ÉCOLE POLYTECHNIQUE DE LOUVAIN

LMECA2215 – VEHICLE DYNAMICS

Group Project

Anti-Roll Bar

Group 8

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1. Introduction

Vehicle dynamics aims to study and understand how a vehicle, i.e. cars, truck, train, etc., behaves and reacts to road/track conditions. Specifically for cars, some of the main characteristics to study are riding and handling. The tuning and overall setting of these two characteristics will define the vehicle and the experience of the driver during its operation. Therefore, riding and handling are crucial aspects of vehicle performance.

Riding determines the comfort of the driver and passengers of the vehicle. It can be defined as the degree to which the passengers are isolated from vibrations and accelerations derived from the road conditions, bumps, potholes, etc. Handling refers to the manner in which the vehicle responds to the driver input in regard to maneuvers, lane changes, cornering, etc., and the ability of the vehicle to keep the intended direction. Typically, to satisfy both ride and handling a tradeoff must be made between a soft spring rate for ride quality and the need to control body roll during cornering for handling. The latter is partially defined by the anti-roll bar. [5]

Consequently, the anti-roll bar is frequently one of the first components of a car's suspension to be tuned specially by racers. Almost every modern car comes equipped with anti-roll bars straight out of the factory. These vital devices allow suspension engineers to alter the ride, handling, and responsiveness of a vehicle. When the right anti-roll bar is chosen, a poorly handling vehicle can become a true sport sedan on the road [1].

1.1. Anti-roll Bar – Definition

Anti-roll bar, anti-sway bar, sway bar or stabilizer bar is a part of vehicle suspensions that limits body roll angle [2]. The bar aims to reduce the body roll of the vehicle during fast cornering or through road irregularities. In simplest terms, the bar connects the right wheel to the left which allows the transmission of the forces due to road irregularities from one wheel to the other one. Its main function is to prevent the rollover of the vehicle by improving the stiffness of the suspension system [6].

Usually, the anti-roll bar is a U-shaped cylindrical piece of metal (typically steel) that joins together the suspension on either side of an axle through short lever arms linked by a torsion spring (figure 1). It is usually attached to the chassis in the middle at two points with rubber bushings and it can be used on front, rear or in both suspensions [3][5].

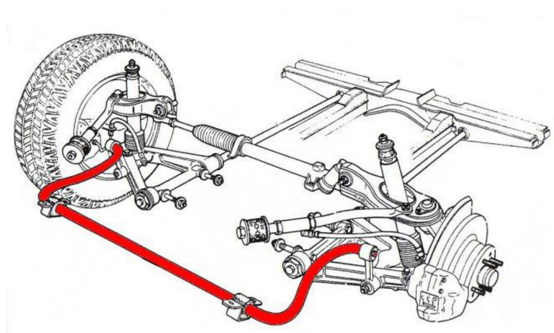

Figure 1- Anti-roll bar (in red) attached to a front axle (suspension).

1.2. Importance of anti-roll bar

Any vehicle will be subject to all kinds of stresses, due to the forces applied to it. Speed, inclination or even road conditions have an influence on these constraints. When a vehicle takes a sharp turn at high speed, a roll angle appears. In vehicle dynamics, three angles are defined respectively: roll, pitch and yaw associated respectively with the X, Y and Z axis (figure 2).

Anti-roll bars play a crucial role in minimizing the lateral tilting of a vehicle. Controlling body roll is imperative for high-performance cars, as it limits the vertical movements of the suspension during intense cornering forces. Due to constraints in suspension linkages, maintaining proper wheel alignment becomes challenging when the wheels experience significant up-and-down motion[3].

The reduction of body roll also enhances the car's transient response, a vital aspect in vehicle performance but especially in racing. Transient response refers to the time it takes for a car to achieve full load transfer, or "take a set," after a steering input. Clearly, if the body exhibits less roll, the time it takes to stabilize is reduced, making the car more responsive to subsequent steering inputs.

While minimizing body roll is a key function of anti-roll bars, an even more significant advantage is their capacity to fine-tune a car's handling. Anti-roll bars impact the roll stiffness of the connected suspension, determining the proportion of the overall cornering load supported by either end of the car. Consequently, anti-roll bars enable adjustments to the balance of front and rear cornering loads, allowing for the desired customization of the car's understeer and oversteer characteristics[3].

The anti-roll bar allows the vehicle and the suspension system to keep its geometry even in curves and thus resulting in a vehicle that performs almost as well in turns as in a straight line. It's important to say that there is no such thing as a quintessential anti-roll bar. Indeed, an anti-roll bar must be studied and adapted for the environment in which the vehicle will be used. For example, a Jeep or a 4X4 car will generally need suspension to be as loose as possible to always have contact between the tires and the ground. For a sports car which will mainly drive on flat roads, harder suspension can be allowed and therefore, also a stiffer anti-roll bar. Finally, road cars are a combination of the two with soft suspension and a stiff bar or the opposite.

