



Description and design of the steering system for a Formula Student car

Descripción y diseño del sistema de dirección para un coche de formula student

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Summary

Our Project has as aim the description and design the elements of the steering system for a formula S.A.E.

The steering system is one of the most important parts of the car because has the task to control the car and guide by the desirable trajectory. The action starts on the hands of the pilot and is transmitted through several elements that have different tasks until turn the wheels. A failure on this mechanism can be fatal to the health of the pilot.

Before start to design the elements of the steering system car, we will study different aspects that have influence on the design of the steering system.

First of all we report to the reader all about the Formula S.A.E. The aim, where take place the race the rules and the history of the competition. We will discover the main objective of the competition the development of young engineers because they have to manufacture the cars themselves.

Then we study the formula S.A.E. rules and we will put on our project the rules the more general rules and the rules directly related with the steering system in order to design our system bear in mind these restrictions that are established by the competition.

We will do a compilation of the general characteristics of a formula S.A.E. in order to know more about this kind of cars comparing with a formula one car that is known for the most of the people.

Subsequently we will study the theoretical knowledge and the technical fundamentals and general comments about the steering in general in order to understand better this system and applied on our formula S.A.E. In this chapter we will find out the characteristics that must has a steering system and the geometry (Ackerman and Jeantaud) of some elements of the system that produce the car has a different performance on the road. Also we will study the different angles that we can give to the

wheel and we will see the different qualities that the vehicle has depending on these angles.

Continually we will start with the design of our steering system. We will start this task separating the elements of the car that have influence on the design of the steering and the elements that really make up the system.

As regards the elements of the car to take in consideration to design our system we will study the measures of the cockpit because will be important in order to situate the elements of the steering system. Then we will be able to start to design the elements. We begin giving a description of the mechanism and continually we will describe the function and the characteristics of each element. We will focus on the steering column, the rack and pinion and the steering arms because we do the difference between the elements that we can manufacture and design and the elements that we will buy to the manufacturers. In order to design the elements that we will design ourselves we will use the Solid works program which we can to draw the elements and to calculate the stress that can support.

To finish we will calculate the budget of the project.

Acknowledgements.

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1.

Introduction.

1.1. Project aim

1.2. Importance of the steering system on a car.

1.3. The steering system on a common car

1.1. Project aim.

In this project we are going to carry out the study and the design of the steering system for a car used on competition races in circuits.

Along the project we will focus in the steering system but also we will watch the steering in a car that we can find travelling in one street in order to understand better the performance of the steering elements in order to after focus in a formula S.A.E. which is a car that requires a steering system more exigent due to is used on races.

By other hand we must know that we are manufacturing a steering system for a car so we will bear in mind different elements of the car which have influence at the time to manufacture the steering system. In this project we will do reference to the characteristics to these parts of the car and the measures, the weight or the design.

The project will be carry out bearing in mind a lot of very different aspects as the total cost of the project, the analysis stress and the materials to manufacture the steering components and the design of the car carefully since there are some technical rules which must be taken in consideration

With regards to the budget, the Formula Student stipulates that there is no a maximum cost so I will make my project and finally I will calculate the total cost.

Once finished the single-seater will have as objective compete in the race of the Formula S.A.E competition that/which it will celebrate in Silverstone circuit the dates from 15th until 18th de Julio 2010.

1.2. Importance of the steering system on a common car.

The steering system is one of the most important parts of any car. Whether this element is vital to the safety driver of the vehicle in question concern.

While the steering, as we have said, is important in a common car which we can drive daily in our life, obviously is even more significant in a formula S.A.E. car since this kind of vehicles are designed to compete in races and the objective of the team and the pilot is always to bring the car to the limit to try to win. A failure of this mechanism during operation of the vehicle could lead to fatal circumstances to the driver who is at the expense of a car without control and with high velocity. As we have seen along the history, a lot of the most serious accidents have been caused due to a failure on the steering system with different fates for the drivers.

Although in this project we will start talking and explaining the elements of a common car to know more about the steering in general in any car, then we focus on the steering system for a competition car which is a little bit different that in a common car.

1.3. The steering system on a common car

The steering system is the mechanism which has the purpose to turn the guidelines wheels making that the pilot can guide his car along the desirable trajectory.

In order to carry out this task the pilot receive a lot of information by their eyes and the brain send a stimulus to their hands which are the elements in contact with the first part of the steering system, the steering wheel. Now the human work has finished it is the time to the mechanism work. The steering system work is to transmit the angle made by the pilot on the steering wheel across the different elements until the steering wheels.

Steering system elements:

- Steering wheel
- Quick disconnect mechanism
- Steering column
- Universal joint
- Steering box (rack-pinion)
- Tie rods
- Ball-and-socket
- Steering arms
- Upright
- Pivot

In our project we will study the theoretically knowledge that has influence on the steering system and basing on these fundaments we will design and describe the steering system elements.

2.

Aims of Project.

A formula S.A.E. car is a car thought to compete in races. Everybody knows that in a race or in any competition the person who take part always try to win and for that try to put in effort as much as possible. In our project in which we are going to design the steering system of a formula S.A.E car, the efforts supported by all the elements of the vehicle are very hard and we keep in mind that the health of the pilot depends directly of a good car design. Particularly when we talk about the steering of a car the responsibility of to carry out a good design is maximum because join the breaking system, is the principal system to control the car and so is the principal element for the safety of the pilot.

By other hand as we can say we are going to design a car to compete in races. However our car is destined to compete in Formula Student. This kind of competition is thought to develop of young engineers because the students of different universities manufacture their own cars with their own resources. Obviously these resources are quite different than of a formula one team because the cars have not equal features. By this reason our project will be carried out bearing in mind the following aspects: a low budget, the formula S.A.E. rules and the time because the project must be finished on 30th of April and the race is from 15th to 18th of July in Silverstone circuit.

3.

Review of Literature.

3.1. The competition: Formula Student

3.1.1. Formula student rules that have influence on the steering system

3.1.2. Differences between a S.A.E. car and a formula one.

3.2. General comments about the steering

3.3. Technical fundamentals

3.1. The competition: Formula Student.

It can say that the formula S.A.E. has its origins

In 70's years when different local American

Universities organized races with cars that had built

themselves with very limited resources. In a few years

it increased the number of universities that participated

in the competition so this great idea which helped the

development of young engineering students crossed to United Kingdom. In 1998 two American vehicles and two English made a demonstration in Britain. Subsequently, the IMechE in collaboration with the automotive company took over management of the competition.

Nowadays, Formula Student is the most prestigious competition of its kind. This competition seeks to bring students from 120 universities round the world in a real experience with that for a year, design, manufacture, develop and compete with a car like a small formula one team with all that this implies (design, finance, purchase of equipment, assembly, testing...) With this ambitious challenge therefore is to develop talented young engineers to develop in the professional world



Figure 1. Fsaе logo



Figure 2. Formula Student logo

There are restrictions on different aspects, so students must demonstrate creativity and all their ingenuity to get the project forward. The challenge of designing the car not only has restrictions as to manufacture car parts but also the reliability of the project, so students should take the vehicle to be marketed with an annual production of 1000 units per year

Cars will be evaluated in a series of both static and dynamic tests to see the performance of the car.

Statics events and maximum scores:

Technical inspection -----	no points
Presentation -----	75 points
Design -----	150 points
Cost and manufacturing -----	100 points

Dynamics events and maximum scores:

Acceleration -----	75 points
Skid Pad -----	50 points
Autocross -----	150 points
Fuel economy -----	100 points
Endurance -----	300 points

Being a total score of 1000 points.

Due to my project it is about the steering of the car, although the autocross test and at endurance test also the steering have importance because the car will have to pass slalom tests, where really the steering is tested is at skid pad event. In this test the car have to run in the next circuit.

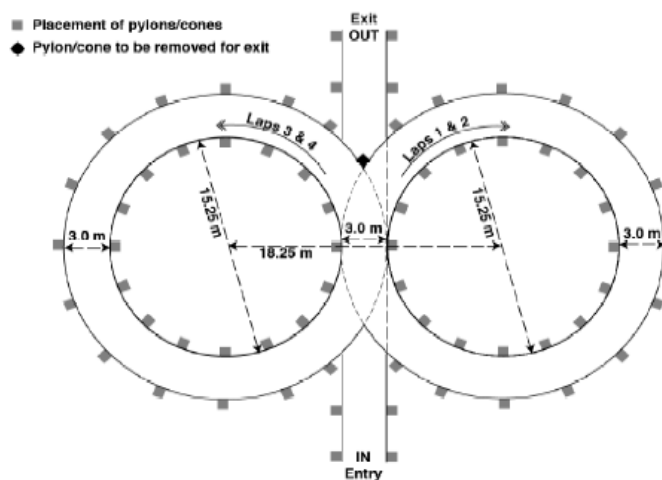


Figure 3. Formula Student event

It is possible calculate the score with the follow equation:

$$\text{Skid pad score} = 47.5 \times \frac{\left(\frac{6.184}{T_{your}}\right)^2 - 1}{\left(\frac{6.184}{T_{min}}\right)^2 - 1} + 2.5$$

Where:

T_{your} : is the average of the left and the right time laps on your best lap including penalties

T_{min} : is the elapsed time of the faster car

Due to the growth and success that this event had teams eligible to participate in formula S.A.E. American, European Formula Student, Formula S.A.E. Australia, in Italian or Brazilian. We focus on the European formula of students and to build the guidance system for a student of the formula that will compete in this kind of competition, in which the race will held at Silverstone circuit (England) for provisional dates 15 to 18 July.

3.1.1. Formula student rules that have influence on the steering system.

We will base our design of the steering system according to the rules and restrictions that impose the Formula Student.

There are a lot of articles about all the aspects of the car as the fuel, the noise caused by the car, the different parts of the vehicle: cockpit, aerodynamic elements, the fuel tank etc, different safety measures as the belt or the cockpit padding etc. But the most general and important for our project are the next:

- The vehicle must be open-wheeled and open-cockpit (a formula style body) with four wheels that are not in a straight line
- The cars normally have a measure around 3 meters but the car must have a wheelbase of at least 1525 mm. The wheelbase is measured from the center of ground contact of the front rear tyres with the wheels pointed straight ahead

DIMENSIONS	FRONT	REAR
Overall length, width, height	2815mm, 1310mm, 1025mm	2815mm, 1310mm, 1025mm
Wheelbase	1525mm	1525mm
Track	1200mm	1100mm

Table 1. Fsaе rules

- The smaller track of the vehicle (front or rear) must be no less than 75 % of the larger track
- There must be no openings through the bodywork into the driver compartment from the front of the vehicle back to the roll bar main hoop or firewall other than that required for the cockpit opening. Minimal openings around the front suspension components are allowed
- Among other requirements, the vehicle's structure must include two roll hoops that are braced, a front bulkhead with support system and impact attenuator, and side impact structures.

Note: the main hoop and the front hoop are classified as ``roll hoops``.

Main hoop: a roll bar located alongside or just behind the driver's torso

Front hoop: a roll bar located above the driver's legs, in proximity to the steering wheel.

- The engine can have a maximum of 610cc. Must be only one round air intake of 20 mm.

- The fuel must be of 100 octane or a maximum of bi-ethanol E-85
- It is possible to use turbo or compressor only if is an own design
- The car must be equipped with a breaking system that acts on all four wheels and is operated by a single control
- The perimeter shear strength of the monocoque laminate should be at least 7.5 KN for a section with a diameter of 25 mm. this must be proven by physical test by measuring the force required to pull or push a 25 mm diameter object through a sample of laminate and the results include in the SEF.

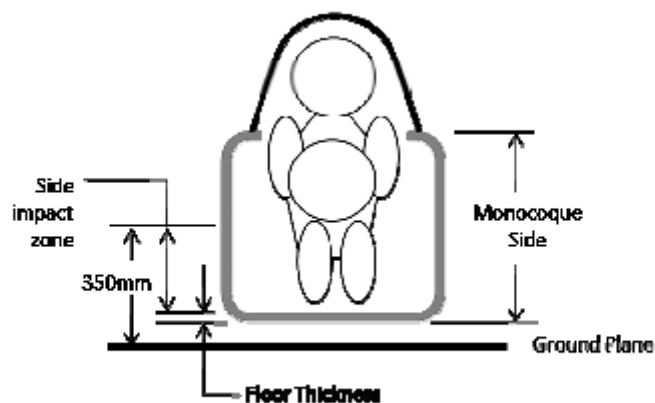


Figure 4. Fsaе rules

As regards of the steering restrictions:

- The steering system must be affect at least two wheels
- The steering system must have positive steering stops that prevent the steering linkages from locking up (the inversion of a four-bar linkage at one of the pivots). The stops may be placed on the uprights or on the rack and must prevent the tyres from contacting suspension, body, or frame members during the track events.
- Allowable steering system free play is limited to seven degrees total measure at the steering wheel
- Real wheel steering is permitted only if mechanical stops limit the turn angle of the rear wheels to (+-3) degrees from the straight ahead position

- The steering wheel must be mechanically connected to the front wheels, i.e. ``steer-by-wire`` of the front wheels is prohibited
- The steering wheel must be attached to the column with a quick disconnect. The driver must be able operate the quick disconnect while in the normal driving position with gloves on
- The steering wheel must have a continuous perimeter that is near circular or near oval, i.e. the outer perimeter profile can have some straight sections, but not concave sections, or cutout wheels are not allowed.
- In any angular position, the top of the steering wheel must be no higher than the top-most surface of the front hoop

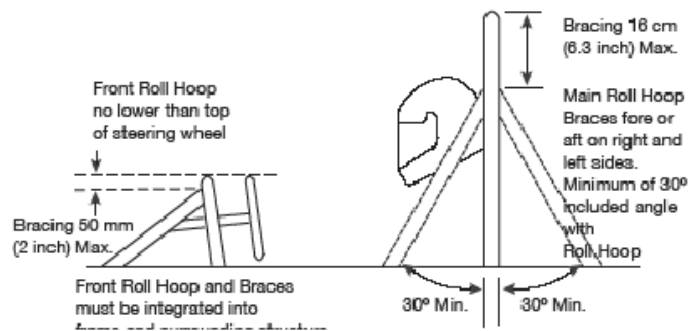


Figure 5. Fsaе rules

- The wheels of the car must be 203.2 mm or more in diameter
- Vehicles may have two types of tyres as follows:
 - Dry tyres: the tyres on the vehicle when it is presented for technical inspection are defined as its ``Dry tyres``. The dry tyres may be any size or type. They may be slicks or treaded.



Figure 6. Dry tire

- Rain tyres: Rain tyres may be any size or type of treaded or grooved tyre provided:
 1. the tread pattern or grooves were molded in by the tyre manufacturer or his appointed agent. Any grooves that have been cut must have documentary proof that it was done in accordance with these rules.
 2. there is a minimum tread depth of 2.4 mm



Figure 7. rain tire

3.1.2. Differences between a common car, formula S.A.E. car and a formula one.

In order to know how is the system which we are going to design, we must to know the characteristics of the car. We know that the car will be a vehicle to compete in close circuits so the features must be high quality. However this car is made for students, young engineers which manufacture the car themselves so it is not a competition for professionals so the aim of the Formula S.A.E. is that the engineers learn about this world.

So we can conclude that the car, will be a vehicle for a competition but with a not very advanced features due to it is not a professional competition and with a reduce budget.

We will do a comparison with a formula one, the highest competition car.

The usually measures of a S.A.E. car are the followings:

Wheelbase: 1500 to 1650 mm

Track: 1200 to 1300 mm

Engine: maximum of 610 cc

Weight: around 300 kg

As regards a formula one the difference clearest difference that we can see is the engine since a formula one has a engine of 2400 cc and reach a velocity of 340 km/h.

With this parameter we are going the difference between the two kinds of cars analyzing the velocities that reach the two cars in the Silverstone circuit where will be the race of formula S.A.E.

SILVERSTONE	Curva	velocidad de entrada Formula SAE	velocidad entrada Formula 1
	1	91.67	235,00
	2	94.83	270,00
	3	66.33	210,00
	4	96.17	175,00
	5	84.50	235,00
	6	89.17	190,00
	7	77.33	105,00
	8	74.17	130,00
	9	67.67	125,00
	10	54.6	90,00

Table 2. Comparison between Fsaе F1

3.2. General comments about the steering.

As we can say before in this project the steering system is the mechanism which has the task to turn the wheels in order the driver can guide the vehicle along the desirable trajectory.

All steering system must satisfy the following characteristics:

Safety: the most important. Depend on the reliability of the mechanism and this one depends directly on the quality of used materials.

