feedback.

Supporting learning processes

In addition to the main learning process there are a number of secondary or supporting learning processes. These are workshops

1) Project Management
2) Personal Development
3) Personal Coaching

Project Management

There are on a weekly basis workshops on project management. In these workshops the lecturer(s) discuss the issues raised up during project work with the whole team. Students are responsible for the input of these workshops.

Personal Development

In these weekly workshops important themes about project collaboration are dealt with. Exercises and experiments are carried out on which students reflect on. New insights will arise from this and results are reported in the process report which again is included in the portfolio.

Personal Coaching

On special request and on a regular basis, e.g. weekly, students make personal appointments with their guiding expert and/or coach. Personal issues on technical or personal aspects are discussed. Results are incorporated in the project work, process report and/or portfolio.

Additional courses

Next to the main learning process of experimental learning and its secondary processes there are a number additional courses on

1) Cultural Differences
2) English Language
3) Project Management (guest lecture(s))
4) Others.

Students Team.

Most students originate from the engineering educations of the faculty of The Hague University of Applied Sciences in Delft. The following engineering educations contribute mostly to the engineering process

- Mechanical Engineering,
- Electronical Engineering,
- Mechatronics,
- Computer Science,
- Technical Physics,
- Technical Mathematics,

Students of the education of

- Technical Business Management.

can be found in the management.

The supporting processes are taken care by students of the educations of the faculties

- Communication & Multimedia Design (CMD)

- Industrial Design Engineering (IDE)

- International Communication Management (ICM)

- International Financial Management and Control (IFMC)

If these students are not participating in the project, then the engineering students will have to do the tasks involved.

Foreign students, international class room, main language

The Hague University of Applied Sciences participates in a number of worldwide coalitions for student exchange. Students of abroad from equivalent educations mentioned above also participate in the Learning Lab projects. Therefore the main language in speech and writing is English.

Therefore the Learning Lab projects have the status of 'international classroom'. Dutch students who want to have international experience may participate in the Learning Lab project without leaving the country.

Lectures

Students are guided and coached by lectures on engineering disciplines, project management, personal development and coaching.

Supporting staff

The project are executed in the Beta factory. This organization unit possesses of a extensive workshop, ready available building materials. Supporting staff are instructors and office assistants (procurement).

Finance and sponsor obligations

Students are considered to be the owner of the projects. This means that they determine to a great extend what is happening in a project in the technical sense. However, the projects are financially supported by the university. The university is the main sponsor for materials, workspace and tools. In return the university expects that the teams contribute to the publicity activities of the university towards its own students, high school students, companies and

stakeholders in the political area. This boils down to representing the university on events like Open House Days, Company Days and many other occasional events. The students participation to these activities is mandatory.

Deliverables and Assessment

Technical deliverables

During his/her stay in the project the student produces a large number of materials. These are ordered according to the learning goals, i.e.

1) Technical
   a) Documents
      According to strict formats in order of the phases of the engineering process documents containing
      i) Reports,
      ii) Calculations,
      iii) Sketches and drawings,
      iv) Notes, overviews,
      v) Special research reports,
      vi) Test reports,
      vii) Issue reports and
      viii) many others.
   b) Software
      i) Programs,
      ii) Posters,
      iii) Organised environment (workshop) and
      iv) many other things.
   c) Hardware
      i) Complete technical systems (car)
      ii) Subsystems (suspension, steering system or drive train of a car)
2) Project Management
   a) Invitations, agenda's, minutes of meetings,
   b) Decision documents including trade-off matrices and

        c) many others.

    3) Personal Development

        Typical documents in this category are

        a) Personal notes,

        b) Diary's,

        c) Test outcomes,

        d) Notes about feedback for improvement or compliment (kudo's) and

        e) many others.

Learning outcomes

During the assessment the deliverables and working processes of the student are examined. The student has to prove that he has achieved the learning goals. The evidence he/she may use consists of all technical deliverables produced by him/her and, in addition to that, all documents concerning the learning process, e.g.

1) Learning goals, general and personal
2) Feedback forms for improvement, compliments (kudo's),
3) Personal notes, photographs, sketches, diary's, etc.,
4) Minutes of meetings, excursions, symposia, etc.,

The collection of technical and learning documents is called portfolio. It may include relevant information from the additional classes.

Assessment

The assessment is a professional discussion of about an hour on the technical and management results achieved by the student and on his reflection skills about his performance. In this discussion the portfolio, i.e. all relevant documents owned by the student, are available in print.

The assessment is preferably done by two lectures involved in the project.

The student is graded with a mark between 6 and 10 for a 'pass' and between 1 and 5 for a 'fail'. In case of a 'fail' the student will receive feedback for improvement.

Background.

In 1981 the Society of Automotive Engineers (SAE) started the Formula SAE competition in the United States with only four schools taking part in the first competition. In 1982 the competition was hosted by University of Texas and became an official SAE event with the first official FSAE rules introduced and was this the only time that there were no requirements for a suspension system and as a result, many cars that took part were in fact large carts. In 1985 there was a major rule change where the successor to 1000 point system that we have today was introduced and also the maximum engine displacement of 610 cm3 and a 23 mm restrictor on the intake of the engine. 1985 was also the first year that the teams had to deliver a cost report and the total project cost could not exceed $2000. 1997 was the first year that a European team took part in the competition when University of Leeds decided to take part and showed that engineering students everywhere could take part in the competition.

The Formula Student (FS) competition started in the UK in 1998 and the first competition was held at the Motor Industry Research Association (MIRA) proving ground with three US cars and four cars from the UK. With the first UK competition being a success The Institution of Mechanical Engineers in partnership with SAE organized the competition in Europe and the to this day the competition has been held at the end of each academic year since then.

The background for this thesis is gain a better knowledge of how race car suspension systems work and with many different types of suspension system what type and setup is best suited to use on this year's car. To find what suspension gives the optimal performance simulations will be done by using MSC Adams Multibody Dynamics Simulation (MDS) software.

2 CHAPTER 2. *RESEARCH.*

Suspension.

Suspension in the term given to the system of springs, dampers and linkages that connect the body of a vehicle to its wheels. This system serves dual purpose: optimizing the vehicle's handling, and keeping the occupants comfortable. In case of a race car, the letter is off course insignificant. The only goal of a race car is maintaining the maximum achievable acceleration in the appropriate direction.

The working principle of a suspension system will be explained first. After that, a set of requirements is formulated.

Figure 6. HU-2 Race Car. Testing it in the circuit of Silverstone (UK).

Working principle.

Tires are the most important parts of a race car. They have to transmit all drive, brake and steering forces to the road through a very small contact path. This makes it very important for a car to keep the tires in optimal contact with the road at all times. That is the task of the suspension system. In case of a race car, the suspension system can be designed specifically for that goal, at the cost of drive comfort.

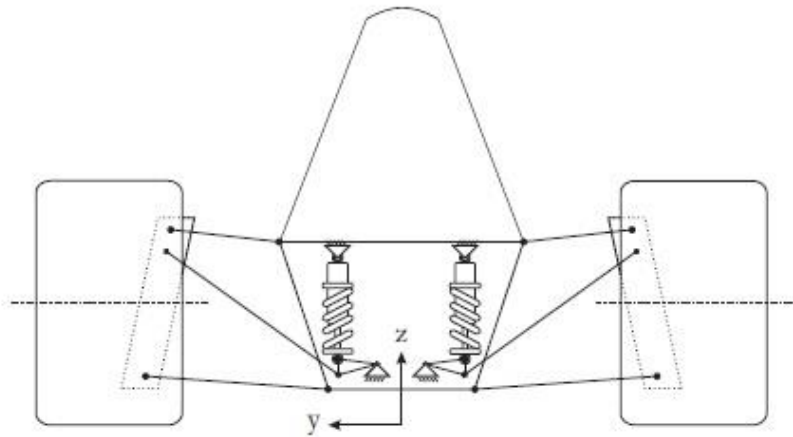A schematic representation of a suspension system can be seen below.

Figure 7. Working principle of the suspension system.

The wheel and brake disc are connected to the upright by bearings. Carbon fiber rods with ball joints on each end connect the upright to the chassis. One of these six rods (the inclined one) is not mounted to the chassis, but to a rocker. If the wheel moves up with respect to the vehicle body, the upright pulls on the rod, which in turn causes the rocker to rotate about its pivot point. A spring-damper is connected to the bell crank on one end, and to the chassis on the other. So by rotating the rocker, the spring-damper is compressed.

The spring-damper system consists of two subsystems: the coil-over damper itself, and the anti-roll system. The coil spring absorbs the energy from a bump by compressing, and releases it again at an uncontrolled rate. The spring will continue to bounce until all of the energy originally put into it is dissipated. Dampers are used to control this energy dissipation. They slow down and reduce the amplitude of the wheel motion by converting kinetic energy into heat.

The anti-roll system consists of a torsion bar with a lever on each end. If the movements on each end of the bar are not exactly the same, it will be twisted. This results in a reaction force.

The **main rocker** connects the pull rod to the two subsystems. The geometry of this rocker determines the movement of the spring-damper and the anti-roll bar as a result of the movement of the pull rod.

Two operating conditions will be explained to show how the subsystems work to control the movements of the suspension.

- **Bump situation.**

If the car drives over a threshold, the left and right wheels will move up an equal amount. This results in the same angular rotation of the left and right main rocker.

The spring-dampers are therefore actuated equally. Since left and right levers of the anti-roll bar are rotated to the same angle in the same direction, it will not create a reaction moment.

- **Cornering situation.**

If the car drives through a corner, it's body will roll to the outside of the bend. As a result, the outer wheel moves up with respect to the chassis, and the inner wheel will move down. This means the main rockers are rotated in opposite directions. The load on the outside spring will become higher, while the inside spring will be (partially) unloaded. The anti-roll bar will be twisted, which results in an opposing moment that tries to keep the vehicle body level.
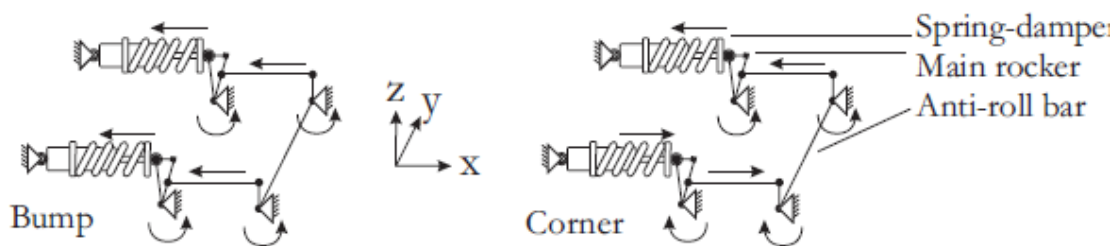
Figure 8. Concerning situation: Bump, corner.

Types of Suspension.

