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Study and dynamic simulation of Brain mountain bike rear suspensions

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APPROVAL

This thesis has been autonomously developed over the past six months in collaboration with the Department of Mechanical Engineering at the University of Padua (Italy) in partial fulfilment of the Master of Science degree in Mechanical Engineering. It will also be presented to the Polytechnic University of Catalonia (UPC) for the Master of Science degree in Industrial Technologies Engineering.

There are no advance technical requirements for the reader, as far as basic knowledge in the areas of mechanics and dynamic simulations.

ABSTRACT

This thesis project aims to study a particular model of rear suspension for mountain bikes called BRAIN, developed by the brand Specialized. Unlike traditional mountain bike suspensions, the BRAIN system was designed to solve a common issue that cyclists experience when riding a full-suspension bicycle: the loss of pedalling performance caused by unnecessary compression of the rear shock absorber. The system can distinguish inputs from the ground (i.e. ground vibrations) and from the cyclist, and it adjusts the suspension accordingly to allow greater pedalling efficiency and comfort.

To do so, the BRAIN system adjusts the rear shock absorber's suspension based on the riding conditions by activating or deactivating a valve system that controls the activation of the rear suspension. In easy words, when the bike moves on smooth terrain, the BRAIN system closes the valves, keeping the suspension rigid and allowing for efficient transmission of maximum pedalling power. However, when the bike moves on rough terrain with obstacles or bumps, vibrations open the valves and allow the suspension to activate and absorb the impacts, fulfilling the purpose of the suspension itself.

It is important to note that the BRAIN system acts like a purely mechanical sensor and does not include any electronic control system. It relies solely on a fully mechanical system that uses oil, a valve system, and a piston. This is an important aspect because electronic suspension control systems are prohibited in many mountain bike competitions.

In this project, dynamic simulations of the BRAIN suspension are carried out using Adams software, comparing the performance of the BRAIN suspension to that of a traditional mountain bike suspension. This study is purely simulation-based and it aims at providing results for a preliminary assessment of the BRAIN suspension's performance and potential benefits, and finally debate about its feasibility for application in off-road motorcycles. Further research and testing would be adequate to validate the simulation results and fully explore the practical application of this technology.

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1. INTRODUCTION

Over the last decades, mountain biking has become an increasingly popular activity worldwide, with more people seeking adventure and thrills on off-road trails. Together with the evolution of the sport, so has done it the technology used in mountain bikes, specially focusing on the study of the suspension systems or shock absorbers. These systems are a basic feature for providing a smooth and comfortable ride, as well for absorbing the shocks and impacts that the rider can encounter on a rough terrain. Accordingly to the suspensions' characteristics, time response and efficiency, they can be the key factor in a competition for gaining a few seconds and winning the race.

1.1. PROBLEM OF STATEMENT

Mountain biking is a demanding sport that requires a combination of skill, strength and endurance. Riders must face multiple challenges in a riding, like going through unpredictable terrains, such as steep inclines, rocky descents or tight turns. However, one of the most significant and shared issue for a mountain bike rider is the **loss of pedalling performance caused by the activation of the rear shock absorber.** This problem arises when the rider applies force to the pedals while accelerating or climbing on a smooth terrain, and the rear suspension compresses unnecessarily. As a result, the suspension absorbs some of the energy that would otherwise go into moving the bike forward, leading to a loss of pedalling power. Overall, this loss is traduced in less efficiency of the riding, meaning more effort and more time required for the rider to complete the trail. In competitive mountain biking, this can lower significantly the possibility of winning the race.

This way, in a typical ride with a double suspension mountain bike, the rider:

- Has to accept the loss of pedalling performance in certain parts of the trail, due to the fact that the rear suspension is always active, with the implications and consequences attached to it
- May have the option to graduate the smoothness of the rear suspension manually from the handlebar of the bike, depending on the suspension system used. While this function ca be helpful and solve the problem, it also adds an extra responsibility for the rider, which may result in distractions or cause the rider lose focus from the pure riding.

1.2. SOLUTION AND MAIN FOCUS OF THE PROJECT

Nowadays in the mountain bike market, one of the most advanced suspension systems is the so called **Brain system**, developed by the brand Specialized, a leading brand in the mountain biking industry for almost 50 years.