Gentleness: it achieves with a precise assembly and a perfect greasing. The hardness in the driving it make difficult and tiring drive the car along the desirable trajectory. It might be caused to badly position the tyres or because there is more friction due to the tyres are flat

Accuracy: it takes doing a neither very hard nor gentle steering. The lack of the steering it might be caused by the next causes:

- Caused by here is too much play in the steering elements
- Caused by a differently debilitate of the right and left tyres
- Caused by the imbalance of the tyres that is the main responsible of the shimmy
- Caused by different pressures of the right and left tyres

Irreversibility: The steering must be semi-reversible. It consists of the steering wheel has to transmit the motion to the wheels, but these, in spite of the land irregularities, don't must transmit the oscillations to the steering wheel. The semi-reversibility allows that the wheels recover their normal position with a small effort done by the driver after turn the steering wheel.

Kinematic conditions.

If we observe a car covering a curve, in order to do the turn correctly, the wheel that is in the interior of the curve must turn more than the other wheel. On the contrary the rear wheels in any time of the turn are parallels. The problem about the difference of the distance covering by the two rear wheels it is solved thanks to a device called differential. However in spite of the differential, always the rear wheels skid overall in sharp curves taken fast.

In order to the car do the curve with precision it is necessary come up with a geometric condition, known as the Ackerman principle which explain that when a vehicle is turning he axis of all the wheels must meet in the same point which it is called instant rotation center.

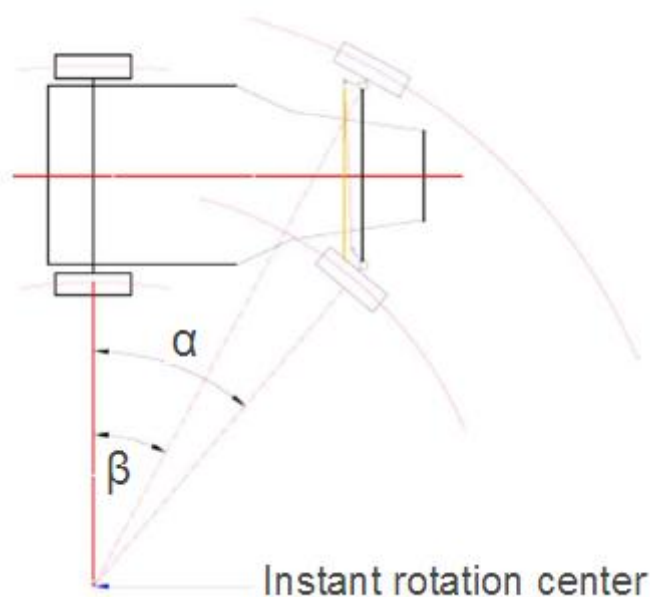


Figure 8. Ackerman principle

We can see in this picture not only the instant rotation center, also the different angle of the right and left wheel. The wheel that is in the interior of the curve describe an α angle bigger than the β angle described by the other wheel. It must be on this way because on the contrary if the front wheels will be parallels will finish broken.

To obtain these angles it is used an articulated trapezium called Jeantaud trapezium which we can show in the next picture.

This trapezium has two parallel sides, one is the tie rod is shorter than the other which is the front axle which is fixed and two sides with the same length but not parallel (the extension of the steering arms). In the next pictures we can see clearly in a real steering system.

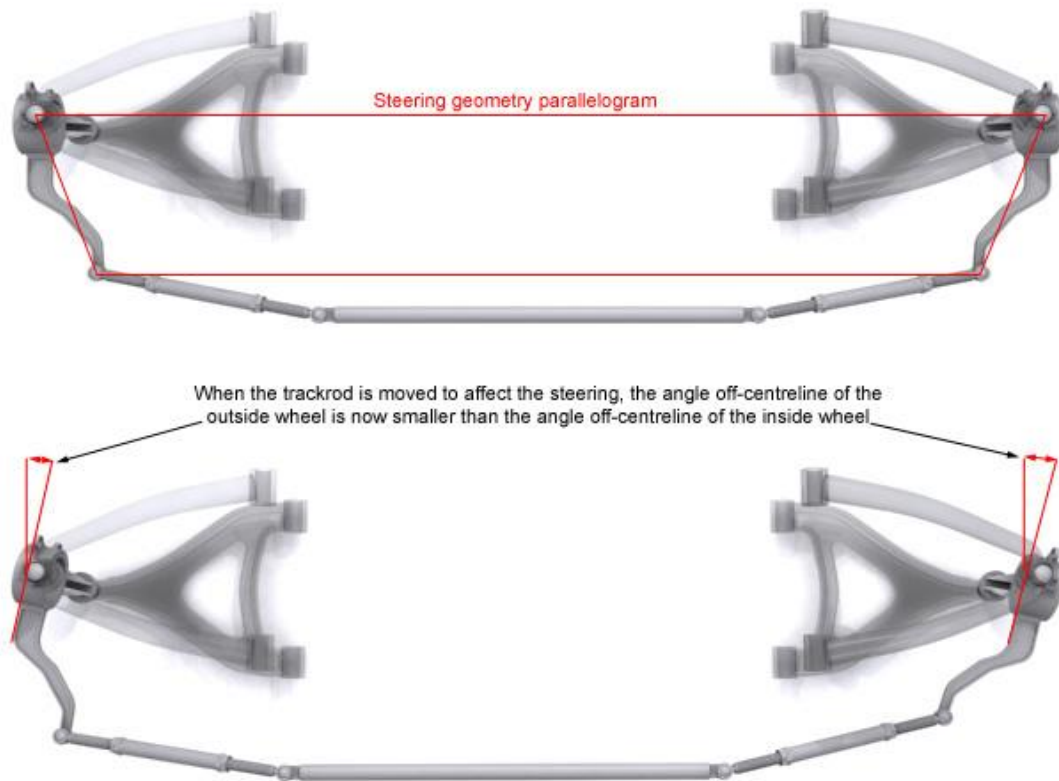


Figure 9. Jeantaud trapezium

The studies executed by Jeantaud established that for the turn center of all the wheels it will be the same, the extension of the steering arms must join with the center of the rear axle as we can show in the next picture.

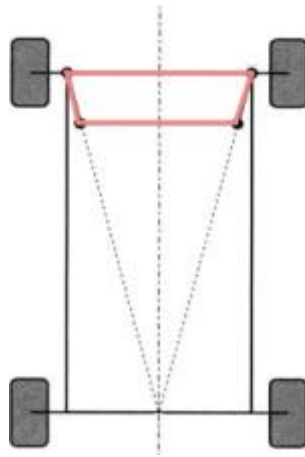


Figure 10 Jeantaud trapezium

With all of this, we can determinate the relationship between the wheelbase, the track and the angles of the interior and exterior wheels in a curve. So if we have the next picture:

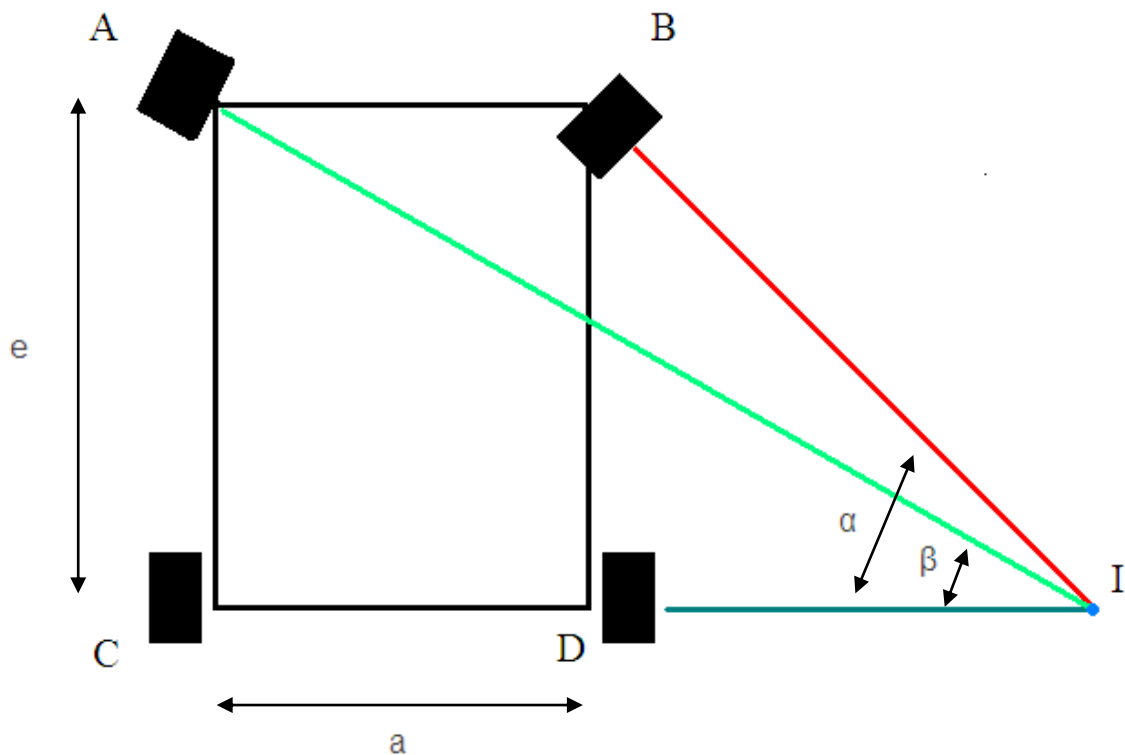


Figure 11. Turn radius of the wheels

Where:

a: track

e: wheelbase

I: instant rotation center

As we can show in the picture we have obtained two rectangles triangles: one of them is ACI and the other BDI.

From BDI:

$$\operatorname{tg} \alpha = \frac{\sin \alpha}{\cos \alpha}$$

$$\sin \alpha = \frac{e}{BI}$$

$$\cos \alpha = \frac{DI}{BI}$$

so:

$$\operatorname{tg} \alpha = \frac{e}{DI} \longrightarrow e = \operatorname{tg} \alpha * DI$$

From ACI:

$$\operatorname{tg} \beta = \frac{\sin \beta}{\cos \beta}$$

$$\sin \beta = \frac{e}{AI}$$

$$\cos \beta = \frac{a+DI}{AI}$$

so:

$$\operatorname{tg} \beta = \frac{e}{a+DI} \longrightarrow e = \operatorname{tg} \beta * (a + DI)$$

So now we have two equations:

$$e = \operatorname{tg} \alpha * DI \quad (1)$$

$$e = \operatorname{tg} \beta * (a + DI) \quad (2)$$

From the (1) equation we find the value of DI:

$$DI = \frac{e}{\operatorname{tg} \alpha}$$

and now we substitute the value on equation (2):

$$e = \operatorname{tg} \beta * \left(a + \frac{e}{\operatorname{tg} \alpha} \right)$$

$$e = \operatorname{tg} \beta a + \frac{\operatorname{tg} \beta e}{\operatorname{tg} \alpha}$$

$$e = \operatorname{tg} \beta \left(a + \frac{e}{\operatorname{tg} \alpha} \right)$$

$$e = \frac{1}{\operatorname{ctg} \beta} (a + e \operatorname{ctg} \alpha)$$

$$\operatorname{ctg} \beta = \frac{a + e \operatorname{ctg} \alpha}{e}$$

$$\operatorname{ctg} \beta e = a + e \operatorname{ctg} \alpha$$

$$\operatorname{ctg} \beta e - e \operatorname{ctg} \alpha = a$$

$$(\operatorname{ctg} \beta - \operatorname{ctg} \alpha) e = a$$

$$\operatorname{ctg} \beta - \operatorname{ctg} \alpha = \frac{a}{e}$$

This equation allows calculate for a vehicle the value of the angle β for any value of the angle α .

We bear in mind that the Formula student rules stipulate that:

$$1 \left(\frac{bd+bt}{2} \right) \leq 0.36$$

where:

l: wheelbase

bd: front track

bt: rear track

In the specific case of Formula S.A.E. due to the characteristics of the circuits it is normal to reduce the wheelbase the maximum as possible in order to the vehicle it will be easier to control.

In the case of the front and rear track the measures it will be conditioned by the next parameters:

Minor track:

- Decrease on the lateral acceleration on this wheel assembly.
- Increase of the temperature on the exterior tyre of the curve
- Higher situation of the roll center with the that really affect to the suspension system

Biggest track:

- Difficulty to drive by and arrow zones of the circuit
- Increase on the acceleration on this wheel assembly
- Decrease of the temperature on the exterior tyre of the curve (better distribution exterior-interior)
- Lower roll center

The election of the track has a lot of influence on the tyres because a short track produce much hot on the exterior tyre. On contrary a long track produce on the tyres do not reach the adequately temperature because with a low temperature the tyres it does not work good.

3.3. Technical fundamentals.

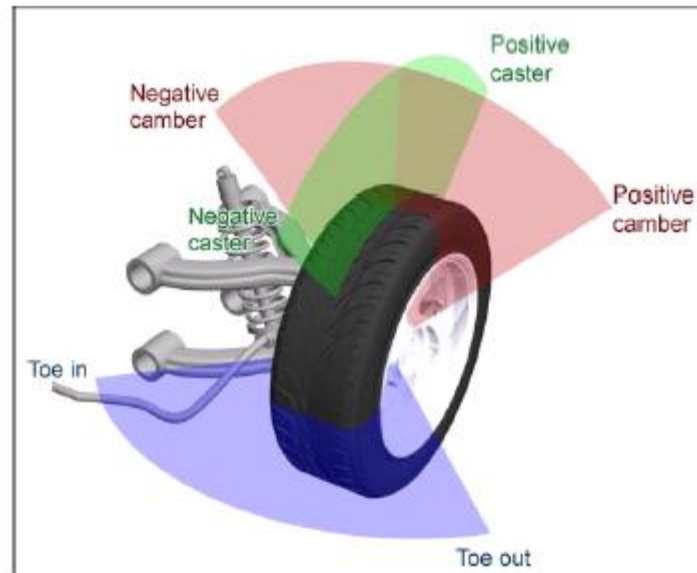


Figure 12. Wheels angles

Toe angle

This is an angle, or linear measurement, formed by a line drawn through the horizontal center of each wheel relative to the center line of the vehicle. Toe can be read as individual, or the total of two wheels on the same axle. Proper toe will reduce scuff and improve tire life by reducing running toe to near zero.

If the pivot and the vertical axis of the wheels will be parallels, the effort to execute it would calculate with the next equation:

$$C = Fr * d$$

Where:

C: resistant torque

Fr: resistance to go round

d: distance of the torque

So we try to reduce this resistant torque decreasing the distance ``d``.

Normally the distance ``d`` although is short, exist and furthermore is necessary that exist a resistant torque in order to give a good stability to the steering because the wheels tend to become disorientated with the irregularities of the road the resistant torque made that the wheels turn to in a good position

By other hand, the inclination angle causes some tendency to turn the steering in a straight line. This angle joins the advance, provoke that the vehicle raise on the front part of the vehicle on the interior wheel of the curve when the advance is positive or of the exterior wheel when the advance is negative.

Due to the weight, the vehicle tends to return to the balance position corresponding to a turn of zero degrees, contributing, the inclination, that the guidelines wheels take again the position in straight line and keeping in this position.

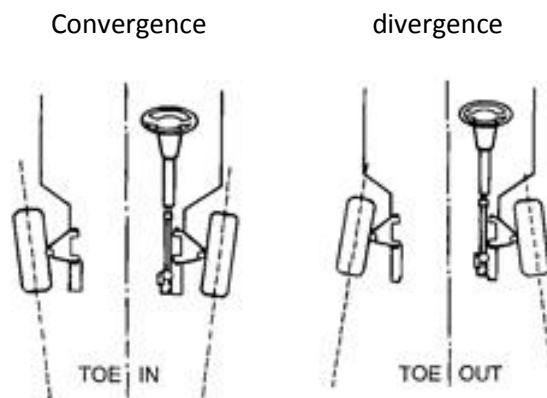


Figure 13. Toe rod

Convergence and divergence

Every longitudinal force tends to modifier the direction of the wheels. This effect is corrected with the convergence.

When the front wheels work only as guidelines wheels (as in our case of a formula S.A.E.), the longitudinal force produced by the resistance to go round, is on back direction and tends to open the wheels.

The convergence depends directly on the camber angle so the total convergence is the algebraic addition of the necessary convergence to bear in mind the effect of the longitudinal forces and the camber angle. Then if the camber is positive, the convergence must be also positive, if the wheels work as guidelines wheels and motor wheels and the camber is negative, the convergence must be negative; lastly if the wheels work as motor wheels and the camber is positive, the convergence may be positive or negative.

The convergence is obtained modifying the length of the steering arm. This fact made that the Jeantaud trapezium experiment a modification since when the car is stopped the uprights are not already perpendiculars to the longitudinal plane of the vehicle.

So we can conclude: is convenient that the convergence is the lowest possible but a low value of convergence is not bad because produce more stability to the car that made a driving more relaxed since the varieties on the road as a pothole tend to be annulated due to the convergence.

As regards the divergence, as with convergence the tyres are worn down because the wheels are not on a straight line. However when there is divergence the wheels ate turned on the out direction of the car making easier the turn of the vehicle. The same than the convergence if the car has not a low value of divergence it will be very difficult to drive the car since with a short turn of the wheel the car will turn a lot.