MacPherson Suspension.

Two of the most popular suspensions systems for passenger cars today are the double wishbone suspension system and the MacPherson's strut suspension system. While it is more usual to see the double wishbone system at the rear end of the car, MacPherson's solution normally finds its place at the front end of the car. Both types of suspensions have their own sets of benefits and limitations, thus let

us look at both the advantages and disadvantages of both systems, starting with the simpler of the two, the MacPherson struts.

MacPherson Struts- The struts are designed with more simplicity, and thus takes up less space horizontally. As a result, passengers get more compartment place in the car. They also display low un-sprung weight, an advantage that reduces the overall weight of the vehicle as well as increases the car's acceleration. Lower un-sprung weight also makes your ride more comfortable. Another major advantage of this system is its ease of manufacturing as well as low cost of manufacture compared to other stand-alone suspension systems. Without an upper arm, the suspension system designers can directly block vibration from reaching the passenger compartment.

Figure 9. MacPherson suspension.

Nevertheless, the MacPherson struts come with their own drawbacks. Being a long, vertical assembly, you would encounter difficulties if you lower your car as they may be collision with the structure of your car. Thus they do not work well with racing cars that are normally lowered. The MacPherson struts also have problems working with wider wheels that have increased scrub

radius, where you would need extra effort to navigate your car in this situation. There is also the problem with the small camber change with vertical movement of the suspension, which could mean the tires have less contact with the road during cornering. This could reduce handling abilities of your vehicle.

Double Wishbone Suspension System.

One of its primary benefits is the increase of negative chamber as a result of the vertical suspension movement of the upper and lower arms. This translates to better stability properties for the car as the tires on the outside maintain more contact with the road surface. Handling performance also increases.

The double suspension system is much more rigid and stable than other suspension systems, thus you would realize that your steering and wheel alignments are constant even when undergoing high amounts of stress.
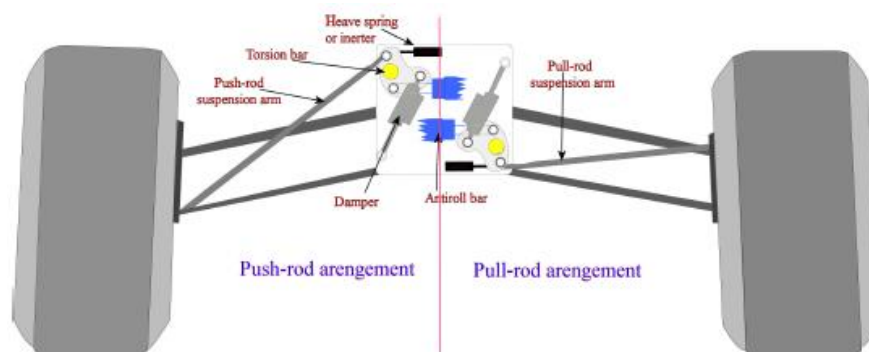

Figure 10. Double wishbone suspension.

Suspension Properties.

Kingpin inclination

Kingpin inclination sometimes called "Steering axis inclination" is the angle from vertical to the steering axis of the tire between the upper and lower ball joint viewed from the front. Kingpin inclination angle affects the lift of the wheel during cornering.

As it lifts the car as it corners and makes the wheels want to steer straight as the weight of the car returns the steering to centre. The kingpin inclination angle also affects the camber angle of the wheels as they turn and the wheel will gain positive camber. This can be beneficial to the handling of the car when making tight turns.

Caster.

The angle of the steering axis between the upper and lower ball joints viewed from the side is commonly known as Caster angle. With a positive caster angle the contact point of the tire to the ground called Mechanical trail, is behind the steering axis this creates a torque on the steering axis as the force on this point acts perpendicular to the steering axis and makes the wheel want to steer straight. With a negative caster angle, the contact point of the tire is in front of the steering axis the effects of a negative caster angle are opposite to a positive caster angle as the forces acting on the contact point wants to turn the wheel when cornering making the car unstable.
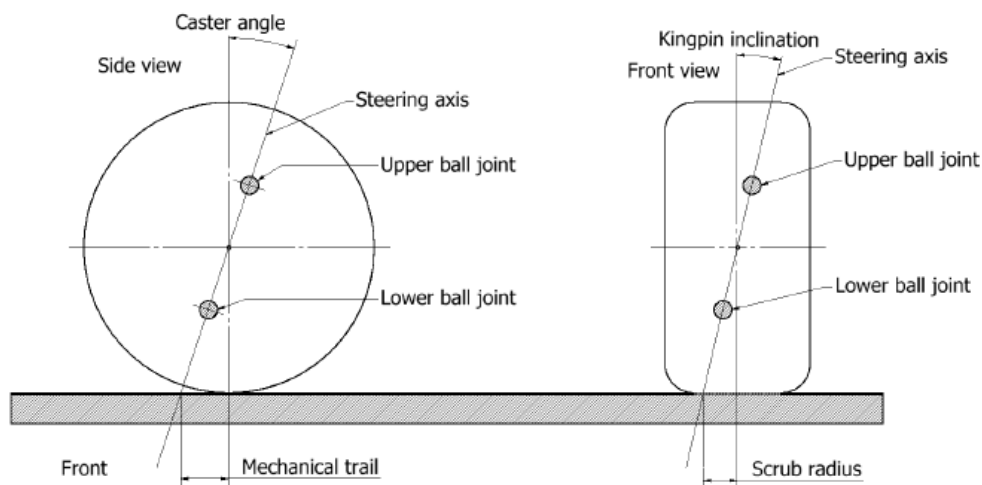

Figure 11. Caster.

Camber.

The angle of the wheel in- or outwards respective to vertical viewed from the front is called a camber angle and will produce lateral force known as camber force. Positive camber is when the top of the wheel is tilted outwards from the vehicle and negative angle when the wheel is tilted in towards the vehicle. Race cars usually have a negative camber to increase high-speed stability

and tire grip when cornering as it compensates for the positive camber gain as a result of the Kingpin Inclination angle and maximizes the contact between the tire and the road.
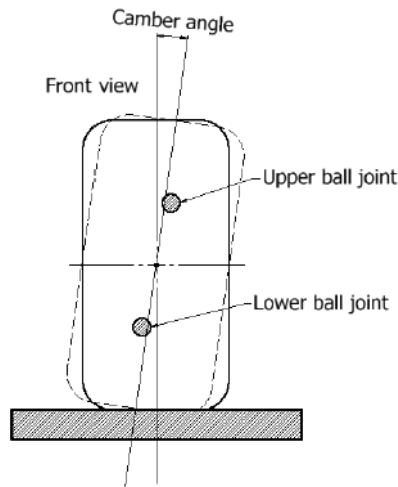

Figure 12. Camber.

Scrub radius.

Scrub radius is the distance from the steering axis to the centre of the contact patch of the tire. The scrub radius creates a lever arm on the steering axis that longitudinal forces act on and depending on the tire grip a net moment can be translated to the steering. Scrub radius is defined as positive and negative depending if it is on the inside or outside of the centreline of the tire. Figure 2.1 shows a negative scrub radius. The scrub radius can affect the toe of the car because of the longitudinal forces that act on the scrub radius arm.

Wheel rate.

The wheel rate of a car is an important factor in fine tuning suspension properties and a change in wheel rate changes the tire normal force at the ground for each tire and by changing the normal force the lateral force changes to affecting the grip and handling of the car.
Wheel rate is the force per unit for vertical displacement of the centre of the wheel and is the spring rate measured at the wheel centre instead of measuring it at the spring.
The spring rate is calculated by the force required to compress the spring divided by the deflection.

3 CHAPTER 3. *Design process*.

Requirements.

To design the suspension system for the HU-2, a set of requirements has to be formulated.

These can be split up in general requirements that apply to all parts designed for HU-2, and demands that apply specifically to the suspension system.

The general requirements are:

1. High reliability.

2. Low weight.

3. Low centre of gravity.

4. Low yaw inertia.

5. Low production costs. This includes both the prototype and series production of

1000 cars/year.

6. Must comply with FSAE rules [1].

The spring-damper system's specific requirements are:

7. The motion ratio (see equation 1) has to suit the chosen dampers.

8. The anti-roll system has to be adjustable. This can be used to control the over- and

understeer behaviour of the car. The system has to be adjustable from 0:5k $\square$ 2k.

9. Accessibility has to be such that settings can quickly be adjusted.

10. Friction (hysteresis) has to be kept low.

11. The system should be free of play.

12. Wheel displacement has to be measured with integrated sensors.

13. The required stiffness of the anti-roll bars and bump springs will be determined by

the designers of the new multilink suspension. An advanced vehicle model will be

used for this.

14. Minimum wheel travel is prescribed by rule B6.1.1 [1]:

B6.1.1 The car must be equipped with a fully operational suspension system with shock absorbers, front and rear, with usable wheel travel of at least 50.8 mm (2 inches), 25.4 mm (1 inch) jounce and 25.4 mm (1 inch) rebound, with driver seated. The judges reserve the right to disqualify cars which do not represent a serious attempt at an operational suspension system or which demonstrate handling inappropriate for an autocross circuit.

15. Visibility is prescribed by rule B6.1.2 [1]:

B6.1.2 All suspension mounting points must be visible at Technical Inspection, either by direct view or by removing any covers.

16. Ground clearance is prescribed by rule B6.2 [1]:

B6.2 The ground clearance must be sufficient to prevent any portion of the car (other than tires) from touching the ground during track events, and with the driver aboard there must be a minimum of 25.4 mm (1 inch).

Manufacturing.

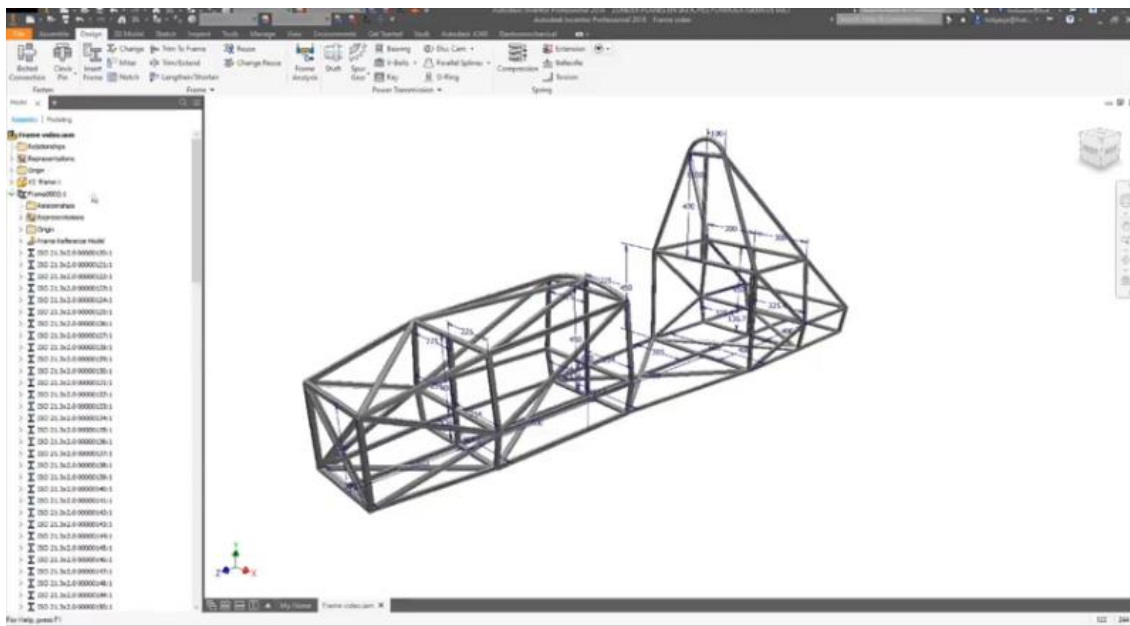The main structure/frame of the HU-2 is built using steel tubes.