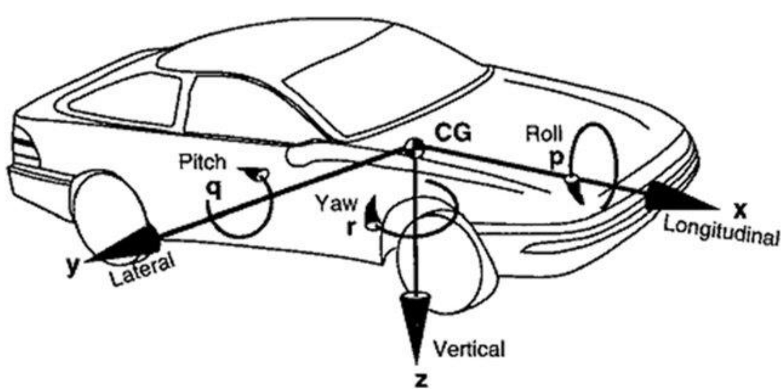

Figure 2- Degree of freedom of a car.

1.3. Operation of anti-roll Bar

The anti-roll bar serves to link the right and left suspension components, resisting the rolling or swaying of a vehicle experienced during cornering or when traversing uneven road surfaces" [2]. Its primary purpose is to diminish the lateral inclination (roll) of the vehicle when navegating curves, sharp turns, or encountering significant bumps. While design variations exist, the overarching goal is to maintain the vehicle's body as level as possible by compelling the shock absorber, spring, or suspension rod of the opposite wheel to move in the same direction as the impacted one.

When one side of the suspension compresses due to cornering-induced body roll, the lever arm on that side twists the main length of the anti-roll bar, attempting to compress the suspension on the opposite side. Consequently, the anti-roll bar induces compression in the opposite wheel's suspension, ensuring a more level lateral posture for the vehicle. In this process, the anti-roll bar effectively increases the spring rate of the suspension during roll [3]. This action also contributes to lowering the vehicle's center of gravity during turns, enhancing stability [4].

The anti-roll bar's ability to reduce body roll is determined by its torsional stiffness (resistance to twist), referred to as "Roll Stiffness." The degree to which the anti-roll bar enhances roll stiffness depends on its own stiffness and the point at which it connects to the suspension. Consequently, as a vehicle compresses the suspension of its outer wheel, the anti-roll bar plays a pivotal role in controlling body roll [3].

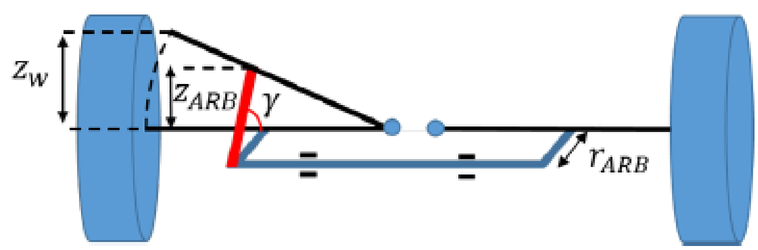

Figure 3- Anti-roll bar (in red) attached to the suspension, diagram of working principle. [7]

2. Dynamic analysis of anti-roll bar

The design of an anti-roll bar involves finding the optimal stiffness that improves the stability, ride and handling of the vehicle. The ideal stiffness needs to be found while taking into consideration the limitations of the bar material.

Currently there are two types of anti-roll bars available: passive and active. Passive anti-roll bars are the traditional ones. The ones that have a specific stiffness. Active anti-roll bars have the ability to modify their stiffness. This ability becomes beneficial when the conditions require different values of stiffness throughout the lifetime. During this document, when referring to anti-roll bar we will be talking about passive ARB and when referring to vehicle, we will be talking about a car. And for simplicity the ARB will be considered to be a simple U-shape, as shown on figure 3.