This **Brain system will be the object of study in this project** for its innovative concept, particularities and benefits. It is a rear suspension system that aims at solving the loss of pedalling power caused by the activation of the rear shock absorber. To do so, it uses a specialized valve that automatically adjusts the rear suspension's activation based on the terrain's roughness and the rider's pedalling input. In other words, the Brain is able to activate and disactivate the rear suspension for using it only when necessary and not produce losses in the pedalling, distinguishing in that way between the inputs from the rider and the terrain, adding a new efficiency dimension to bicycle rides. In a simplified way:

- When the bike is rolling on a smooth terrain, the valve remains closed, which causes the rear suspension to remain rigid and only responsive to the rider's pedalling, without any kind of compression.
- At the moment the bike hits a bump, the valve opens, allowing the suspension to work under normal conditions and compress and absorb the shock, acting like a normal suspension.

This simple idea of automatically rigidizing and disrigidizing the rear suspension is what Brain's intelligent design allows. This enables riders to maintain their pedalling power and efficiency even on smooth terrain, giving them a competitive edge and enhancing their overall performance.

The main characteristics of the Brain system are:

- It is a fully mechanical system, where no electronic control systems are involved (which may be illegal in some competitions)
- It is completely automatic, which means the rider does not have to take control of anything and can focus on the riding and sorting out the terrain.

1.3. THESIS OBJECTIVES

The main purpose of this Thesis is to explore the mechanics and functionality of the Brain suspension system and its impact on mountain biking performance. For that, it will be simulated the system dynamically using MSC Adams software, from Hexagon, a leading software tool for modelling and analysing the dynamic of mechanical systems. In summary, the principal objectives of this project will be:

- ✓ Comprehend and study the Brain system.
- ✓ Create a functional dynamic model of a mountain bike in Adams, collecting data of all the parameters necessary to carry out the simulation to make it as realistic as possible.
- ✓ Study the benefits of the Brain system, executing dynamic simulations under different terrains and conditions.

Moreover, it will be discussed the scaling of the application of the Brain to off-road motorcycles, and so explore the potential for another application of the Brain technology, which has a total different dynamic from a mountain bike.

This study is purely simulation-based and does not intend to design a bicycle suspension system, but to provide results of the Brain suspension's performance and potential benefits and debate its possibility of application in off-road motorcycles. Further research and testing would be necessary to validate the simulation results and fully explore the practical application of this technology.

2. SUSPENSIONS SYSTEMS

2.1. STATE OF THE ART

In modern vehicles, suspensions are an integral part of the vehicle by **isolating the chassis from the road or terrain** in order to provide comfort, safety, and stability. A vehicle suspension system mainly consists of a combination of springs, dampers and linkages, as well as other components that work together, to absorb shocks and vibrations, allowing the vehicle to maintain contact with the road and providing smooth and controlled motion.

One of the key concepts in vehicle suspensions is the notion of **ride quality**, which is influenced by factors such as vibration isolation, stability, handling, and traction. Achieving optimal ride quality requires careful engineering and design considerations, including selecting appropriate suspension components, tuning their parameters, and integrating them into the overall vehicle system.

Vehicle suspensions can be classified into **several types based on their configuration**:

- Independent suspensions allow each wheel to move independently, providing better ride comfort and handling
- Dependent suspensions connect the wheels together, causing them to move as a single unit.
- Semi-independent suspensions combine features of both independent and dependent suspensions.

While the need of a suspension system becomes more critical as the speed of the vehicle increases, a wide range of vehicles make use of suspensions, including bicycles, cars, trucks, motorcycles, off-road vehicles and heavy-duty vehicles. For example:

- **Passenger cars** typically have independent suspensions in the form of MacPherson struts or double wishbone suspensions, while trucks may have dependent suspensions in the form of solid axles or leaf springs.
- **Off-road vehicles** such as **motorcycles** often have specialized suspensions designed to handle rough terrains and provide enhanced traction and stability.
- R**oad bicycles** typically have rigid frames and forks with no suspension, while **mountain bikes** have front and rear suspension systems to handle rough terrain. These suspension systems can be in the form of coil or air shocks, or a combination of both.

The **design and analysis of vehicle suspensions** involve a multidisciplinary approach, including mechanical engineering, materials science, and control systems. Suspension design parameters, such as spring stiffness, damping coefficient, linkage geometry, and kinematics, can significantly affect the performance and behaviour of the vehicle, including its ride comfort, handling, and stability.