So what is better for a formula S.A.E. car?

On a formula S.A.E. which is a competition car the pilot can sacrifice the stability of the car in order to turn easier on a curve. By this reason, in races it can be

used a low value of divergence but always applied on the front wheel assembly because we applied on the rear wheel assembly the car will be very difficult to drive.

By other hand the election of convergence or divergence it depends on the circuit because on curves the convergence does not facilitate the turn as the divergence but on a straight line the divergence is the bad factor.

In our case the circuit where the competition take place on Silverstone circuit. This circuit has a first part very fast with straight lines and fast curves and a final part with slow curves where the divergence will help to the pilot. As the most part of the circuit is fast we will choose between 0° and 1° degrees of divergence.

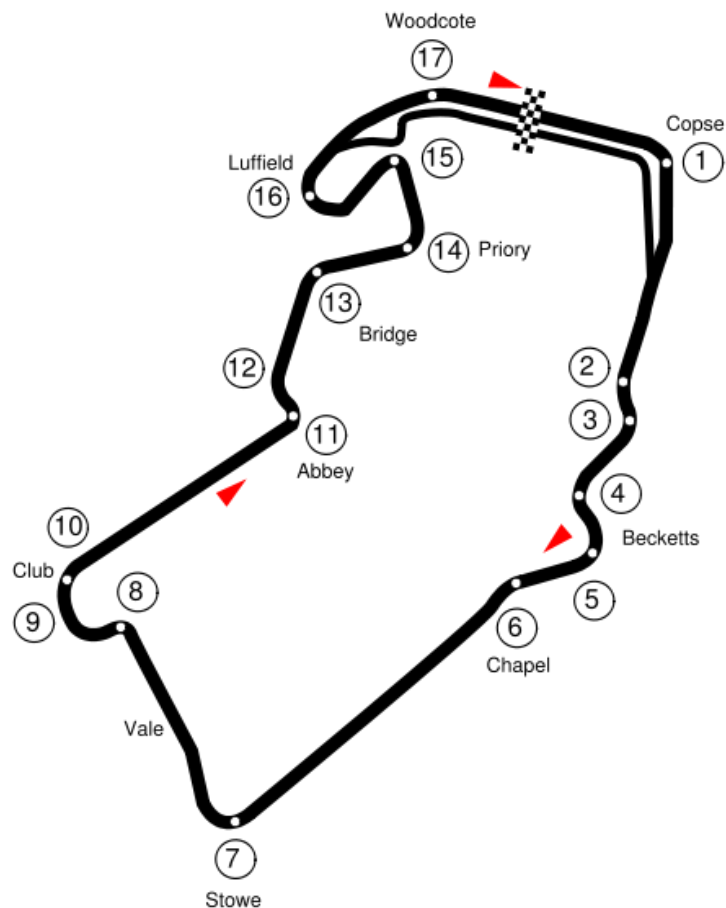


Figure 14. Silverstone circuit

Camber angle.

Caster is a line drawn through the steering axis, compared to vertical. If the axis is tilted back at the top, the angle is positive, tilted forward is negative. Camber improves stability, steering wheel return and cornering.

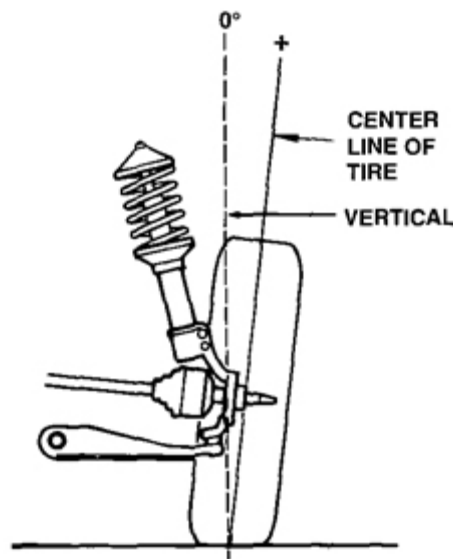
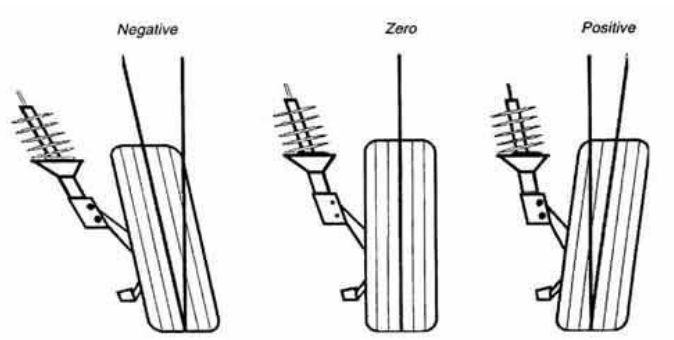


Figure 15. Camber angle

If the wheel has a inclination in the outside direction of the car the angle is positive and on the contrary the angle is negative

Nowadays the majority of vehicles have a camber angle around 1° on their front wheels.



The upright supports flexure efforts equivalent to the momentum $M = W \cdot L$

Where: W: weight

 L: distance

The fact to change the camber has influence on the toe angle because if the camber angle increases the toe angle decreases and vice versa.

Also this angle has a lot of influence on the tyres because an excessive value of the camber angle produces a high wear down of the tyres. If the camber angle is positive the wear is produced on the exterior of the tyre and with a negative angle the wear is produced on the interior of the tyre.

The camber angle equal to the caster angle provides the steering to keep the straight line by the cone effect. The external and internal circumferences turn in different velocities since have different diameters and this is the same movement that a cone will have if go round over a plane surface. As this movement is produced on both guidelines wheels so the same force appears on each wheel doing the vehicle improve the steering stability.

Finally the suspension has a very important role regard the camber angle.

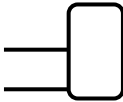
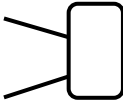
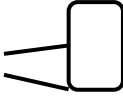

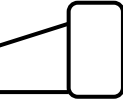
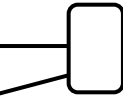
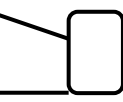
Suspension configuration	Wheel displacement	Camber angle	Roll center
Body 	↑ ↓	0°	Negative Positive
Body 	↑ ↓	↑ ↓	Only negative
Body 	↑ ↓	↑ ↓	Only positive
Body 	↑ ↓	↓ ↓	Only positive
Body 	↑ ↓	↓ ↑	Mainly positive
Body 	↑ ↓	↑ ↓	Mainly negative
Body 	↑ ↓	↑ ↓	Mainly negative

Table 3. Camber angle

Caster angle.

Caster is a line drawn through the steering axis, compared to vertical. If the axis is tilted back at the top, the angle is positive, tilted forward is negative. Caster improves stability, steering wheel return and cornering.

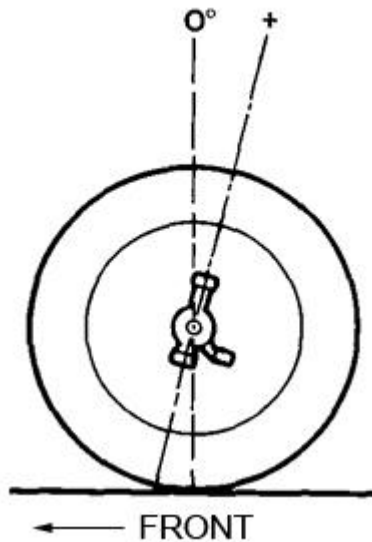


Figure 16. Caster angle

In a formula S.A.E. the propulsion is produced by the rear wheels so the front axle moves on back direction a little producing instability on the steering. We can solve this problem given a certain camber to the pivot doing the extension line of the axis pivot cut with the displacement line in front of the wheel. With this appears an action on the wheel that provides stability to the steering.

The caster angle can also obtain situating the pivot in front of the vertical of the wheel axis. On both process the wheel is dragged and then it produces stability on the front wheels. We will bear in mind in this system the effects of the direction radius and the toe angle.

In this case only act the backward movement forces produced by the toe angle of the pivots.

The caster angle also depends of the camber angle. If the camber is of a considerable importance, even the caster may be negative in order to reduce the

re-position effect. In fact a lot of modern vehicles when are stopped have a negative caster.

The caster effect must not be very important since increase the turn effort. In other hand if the caster is very intense the return of the wheel is made a very high velocity and can produce an abnormal position of the wheel and appear oscillations.

On cars that has the engine on the back and also has a rack inside the steering box, as in our case, the caster has a higher value being always no very high. Normally on this kind of cars the caster angle has a value between 5° and 10° degrees in order to avoid the instability when the car suffer an acceleration produce by the fact to has the engine on the back.

Drift effect

When a car is in a curve, the vehicle does not continue exactly by the trajectory that guide the guidelines wheels since due to the effect of the transversal forces which appear on the tyres the car is displaced guiding a trajectory that form an angle with the rim. This angle is denominated as drift angle. So the tyre drift is the change of the trajectory produced by the out of shape of the tyre. It cannot confuse the drift with a lost of grip or with a skid. The lost of grip can produce the skid but it has not influence on the drift. The drift depends on the velocity, the weight of the car, the pressure and the width of the tyre and the width of the rim.

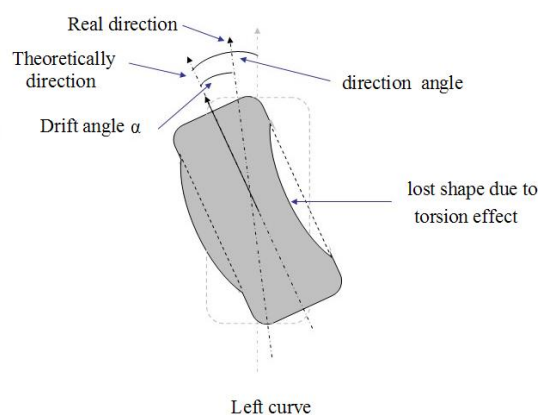


Figure 17. Drift angle

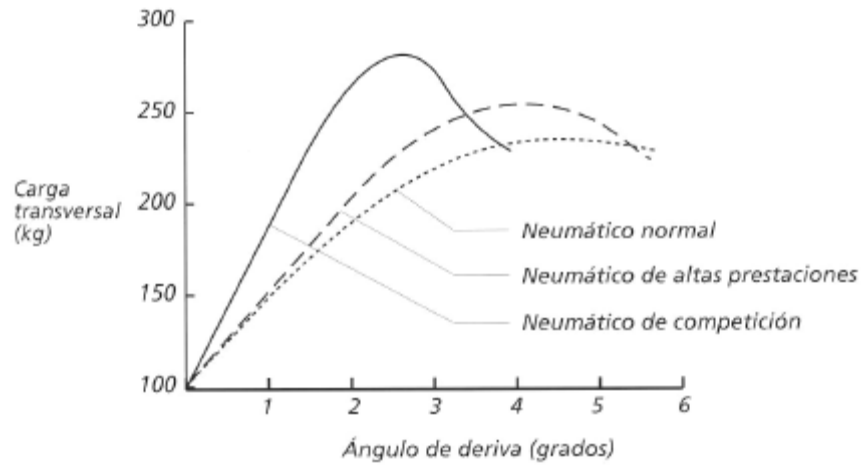


Figure 17'. Drift angle vs transversal force

4.

Design process results and discussions.

4.1. Introduction.

4.2. Elements of the car that have influence on the steering system design.

4.2.1. The cockpit and seat

4.3. Calculation of the force to turn the wheels

4.4. Description of the steering system elements.

4.5. Budget

4.1. Introduction.

In this part of the project we will start to explain the different functions of the steering system elements. Once finish, we will investigate the different possible solves to the design of each element explaining the reason of each one. We are going to do all of this, taking in consideration the Formula S.A.E. rules and the theoretical fundamentals that we have shown in the previous chapters. On this way in the next chapter the best solution for each element will be choose in order to a possible manufacture of the vehicle in a future.

We have the problem that we don't have the measures of the chassis so we are going to do our steering system with a supposedly measures

4.2. Elements of the car that have influence on the steering system design.

4.2.1. The cockpit.

The criterion to design a cockpit is to create a comfortable place to the driver. The cockpit must be sufficiently spacious to allow the necessary movements of the pilot to have a good control of the car. By other hand the cockpit must not be excessively big because this fact decreases the aerodynamics capacities and the acceleration due to the car is heavier.



Figure 18. Cockpit

In our project we design the steering system so the design of the cockpit is not our responsibility, being a task of a project in which the chassis of the car is designed. However this part of the single-seater has influence on the steering system design so we will do a study of a rough estimate measures that could have a Formula S.A.E. car based on a possible pilot measures, without give much details of the cockpit design.

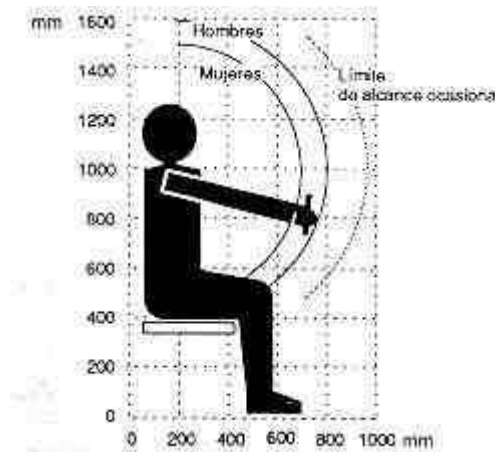


Figure 19. arms movement for a seated man

The size of the cockpit depends directly of the measures and the position of the driver. This position also will have influence on the gravity center of the vehicle.

The position of the pilot is based on different aspects: the comfort to the pilot as much as possible, to improve the features of the car principally decrease the weight and the car has good aerodynamics conditions. Bear in mind all of this considerations we choose a normal position of the driver to this kind of competition. The pilot will be situated near to the floor, with the legs stretched out on the front direction. By other hand the pilot will be situated so back as possible in the cockpit in order to allow the movements of the driver arms. As regards with the knees and the arms, will be not totally extended. The arms will be with an angle bigger than 90° degrees with the steering wheel and a little bit curved. The knees will form an angle nearly to 180° degrees with the horizontal of the vehicle. Summing up a really like position that in a formula one.

In order to calculate the approximately measures of the cockpit we will make a study of the measures for a possible driver. We will mesh different parts of the body of different people and finally we will do an arithmetic mean of each measure.

Distances	1	2	3	4	5	6	7	Arithmetic mean
Floor to knee	53	54	57	53	55	54	58	55
Knee to hip	45	52	51	49	51	50	52	50
Shoulder to elbow	31	33	32	29	32	31	32	31.5
Elbow to knuckles	33	33	37	34	35	33	35	34
Hip to head	75.5	76	79	74	76	76	78	76
Shoulder to head	28	29	31	30	30	28	29	29
Widths								
Waist	34	34	36	34.5	34	34	35	34.5
Shoulder	45.5	40	44	41	42	41	42	42
Chest	25.5	28	31	26	29	27	29	28

Table 4. Measures for a pilot model

This study has been done with seven voluntaries between 22 and 26 years old, discount the highest and lowest values of the sampling.

Now, we have our pilot model and with the position of the driver we can design the approximately measures of the cockpit in order to design the steering system.

The measures of the model of the pilot are the followings:

Distances:

Floor to knee: 55 cm

Knee to waist: 50 cm

Shoulder to elbow: 31.5 cm

Elbow to knuckles: 34 cm

Waist to head: 76 cm

Shoulder to head: 29 cm

Widths:

Waist: 34.5 cm

Shoulder: 42 cm

Chest: 28 cm

Weight:

71 kg

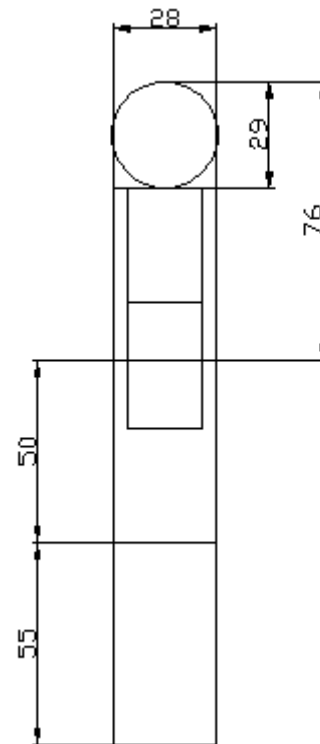


Figure 20. Pilot model

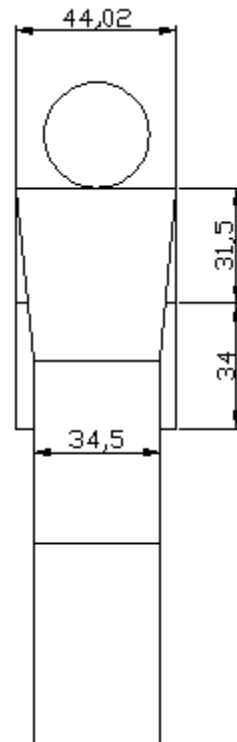


Figure 21. Pilot model

With the following values for the angles:

$$\alpha = 20^\circ$$

$$\beta = 20^\circ$$

$$\theta = 15^\circ$$

Horizontal measures:

$$\cos 20 = \frac{x_1}{55} \longrightarrow X_1 = 47.6 \text{ cm}$$

$$\cos 20 = \frac{x_2}{50} \longrightarrow X_2 = 43.3 \text{ cm}$$

$$\sin 20 = \frac{x_3}{76} \longrightarrow X_3 = 26 \text{ cm}$$

$$\cos 15 = \frac{x_4}{34} \longrightarrow X_4 = 33 \text{ cm}$$

$$\cos 15 = \frac{x_5}{31.5} \longrightarrow X_5 = 30.4 \text{ cm}$$

$$\sin 20 = \frac{x_6}{29} \longrightarrow X_6 = 10 \text{ cm}$$

Vertical measures:

$$\cos 20 = \frac{y_1}{76} \longrightarrow Y_1 = 65.81 \text{ cm}$$

$$\tan 20 = \frac{10}{Y_1'} \longrightarrow Y_1' = 27.47 \text{ cm}$$

$$Y_1'' = Y_1 - Y_1' = 43.94 \text{ cm}$$

$$\sin 20 = \frac{y_2}{55} \longrightarrow Y_2 = 43.3 \text{ cm}$$

Front measures of the car

This measure is determined with the width of the waist and the shoulders in order the drive is comfortable at the time to drive but the most limited possible with the purpose to make the car lighter and more aerodynamic.