And equation related to the motion ratio can be defined,

$$i_{ARB} = \frac{z_{ARB}}{z_{\omega}} = \frac{F_{ARB,\omega}}{F_{ARB}}$$

(1)

F_{ARB}, is the force produced at the anti-roll bar ends and $F_{ARB,\omega}$ is the force acting on the wheel. The ARB is assumed to have a stiffness k_{γ} and an arm length r_{ARB}. By exciting the left wheel (figure 3) and keeping the right one stationary, a torsion in the ARB is induced. Therefore, the corresponding forces acting on each wheel induced by the ARB produced forces can be calculated by, [7]

$$F_{ARB,\omega} = \frac{k_{\gamma}\gamma}{2r_{ARB}} i_{ARB} = \frac{T_{ARB}}{2r_{ARB}} i_{ARB}$$

(2)

Where γ is the torsion angle and the furthest right side of the equation is used for a non-conventional ARB where T_{ARB} is the torque produced by the ARB. [7]

2.1. Half car model

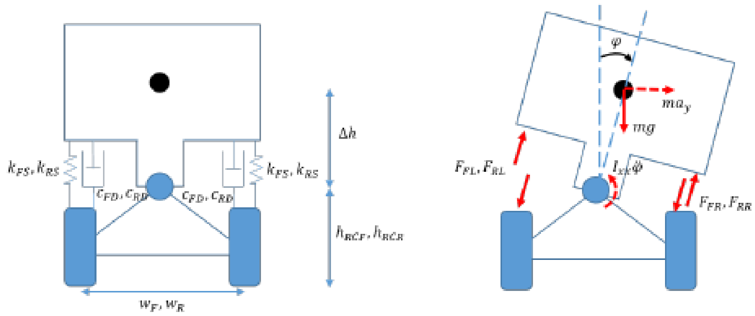

Figure 4- Half car model, with a_y as lateral acceleration which creates the roll angle ϕ. [7]

Given the figure above the following relation can be obtained to relate the roll angle to the torsion angle shown on figure 3, assuming that the torsion angle is small. Equation (3) applicable for both the front and rear axles respectively.

$$\gamma = \frac{\omega\, i_{ARB}}{r_{ARB}}\varphi \tag{3}$$

The resulting equilibrium around the roll center is described by,

$$I_{xx}\ddot{\varphi} = ma_y\,\Delta h + mg\Delta h\varphi - k_{\varphi,FS}\,\varphi - k_{\varphi,FARB}\,\varphi - c_{\varphi,FD}\,\dot{\varphi} - k_{\varphi,RS}\,\varphi - k_{\varphi,RARB}\,\varphi - c_{\varphi,RD}\,\dot{\varphi} \tag{4}$$

Where,

$k_{\varphi,FS}$, $k_{\varphi,RS}$ are the roll stiffness from the front suspension and the rear suspension respectively.

$k_{\varphi,FARB}$, $k_{\varphi,RARB}$ are the roll stiffness from the front ARB and the rear ARB respectively.

$c_{\varphi,FD}$, $c_{\varphi,RD}$ are the roll damping from the front suspension and the rear suspension respectively.

These are calculated by,

$$k_{\varphi,FS} = k_{FS}\left({i_{FS}}^2\right)\left(\frac{{\omega_F}^2}{2}\right) \tag{5}$$

With the corresponding values of stiffness, motion ratio and wheelbase (figure 4) respectively for front, rear suspension and ARB.

By means of the transfer function obtained from the Laplace transform, the following behavior can be concluded:

- An increase in roll stiffness reduces damping,
- An increase in damper constants increases the roll damping and vice versa.

3. Oversteering and Understeering

As previously stated, handling is a measure of the vehicle-driver combination. Generally, the driver observes the vehicle direction and position and consequently corrects the input to achieve the desired motion.

To put it simply, understeer is characterized by the behavior of the car where the mass is directed towards the front axle of the car, and it pulls the rear with it. conversely, during an oversteer, the train will gain more speed and will want to "catch up with the front axle"; the car will tend to make a U-turn.