The **requirement for a suspension system** is dependent on the type of vehicle and its intended use, and for every different type of vehicle, the suspension can have different requirements based on the design, weight, and operating conditions. For example, passenger cars and motorcycles are typically designed to operate at a wide range of speeds, from low speeds in urban areas to high speeds on highways. These vehicles usually have suspension systems to provide comfort and stability across the entire speed range, absorbing shocks and vibrations from the road.

2.2. SUSPENSION FUNCTIONS AND MAIN COMPONENTS

As it was already noted, the suspension system's purpose is to absorb road irregularities. Nevertheless, due to various operating circumstances, a vehicle's suspension must also meet a number of requirements with occasionally competing objectives. It is remarkable to highlight that all forces and moments between the vehicle's body and the ground pass through the suspension system, which connects the two of them. So, a **vehicle's dynamic behaviour** is directly influenced by the suspension system.

The functionality of a suspension system is commonly approached by engineers with the following **key concepts**:

- → **Ride Comfort**: suspension systems are primarily designed to provide a comfortable ride for passengers by isolating the vehicle from road irregularities. They absorb and dampen energy from bumps, potholes and other obstacles on the road, reducing the transmitted vibrations and impacts to the vehicle and its occupants, and so increasing the riding comfort.
- → **Vehicle Stability**: suspension systems also play a crucial role in maintaining vehicle stability. They help to keep the tires in contact with the road surface, providing traction and preventing skidding or slipping. They help to distribute the vehicle's weight evenly among all the wheels, optimizing tire grip and improving stability during cornering, braking, and acceleration.
- → **Handling and manoeuvrability**: suspension systems influence the handling and manoeuvrability of a vehicle. They determine the vehicle's response to steering inputs, helping to maintain control and stability during cornering and manoeuvres. Suspension systems also affect the vehicle's roll, pitch, and yaw motions, which impact its overall handling performance.
- → **Load Carrying Capacity**: suspension systems are designed to support the weight of the vehicle and its occupants, as well as any additional loads or cargo. They provide the necessary structural strength to withstand the vertical and lateral forces exerted on the vehicle due to its weight and external loads.

As shown in *Fig. 1*, in a general line, the basic parts of a vehicle suspension system are the mechanism, spring, shock absorber, bushing and tires:

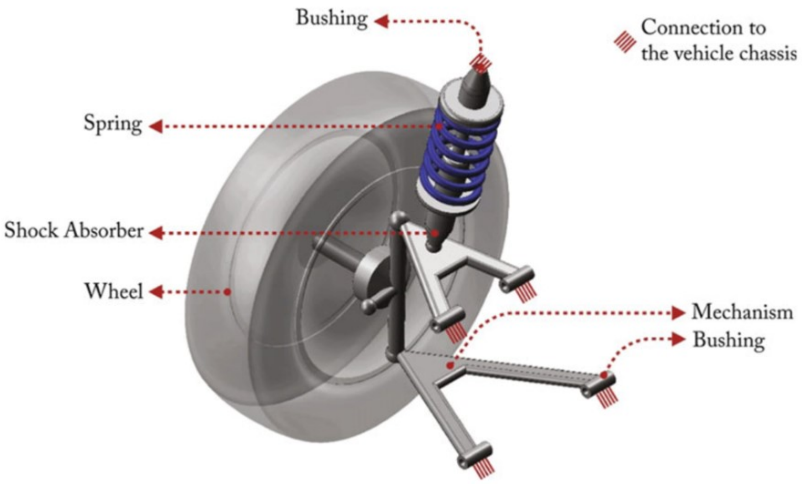


Figure 1. Main components of a basic suspension system. Source: [R1]

- **Mechanism**: one or more arms that connect a wheel to the vehicle's body make up the suspension mechanism. Between the vehicle body and the ground, they transfer all forces and moments in a variety of directions. Some of the suspension's most crucial properties are determined by this part. It establishes the wheel angles, suspension geometry and their corresponding relative motions. Wheel angle variation during suspension travel alters tire forces, which has an impact on the car's road grip and handling. A suspension system's mechanism is where most of its weight comes from. While light materials improve ride quality but are more expensive, using heavy materials in its construction reduces the quality of the ride.
- **Springs**: they are a fundamental component of suspension systems and are responsible for absorbing and storing energy from bumps and other road irregularities. They can be of various types, such as coil springs, leaf springs, torsion bars, or air springs, and provide the necessary compliance and flexibility to the suspension system.
- **Dampers**: also known as shock absorbers or shock dampers, they work in conjunction with springs to dampen the oscillations of the suspension system. They control the speed of the spring's movement, dissipate the energy absorbed by the springs as heat, and help maintain tire contact with the road surface.
- **Bushings**: they are rubber or polyurethane components that provide flexibility and damping in suspension systems. They are used in various joints and connections, such as control arm bushings, strut mount bushings and sway bar bushings, to dampen vibrations, reduce noise, and provide smooth articulation of suspension components.
- **Wheel tires**: they are a critical component of suspension systems, as they provide the actual contact point between the vehicle and the road surface. Tires absorb energy from road irregularities by flexing and deforming, providing additional cushioning and contributing to the overall performance of the suspension system.