The seat

As regards with the seat of the pilot the most used on this kind of competition. It is a really good option because is light, around 2 kg and is cheap. The seat is manufactured by hand so it will be adapted to the cockpit measures.

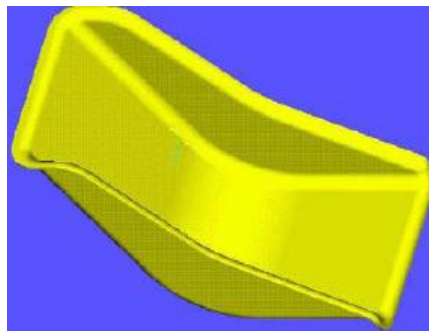
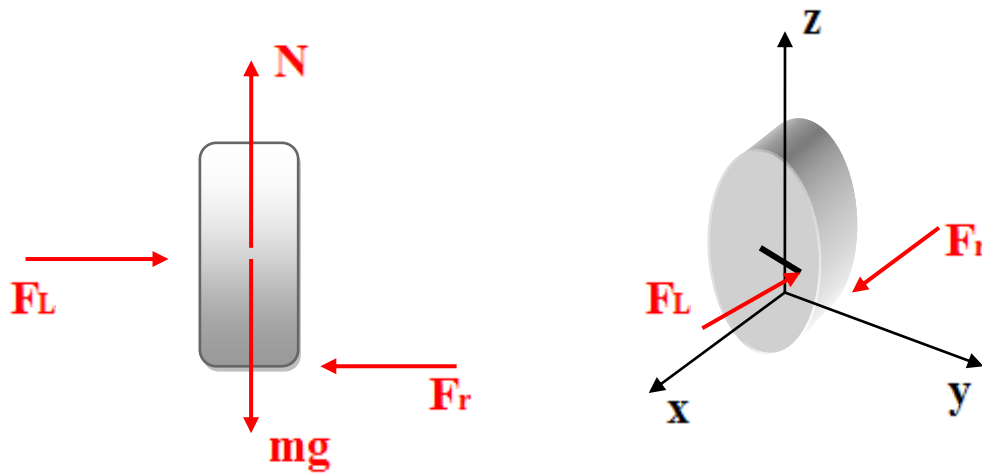


Figure 23. Seat

4.3. Calculation of the force to turn the wheels

Once we have done the design the total elements of the steering arms we are going to calculate the force that must to do the driver to turn the wheels.

We will study the highest value of the force to turn the wheels. This force appears when the car is stopped and it starts the movement of the wheel.



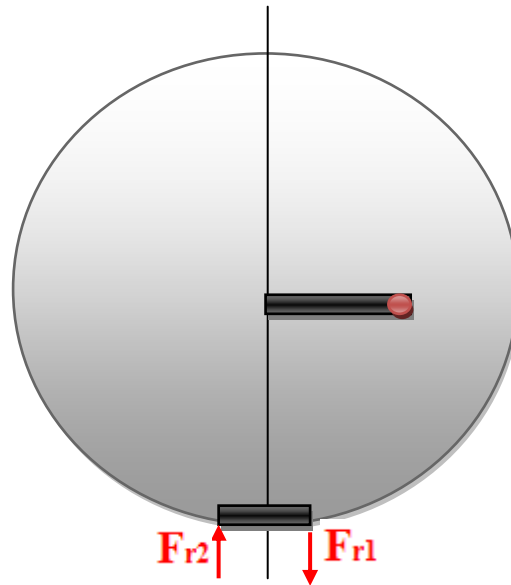
F_r = friction force

mg = weight

F_L = lateral force

N = normal

The wheel rest on the floor in a surface not in a point so it appears two friction forces as we can show in the next picture.



In the picture the big black square is a sketch of the steering arm, the red point is the application point of the lateral force, the distance between the red point and the middle in horizontal direction is R_s (steering arm length), the small black square is the contact surface between wheel and floor and F_{r1} and F_{r2} are the friction forces that appears in the contact surface of the wheel which are an a distance r_1 and r_2 of the middle.

F_{r1} and F_{r2} but in different direction are equals and r_1 and r_2 are equals to so:

$$r_1 = r_2 = r$$

Now we can do the Calculations:

$$\sum F_x = 0; F_L - F_r = 0 \quad (1)$$

$$\sum F_y = 0; N - mg = 0 \quad (2)$$

$$\sum M_y = 0; F_L * R_s - 2 * F_r * r = 0 \quad (3)$$

From equation (1) we calculate:

$$F_L = F_r$$

From (2) we have:

$$N = mg$$

This kind of vehicles have a weight around 250 kg without the weight of the driver. We take a weight of 300 kg that is an excessive weight for these cars but on this way we establish a safety coefficient. The weight of the pilot will be 71 kg (*show on chapter 4 measures of pilot model*) so we take 80 kg for the same reason that before. By other hand the 45 per cent of the car weight is on the front wheel assembly on these cars.

So the weight will be:

$$(300 \text{ kg} + 80 \text{ kg}) * 45 / 100 = 171 \text{ kg}$$

And now each wheel supports the half of this weight:

$$171 / 2 = 85.5 \text{ kg} \longrightarrow 85.5 \text{ kg} * 9.81 = 838.755 \text{ N}$$

$$N = 838.755 \text{ N}$$

Now we are going to calculate the F_r .

$$F_r = \mu * N;$$

Where μ is the friction coefficient. On the same way than before we are going to take a high value of μ in order to establish a safety coefficient. So we take $\mu = 1$.

Now we calculate the friction force:

$$F_r = \mu * N = 838.755$$

And from equation (1) $F_r = F_L$ so:

$$F_L = 838.755 \text{ N}$$

It is the force that the rack has to transmit to the tie rods and these to the steering arms to move the wheel.

Now we can calculate the torque on the pinion. To calculate the torque we use the following equation:

$$T = F * r_{\text{pinion}}$$

In our case we have a pinion with a diameter of 24 mm (*show in chapter 4.3*) so:

$$T = 838.755 * 24 = 20130 \text{ N*mm}$$

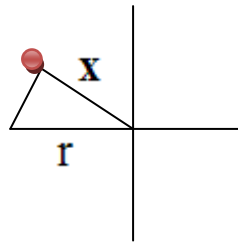
This is the torque in the pinion and it is transmitted through the steering column until the steering wheel.

Finally we will to calculate the necessary tangential force that must be made in the steering wheel by the driver to turn the wheels.

$$T = F * R_{\text{steering wheel}}$$

Firstly we have to calculate the steering wheel radius because our steering wheel is not a perfect circle it has 200mm in the vertical direction and 250mm in the horizontal direction (*show in chapter 4.3*).

By other hand the hands of the driver will be making an angle of 30° degrees with the horizontal direction, in the same position that ten to past in a clock.



The red point represents the position of left hand of the driver. We have to calculate x , being $r = 250/2 = 125$ mm.

$$x = \cos 30^\circ * r = \cos 30^\circ * 125 = 108.25 \text{ mm}$$

And finally we calculate the necessary tangential force that the driver must produce to turn the wheels:

$$T = F * R_{\text{steering wheel}} \longrightarrow F = T / R_{\text{steering wheel}}$$

$$F = \frac{20130 \text{ N*mm}}{108.25 \text{ mm}}$$

$$F = 185.95 \text{ N}$$

It is the force when the car is stopped, the moment when the force to turn the wheels has the highest value. Also We have to bear in mind the high values of the weight and the μ that we have taken in order to put a safety coefficient in the calculations.

With this force we can calculate if the material for the steering column is adequate for the torque that is transmitted by the force on the steering wheel.

The steering column support torsion efforts so:

$$\tau_{\max} = \frac{T * r}{J}$$

Where:

T: torque in the steering column

R: radio columna

$$J: \text{Inertia for hollow columns} \rightarrow \Pi * \left(\frac{\frac{D^4}{16} - \frac{d^4}{16}}{4} \right)$$

Where: D = 18mm; d = 16 mm (*show in chapter 4.3*)

$$\tau_{\max} = \frac{20130 * 9}{7744.02} = 93.58 \text{ MPa}$$

The SAE 1015 steel with which we have made the steering column supports 386.1 Mpa and we have a value of around 100 MPa so the design is correct

4.4. Description of the steering system elements

In this chapter we be able to see the elements which to made up the steering system of one car and more in detail which are used in a competition vehicle.

The weight of the car has importance on the performance of the car since depending of the weight the car has a different performance on the road. So we can distinguish in two parts different elements of the car: The elements which belong to the hang weight and the other that belong to the not hang weight.

The not hang weight: is the part of the total weight of the car which is not support by the suspension. This weight support all the disruptions of the road so we try to reduce this weight the much as possible

- Rims
- Upright
- Brakes
- The bearings, springs and shocks absorbers (elements of the suspension)

The hang weight: Is the weight that is supported by the suspension. This part is the heavier part of the car.

- Steering box
- Steering column
- Steering wheel
- Chassis, engine, driver, fuel, bodywork and one part of the suspension.

Now we are going to start with the design of the elements. We can difference between the elements that we will design ourselves and the elements which we will buy to the manufacturers.

Elements to design

Steering column

Rack and pinion

Tie rods

Steering arms

Upright

Pivot

Elements to buy

Steering wheel

Quick disconnect device

Universal joint

Ball-and-socket joint

Steering wheel

Is the element that joins the driver with the steering system in order to control of the car. The steering wheels change according with the manufacturer since the steering wheels can have different radius. Important characteristics on the steering wheel are the feel and the thickness that must be comfortable to the driver. Also the shape of the exterior radio can has different shapes trying to achieve the most comfort to the pilot. The steering wheel joins with the steering column through a device that is called quick disconnect device which has the function to separate the steering wheel of the steering column in a few seconds.

On the competition world the same that on the common car the purpose of the steering wheel is transmit a tangential force to the steering column with the most possible accuracy. The steering wheel is inside the cockpit and it will be situated on a correct position according with the driver.

The steering wheel has three important points according with the design: the interior diameter, the cover and the diameter.

The interior diameter is on where the pilot puts their hands and if the driver can grab the steering wheel without problems, he will be able to do the necessary tangential force along the curve. As Eastman Kodak studied on 1983 the value recommended for this diameter ranges between 18 and 53 mm, however the manufacturers normally make designs about 30 mm and usually are oval shape to improve the hold making the driving more comfortable. So we choose this thickness for our steering wheel.

The steering wheel cover is also important because decrease the tiredness of the driver if the friction with the gloves is high preventing the slide between the steering wheel with the gloves of the pilot when he is turning. A good election for the cover is suede because is hardwearing and have good friction properties when joins with the gloves of the pilot which usually also are made of suede.

The diameter of the steering wheel determine the easily to drive the car. The tangential force applied over the steering wheel is between 20 and 200 N (according the studies of the Eastman Kodak 1983). This force depends on the position of the wheels according with the pilot.

The pilot applied the force on the exterior diameter of the steering wheel so the momentum applied on the steering column will increase if we increase the radio of the steering wheel although the applied force have the same value. But by other a big exterior diameter will cause problems at the time to turn it inside a cockpit that has a limited size.

In order to adapt the steering wheel to the cockpit on a correct position the most of the manufacturers create the steering wheels with the down part horizontal in order to achieve more distance between the legs of the pilot and the steering wheel.

We will chose this kind of design because is a perfect model for the position of the pilot in a competition car where the pilot is with their legs full-length save.

Once we have established the kind of design of the steering wheel, finally we are going to choose it.

We have three possibilities to choose the steering wheel:

Possible solution 1:

The first possibility is Sparco 015P260F:

Diameter: 260 mm

Price: 289 \$

Grip: a good grip of suede



Figure 24. Sparco steering wheel

Possible solution 2:

The second possibility is Sparco 015P310:

Dimensions: 310 * 260 mm

Price: 239 \$

Grip: a good grip of suede



Figure 25. Sparco steering wheel

Possible solution 3:

The third possibility is OMP Indy:

Dimensions: 250 * 200 mm

Price: 240 \$

Grip: black suede crown



Figure 26. Sparco steering wheel

Steering wheel selected:

Once analyze the possibilities to choose the steering wheel, finally we have chosen the solution 3 OMP Indy because between the three possibilities it is cheap and overall the measures are the best to adapt to our cockpit. It has 200 mm in vertical direction and 250 mm in horizontal direction, furthermore the down part is horizontally o allow more space between the driver with the steering wheel

Now we are going to talk about the position of the steering wheel. According with the Formula S.A.E. rules, the exterior diameter must be down of the safety front hoop. The most convenient at the time to fix the position of the steering wheel is to maximize the distance with the legs of the pilot. Furthermore we bear in mind that the arms of the driver will not be totally on a straight line making an angle with the steering wheel bigger than 90° degrees.

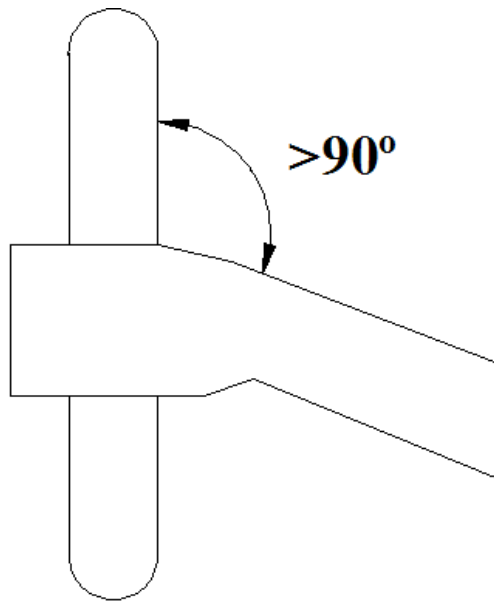


Figure 27. Ssteering wheel angle

In our case this angle will be $\theta = 90^\circ + 15^\circ = 105^\circ$ (see on chapter 4 calculation of the driver measures angle θ).

So now with the calculations that we have done in the previous chapter, we will be able to calculate the position of the steering wheel.

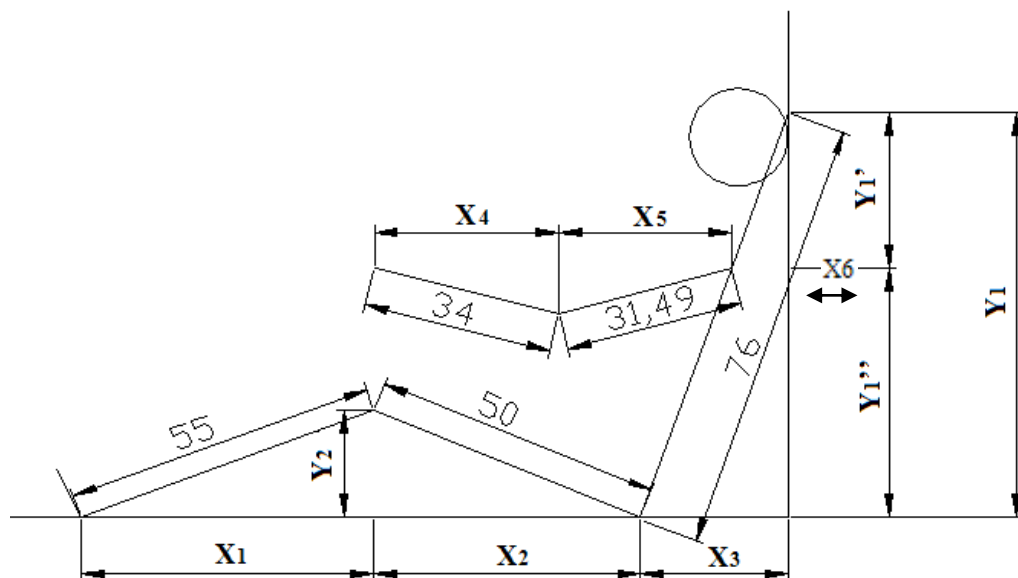


Figure 28. Measures Calculus

Showing this picture with the approximately measures of a driver, we can situate the steering wheel in the cockpit.