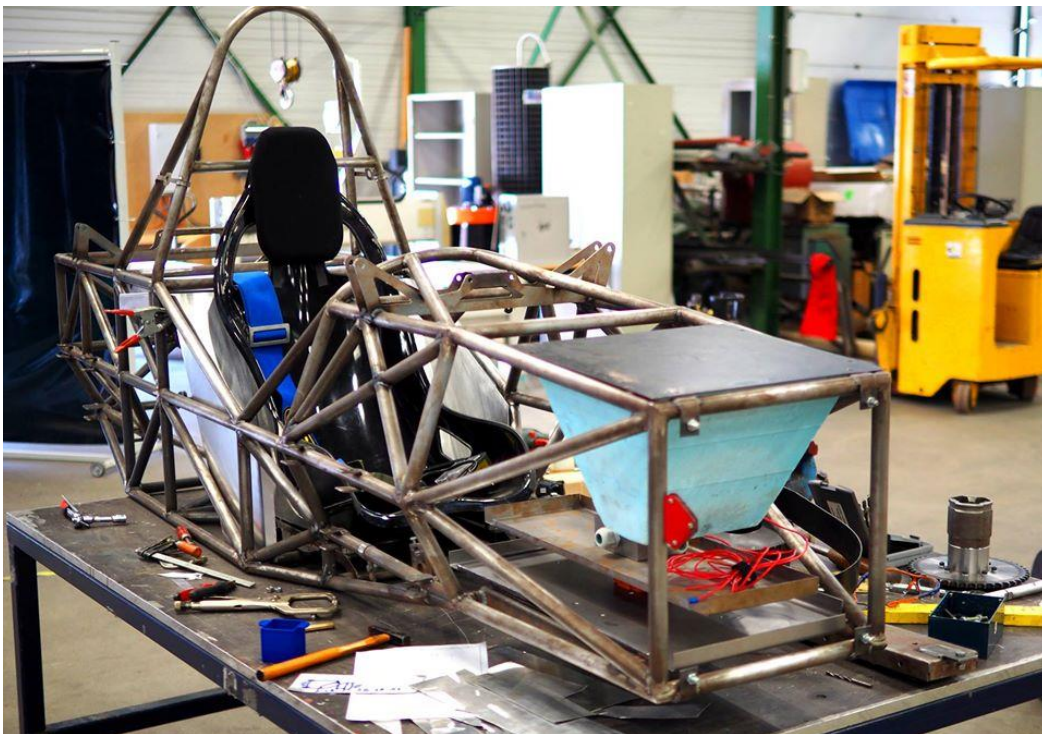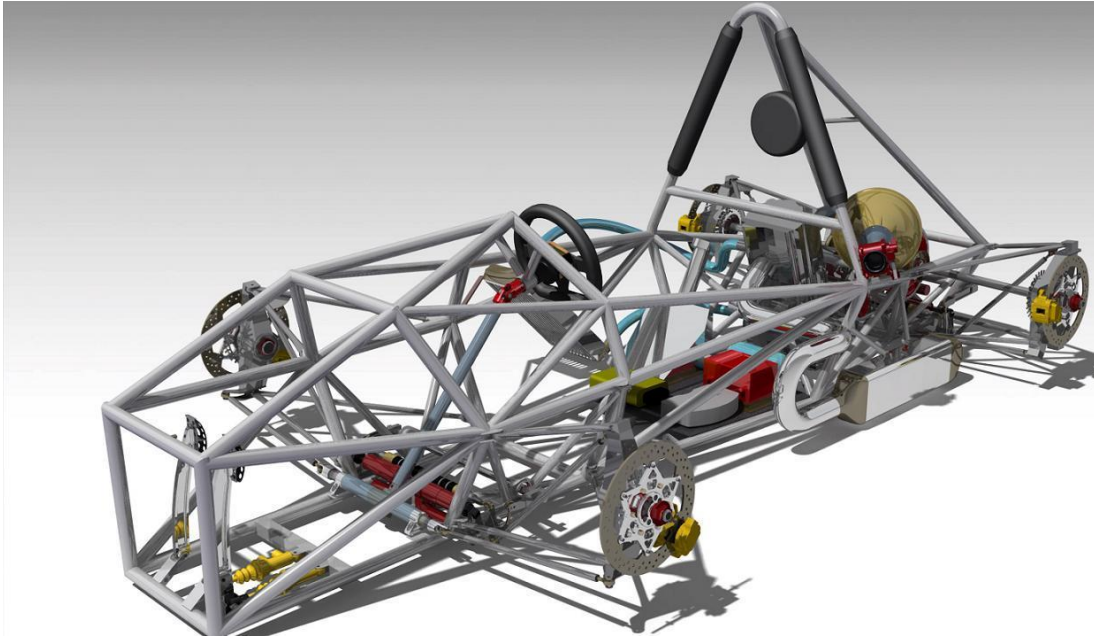Figure 13. Structure and frame of the HU-2 race car.

Figure 14. Building and manufacturing race car structure at Beta factory workshop, Delft.
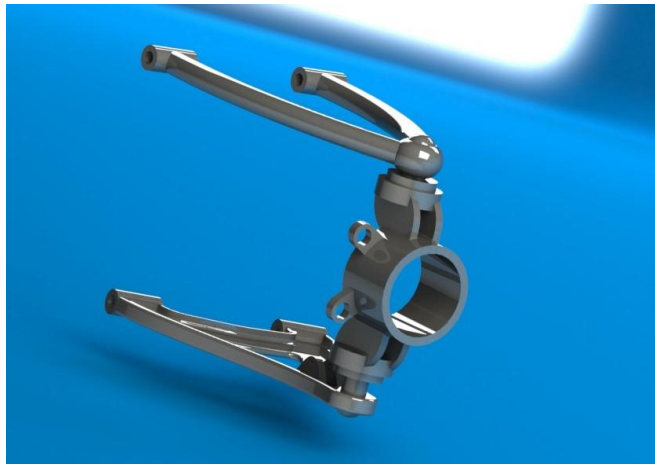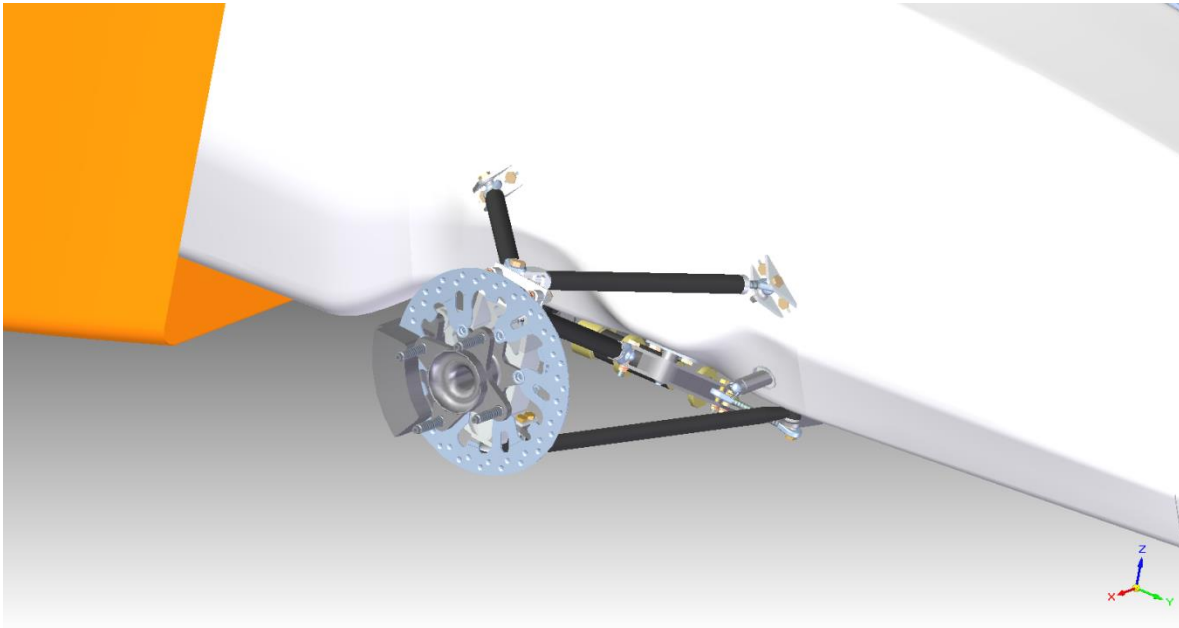
Details of the suspension system.

Figure 15. Upright, suspension.

Tasks.

1- Look if the old wheel hub fits in the new upright (in Inventor).

Figure 16. Wheel hub.

2- Old wheel hub in the folder in Autodesk 360 under the name Upright.

Specification.

1- When they started there was no old part of the Wheel hub, so they created a new one with the dimensions that they measured. But when the design of the new upright was finished, they found the old Wheel hub part.

Now they want to use the old wheel hub and its parts, but they saw the one that they made was a little different than the one that is in the old car right now. We as a new members of the design of the suspension need to look if the old wheel hub fits in the new upright in inventor. If not, the wheel hub or upright need some changes.

2- Also it is necessary to look at the fitting of the bearing.

3- The diameter of the hole in the upright needs to be smaller. We decided to choose another bearing, make it smaller than the bearing that they have chosen .

Fixed Requirement.

1- The Upright must be smaller than 240 x 150 x 40 mm.

2- The current dimensions are 220 x 100 x 30 mm.

3- The <u>Upright</u> needs to be 20 % lighter than the current. The current Uproght weighs about 1 kg.

4- The <u>Upright</u> needs to be inexpensive. Cost reduction of 10 %.

5- The design must be producible.

6- FSAE requirements that are associated with the Upright.

For all that, we have decided to make some modification.