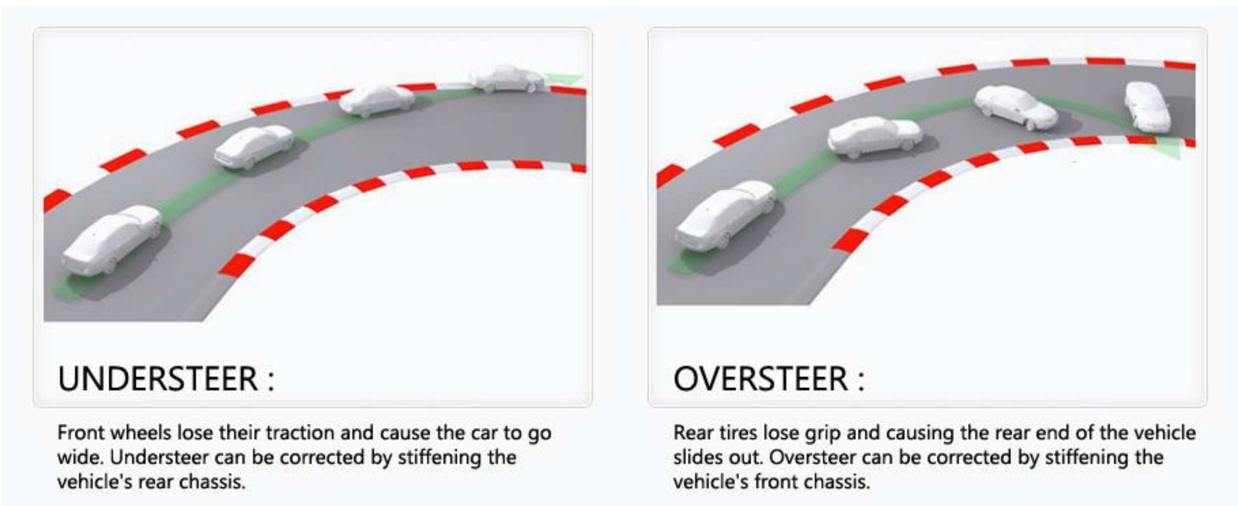

Figure 5- Oversteer and understeer phenomenon.

During this document the vehicle response will be characterized by specific steering inputs. The behavior of the car at low cornering speeds is not of interest for this analysis because the car does not develop lateral forces. Therefore, the aim will be to analyze the behavior of the car at high speed.

An interpretation of the understeer gradient can be given by equation (6), it explains how the steer angle must be changed with the radius of the turn or the lateral acceleration (figure 5). [11]

$$\delta = 57.3\frac{L}{R} + Ka_y \tag{6}$$

Where,
δ, steer angle at the front wheels [deg]
L, wheelbase [m]
R, radius of turn [m]
K, understeer gradient [deg/(m/s2)]
a_y, lateral acceleration [m/s2]

But practically the understeer gradient is expressed like shown on equation (7). It determines the magnitude and the direction of the steering inputs required. Each term on the equation is the ratio of the load on the axle to the cornering stiffness of the tires on the axle (front or rear). [11]

$$K = \frac{w_F}{C_{\alpha F}} - \frac{w_R}{C_{\alpha R}} \tag{7}$$

Where,
w_F / w_R, load on the front/rear axle [N]

$C_{\alpha F}/C_{\alpha R}$, cornering stiffness on the front/rear tires [N/deg]

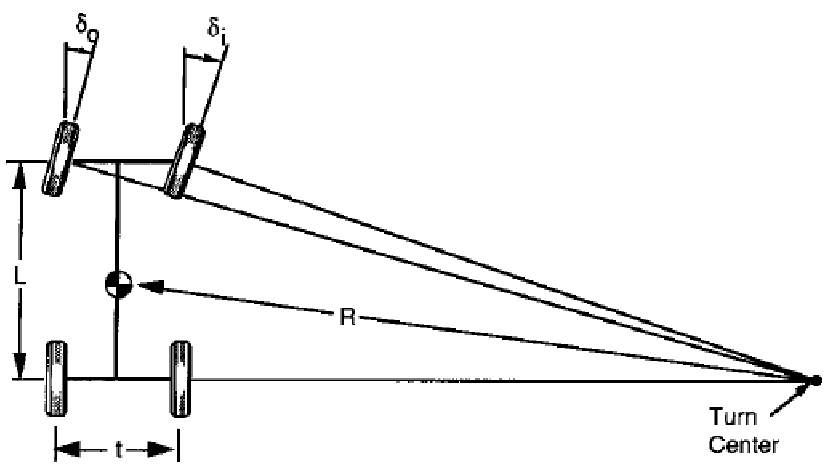

Figure 6- Geometry of a turning vehicle. [11]

Three possibilities exist for this understeering gradient:

3.1. Neutral steering

$$K = 0, \alpha_f = \alpha_r$$

With a constant radius turn, no change in steer angle will be needed as speed is varied. This case implies a balance in the vehicle such that the force of the lateral acceleration at the center of gravity creates an equal increase of slip angles at the front and rear wheels. [11]

3.2. Understeer

$$K > 0, \alpha_f > \alpha_r$$

With a constant radius turn, the steer angle will have to increase with speed in proportion to K times the lateral acceleration. Meaning that the steer angle increases linearly with lateral acceleration and with the square of the speed. During this case the lateral acceleration at the center of gravity causes the front wheels a bigger slip sideways than the rear wheels. Thus, the front wheels must be steered to a greater angle to maintain the radius of turn. [11]

3.3. Oversteer

$$K < 0, \alpha_f < \alpha_r$$

With a constant radius turn, the steer angle will have to decrease as speed and lateral acceleration increase. During this case the lateral acceleration at the center of gravity causes the rear wheels a bigger slip angle than the front wheels. Thus, the increase in lateral acceleration causes the rear wheels to drift out further and the steer angles has to be reduced to maintain the radius of turn. [11]

Although tire cornering stiffness was used to characterize understeering and oversteering it's important to remember that multiple factors influence cornering forces. The suspensions and steering systems are the primary influences, one of the suspension factors affecting handling is the ARB.