2.3. MOUNTAIN BIKE SUSPENSIONS SYSTEMS

In this section we are going to focus our attention on bicycle suspension systems, and specially on mountain bikes, also known as MTBs. Mountain bike suspension systems are designed for off-road terrain to **make riding more comfortable and improve control by absorbing the**

impacts of the terrain, especially when riding over rocks, roots, and other obstacles commonly found in off-road trails. Specifically talking about mountain bikes, they are the number-one sold type of bicycle in the last years over Europe and US.

Mountain bike models can be equipped with just the front suspension or with both front and rear suspensions, and these front and rear shock absorbers are considered to be composed of an elastic and viscous element mounted in parallel, as seen in the next *Figure 2 and Figure 3*. Some bicycles have a **switch that allows the suspension to be turned off for a rigid ride**, which can be very useful but can also be a distraction for the person on the riding:

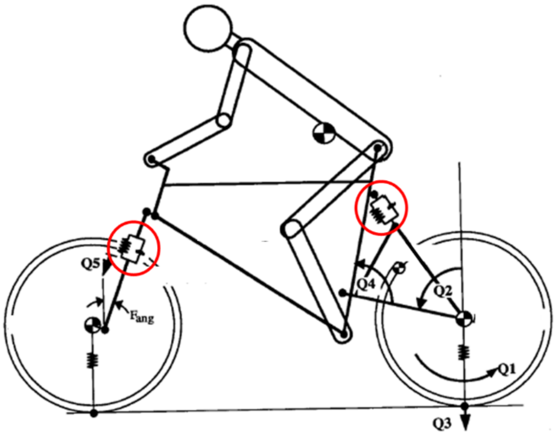


Figure 2. Dynamic modeling of the suspensions as spring-damper elements. Source: [R19]

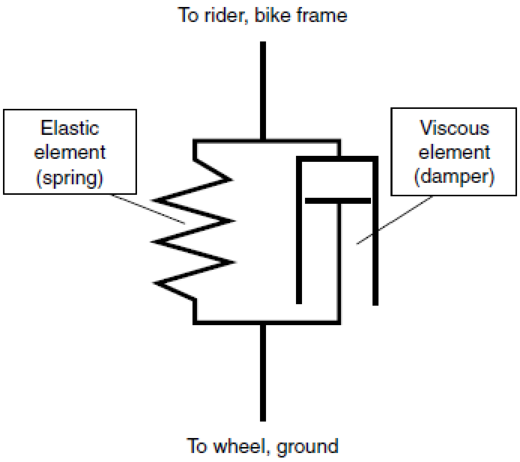


Figure 3. Components of a shock absorber device. Source: [R2]

For the upcoming simulation with Adams, the shock absorbers will be modeled according to these principles, as a spring-damper element in parallel. These elements have separate mechanical properties and can be adjusted according to the rider's preferences and the terrain they are riding on:

- The **elastic element** is usually a steel spring or air chamber that can be pre-constrained or inflated
- The **viscous element** is often a piston and cylinder chamber filled with oil that passes through orifices in the piston.