Horizontally position:

$$X_4 + X_5 + X_6 = 32.84 + 30.42 + 10 = 73.26 \text{ cm}$$

Vertically position:

$$Y_1'' = 43.94 \text{ cm}$$

Checking the design:

If the diameter steering wheel in vertical position = 20 cm.

$$Y_1'' - Y_2 - 20/2 = 15.14 \text{ cm}$$

It is the distance of the space between the driver with the steering wheel a good measure for the comfort of the driver

We bear in mind in this design the rule of Formula S.A.E that says: In any angular position, the top of the steering wheel must be no higher than the top-most surface of the front hoop.

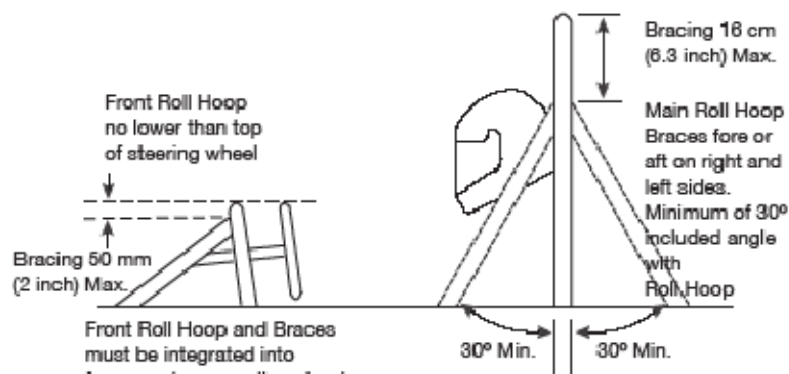


Figure 29. Fsaе rules

Quick disconnect device

For this element the Formula S.A.E. rules specify that is obligatory that a quick disconnect device joins the steering wheel with the steering column. This device allows to separate quickly the steering wheel from the steering column in order the pilot can leave the car in a few seconds.

We are going to study the different kinds of devices that we can choose and which is the best for our project. We have found two principal kinds of quick disconnect devices.

Hex drive mechanism:

This device is called on this way because the torque of the steering wheel is transmitted by a hexagonal joint as we can show in the picture. Generally the steering wheel is located on the steering shaft, using a groove in the hex drive, and is located by a spring loaded pin which locks into the groove. The steering wheel is released from the steering shaft by punishing the pin against the spring until a smaller diameter section of the pin, allows the steering wheel to be removed.



Figure 30. Hex drive

The advantage of this kind of devices is the low cost, around the 100\$. However the design produces the bad working order when it is used frequently due to the contact area is very short and starts to wear down.

Gear assembly mechanism.

These devices are a more expensive alternative, but on the contrary the torque of the steering wheel is transmitted by one gear assembly so the value of the torque and the contact area are bigger and cause the increase the life of the element.

We join the mechanism with the steering wheel through piece with triangle shape in which we will put three screws.



Figure 31. Quick disconnect device

The advantage of this kind of mechanism is the long life and the possibility to putting electrical cable though the mechanism. The disadvantage is the high cost around 200\$.

Nowadays the most frequently is the use of this last kind of mechanism and we also will choose the gear assembly mechanism for our vehicle.

Possible solution 1:

The first possible solution is quick disconnect device RTQ3

Price: 204.95 \$



Figure 32. Quick disconnect device

Possible solution 2:

The second possible solution is quick disconnect device STRQ-1000

Price: 109.95 \$



Figure 33. Quick disconnect device

Finally our choice will be the second one because although the first mechanism is lighter the second one because does not vary a lot the weight and is quite cheaper.

Steering column

This torsion bar joins the steering wheel with steering box through the quick disconnect mechanism. This bar only support the torsion effect produced by the turn of the steering wheel so it is not necessary a high quality steel. Also appears short compression efforts when the pilot leaning on the steering wheel, but are insignificant.

In order to do the design of the steering column we will see the Formula S.A.E. rules and the effort analysis.

According with the Formula S.A.E. rules the steering column cannot be one bar with only one direction due to different aspects. One of this is the safety of the driver since in case of accident, on a front crash, if the steering column only has on direction it will be easy that go out in direction to the pilot being very dangerous. The other aspects depend on the design for the comfort of the driver. Using a universal joint we can join two parts of the steering column making an angle allowing increase the distance between this element and the legs of the pilot and also increase the entry pinion angle into the steering box.

Our design

Measures: we will design a steering column with a diameter of 18 mm a very normal measure in this kind of cars and which will be fit with our steering box perfectly. The thickness will be 2 mm since the steering column is a hollow bar.

Material: The steering column support torsion efforts so we do not need a high quality steel. We will use SAE 1015.

Composition

Element	Weight %
C	0.13-0.18
Mn	0.30-0.60
P	0.04 (max)
S	0.05 (max)

Mechanical Properties

Properties		Conditions	
		T (°C)	Treatment
Density ($\times 1000 \text{ kg/m}^3$)	7.7-8.03	25	
Poisson's Ratio	0.27-0.30	25	
Elastic Modulus (GPa)	190-210	25	
Tensile Strength (Mpa)	386.1	25	annealed at 870°C more
Yield Strength (Mpa)	284.4		
Elongation (%)	37.0		
Reduction in Area (%)	69.7		
Hardness (HB)	111	25	annealed at 870°C more
Impact Strength (J) (Izod)	115	25	annealed at 870°C more

Thermal Properties

Properties		Conditions	
		T (°C)	Treatment
Thermal Expansion ($10^{-6}/^{\circ}\text{C}$)	11.9	0-100 more	

Figure 34. AISI 1015 steel

Situation: the steering column will start on the steering wheel until the universal joint that is fixed with the chassis. Here it is produced the change of angle on the steering column and starts the second part of the element that join the universal joint with the steering box. The angle between the two parts of the steering column will be $\delta < 180^{\circ}$. When we fixe the steering box and with the exact measures of the cockpit, we will be able to calculate the angle that it always will be $\delta < 180$ and the difference with the horizontal between γ ϕ around 15° and 20° degrees being the value of ϕ between 15° and 20° .

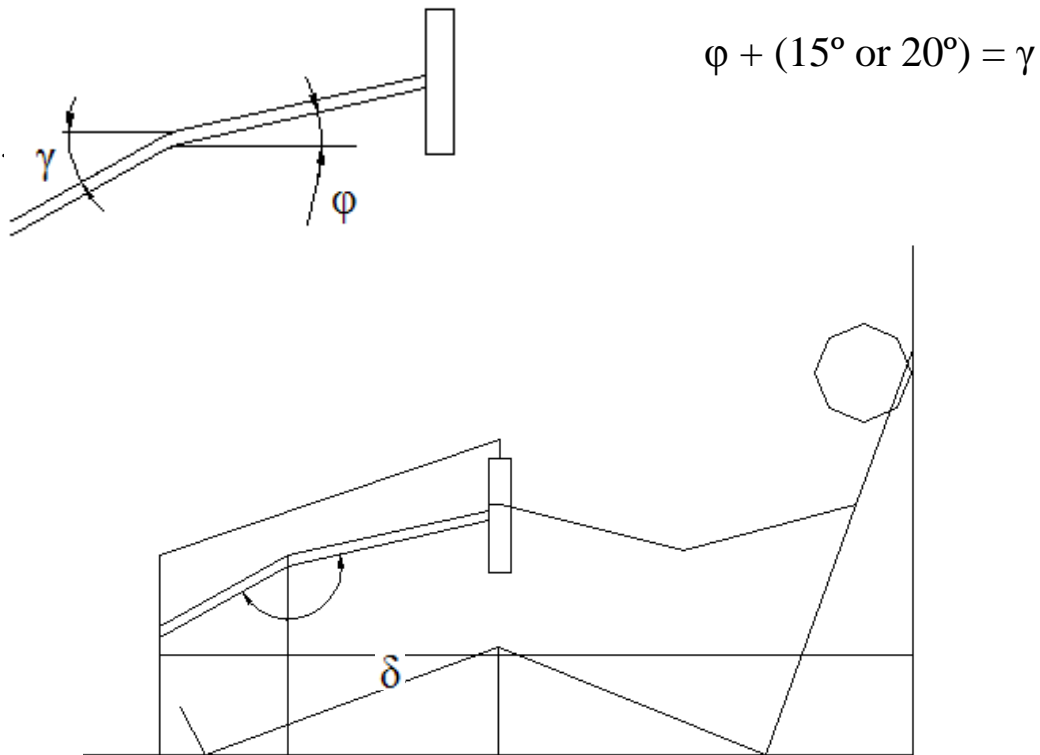


Figure 35. Steering wheel situation



Figure 35'. Assembly steering wheel-quick disconnect-steering column

Universal joint

This kind of joint is very utilized on the self-propulsion industry in order to manufacture the steering columns, keeping the torque between bars with different angles

The most common kind of these devices for short angles between bars is the pin and block which works efficiently with angles bigger than 35° degrees.

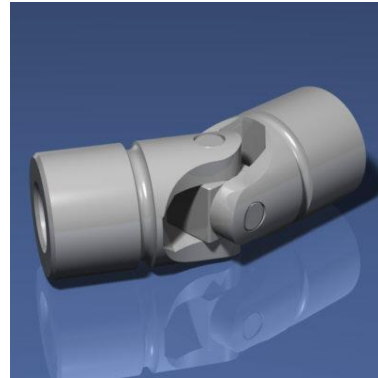


Figure 36. Universal joint

The most of the universal joints for the competition require a bar of $\frac{3}{4}$ inches with a plane final in order to transmit the torque through the join.

We will choose the Fr1820 UNIVERSAL JOINT STEEL N which cost 59.95 \$

Steering box

Is the part of the steering system defining as the joint of gear assemblies that convert the torque transmitting by the steering column on a horizontal force. In other words in the steering box the rotational movement transmitted by the steering column is converted on a rectilinear movement. At the same time the rack and pinion produces a decrease on the effort executed by the pilot from the turn of the steering wheel until the turn of the wheels avoiding on this way the extreme tiredness of the driver.

The effort necessary to turn the wheels is higher when the vehicle is stopped and decrease in accordance with the increase of the velocity. However we can say that this effort depends mainly on the resistance made between the wheels and the floor due to the friction which is function of the velocity and the weight of the vehicle.

Exist different kinds of steering box with their respective characteristics, although in general in the competition world is used the rack and pinion. We are going to do a brief description of the other kinds of steering box.

WORM AND SECTOR



Figure 37. Worm and sector

WORM AND ROLLER



Figure 38. Worm and roller

WORM AND NUT OR RECIRCULATING BALL



Figure 39. Worm and nut

CAM AND LEVER



Figure 40. Cam and lever

The location on the car is very significantly since the geometry formed by the steering box, tie rods and the end of the steering arms will form the Jeantaud trapezium which will have a lot of influence on the performance of the car at the time to drive it.

Worm and sector

In this type of steering box, the end of the shaft from the steering wheel has a worm gear attached to it. It meshes directly with a sector gear (so called because it is a section of a full gear wheel). When the steering wheel is turned, the shaft turns the

worm gear, and the sector gear pivots around its axis as its teeth are moved along the worm gear. The sector gear is mounted on the cross shaft which passes through the steering box and out the bottom where it is splined, and the pitman arm is attached to the splines. When the sector gear turns, it turns the cross shaft, which turns the pitman arm, giving the output motion that is fed into the mechanical linkage on the track rod. The following diagram shows the active components that the present inside the worm and sector steering box. The box itself is sealed and filled with grease.

1. Sector shaft seal
2. Input worm gear and rack
3. Worm ball
4. Ball return guide
5. Worm thrust bearing adjuster
6. Locknut
7. Worm thrust bearing
8. Sector shaft
9. Input worm gear and rack

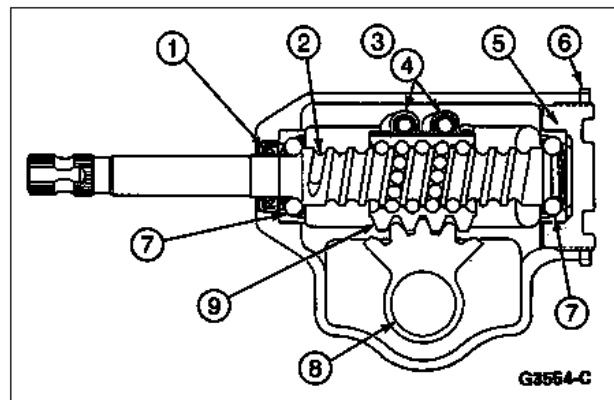


Figure 41. Worm and roller

Worm and roller

The worm and roller steering box is similar in design to the worm and sector box. The difference here is that instead of having a sector gear that meshes with the worm gear, there is a roller instead. The roller is mounted on a roller bearing shaft and is held captive on the end of the cross shaft. As the worm gear turns, the roller is forced to move along it but because it is held captive on the cross shaft, it twists the cross shaft. Typically in these designs, the worm gear is actually an hourglass shape so that it is wider at the ends. Without the hourglass shape, the roller might disengage from it at the extends of its travel.

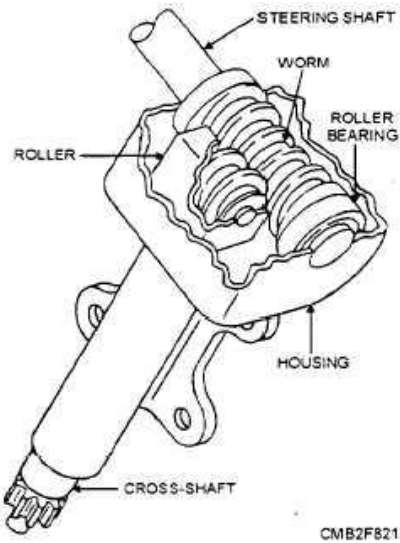


Figure 42. Worm and roller parts

Worm and nut or recirculating ball

This is by far the most common type of steering box for pitman arm systems. In a recirculating ball steering box, the worm drive has many more turns on it with a finer pitch. A box or nut is clamped over the worm drive that contains dozens of ball bearings. These loop around the worm drive and then out into a recirculating channel within the nut where they are fed back into the worm drive again. Hence recirculating. As the steering wheel is turned, the worm drive turns and forces the ball bearings to press against the channel inside the nut. This forces the nut to move along the worm drive. The nut itself has a couple of gear teeth cast into the outside of it and these mesh with the teeth on a sector gear mechanism. This system has much less free play or slack in it than the other designs, hence why it is used the most.

The example below shows a recirculating ball mechanism with the nut shown in cutaway so you can see the ball bearings and the recirculation channel.

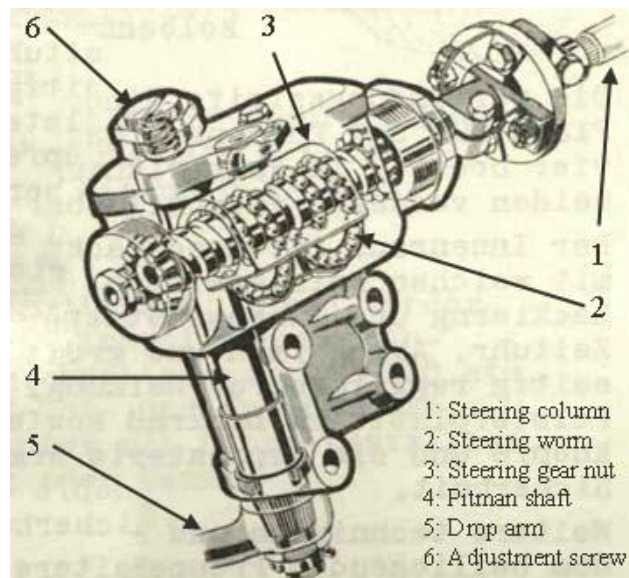


Figure 43. Worm and nut parts

Cam and lever

Cam and lever steering boxes are very similar to worm and sector steering boxes. The worm drive is known as a cam and has a much shallower pitch and the sector gear is replaced with two studs that sit in the cam channels. As the worm gear is turned, the studs slide along the cam channels which forces the cross shaft to rotate, turning the pitman arm.

One of the design features of this style is that it turns the cross shaft 90°degrees to the normal so it exists through the side of the steering box instead of the bottom. This can result in a very compact design when necessary.