Consequently, more roll moment on the front axle contributes to understeer and more roll moment on the rear axle contributes to oversteer [11]. A different calibration of the anti-roll bars between the front and the rear is sometimes preferable depending on the case. For example, an equivalent stiffness for each bar will not be useful and will not have a significant impact on the understeer or oversteer character of the car. But usually, we prefer an understeering car for road cars because it is easier for an average person to control their vehicle in this scenario (hard braking). On the other hand, for motor sports oversteering is preferable, understeering is not suitable because it causes a loss of speed whereas with a little training you can easily control the sliding of the rear axle by counter steering and even gain speed.

When a car takes a turn or accelerates in a straight line, the vehicle undergoes a mass transfer. The forces exerted on it will vary the normal force of the tires on the ground and therefore we have the impression that the center of mass "moves". This phenomenon is problematic because in certain situations you can lose control of the vehicle, there are different methods to reduce the transfer of the mass of a vehicle but the "simplest" is still the anti-roll bar.

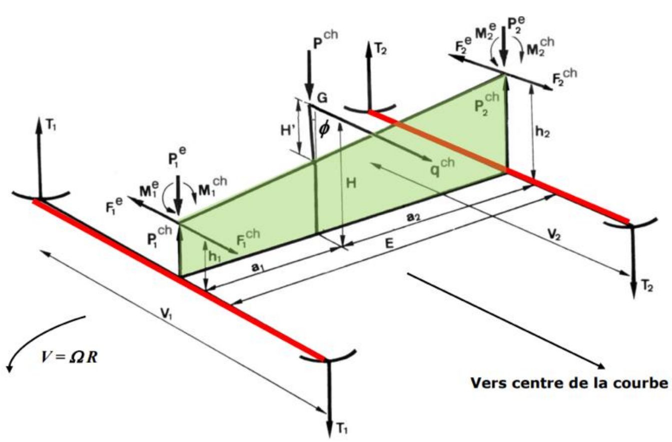

Figure 7- Load transfer in steady state cornering [15].

$$T_1 = m^{ch} q \frac{a_2}{E} . \frac{h_1}{v_1} + \frac{K_1 \phi}{v_1} \qquad T_2 = m^{ch} q \frac{a_1}{E} . \frac{h_2}{v_2} + \frac{K_2 \phi}{v_2} \tag{8}$$

Where,

$T1$, Force of the front axle [N]

m^{ch}, mass of the chassis [m]

q, centripetal acceleration [m/s2]

E, distance between the two axles [m]

a_2, distance between rear axle and center of masse of the chassis [m]

h_1, height of the roll center of the front axle [m]

v_1, front axle width[m]

K_1, front anti-roll bar stiffness [dyn/cm]

ϕ, roll angle [rad]

More precisely, the stiffness of the anti-roll bar will increase the force applied to the outer wheels and reduce that of the inner wheels, thus the lateral force exerted on the vehicle will be less and the roll will also decrease.

4. Numerical Simulation

Thanks to the Robotran model provided by the supervisory team, we were able to digitally model the impact of the anti-roll bar on the behavior of a car. We have added several functions so that the program best meets our expectations, mass transfer in a straight line and in turns, etc. With the numerical results obtained we were able to quantify our research and have a visual overview.