Current Dimensions of Upright. 232 x 148 x 30 mm

Diameter of the hole 85 mm.

Wheelhub dimensions 120 x 45 mm

Ball Bearing fits Wheelhub. SKF 3208A (*External diameter* 85 mm; *Internal Diameter* 45 mm).

Subsystems of the Suspension
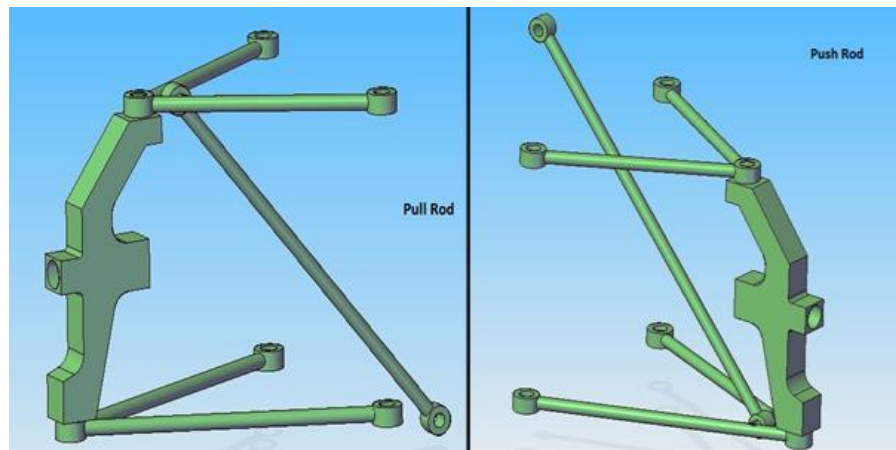
Wishbones (Upper and Lower).

Push Rod.

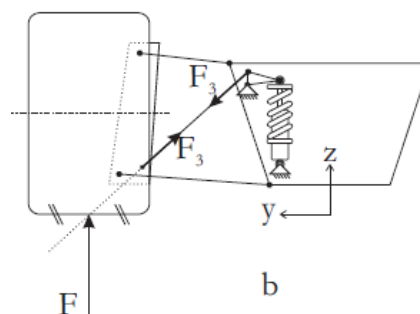Figure 17. Configuration left & right wishbone suspension.

Figure 18. Push Rod.

Specification final Concept.

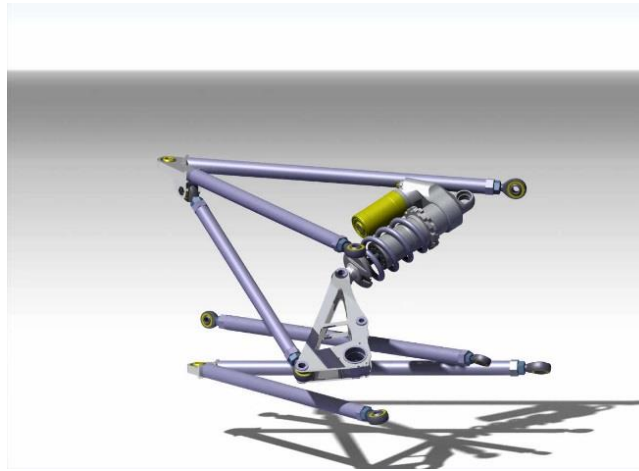1- Suspension type. ***Double Wishbone, Push Rod***.

Figure 19. Double wishbone suspension.

In motorsports the application of the *double wishbone* suspension set up, is the preferred system and this is used in F1. This is partially because it allows the engineers more freedom to choose camber levels and roll centre settings. Which ultimately will affect the car's handling in certain situations and could affect lap times/handling effectiveness of the vehicle.

Each wishbone has two mounting points to the car's chassis and one joint at the knuckle. The shock absorbers and coil springs, mount to the wishbones to control vertical movement.

The main advantages of the double wishbone suspension set up is that it is reasonably easy to work out the effects of the moving joints. This allows engineers to easily tune the kinematic of the set up to optimize wheel motion. In Motorsports where a tenth of a second a lap can mean the difference between winning and losing, having a suspension set up with easy adjustments, will yield greater performance for competitiveness.

Double wishbone suspension is more effective in working out the loads that different parts of the suspension are subjected to under loads, which could mean continued development and progression of lightweight parts especially in a racing environment.

The design also provides increasing level of negative camber, throughout suspension motion uding full jounce travel. Unlike the MacPherson strut design which provides negative camber

gains, only at the beginning of jounce travel and then reverses into positive camber gains at high jounce level amounts. The Double Wishbone design has disadvantage, in that it is slightly more complex than other systems like a MacPherson strut and will be more expensive to manufacture.
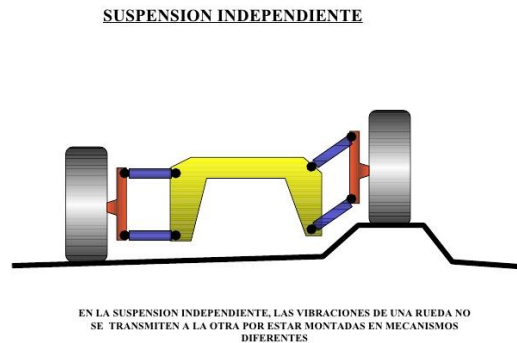
2- Independent Suspension System.

Figure 20. Independent suspension.

Geometry of the suspension.
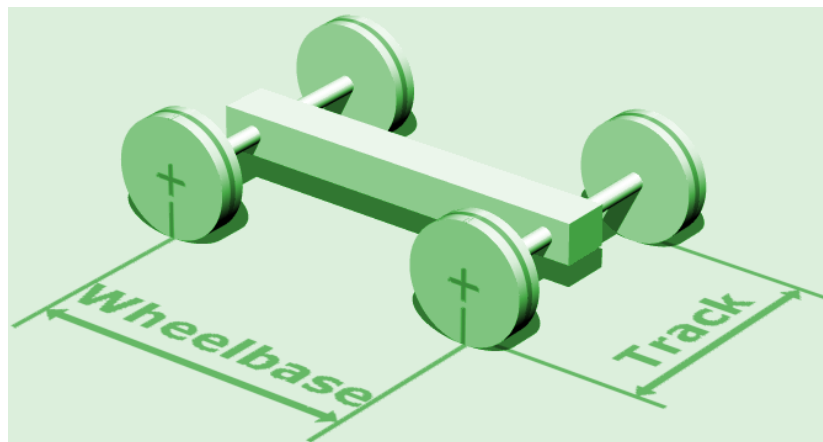
Figure 21. Wheelbase & track concept.

In order to know how the suspension is, we must give an description of the main parts of this suspension System which give together the suspension system.

Track.

The **axle track** in automobiles and other wheeled vehicles which have two or more wheels on an axle, is the distance between the centerline of two roadwheels on the same axle, each on the other side of the vehicle. In a case of the axle with dual wheels, the centerline in the middle of the dual wheel is used for the axle track specification.

In a car, or any vehicle, with two axles, this will be expressed as "front track" and "rear track". However the front wheels and/or rear wheels on either side of a vehicle do not necessarily have to be mounted on the same axle for the distance that they are apart to be called the "track".
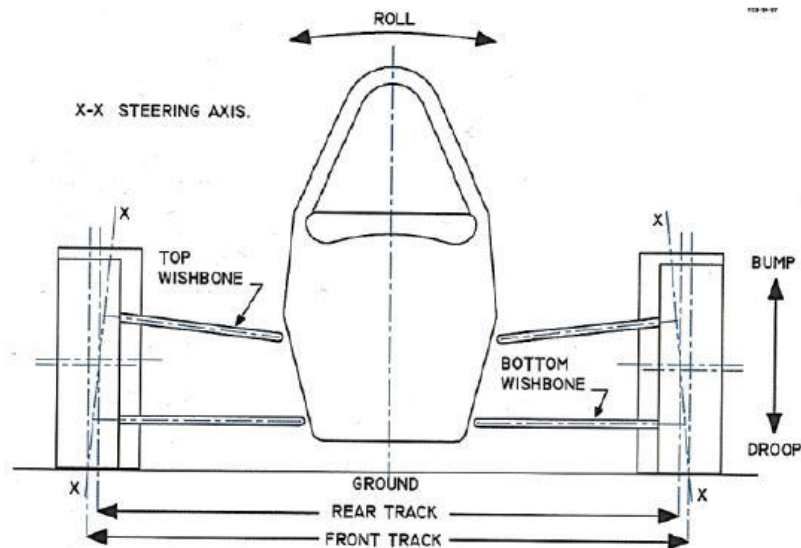
Figure 22. Rear & front track.

Wheelbase

In both road and rail vehicles, the wheelbase is the distance between the centers of the front and rear wheels. For road vehicles with more than two axles (e.g. some trucks), the wheelbase is defined as the distance between the steering (front) axle and the center point of the driving axle group. In the case of a tri-axle truck, the wheelbase would be the distance between the steering axle and a point midway between the two rear axles.
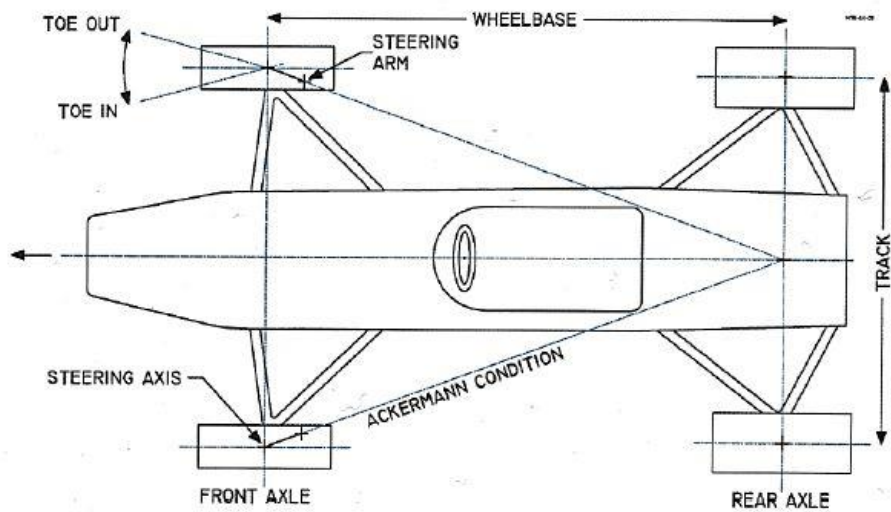
Figure 23. Wheelbase concept.

Center of mass.

What is the Center Mass?

The **Center of Mass** of a distribution of mass in space is the unique point where the weighted relative position of the distributed mass sums to zero or the point where if a force is applied causes it to move in direction of force without rotation. The distribution of mass is balanced around the center of mass and the average of the weighted position coordinates of the distributed mass defines its coordinates. Calculations in mechanics are often simplified when formulated with respect to the center of mass.