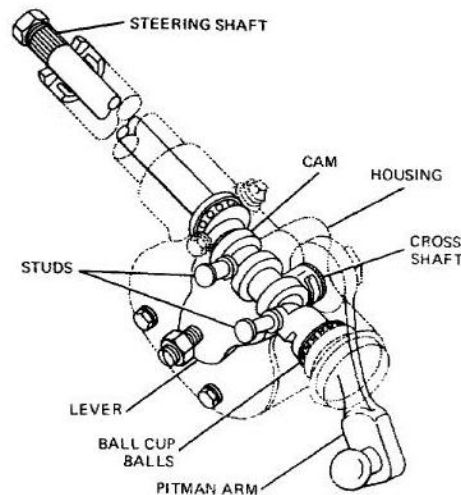


Figure 44. Cam and lever

The rack and pinion

In general

Before the appearance of the car the use of the rack and pinion was limited only to small vehicles because the steering proved too heavy and the improvements were not sufficiently suitable so it was necessary to make a lot of turns with the steering wheel in order to guide the wheels on the desirable trajectory. Nowadays this problem has been solved with the power-assisted steering.

Actually the rack and pinion is very used by the fact that is cheap and the assembly is simply allowing the incorporation system that help on the driving as the power-assisted steering.

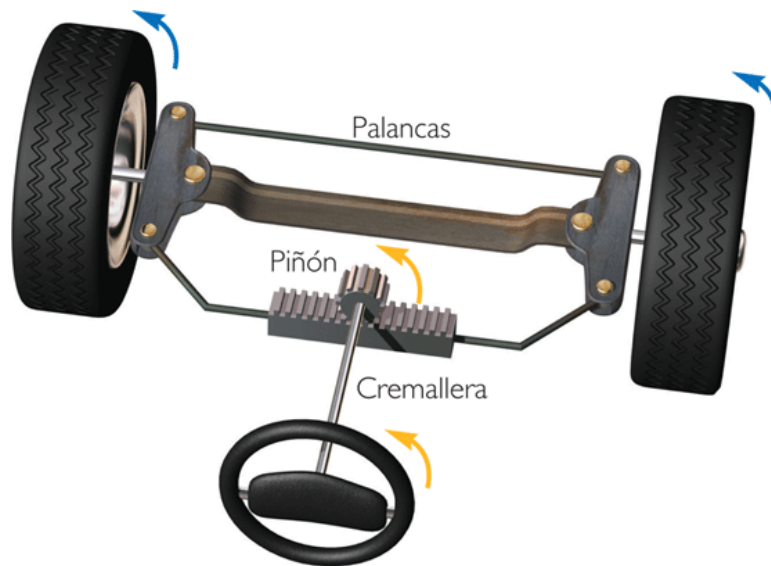


Figure 45. Rack and pinion

The system is connected directly with the tie rod and this one with the wheels having a high mechanical output. It is a great accuracy system, particularly in cars with the motor on the front part and with front-wheel-drive since decrease enormously the effort to do, is very smooth, and has a good recuperation and is safe.

The steering column ends with a pinion (generally helicoids) that engages constantly with a bar that is a rack. The rack moves inside a framework that is used as a guide and as protection of the outside agents. The rack is directly jointed with the tie rods with the ball-socket-joints transmitting the movement to the wheels.

There are steering systems that have a power-assisted steering. This mechanism has the task of decrease the necessary effort at the time to drive the car. On the common cars the most used is the hydraulic system although is also used the pneumatic system or with an electrical system in the steering column.

But in our case of a formula S.A.E. we will not use a power-assisted steering.

In our case

We have chosen the rack and pinion due is by far the most steering box used in a car and in particular because is light, simply and cheap. For this reason, is the election on the cars used to compete on circuits since the rack and pinion provide a lot of information to the pilot about the track due to have not auxiliary mechanisms that limit the feeling of the pilot.

Once transmitted the torque of the steering column through the pinion to the rack, the longitudinal movement of the rack is transmitted to the tie rods through of an axial ball-and-socket joint.

Inside the steering box the pinion will must be quite small and to transmit the high efforts to move the steering the modulus must be big so it must has a few number of teeth.

Both the pinion and the rack must be made of a high quality steel and are case-hardened (*material treatment*) since have to support high efforts.

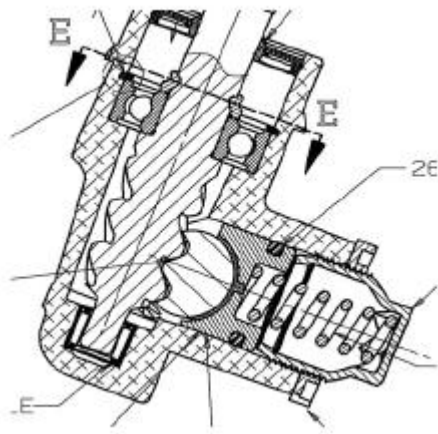


Figure 46. Rack and pinion lateral

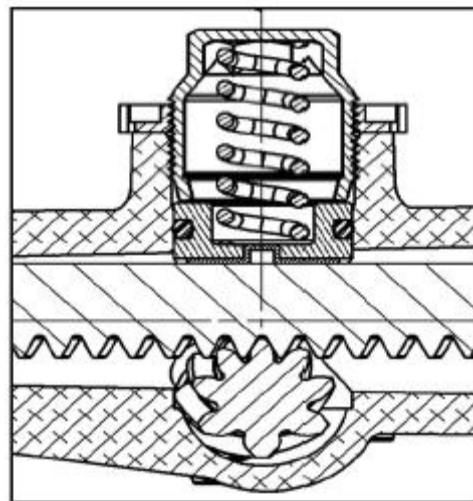


Figure 47. Rack and pinion front

Our design

In order to make the design of our rack-pinion for the steering box, we base our work on the choice of the rack and the pinion which will produce a greater lateral displacement of the wheels with the same turn of the steering wheel.

We start saying that our steering column has a radius of 18 mm an adequate value for this kind of cars.

The other start point is that the rack and the pinion must be the same modulus and the same material. A suitable material for these elements is SAE 1045 steel which is easy to mechanize.

Carbon steel SAE 1045

(submitted by the website administration)

SAE 1045			
Chemical composition: C=0.45%, Mn=0.75%, P=0.04% max, S=0.05% max			
Property	Value in metric unit		Value in US unit
Density	7.872 *10 ³	kg/m ³	491.4 lb/ft ³
Modulus of elasticity	201	GPa	29100 ksi
Thermal expansion (20 °C)	11.7*10 ⁻⁶	°C ⁻¹	6.5*10 ⁻⁶ in/(in* °F)
Specific heat capacity	486	J/(kg*K)	0.116 BTU/(lb*°F)
Thermal conductivity	50.9	W/(m*K)	353 BTU*in/(hr*ft ² *°F)
Electric resistivity	1.62*10 ⁻⁷	Ohm*m	1.62*10 ⁻⁵ Ohm*cm
Tensile strength (hot rolled)	565	MPa	81900 psi
Yield strength (hot rolled)	310	MPa	45000 psi
Elongation (hot rolled)	16	%	16 %
Hardness (hot rolled)	84	RB	84 RB
Tensile strength (cold drawn)	625	MPa	90600 psi
Yield strength (cold drawn)	530	MPa	76900 psi
Elongation (cold drawn)	12	%	12 %
Hardness (cold drawn)	88	RB	88 RB

Figure 48. Rack and pinion SAE 1045

In the followings pictures we can show the necessary parameters of the rack and pinion which we will operate to calculate the best possible design for our steering box.

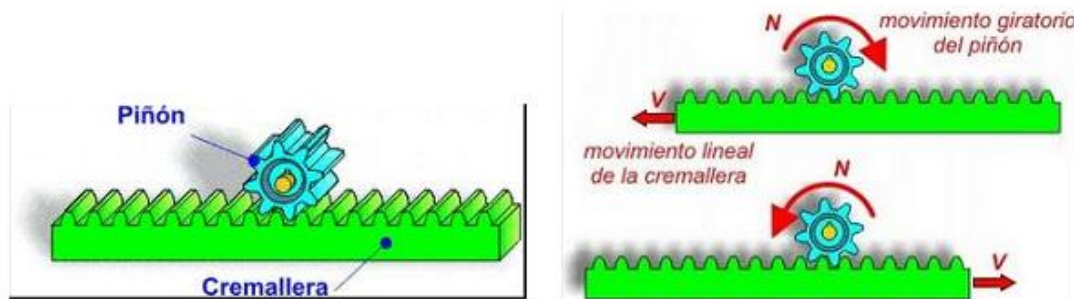


Figure 49. Rack and pinion parameters

N: velocity of the pinion turn

V: velocity of the rack

Z: number of pinion teeth

n: number of rack teeth in one cm

In order to calculate the velocity of the rack it is used the following equation:

$$v = N \left(\frac{Z}{n} \right) \text{ cm/sg}$$

And to calculate the distance that advance the rack in one complete turn of the pinion is:

$$d = \frac{Z}{n} \text{ cm}$$

So we are going the possible design of the racks and pinions and the possible joints of these elements.

Parameters of pinions:

	Pinion 1	Pinion 2
Modulus	2	2
Z	11	12
D	27.8	28
C	22	24
E	20	20
Allowable torque (kgf.m) bending strength	3.5	2.9
Allowable torque (kgf.m) surface durability	1.12	1.15

Table 5. Pinions parameters

Parameters of the racks:

	Rack 1	Rack 2	Rack 3
Modulus	2	2	2
N	14	46	79
Total lenght	98	303	505
B	20	20	20
C	25	25	25
D	23	23	23
Allowable force (kgf) bending strength	391	391	391
Allowable force (kgf) surface durability	79	79	79

Table 6. racks parameters

With all the parameters of the two tables, we are going to choose the best option for our rack and pinion. The optimum design, will be that achieve a high value of the lateral displacement of the rack. We discount the rack 3 because the total length is larger than the width of our cockpit so it is not valid.

So:

Design 1:

Pinion 1 with rack one

We calculate the number of teeth in one cm of the rack:

$$n = \frac{14}{98} = 0.143 \text{ teeth/cm}$$

And now we calculate the displacement of the rack advance:

$$d = \frac{z}{n} = \frac{11}{0.143} = 76.92 \text{ cm}$$

Design 2:

Pinion 2 with rack 2

We calculate the number of teeth in one cm of the rack:

$$n = \frac{46}{303} = 0.15 \text{ teeth/cm}$$

And now we calculate the displacement of the rack advance:

$$d = \frac{z}{n} = \frac{12}{0.15} = 80 \text{ cm}$$

Design 3:

Pinion 1 with rack 2

Now we calculate the displacement of the rack advance:

$$d = \frac{z}{n} = \frac{11}{0.15} = 73.3 \text{ cm}$$

Design 4:**Pinion 2 with rack 1**

Now we calculate the displacement of the rack advance:

$$d = \frac{z}{n} = \frac{12}{0.143} = 83.9 \text{ cm}$$

Now we are going to do a graphical representation:

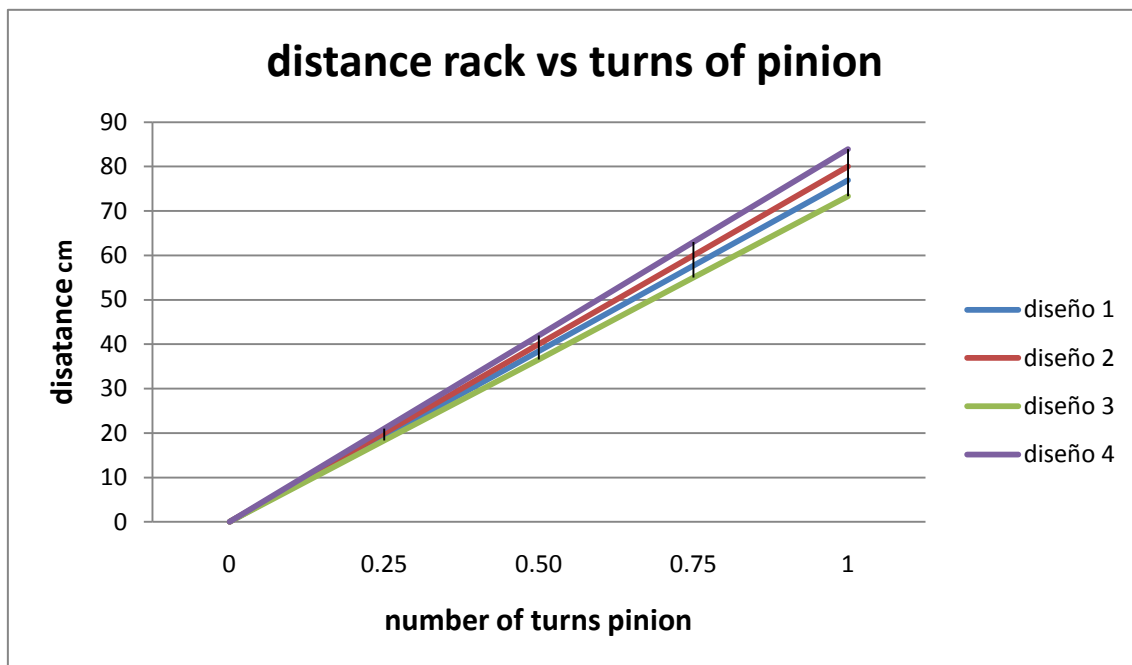


Table 7. Graph designs

As regards the velocity with the rack is moved, we can calculate as we can say before with the following equation:

$$v = N \left(\frac{z}{n} \right)$$

But in this case we are not going to do the calculations because we are looking for the best design, and now we are interested in achieve a greater velocity of the rack not a determined velocity only which design produce the highest value on the velocity

of the rack. So if we take any value for the velocity of pinion turn and the same for all the designs we obtain the same result because the velocity multiply to the lateral displacement of the rack ($d = z/n$) so the design with the highest value of d also will be the highest value of v .

Finally we can conclude that our design will be the pinion 2 with the rack 1.

Pinion2	Modulus 2	Z 12	D 28	C 24	E 20	Material SAE 1045	
Rack 1	Modulus 2	n 14	Total length 98	B 20	C 25	D 23	Material SAE 1045

Table 8. The design chosen

Position:

The position of the steering box will be determinate with the dimensions of the wheel. For Formula S.A.E. we will choose a wheel for the competition with the followings dimensions:

$$20.0 \times 7.0 - 13 \text{ inches}$$

If we translate to cm, we have an exterior diameter of $20 \times 2.5 = 50$ cm. Bearing in mind that the steering box is joined with the wheel through the tie rods and the steering arms at the middle of the wheel. So we can obtain the distance of the steering box with the road and if we had the exact measures of the cockpit we could calculate the distance of the steering box with the cockpit floor but the project of the chassis is studied in other project.

Finally the distance of the steering box to the road is:

$$50 / 2 = 25 \text{ cm}$$

Tie rod

In our case in which we have chosen the rack and pinion for our steering box the tie rods are the bars which join the rack with the steering arms. The join is made through ball-and-socket joint. The connection between the ball-and-socket joint and the steering arms is thread, making possible the variation of the distance from the end of the rack to the end of the steering arms. Then the joint secures through with nuts and locknuts. This is used to adjust the parallelism between the wheels.

The tie rods must be made of alloyed steel since must be support the knocks to come from the wheels through the upright and the steering arms.

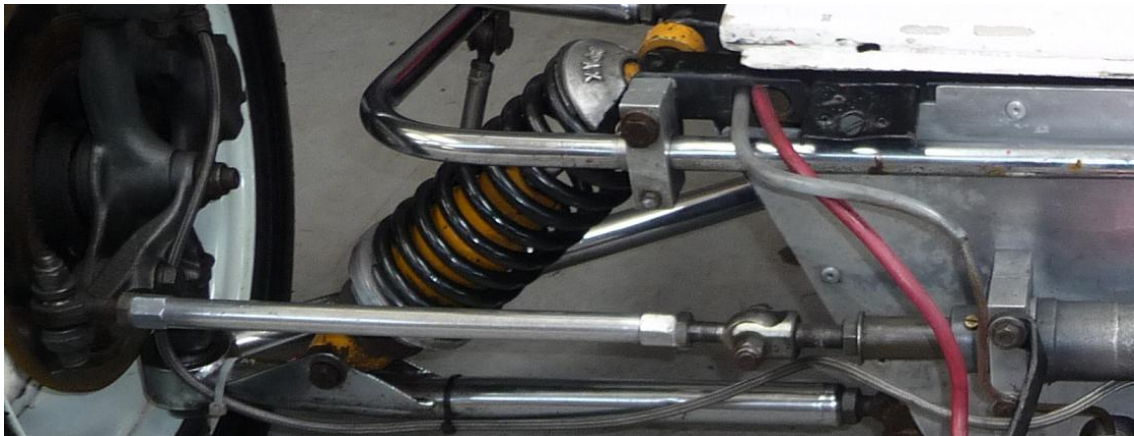


Figure 50. Tie rod

Our design

Material:

The tie rods support compression and traction efforts so for this element we will use AISI/SAE 1023 steel with a treatment of the surface in order to protect against the corrosion.