4.1. Roll angle in cornering

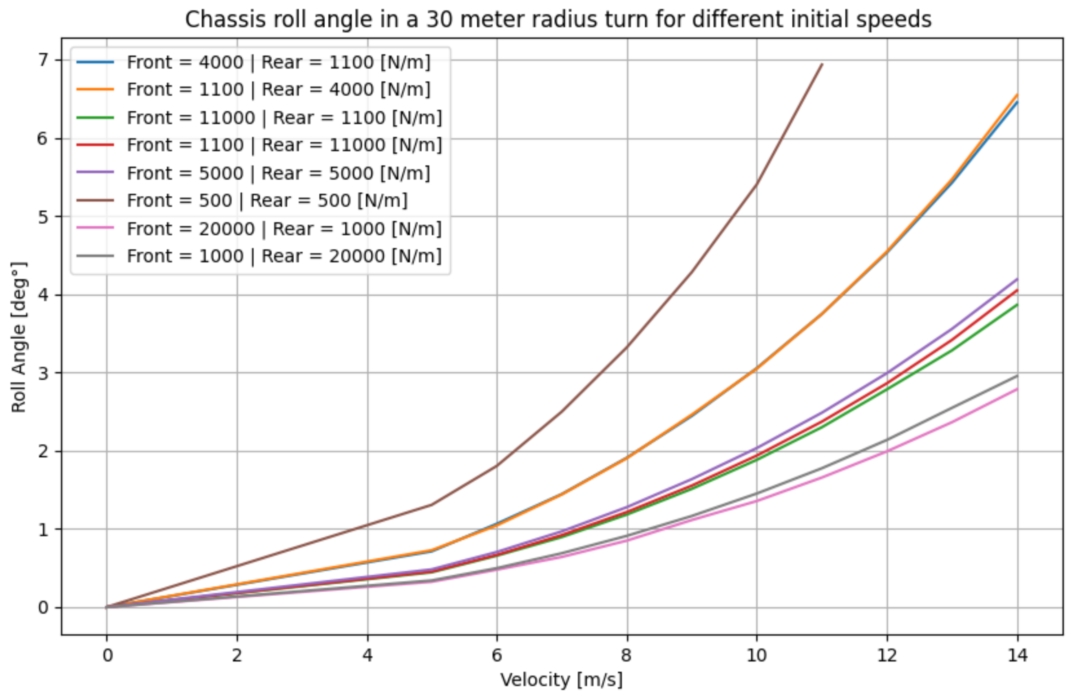

Figure 8- Roll angle – Velocity with different axle stiffnesses (Robotran).

This first graph highlights the impact of axle stiffness. We see that the roll angle of the chassis is much greater with low stiffness values. We obtain a difference of almost six degrees for the same speed between the stiffest and softest anti-roll bars. On the other hand, it is important to note that the difference in stiffness between the axle bar and the rear has little or no importance. It is above all the total stiffness which plays an important role since we measure the roll of the chassis here and can approximate a block of equivalent stiffness.

4.2. Anti-Roll Bar Stiffness on Oversteering and Understeering

An important point to consider in the design of a car is its under/oversteer character. The anti-roll bar is an important element that influences how the car will behave when cornering, which is why it is important to understand and see the differences in the behavior of a vehicle between several anti-roll bar configurations.

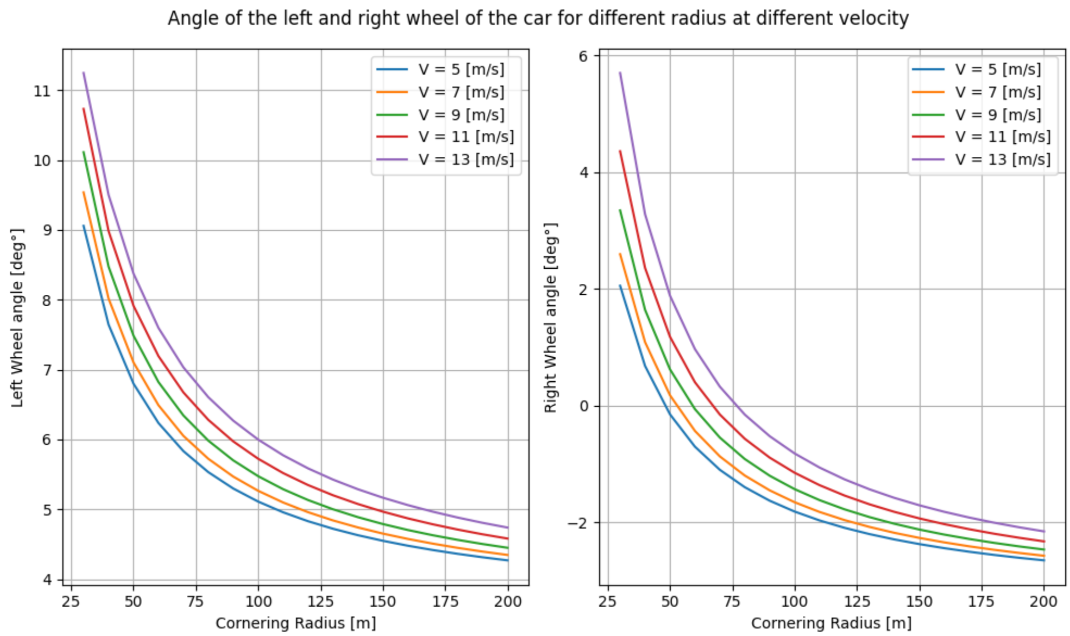

Figure 9- Left/Right wheel angle – Cornering radius, with different velocities (Robotran).

The chart above shows several things. Firstly, as one might expect, it will be necessary to steer much more during a tight turn but also when the vehicle speed is higher. Secondly, in our simulation the vehicle is turning left so the outside wheel (right wheel) will be further away from the center of the turn than the left wheel (1.9m exactly which corresponds to the width of the axle). Consequently, and as illustrated in the graph, the right wheel will have to rotate at a smaller angle than the left wheel.