In general, mountain bike suspension systems are composed by:

- **Front suspension forks**: they are similar to those used in motorcycles, but typically smaller and lighter. They are attached to the front wheel of the mountain bike and provide vertical movement to absorb forces from the terrain. Front suspension forks typically contain springs and dampers to absorb and dampen impacts, vibrations, and forces from the terrain, allowing the front wheel to move up and down independently of the frame, helping maintain traction, stability, and control,.
- **Rear suspension shock absorbers**: they are typically used in full-suspension mountain bikes, which have both front and rear suspension. Rear shocks are attached to the rear triangle of the frame and the rear wheel and work in conjunction with the front suspension fork to provide a balanced suspension system. They absorb and dissipate forces from the rear wheel, providing damping to control the motion of the rear suspension. They help to minimize impacts, vibrations, and forces from the terrain, allowing the rear wheel to move independently of the frame and improving traction, stability, and control.
- **Linkages and Pivot Points**: Some mountain bikes use linkages and pivot points in their suspension system to provide a more progressive and controlled suspension ovement. These linkages and pivot points can alter the leverage ratio, damping characteristics, and travel of the suspension, allowing for better traction, stability, and control. Linkages and pivot points can be found in both front and rear suspension systems, and they are often used in higher-end mountain bikes designed for aggressive riding and racing.
- **Adjustments:** Many mountain bike suspension systems also come with adjustable features that allow riders to fine-tune the performance according to their preferences and the terrain they are riding. These adjustments may include compression damping, rebound damping, air pressure, and travel settings. Compression damping controls the speed at which the suspension compresses, while rebound damping controls the speed at which it extends. Air pressure adjustments are used in air suspension systems to adjust the stiffness or sag of the suspension, while travel settings allow riders to adjust the amount of suspension travel available. These adjustable features give riders the ability to customize the performance of their suspension system to suit their riding style, weight, and the specific terrain they are riding, providing optimal performance and comfort

2.3.1. MAIN FUNCTIONALITIES OF THE SUSPENSION

In essence, the primary functions of a mountain bike suspension system are:

- → To maintain continuous contact between the wheels and the ground.
- → To ensure that the **unsprung mass** of the bike (all parts not directly attached to the wheels) moves in the most rectilinear trajectory possible with respect to the ground.

The two key components of the suspension have its distinct purpose, and the combination of both functionalities provides the most optimal riding experience possible:

1. **The spring or elastic element** absorbs the energy that is produced during the displacement of the suspended mass, such as when riding over bumps or when experiencing inertia during acceleration or braking. A spring compresses more as the

load on it increases. Once the cause that produces the displacement has ceased, the spring returns the system to its initial position

2. **The damper or shock absorber** helps control the motion of suspension by reducing or preventing oscillations. Its purpose is to dampen or absorb the energy from the suspension's movement, and reduce the bouncing and oscillation that can occur when riding over rough terrain. It works by converting the kinetic energy of the suspension into heat energy, which is dissipated through the fluid inside the damper. While the travel of the spring depends on the force applied to it, the damping force of the shock absorber depends on the speed of travel. A shock absorber stiffens as the travel speed increases.

An important concept to keep in mind while working with suspensions is the so-called **SAG**:

- Definition: It is the is the amount of pre-compression in the suspension caused by the weight of the rider, so in that way, when the rider gets on the bike, the suspension compresses to a certain extent, the SAG.
- Quantifying the SAG: It is measured as a percentage of the total suspension travel and the optimal value for a rear suspension mountain bike can vary depending on the bike model, terrain type, and rider's riding style. As a general starting point, a value of 25-30% SAG can be used on rear suspension mountain bikes.
- Utility: It is used as a parameter to adjust and customize the suspension settings to optimize the bike's performance and comfort. Determining it properly is for:
  - Ensuring that the wheels **remain in contact with the ground**
  - **A**void losing traction when encountering holes or changes in gradient,

2.3.2. SUSPENSION GEOMETRIES

Suspension systems come in many forms, with rear suspension systems being particularly varied. Mountain bikes use very different geometries of rear suspensions to handle the rough and unpredictable terrain encountered on off-road trails. In this section, a brief explanation of the most typical geometries and its characteristics is made:

Figure 4. Different configurations: a) Single pivot, b) single pivot articulated c) virtual pivot d) Horst Link. Source: bikingpoint.es and others