Measures:

The formula S.A.E. stipulates that the front track must be a minimum of 1200 mm so the distance of the tie rods will define with the measure of the rack the front track of the formula S.A.E.

$$\text{Track} = \text{rack measure} + \text{tie rod measure} * 2 =$$

We will determinate the measure of the tie rods with the team which carry out the suspension design because they have to do the task of the design the suspension arms and springs that will join with upright.

Now we will join the tie rod with the steering arm through a ball-and-socket joint.

Ball-and-socket joint

The ball-and- socket joint allows the oscillations produced by the movement of the steering (the movement of the rack and he steering arms are in different plane) and the effect of the suspension (the wheels and the steering arms oscillate with the suspension whereas the rack is joined rigidly to the chassis). These elements consist of three parts: one ball, one bearing situated behind the ball in order to



Figure 51. Ball socket joint

reduce the friction and the framework that contains them. The ball is connected with a thread rod in where is connected one of the elements to articulate. The other element is connected with another thread rod that comes from the framework.

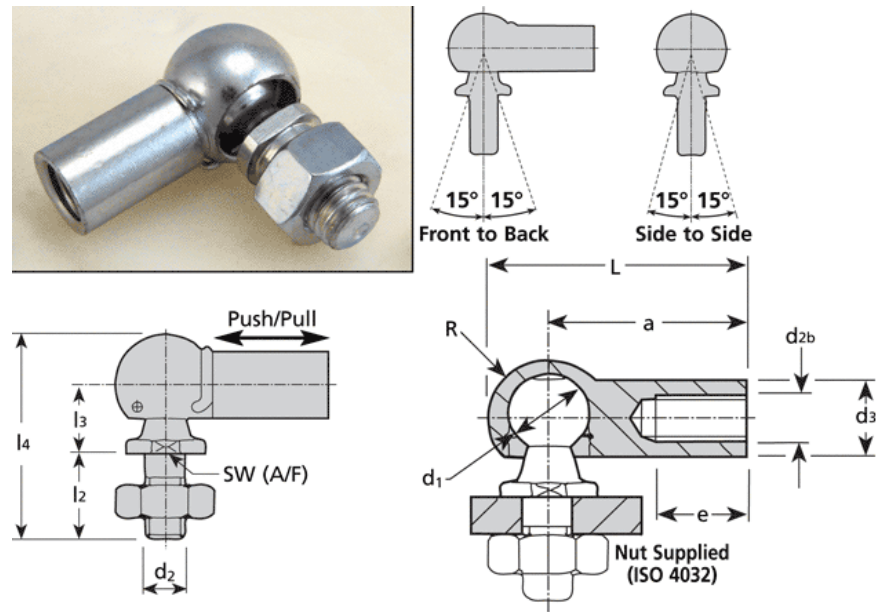


Figure 52. Ball socket joint measures

Steering arms

The steering arms are the last part of the Ackerman quadrilateral. In his movement, through the ball-and-socket joints, push or pull from the steering arms which transmit the movement to the upright that is element that fix the wheel causing finally the turn of the wheels.

As we can explain in a previous chapter and as we also can show in the pictures we will situated the steering arms with an angle that in the stop position the extensions of the lines that join the ends of the steering arms coincide on the center of the rear axle according with the Jeantaud trapezium



Figure 53. Jeantaud trapezium

Our design

We thought firstly to design a upright with the steering arm include. However we do not choose this option because with a separate steering arm the efforts are not so concentrate in the upright. We are going to see the stress analysis for the steering arm when the driver turns the wheel and the tie rods transmit a force to the steering arms. The force applied in the steering arm is the force calculated previously in the chapter 4.3.

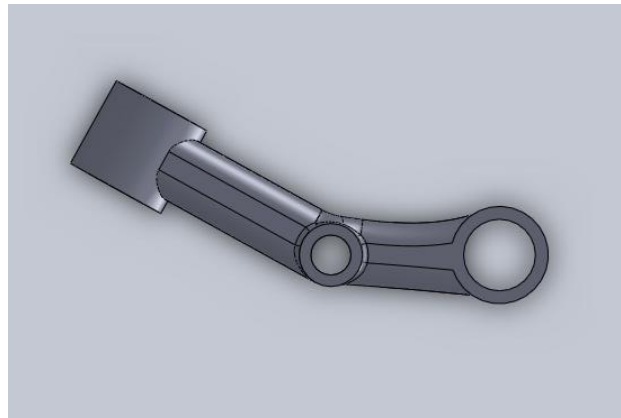


Figure 54. Steering arm in solid works

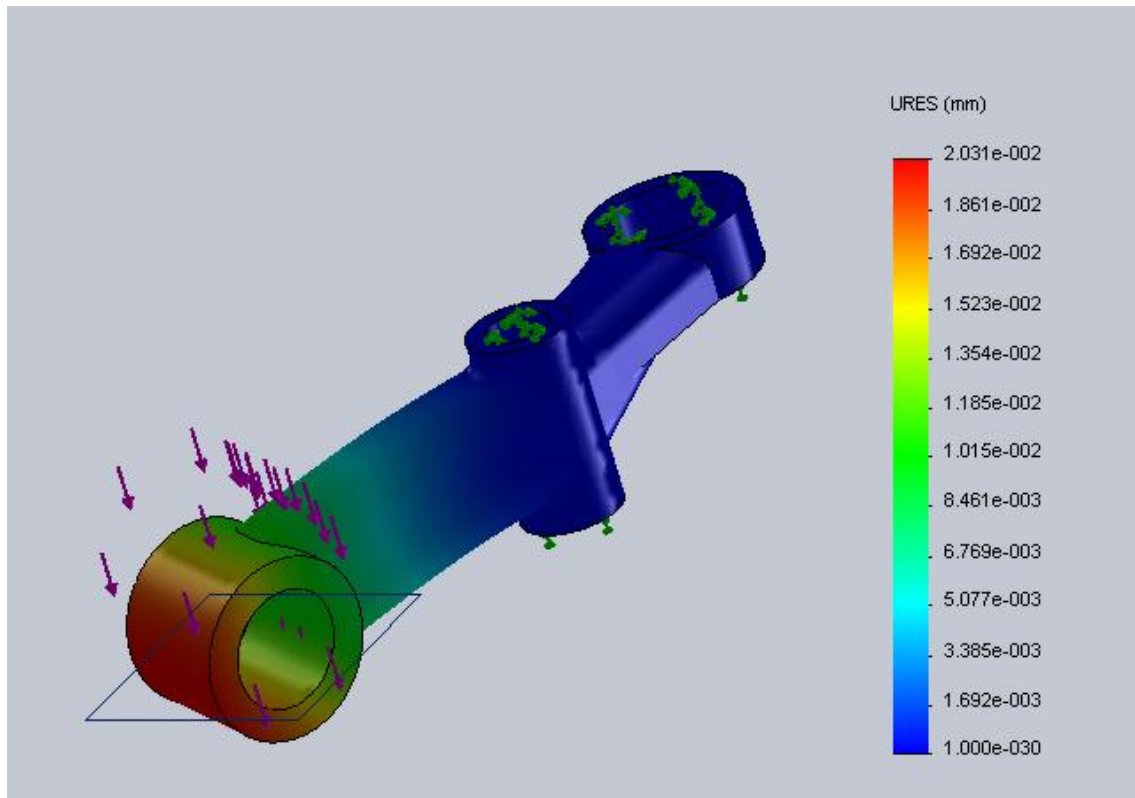


Figure 55. Stress analysis in solid works of the steering arm

As we can see in the picture the deformation is produced in the joint with the tie rod and with the force that we have applied the steering arm support the effort correctly because have a maximum deformation of $2.031\text{e-}002$ mm

Upright

There are two kinds of uprights: the front and the rear uprights. Both are quite different since have different tasks on the car. The front uprights turn around the pivot and move the wheel due to the force that has transmitted the steering wheel.

Furthermore the upright have two more functions: to fix the wheel and join the wheel with the suspension arms.

These elements must be very stiff in order to support the knocks that in frequently occasions will be very violent but at the same time they must be sufficiently tough in order to do not finish braked.

Our design

We have designed, as we have said before, the upright separately of the steering arm in order to decrease the efforts on this element. By other hand we have designed the upright in order to be light. Finally the last parameter, we are going to design the upright inside a rim of 13 inches

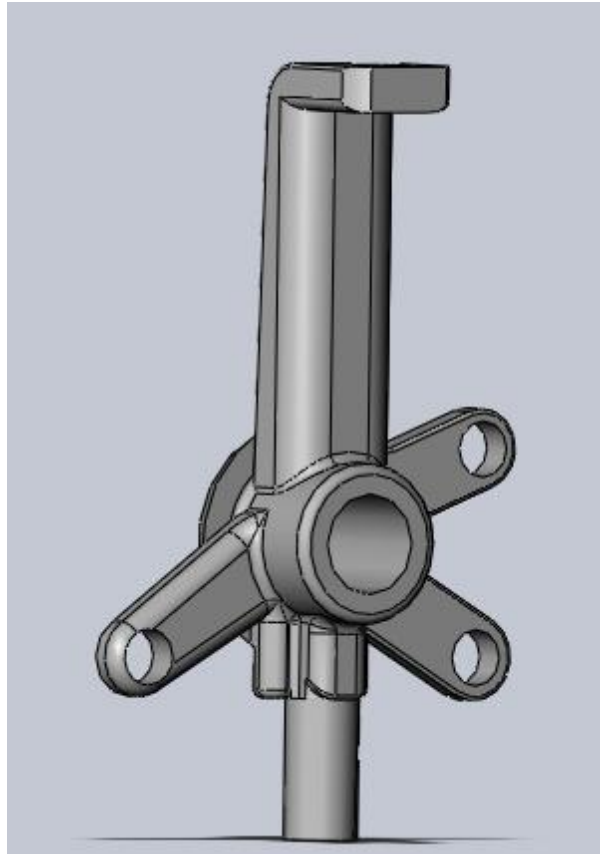


Figure 56. Upright in solid works

Now we are going to see the stress analysis hen we apply the force.

Front upright

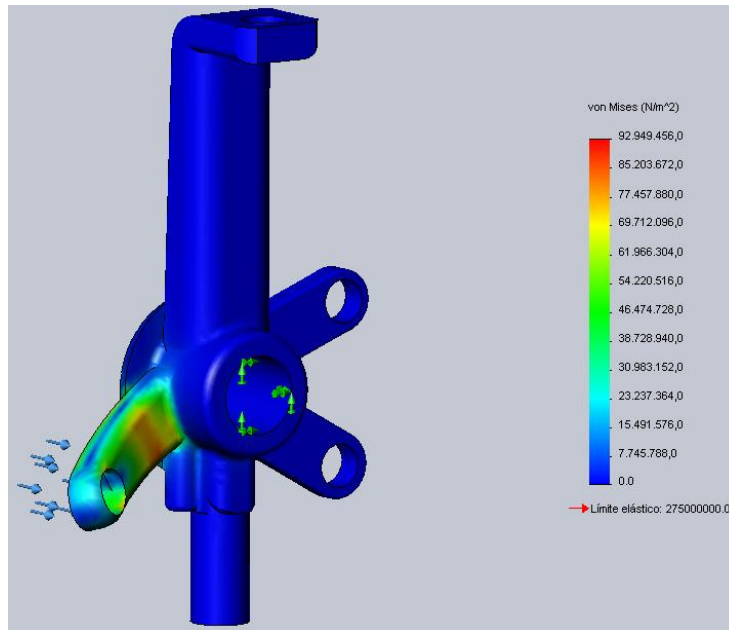


Figure 57. Stress analysis of the upright

Back upright

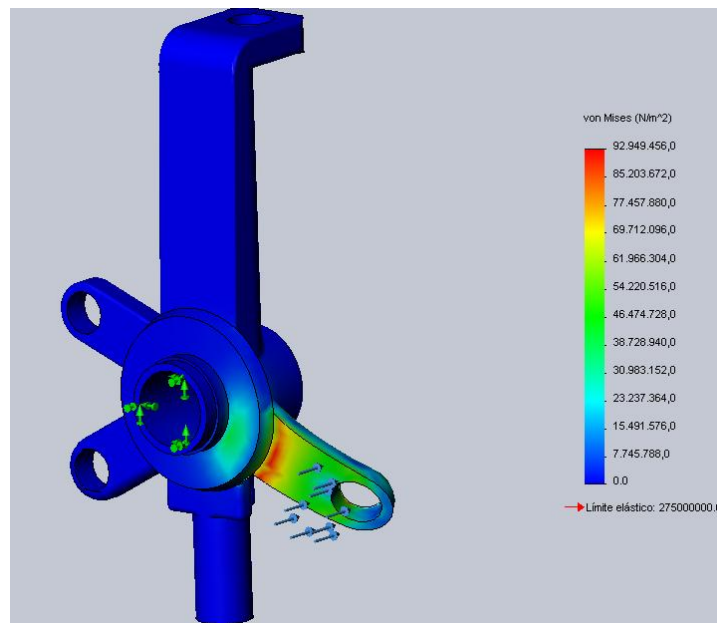


Figure 58. Stress analysis of the upright

The displacement

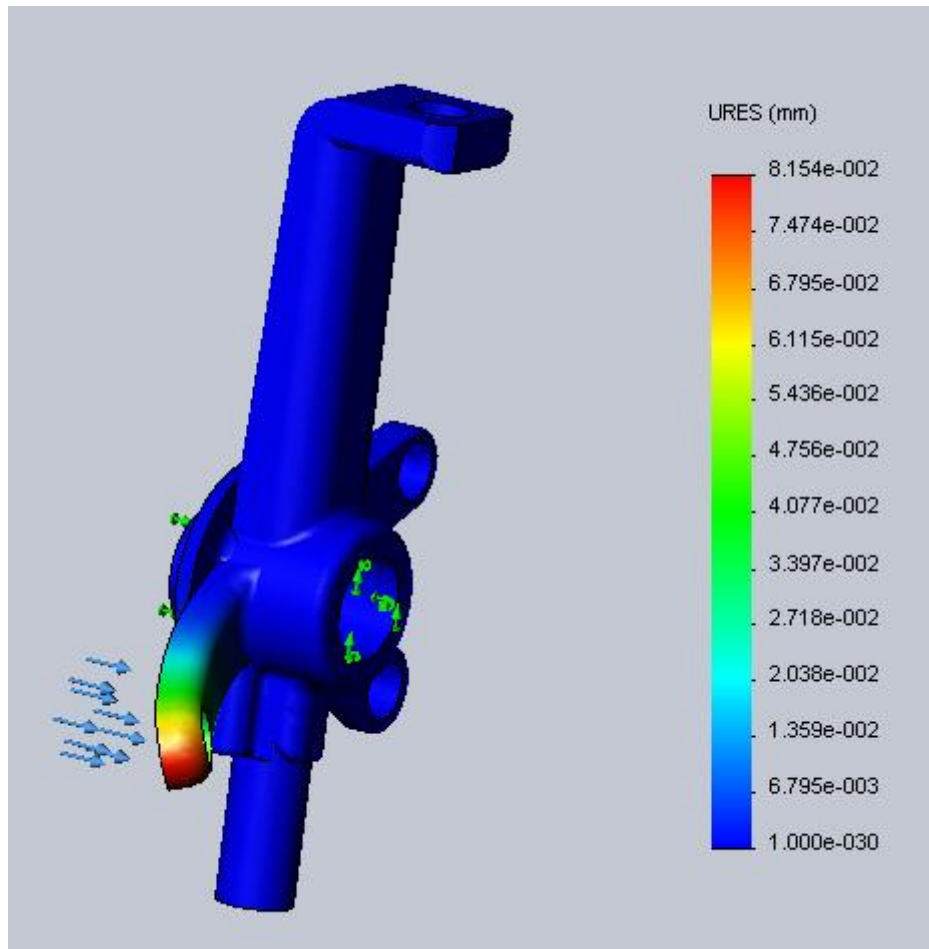


Figure 59. Displacement

When we apply the force on the steering arm this one transmits the force to the upright and as we can show in the picture the maximum deflection is 8.154×10^{-2} mm.

The assembly:

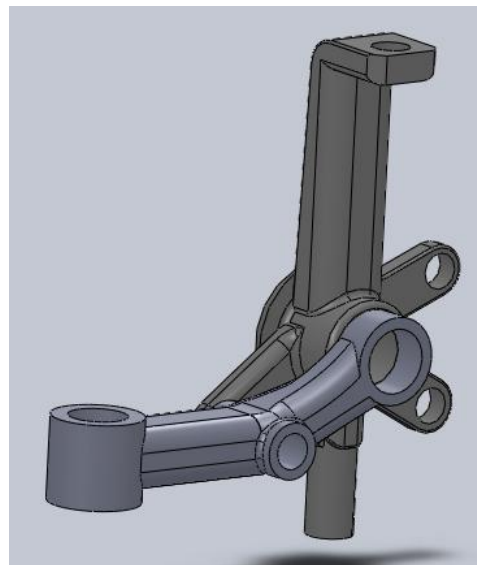


Figure 60. Assembly

Pivot

The pivot is the rotate axis of the join steering arm, upright and wheel and furthermore the joint of the wheel with the suspension and chassis.