In the case of a single rigid body, the center of mass is fixed in relation to the body, and if the body has uniform density, it will be located at the centroid. The center of mass may be located outside the physical body, as is sometimes the case for hollow or open-shaped objects, such as a horseshoe. In the case of a distribution of separate bodies, such as the planets of the Solar System, the center of mass may not correspond to the position of any individual member of the system.

The center of mass is a useful reference point for calculations in mechanics that involve masses distributed in space, such as the linear and angular momentum of planetary bodies and rigid body dynamics. In orbital mechanics, the equations of motion of planets are formulated as point masses located at the centers of mass. The center of mass frame is an inertial frame in which the center of mass of a system is at rest with respect to the origin of the coordinate system.
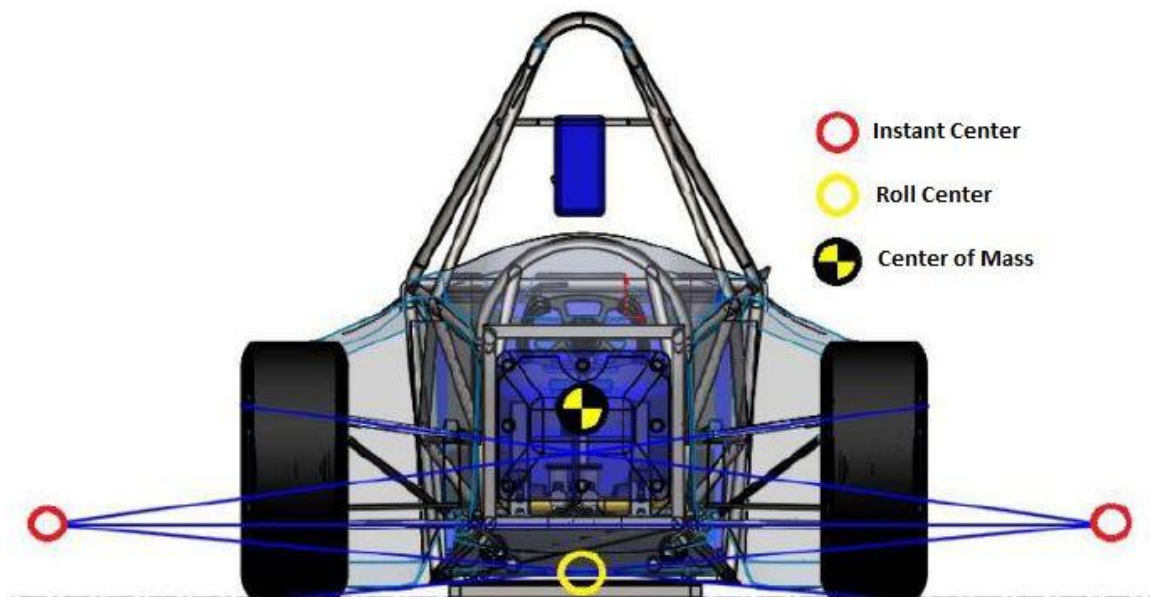
Figure 24. Location of the center of the mass race car.

Instant Center.

"Point on a rigid body whose velocity is zero at a given instant" Instantaneous: May only have zero velocity at the instant under consideration. Idea: If we know the location of an instant center in 2D motion and we know the angular velocity of the rigid body, the velocities of all other points are easy to determine.

Spring and damper.

The spring and damper like mentioned earlier will be mounted to the chassis and connected to the wheel through the bell crank and push rod. This configuration reduces unsprung weight and

improves the response of the suspension system. The suspension system uses coil over springs where the springs are mounted to the outside of the damper with an adjustable preload on the spring to adjust the ride height of the car.

The dampers are twin tube with adjustable high and low-speed rebound and compression these settings are important in fine-tuning the suspension. In twin-tube dampers, there are two chambers full of oil in the damper and when the damper is moved the piston moves the oil through the needle valves. The needle valves control the flow of liquid through the orifice in the valve seat restricting the flow of the oil and thus providing controllable flow. The Öhlins TTX MkII has a gas chamber that pressurizes the oil inside the damper with a piston that separates the gas from the oil. By having the oil inside the damper pressurized, improves the performance of the damper and prevents air bubbles forming in the oil and reduces hysteresis

Anti-roll bar

The anti-roll bars are used to increase the roll stiffness of the car during lateral acceleration and are an important factor in fine-tuning the roll stiffness of the car. The anti-roll bar works by taking the linear motion of the suspension and provide torsional stiffness through a rod or tube. This transfers some of the forces of the vertical forces between the tires during cornering and increases grip. The anti-roll bars are mounted low in the chassis to lower the CoG and have links to the bell cranks.
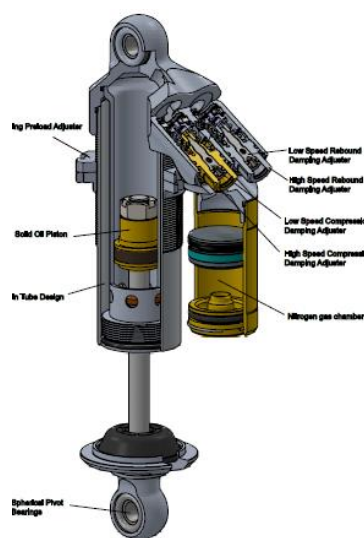
Figure 25. Shock absorber.
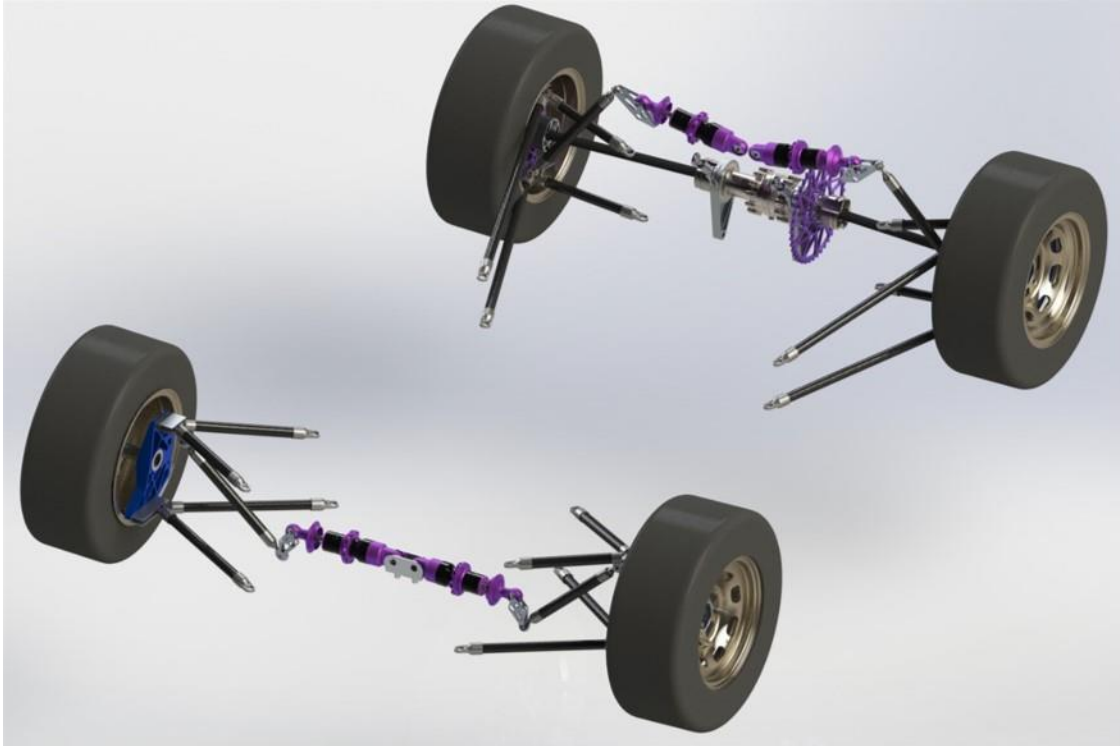
Figure 26. front & rear schematic suspension.

Comparison between Steel alloy and Carbon Fiber. Weight-Cost.

Front Suspension

Push rod. 1 Tube.
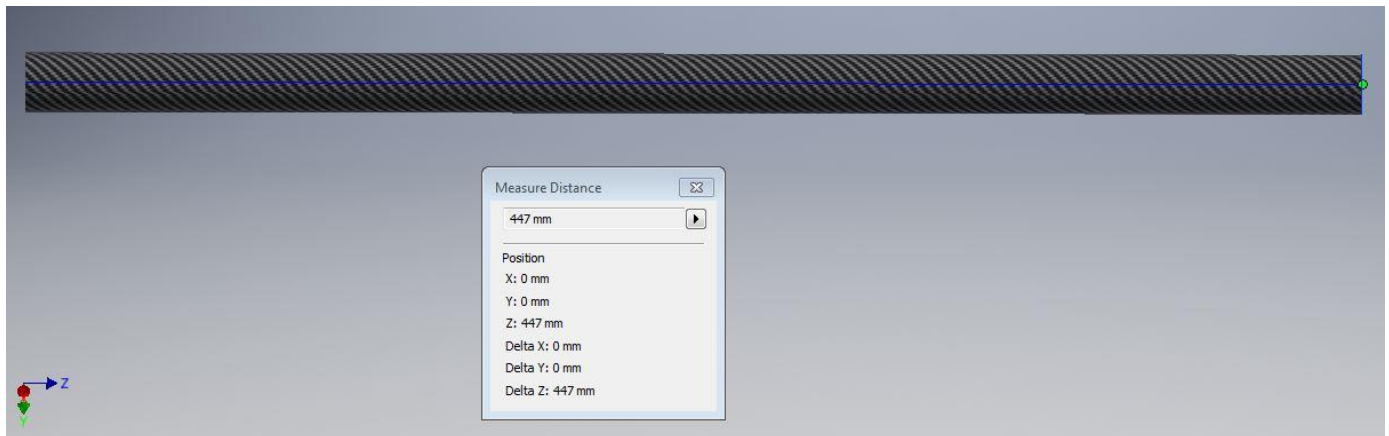
Figure 27. Front bar suspension dimension.

Material	Weight (kg)	Length (mm)	Cost (€)
Steel alloy	1,014	447	34,38 ↑
Carbon Fiber	0,203	447	7,56 ↓

Table 1. Difference costs between Steel alloy and Carbon Fiber to the Front Push Rod.

Costs:

Carbon Fiber: 100 € per 1300 mm.

Steel Alloy: 22 € per 1300 mm.

Rear Suspension.