In addition, the difference in angle and especially the fact that from a certain radius the angle of the right wheel becomes negative is due to the camber angle which is also negative. This parameter also allows, like the anti-roll bar, to reduce the effect of mass transfer.

Now, let's focus on the variation of the steering angle as a function of the stiffness of the anti-roll bar for a given speed of 10 meter/sec. As we can see, for wide turns with a large radius there is little or no difference, which is why we will concentrate our analysis on tighter turns.

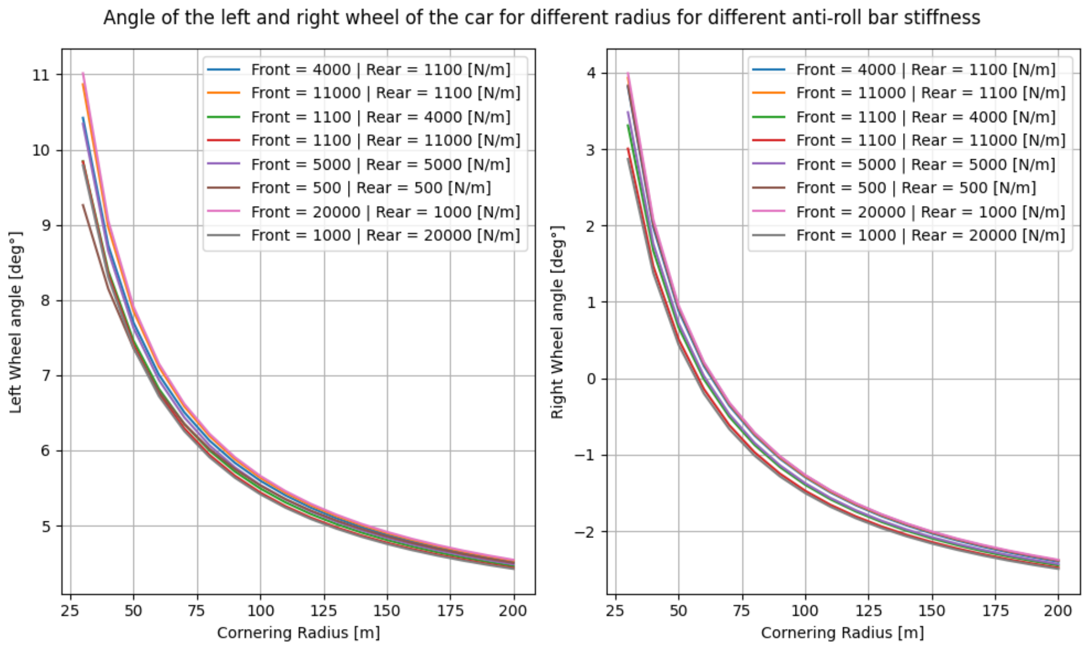

Figure 10- Left/Right wheel angle – Cornering radius, with different ARB stiffness (Robotran).

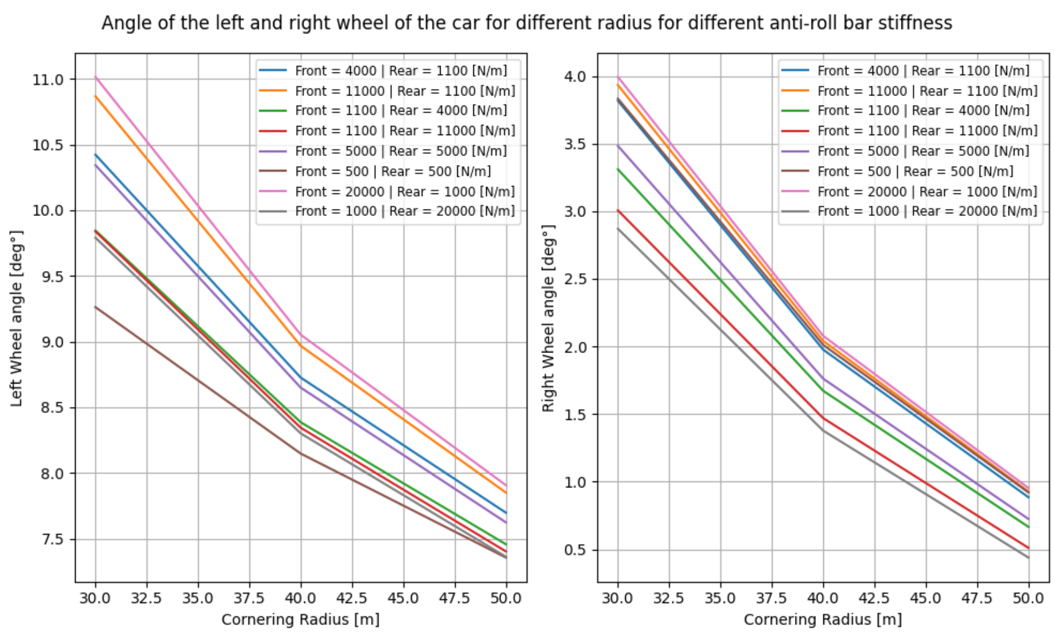

Figure 11- Left/Right wheel angle – Cornering radius, with different ARB stiffness (Robotran).