This element is cementated and rectified (*treatments of metals*) in order to make easier the turn of the upright. The pivot is made with a high quality steel because it supports high values of a shear force.

Depending on the suspension kind manufactured on the vehicle, it will be better different uses of the steering mechanisms. In our case, in a competition car, the caster must be decreased the much as possible so the pivot will be nearly perpendicular with the floor.

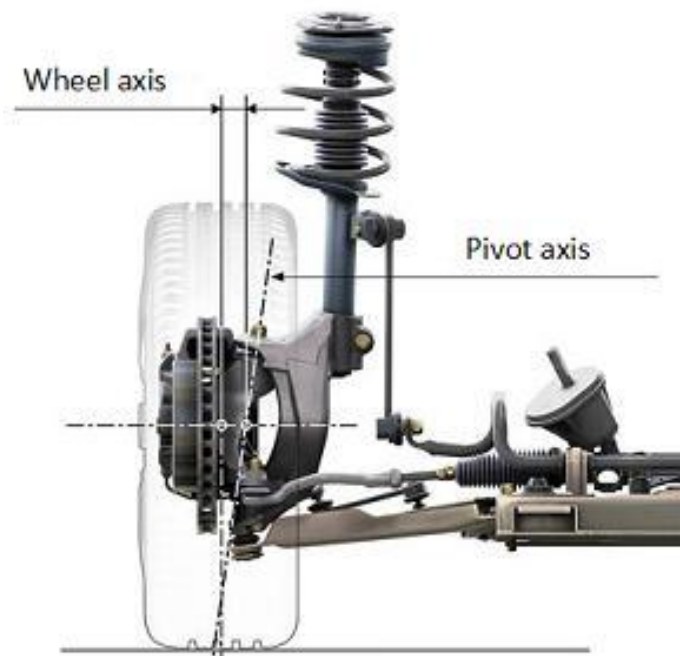


Figure 61. The pivot

Wheels

This element is the last element on the steering system and the suspension system. The tyres are supplied by the manufacturers. We choose the *Goodyear* as the brand of the tyres. The tyres for 2010 that goodyear supply are the followings.

Kinds of tyres:

Slicks: 20.0 x 7.0 – 13 ``SAE``



Figure 62. Slick tyre

Rain wheels: D*1883 20 x 6.5 – 13 R065



Figure 63. rain tyre

4.5. Budget.

The total cost of the elements which we will buy:

Elements	Price per unit	Number of units	Total price
Steering wheel	240 \$	1	240 \$
Quick disconnect	109.95 \$	1	109.95 \$
Universal joint	59.95 \$	1	59.95 \$
Ball-socket joint	4.10 \$	4	16.40 \$
		Final price	426.3 \$

Table 9. Budget

5.

Conclusions.

Finally we have finished our design. We have to design the steering system for a formula S.A.E. car describing all the elements and choosing the better options to make it and to can adapted in a total project to a car with the characteristics of Formula S.A.E.

We started the project investigating about this kind of vehicles and about the steering system in general in a car. The first step was to know the formula S.A.E. rules and the theoretical fundamentals about the steering as Ackerman or the Jeanteud Trapezium. These concepts have been in mind during the design of our elements.

The elements rack and pinion, tie rods, steering arms and the upright we have determinate the Jeantaud trapezium and we have obtained the connection between the turn angles of the front wheels with the wheelbase and the tracks. According to Jeantaud studies we have design the elements in order to the extensions of the lines that join the end of the tie rods with the point where the steering arm is joined with the upright finish on the center of the rear track in order to achieve a good performance of the vehicle.

As regards the elements, we have done the difference between the elements which will be designed by ourselves and the elements which we will buy to the manufacturers.

Talking about the elements which have been designed by ourselves we can say that we have done this task basing our designs in three parameters: comfort and safety for the pilot, improve the features of the car and the price, trying that the design is the cheapest as possible.

To situate the steering wheel and the steering column we have make a study between seven people in order to achieve the measures of a possible pilot. Once finish this task, we have calculate the position of the steering wheel achieving that the pilot drive in a good position avoiding an extreme tiredness and respecting the SAE rules that say the top of the steering wheel must be no higher than the top-most surface of the front hoop.

For the steering column we have calculated the torque produced in the element when the drive applies the maximum force to turn the wheels producing fatigue effort on the steel of 93.58 MPa and the steel chosen by our is the SAE 1015 that support until 386.1 MPa so the design for the steering column is correct.

To design the rack and pinion we had to check for a steering column with 18 mm in diameter which was the most suitable design. We needed to achieve a larger advance distance for the rack with the same turn in the pinion. We have done four designs with two pinions and two racks. With the first design we achieve a distance of 76.92 cm, with the second 80 cm, with the third 73.3 cm and with the fourth 83.9 cm so we have chosen the fourth design since with the same turn of the steering wheel we achieve a larger advance distance of the rack in consequence a high value of the wheels turn. On this way we improve the steering system because in a curve the pilot has not to turn a lot the steering wheel so the tiredness in the driving will decrease.

We thought to do a foundation steering arm with the upright but finally we chose to separate in two pieces the steering arm and the upright in order to improve the features of the car. With the first design appear a lot of efforts in the upright so we chose separate in two pieces. As we shown in the previous chapter with our design the upright suffer a flexion efforts but with a very short displacement for the high value of the force, transmitted by the tie rods, which we have calculated with an excessive weight and friction coefficient to establish a safety coefficient. The weight is a parameter that always is important decrease as much as possible and with this design we achieve that the upright is lighter than the other.

Finally we have shown the budget for the elements to buy to the manufacturers and it is a total of 426.3 \$ that have been chosen trying obtained low prices for each element but satisfying our necessities.

6.

Recommendations.

From my point of view it will be interesting to continue with the design of the upright and the steering arms in order to improve these elements trying to decrease the weight of these elements maintaining the features and that the design of the element is no too expensive.

By other hand this kind of cars has not power-assisted steering but it will be interesting to decrease the force made by the driver to turn the wheels.

7.

References.

In this chapter we are going to write the web pages which have been used to make this project:

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Catalogue Demontweeke

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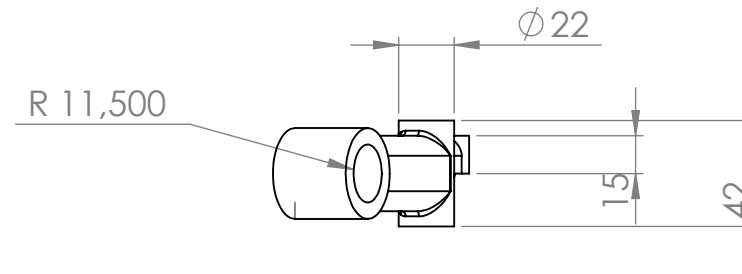
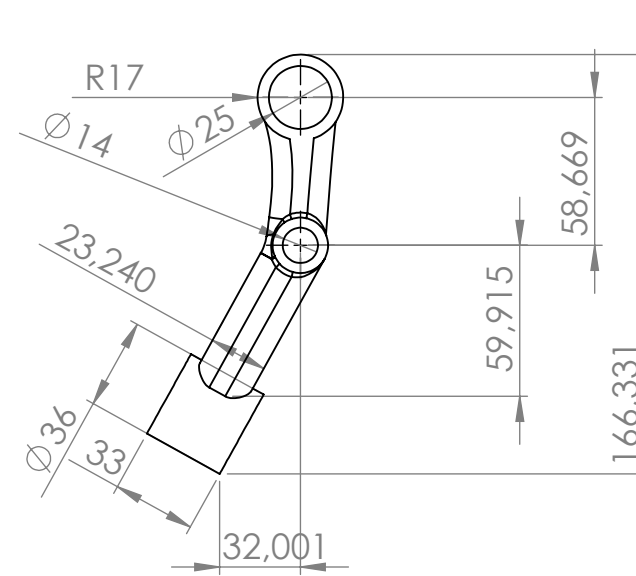
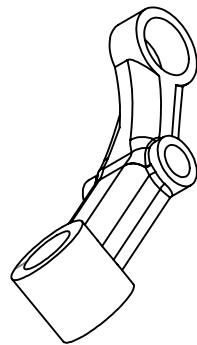
10.1. Glossary.

10.2. Planes

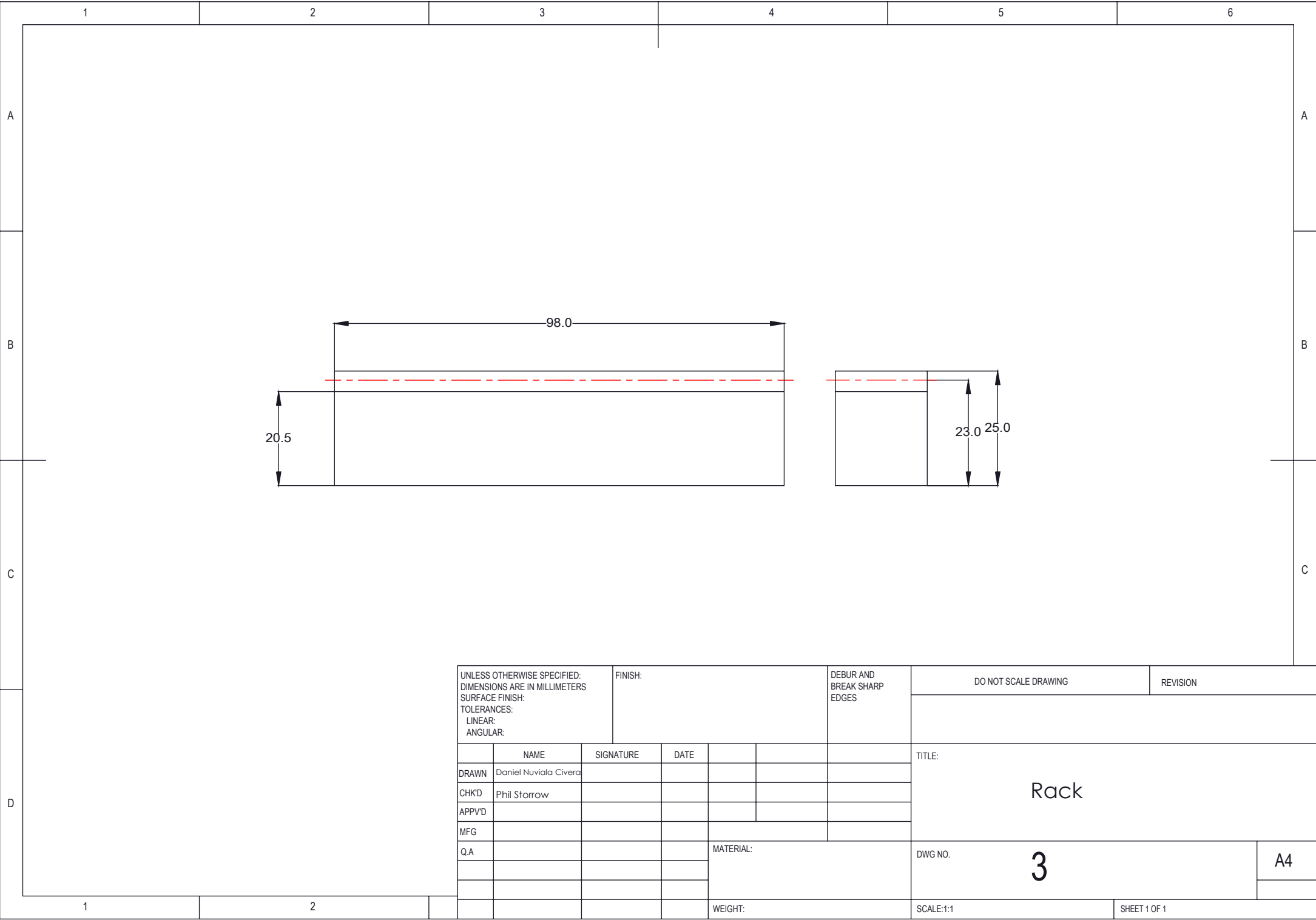
10.1. Glossary.

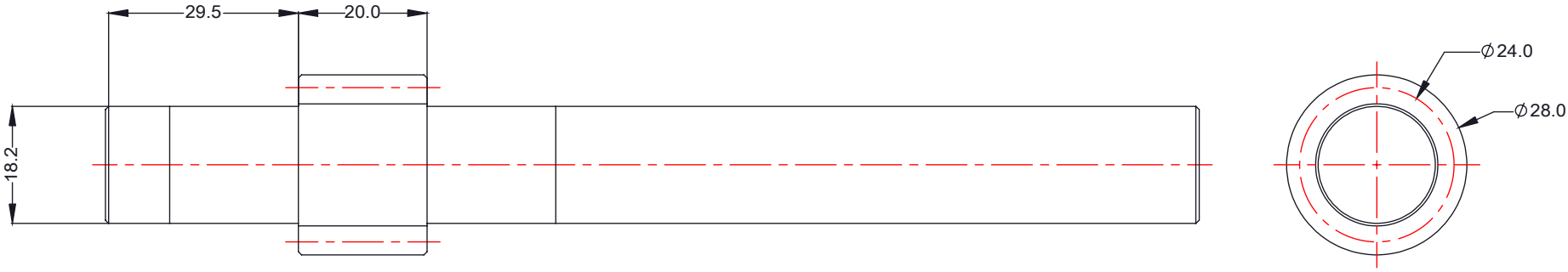
- **Wheelbase:** it is the distance between the front track and the rear track
- **Track:** it is the distance between the pivots of the right and left wheels
- **Roll center:** is the notional point at which the cornering forces in the suspension are reacted to the vehicle body
- **Torsion bar:** is a bar that supports torsion efforts. These efforts are produced by a tangential force in one point that is not the center on a circular bar.
- **Single-seater:** it is a car in which only can be one person. Normally in this kind of cars the place where drive the pilot is called cockpit
- **Friction:** force that appears contrary to the movement due to the contact between two surfaces.
- **Gear assembly:** It is a mechanism in which two elements transmit a movement between them through, a part of the pieces that is called teeth.
- **Power assisted steering:** it is a mechanism used on the steering system to make the turn on the steering wheel easy because the driver has to do less force. Principally there are two kinds: hydraulic and electrical.
- **Front wheel drive:** is a form of engine/transmission layout used in motor vehicles, where the engine drives the front wheels only. Most modern front-wheel drive vehicles feature a transverse engine, rather than the conventional longitudinal engine arrangement generally found in rear-wheel drive and four-wheel drive vehicles

- **Front wheel assembly:** is the joint of the elements of the front part of the car.
- **Rear wheel assembly:** Is the joint of the elements of the rear part of the car
- **Not hang weight:** It is the part and elements of the car weigh that are not supported by the suspension system.
- **Hang weight:** it is the part and elements of the car weight that are supported by the suspension system.
- **Torque:** is the tendency of a force to rotate an object about an axis fulcrum, or pivot. Just as a force is a push or a pull, a torque can be thought of as a twist
- **Rim:** It is the part of the wheel generally made of aluminium or steel that is inside of the tire supporting it.
- **Instant rotation center:** also called *instantaneous centre*, for a plane figure moving in a two dimensional plane is a point in its plane around which all other points on the figure, for one instant, are rotating. This point itself is the only point that is not moving at that instant.
- **Kinematic:** is the science that studies the movement of a particle on the space.
- **Dynamic:** is the science that study the movement of a particle produced by a force
- **Aerodynamic:** is a branch of dynamics concerned with studying the motion of air, particularly when it interacts with a moving object. Aerodynamics is a subfield of fluid dynamics and gas dynamics, with much theory shared between them



SI NO SE INDICA LO CONTRARIO: LAS COTAS SE EXPRESAN EN MM ACABADO SUPERFICIAL: TOLERANCIAS: LINEAL: ANGULAR:			ACABADO:			REBARBAR Y ROMPER ARISTAS VIVAS			NO CAMBIE LA ESCALA			REVISIÓN				
									<div>TÍTULO:</div> <div>Steering arm</div>							
	NOMBRE	FIRMA	FECHA													
DIBUJ.	Daniel Nuvala Civera															
VERIF.	Phil Storrow															
APROB.																
FABR.																
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				PESO:			ESCALA:1:2			HOJA 1 DE 1						





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	NAME	SIGNATURE	DATE				TITLE: Pinion				
DRAWN	Daniel Nuviola Civera										
CHK'D	Phil Storrow										
APPV'D											
MFG											
Q.A				MATERIAL:			DWG NO.		4		A4
				WEIGHT:			SCALE:1:1		SHEET 1 OF 1		

‘ ‘If you have the control, you are not in the limit’ ’

Ayrton Senna