Push rod. 1 Tube.
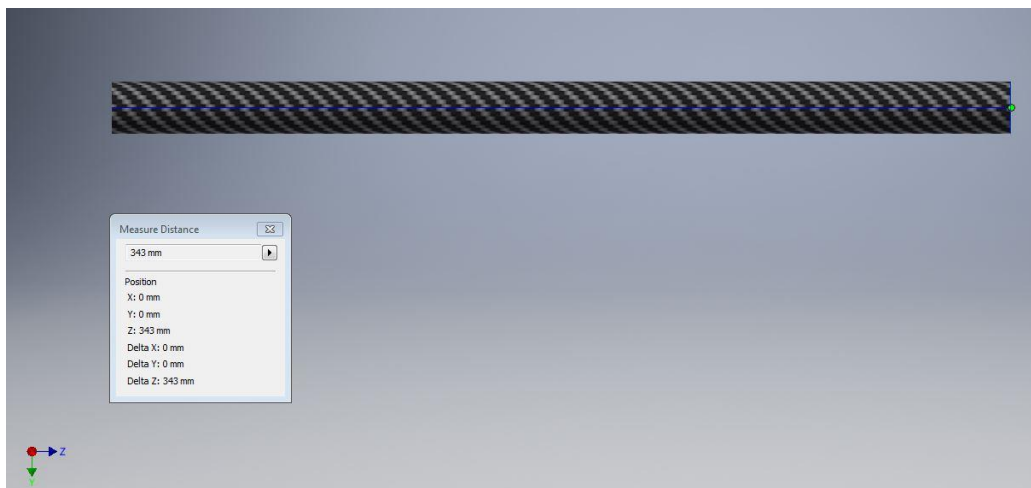
Figure 28. Rear bar suspension dimension.

Material	Weight (kg)	Length (mm)	Cost (€)
Steel alloy	0,761	343	26,38 ↑
Carbon Fiber	0,153	343	5,80 ↓

Table 2. Difference costs between Steel alloy and Carbon Fiber to the Rear Push Rod.
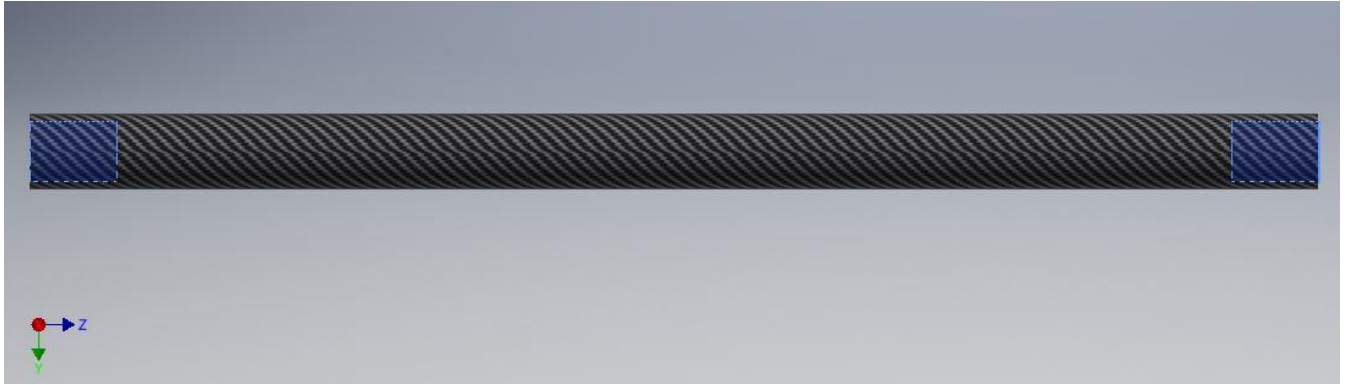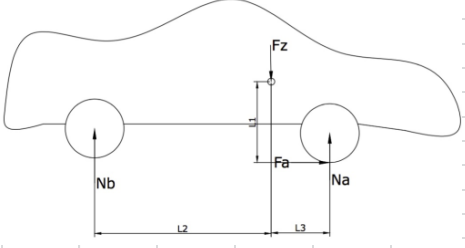
Figure 29. Details of the lateral inserts of the bar suspension.

4 CHAPTER 4. *Calculation of the suspension system.*
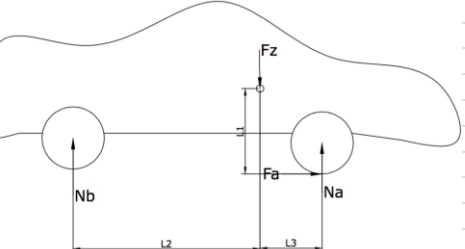
Braking force.

Fa	-3616,9 N				m	375	kg	
					m	3678,75	N	
L1	0,309 m				g	9,81	m/s²	
L2	0,942 m				v	27,7778	m/s	
L3	0,628 m				s	80	m	
					t	2,879998	sec	
moment b:		Fa(max)	1345,849 N		a	-9,64508	m/s²	
	3465,383 N				Fg	-0,98319	gN	
	-1117,62 N							
	1,57 m	∑ Fy = 0						
Na	1495,388 N	Nb	2183,362 N					
N'a	747,694 N	N'b	1091,681 N					

Acceleration.

Fa	2604,1688 N				m	375	kg	
					v	27,7778	m/s	
L1	0,309 m				t	4	s	
L2	0,942 m				a	6,94445	m/s²	
L3	0,628 m							
moment b:		Fa(max)	863,0638 N					
	2310,255 N							
	804,68814 N							
	1,57 m	∑ Fy = 0						
Na	958,95978 N	Nb	2719,79 N					
N'a	479,47989 N	N'b	1359,895 N					

Rear.

L1	0,309	m
L2	1,225	m
Fz	2207,25	N
Fc	1986,525	N
Fn_t	3678,75	N
Moment F1 = 0		
L2*Fn2 - L2/2 *Fz -L1*Fc = 0		
Fn2	1604,716	N
Fw2	1444,244	N
∑ Fy = 0		
Fn1 + Fn2 - Fz = 0		
Fn1	602,5342	N
Fw1	542,2808	N

Total.

L1	1,57	m	α	0,567232	rad	32,5 °
L2	1,225	m	β	0,39043	rad	22,37 °
Lr(4/10*L1)	0,628	m	γ	0,178024	rad	10,2 °
Lf(6/10*L1)	0,942	m	Fx11	612,3664	N	
g	9,81	m/s²	Fx12	558,4938	N	
m	375	kg	Fx21	662,2	N	
m	3678,75	N	Fx22	662,2	N	
µ	0,9					
Fc_total	3310,875	N				

Moment w3 =0:
L2*Fw4y - Lf*cos(γ)Fc - 0,5*L2*sin(γ)Fc +L1*Fw2 + L1*Fw1 -(Fx11y*L2 - Fx21*L2)= 0

1,225	m
-3069,55	N
-359,112	N
2267,463	N
851,3808	N
-1622,39	N
Fw4y	1577,315 N
Fw4	4144,435 N
Fn4	4604,928 N

∑ Fy = 0		∑ Fx = 0	
Fc*sin(γ) - Fw4y-Fw3y*sin(α) = 0		Fw4*cos(β) + Fw3x*cos(α) − Fc*cos(γ) + Fw2 + Fw1 = 0	
	586,3054 N		3832,5471 N
	1577,315 N		-3258,549 N
	0,5373 N		1444,2442 N
Fw3y	-991,009 N		542,28078 N
		Fw3x	2560,5235 N
Fw3	2745,611 N		
Fn3	3050,679 N		

Wheel.

I	0,1935	m
J	0,173	m
K	0,232	m
L	0,185	m
α	0,102974	rad	5,9 °
β_front	0,890118	rad	51 °
β_rear	0,757822	rad	43,42 °

Rear outside

		∑ Fx = 0		∑ Mp = 0		∑ Fy = 0	
		Fw2 + F1 + cos(α)F2 - cos(β)F3 = 0		J*Fw2 - 0,5L*Fn2 - I*cos(α)F2 = 0		Fn2 - sin(α)F2 - sin(β)F3 = 0	
Fw2	1444,244 N	1444,244 N		249,8542 N		1604,716 N	
Fn2	1604,716 N	524,1242 N		-148,436 N		-54,163 N	
		-1638,52 N		0,192475 N		0,687341 N	
		F1 -329,851 N		F2 526,9154 N		F3 2255,871 N	

Rear inside

		∑ Fx = 0		∑ Mp = 0		∑ Fy = 0	
		Fw1 + F1 + cos(a)F2 - cos(b)F3 = 0		J*Fw1 - 0,5L*Fn1 - I*cos(a)F2 = 0		Fn1 - sin(a)F2 - sin(b)F3 = 0	
Fw1	542,2808 N	542,2808 N		93,81458 N		602,5342 N	
Fn1	602,5342 N	196,7967 N		-55,7344 N		-20,337 N	
		-615,226 N		0,192475 N		0,687341 N	
		F1 123,8515 N		F2 197,8447 N		F3 847,0281 N	
	Highest rear	329,8509 N		526,9154 N		2255,871 N	

Front outside

		∑ Fx = 0		∑ Mp = 0		∑ Fy = 0	
		Fw4 + F1 + cos(a)F2 - cos(b)F3 = 0		J*Fw4 - 0,5L*Fn4 - I*cos(a)F2 = 0		Fn4 - sin(a)F2 - sin(b)F3 = 0	
Fw4	4144,435 N	4144,435 N		796,6525 N		4604,928 N	
Fn4	4604,928 N	1915,745 N		-425,956 N		-197,973 N	
		-3568,68 N		0,192475 N		0,777146 N	
		F1 2491,498 N		F2 1925,947 N		F3 5670,691 N	

Front inside

		∑ Fx = 0		∑ Mp = 0		∑ Fy = 0	
		Fw3 + F1 + cos(a)F2 - cos(b)F3 = 0		J*Fw3 - 0,5L*Fn3 - I*cos(a)F2 = 0		Fn3 - sin(a)F2 - sin(b)F3 = 0	
Fw3	2745,611 N	2745,611 N		474,9907 N		3050,679 N	
Fn3	3050,679 N	1001,704 N		-282,188 N		-102,968 N	
		-3793 N		0,192475 N		0,777146 N	
		F1 -45,681 N		F2 1001,704 N		F3 3792,996 N	
	Highest front	2491,498 N		1925,947 N		5670,691 N	

Wishbones.