1. **Single pivot suspension**
    - It is one of the simplest systems, given its few joints and elements for the rear shock system
    - The swingarm (in one piece) pivots around a single joint and directly attacks the shock absorber.
    - Wheel path is described as an arc of constant radius
2. **Articulated single pivot suspension**
    - It is based on the same operation of the Monopivote system but adding more joints
    - The swingarm rotates around a single pivot and indirectly attaches to the shock absorber, through linkages. It can have 4 or 5 pivots
    - In the same way, wheel path is described as an arc of constant radius
3. **Virtual pivot point suspension**
    - This configuration has become very popular. There is no main pivot (fixed on the frame) on which the swingarm articulates, rather it turns out to float in the air and changes place depending on the function. of suspension compression
    - The system is based on balancing the downward movement of the suspension when pedalling with an opposite upward movement of the same force and intensity, in such a way that the suspension would be neutralized
    - The trajectory of the wheel can be described as an S shape (due to the SAG and the movement of the suspension itself)
4. **Horst Link suspension**
    - In this rear suspension system, the shock absorber is in a vertical position and there are more articulations
    - The key to the system is the pivot located in the chainstay, in front of the dropout, called the Horst Link (designed by Horst Leitner and patented by

Specialized). This "breaks" the chainstay and therefore there is no longer a rigid arm between the main pivot and the axis of the rear wheel, giving mobility and independence to the rear wheel, especially the brake

- The trajectory of the wheel is described as a very open arc, almost vertical to the ground.

It is noteworthy to highlight that mountain bike design is a highly open science, and there are many other designs of rear suspension depending on the desired characteristics.

2.3.3. PROBLEMATIC OF THE REAR SUSPENSIONS

As it has been said along the project, bicycle suspensions are designed to improve comfort, handling and control of the bike by absorbing energy variations caused by terrain irregularities. They help to smooth out the ride by allowing the wheels to move independently from the rest of the bike. However, one of the most significant and shared issue for a mountain bike rider is **the loss of pedalling performance caused by the activation of the rear shock absorber in moments when it is not necessary**. This problem appears when the rider applies force to the pedals while accelerating or climbing on a smooth terrain, and the rear suspension compresses unnecessarily. As a result:

- The suspension absorbs some of the energy that would otherwise go into moving the bike forward, leading to a loss of pedalling power
- This loss is traduced in a **less efficient riding**, meaning more effort and more time required for the rider to complete the trail. In competitive mountain biking, this can lower significantly the possibility of winning the race.

This small and repetitive movements of the suspension are called **BOBBING**, and can be a concern for bicycle manufacturers and competitive cyclists in events where climbing or smooth terrain quick velocity riding is a significant factor. Overall, in actual modern system configurations, the benefits the suspensions provide are much higher than the losses, but it is still a factor to pay attention to. It is up to the riders to **compromise the comfort over performance**, changing the stiffness of the rear suspensions to have less bouncing but increasing the physical stress in the riding.

2.3.4. LITERATURE: LOSS IN PEDALLING DUE TO SHOCK ABSORBER COMPRESSION

To test the **effectiveness of different suspension systems**, many researchers have measured the amount of energy expended by cyclists. This can be relevant in high-load situations like climbing or sprinting, especially if there is interaction between the front chain-ring and the rear suspension.

Studies have shown that the power dissipated in the rear suspension represents only a small fraction of the total power developed by the cyclist, but not for that negligible. Quoting the deep research of *[R2]* Bicycle shock absorption systems - Henri Nielens and Thierry Lejeune it has been stated the research of other authors like:

- Wang and Hull *[R3]* found that power dissipated in the rear suspension was only 6.9W when cycling uphill at 6.5 meters per second (23.4 km/h) on a 6% grade smooth surface, which represents only 1.3% of the total power developed by the cyclist.
- The same author Wang and Hull *[R4]* studied the optimal rear suspension pivot point location in terms of energy loss minimisation. The vertical position of the pivot point was the most critical factor. Their model showed that power dissipated in the rear suspension could be reduced to 1.2W when the pivot point was positioned on the seat tube
- The study carried out by Karchin and Hull *[R5]* was based on 11 experienced cyclists who were ask to ride a bike at approximate 300W (6% grade on a treadmill at 24.8 km/h) in a seated and standing position, indicating power dissipation in the rear suspension was around 6.5W in the optimal position.

2.4. AIM OF THE PROJECT

To face this problem, it will be studied a particular rear suspension system called **Brain**, from the brand Specialized, which aims to solve the loss of pedalling power caused by the activation of the rear shock absorber. To do so, it uses a specialized valve system that automatically adjusts the rear suspension's activation based on the terrain's roughness and the rider's pedalling input. In that way, the Brain is able to activate and disactivate the rear suspension for using it only when necessary and not produce losses in the pedalling, adding a new efficiency dimension to bicycle rides.