So basically, for a same radius but a different anti-roll bar stiffness we have almost a maximum difference of two degrees for the left wheel. We also note that for the same total stiffness of the vehicle, the steering angle of the left wheel is a degree greater for a stiffer front anti-roll bar than the reverse. In short, it will be necessary to turn the wheel a tenth more, we can therefore confirm that a stiffer anti-roll bar at the front promotes the understeer character of a vehicle.

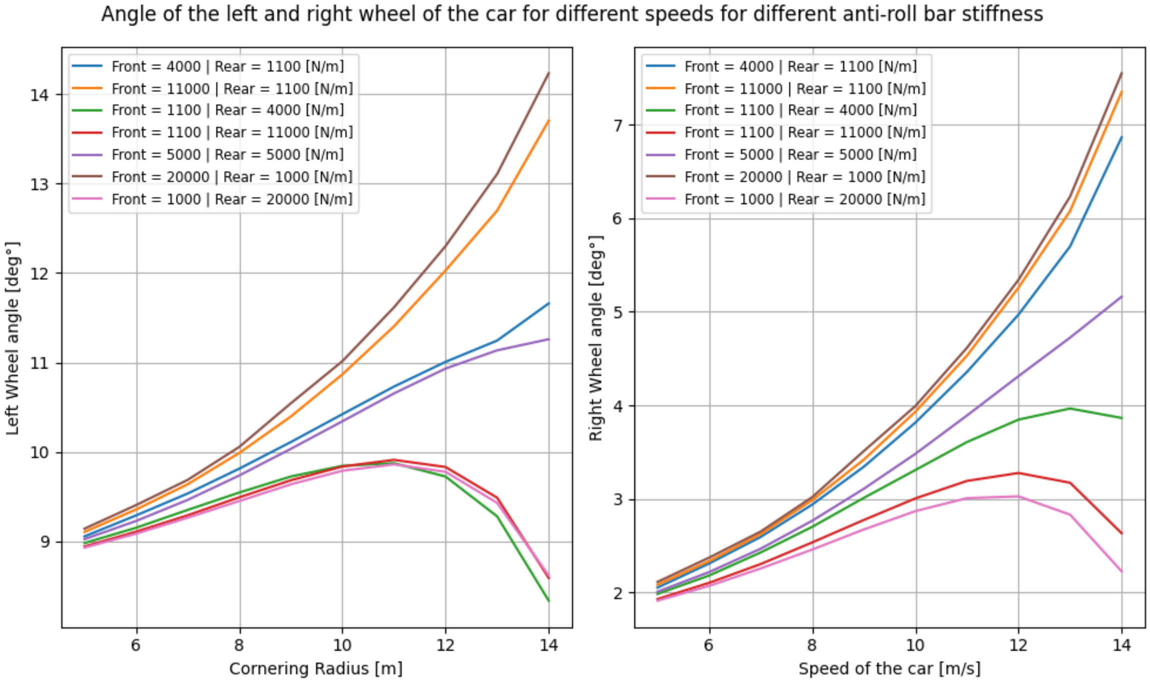

Figure 12- Left/Right wheel angle – Cornering radius/Speed, with different ARB stiffness (Robotran).

Finally, the graph above is undoubtedly the most representative of the variation in the behavior of a vehicle depending on the configuration of the anti-roll bars. Indeed, in agreement with the theory we can see that increasing the stiffness of the front axle compared to the rear increases the understeer character of the car and therefore it will be necessary to steer much harder. On the other hand, even more interesting from a certain speed and for a rear stiffness much greater than at the front the vehicle becomes extremely oversteering and the more you increase the speed the less steering will be necessary! This behavior is also very dangerous for a non-sporty car because if you take a turn too quickly you will then have to counter-steer, therefore turning the wheels in the opposite direction to the turn, which is counter-intuitive.

For a normal car, the engine is often at the front and therefore a large part of the weight as well, however the power of the engine is often applied to the front wheels, these elements also influence the behavior of the car. This is why it is important to mention that each car will have its own anti-roll bar design and parameter., therefore we will probably obtain different results for another vehicle.

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