Rear Wishbones

Rear lower

L1	0,22091 m						
L2	0,265 m						
α	0,610865 rad	35 °					
β	0,959931 rad	55 °					
γ	0,523599 rad	30 °					
Frear	2354,861 N						
Fwishb	1177,431 N						
Fx	-329,851 N						

Method of Joints

		A		B			
∑ Fy = 0		∑ Fy = 0		∑ Fy = 0			
Fa	2052,788 N	Fay	1177,431 N	Fby	0 N		
				∑ Fx = 0			
∑ Fx =0		∑ Fx=0		Fbx	-2011,4 N		
Fb	-2011,4 N	Fax	1681,545 N				
				F3x	2255,871 N		
				F3	1953,642 N		
Highest	2052,788 N						

Rear upper

L1	0,12639 m						
L2	0,18 m						
α	0,610865 rad	35 °				a	2 m/s²
β	0,959931 rad	55 °					
γ	0,523599 rad	30 °					
Frear	2354,861 N						
Fwishb	1177,431 N						
Fx	-526,915 N						

Method of Joints

		A		B		
∑ Fy = 0		∑ Fy = 0		∑ Fy = 0		
Fa	2052,788 N	Fay	1177,431 N	Fby	0 N	
				∑ Fx = 0		
∑ Fx =0		∑ Fx=0		Fbx	-2208,46 N	
Fb	-2208,46 N	Fax	1681,545 N			
Highest	2208,461 N					

Front Wishbones
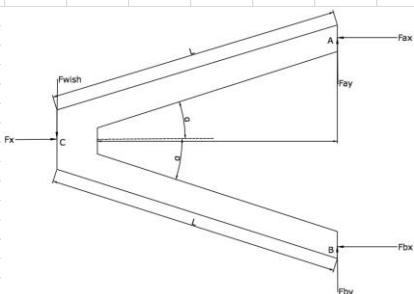
Front lower

L	0,421 m		
α	0,523599 rad	30 °	
β	1,047198 rad	60 °	
γ	0 rad	0 °	
Ffront	1471,106 N		
Fwisb	735,5532 N		
Fx	2491,498 N		

Moment a = 0			∑ Fx = 0	
cos(α)*L*Fwish + sin(α)*L*Fx - 2(sin(α)*L)*Fbx = 0			Fx-Fbx-Fax = 0	
	268,1803 N		Fax	608,7415 N
	524,4604 N			
	0,421 N			
Fbx	1882,757 N			

Method of joints A		Method of joints C		
∑ Fx = 0		∑ Fx = 0		
Fa*sin(β) - Fax = 0		Fx - cos(α)Fa - cos(α)Fb = 0		
Fa	702,9141 N		2491,498 N	
			608,7415 N	
			0,866025 N	
		Fb	2174,02 N	
			F3x	5670,691 N
			F3	5670,691 N
Highest	2174,02 N			

Highest total	5670,691 N

Front upper

L	0,323 m		
α	0,523599 rad	30 °	
β	1,047198 rad	60 °	
γ	0,136136 rad	7,8 °	
Ffront	1471,106 N		
Fwish	735,5532 N		
Fx	1925,947 N		

Moment a = 0			∑ Fx = 0	
cos(α)*L*Fwish + sin(α)*L*Fx - 2(sin(α)*L)*Fbx = 0			Fx-Fbx-Fax = 0	
	205,7535 N		Fax	325,9658 N
	311,0405 N			
	0,323 N			
Fbx	1599,981 N			

Method of joints A		Method of joints C	
∑ Fx = 0		∑ Fx = 0	
Fa*sin(β) - Fax = 0		Fx - cos(α)Fa - cos(α)Fb = 0	
Fa	376,3929 N		1925,947 N
			325,9658 N
			0,866025 N
		Fb	1847,499 N
Highest	1847,499 N		

Pressure.

F_max	5670,69088	N			
r_in	8	mm			
r_out	10	mm			
pi	3,141592				
A	113,097312	mm²			
pressure	50,13992623	N/mm²			
compr str	570	N/mm²		8,796478	%
	110	N/mm²		45,58175	%

Table 3. Pressures final results.

5 CHAPTER 5. *Autodesk Inventor 3D MODELS.*

Bell Crank bracket.
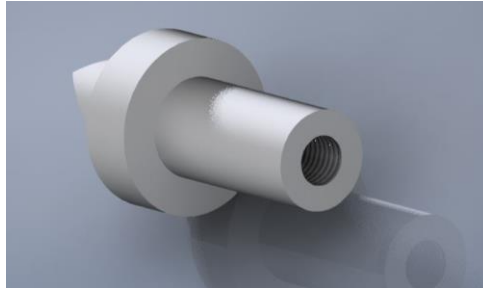
Figure 30. Bell crank bracket.

Bell Crank Front Plate.
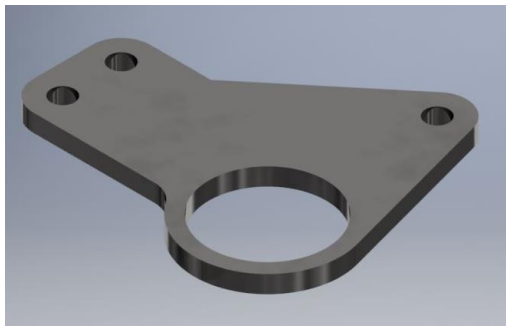
Figure 31. Bell crank front plate.

Bell Crank Rear Plate.
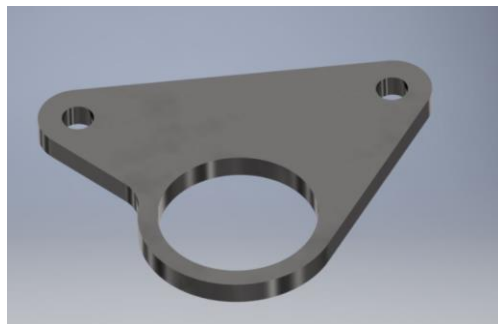
Figure 32. Bell crank rear plate.

Bell Crank Spacer.
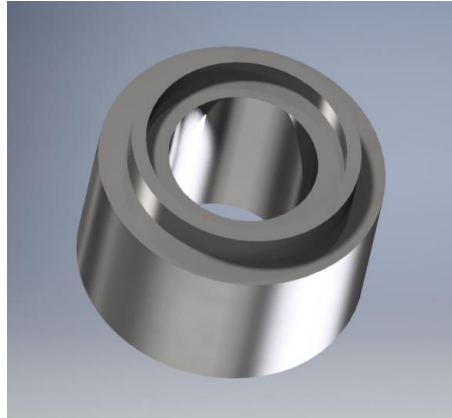
Figure 33. Bell crank spacer.

Lower Wishbone insert.
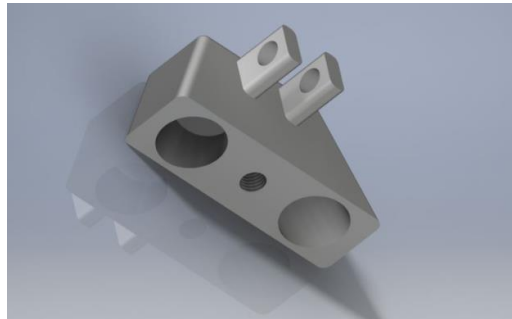
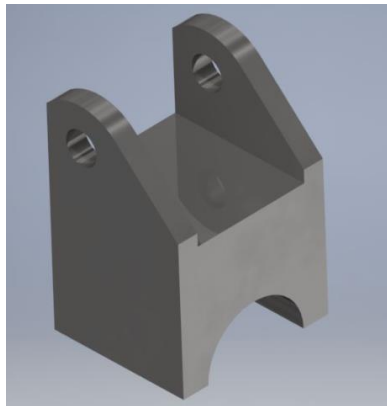Figure 34. Lower wishbone insert.

Shock Absorber Bracket.

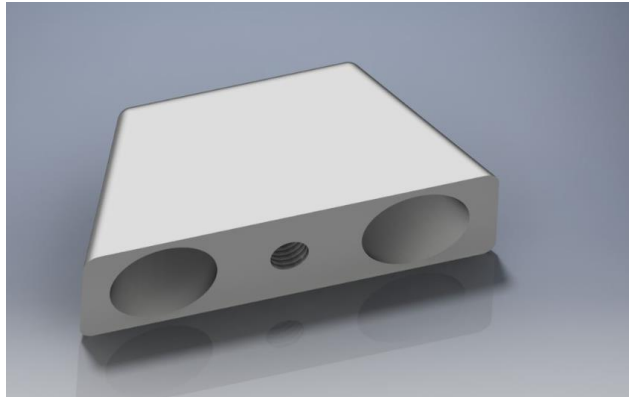
Figure 35. Shock absorber bracket.

Upper Wishbone insert.
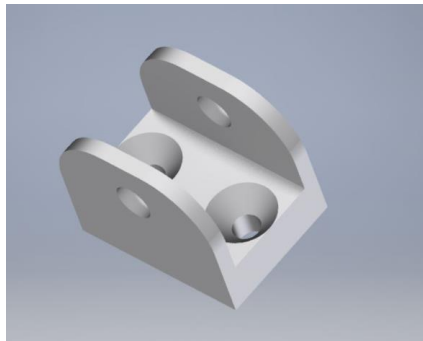

Figure 36. Upper wishbone insert.

Upright bracket.

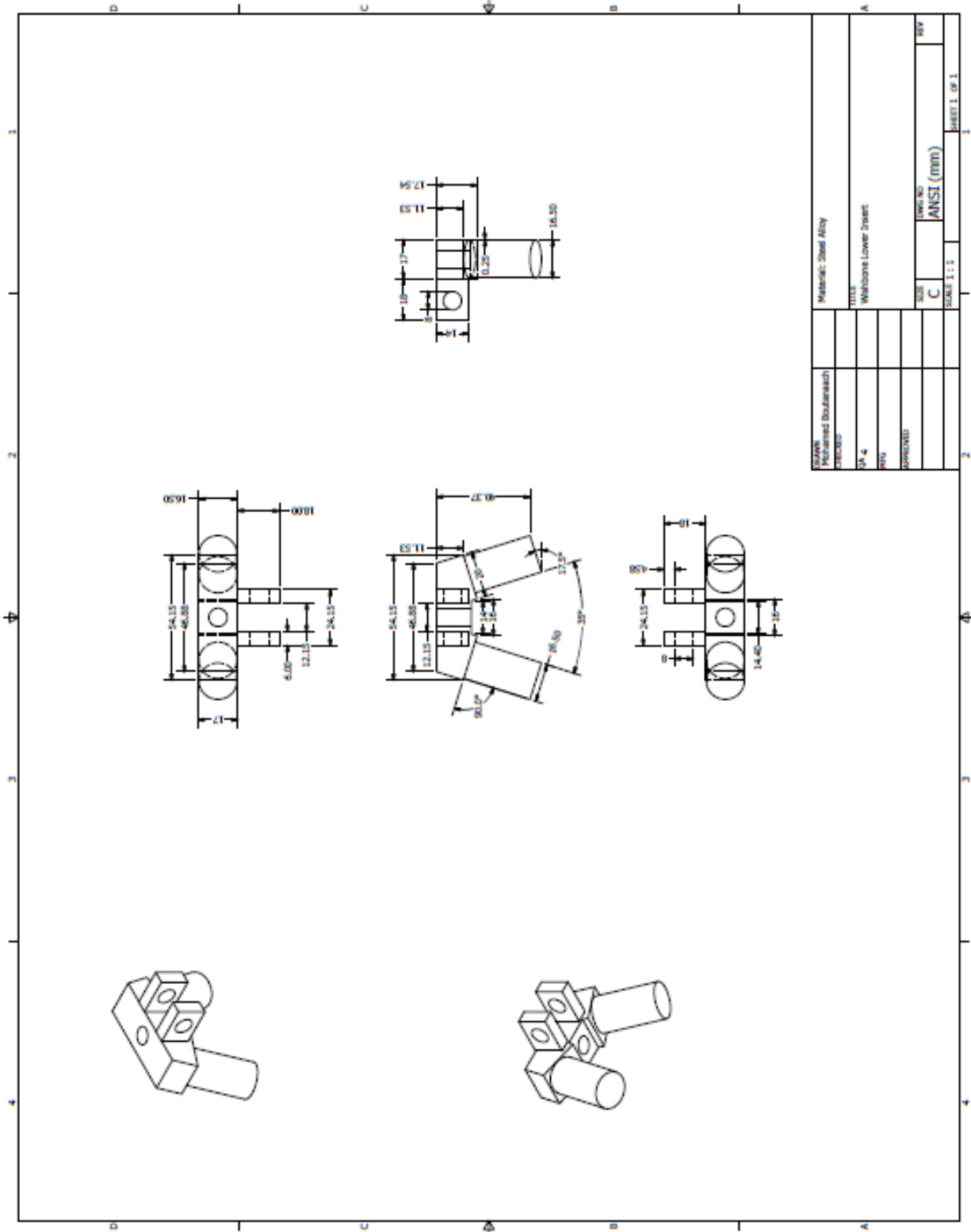
Figure 37. Upright bracket.

Upright.

Figure 38. Upright 3D model.

Working drawings of the front and rear spring-damper system.

Dimensions and annotations visible on the technical drawing:

- 41,13
- 30,36
- 26,73
- 14,00
- 6,50
- 6,50 (Ø6,50)
- 21,09
- 18,00
- 8,00
- 14,00
- 49,60
- 42,35
- 125,81°
- 54°
- 27°
- 27°
- 30
- 10,77
- Ø6,90

Title block:
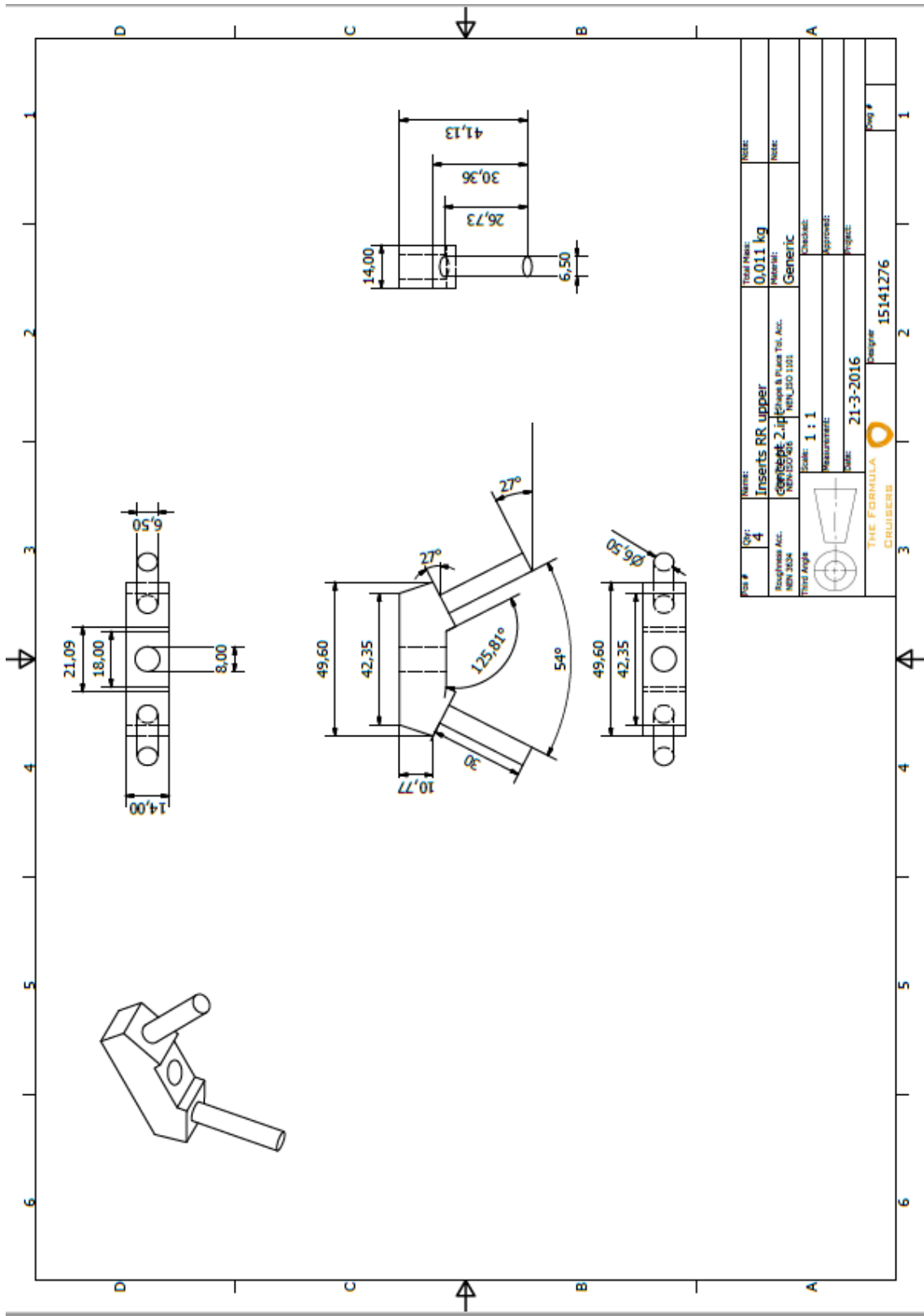
Qty: 4	Name: Inserts RR upper	Total Mass: 0,011 kg
	content 2.ipt	Material: Generic
Roughness Acc. NEN 2634	Shape & Place Tol. Acc. NEN_ISO 1101	
Third Angle		Scale: 1 : 1
		Measurement:
	Date: 21-3-2016	
	Designer: 15141276	

THE FORMULA CRUISERS

Notes:

6 CHAPTER 6. *Conclusion*.

As the main objectives of this thesis were to gain a better understanding of how suspension systems work and combine theory and practical knowledge by designing and manufacturing the suspension system.

In the thesis suspension properties like camber, caster and kingpin inclination angle was explained and what effects on the overall handling of the car they have.

The manufacturing process is also explained and how the design could be as simple as possible without sacrificing performance.

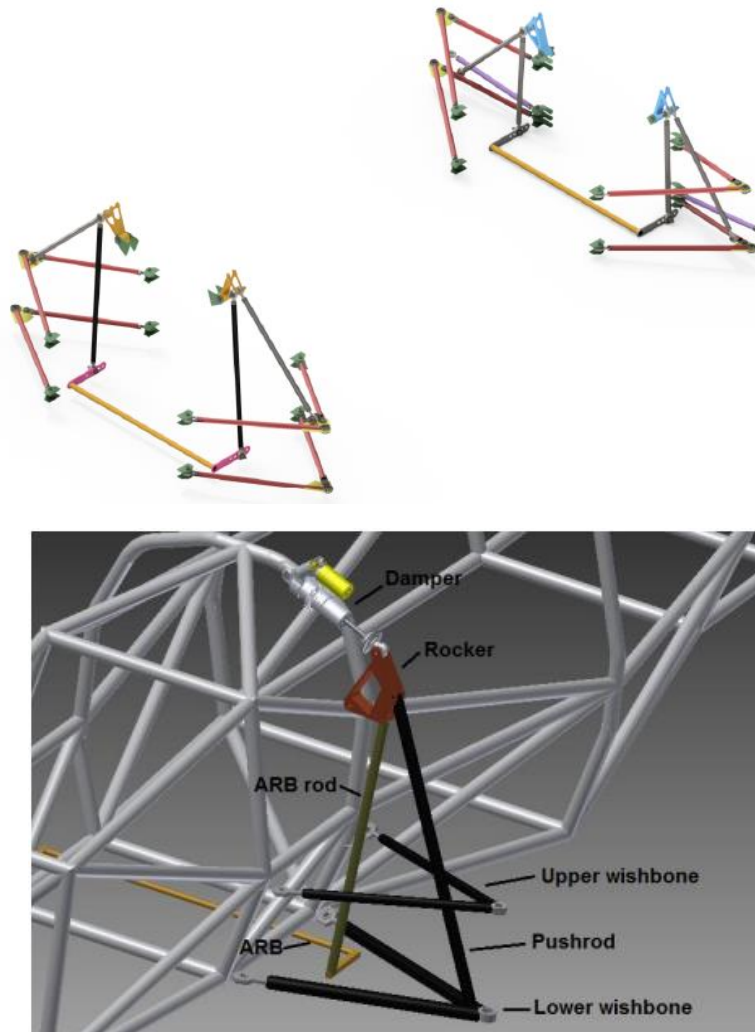3D model of the final assembly is as follow:

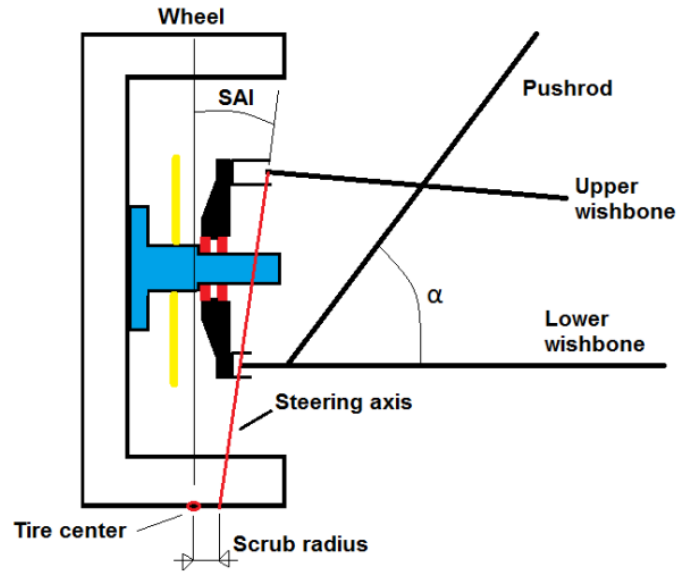Figure 39. Final configuration adopted for the HU-2 race car. The Hague University of applied sciences.

Figure 40. Suspension system details.

Figure 40. The HU-2 race car testing on the road in Silverstone (UK).

7 CHAPTER 7. *References*.

Formula Student. General Technical Requirement, 2016.

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