In this study, the gain of the brain in comparison to normal suspensions will be quantified in terms of power and efficiency. However, it should be noted that the results may vary from the cited research, as there are many factors that may affect the results, such as the type and length of the terrain, as well as number of smooth, bumpy or climbing parts.

3. BRAIN SYSTEM

As it has been already stated, the Brain system is a damping technology that was created to solve a common problem among the bikers, which is the **loss of pedalling caused by the compression of the rear shock absorber** while pedalling, specifically in moments of sprinting in smooth or uphill terrains. This unwanted movements of the rear spring can be avoided with this innovative system, as it allows the suspension to act only when necessary and in a totally automatic way. As the creator brand Specialized quoted, "*it is called Brain because it does the thinking for you*"; as there is no need of control from the rider's side, avoiding possible distractions to the rider, who can focus entirely on enjoying the riding. Therefore, this technology will distinguish between the rider-induced shocks and those coming from the ground, ensuring that there is no energy wasted through the compression of the shock absorber.

For doing so, the mountain bike suspension system consists of **the rear shock absorber** (the rear suspension itself) and the **rear suspension kinematics** (the Brain), working in phase. It is important to remark that the rear suspension and the Brain technology are not together, as this last one is located in the rear wheel hub, but they are connected through an hydraulic connection:

Figure 5. Rear shock absorber and Brain technology in an Specialized mountain bike bicycle mode. Source: Specialized.

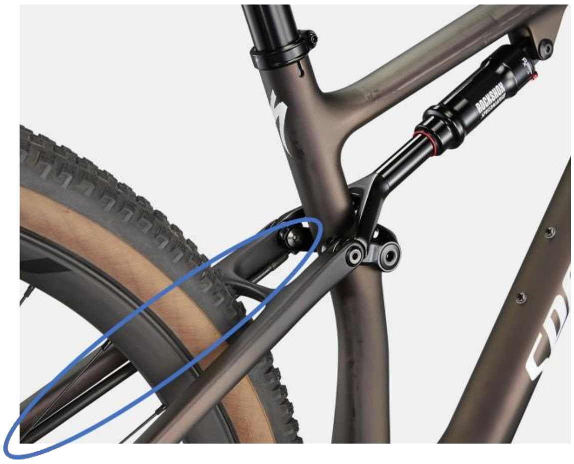


Figure 6. Hydraulic connection coming from the Brain. Source: Specialized and own

The main benefit of this system is that "it reads the ground", in terms that it is able to understand when the ground is smooth or bumpy, and choosing when to allow the rear suspension to act or not. This is made by a **system of valves**, that can control the compression of the suspension (opening and closing the suspensions accordingly). The Brain's inertia valve controls the flow of oil to the shock through these hydraulic connection, which is locked unless activated by a bump in the road. In easy words:

- When the bike is moving on smooth ground or while pedalling, the "Brain" system closes the valves, keeping the suspension stiff and efficient in power transmission.
- Instead, when the bike is moving over rough terrain, the vibrations open the valves and allow the suspension to kick in to absorb shocks.

Explaining deeply this connection, the Brain uses a specially designed shock that features a piston that moves in a cylinder, and it is equipped with two air chambers separated by a floating piston. In one of those chambers there is the so-called "Brain inertia valve", that adjusts the amount of oil that flows to the shock piston, being sensitive to ground vibrations, and the brass mass, that will stay in place when encountering a bump, allowing the flow of oil to the rear chamber. Looking at *Figure 7:*

1. In the beginning the oil is located in the top part of the Brain system
2. When encountering the bump, the rear wheel and consequently the Brain attached to rear wheel hub go up. The particularity of the brass mass is that it stays in place, allowing oil to flow from the top chamber to the rear cylinder.
3. In that moment the hydraulic connection will activate the suspension, and the compression of the air, due to the floating piston and the oil that has gone to the cylinder, will determine the damping of the suspension.
4. The moment the bump is no longer present, no more forces or vibrations from the ground will be applied, and the piston will push the oil forwards to the top chamber, blocking again the rear suspension (making it rigid).

Figure 7. Sectioned view of the Brain technology, where it can be seen the "brain valve" and the floating piston. Source: Specialized and own.

All this has occurred **because the input was coming from ground**, in which the direction can be assumed from the bottom to the top. Changing the direction of this input, and **supposing it comes from the pedalling of the rider**, it could be assumed that it goes from the top to the bottom. And **<u>here relies the main benefit of the Brain</u>**: in that situation the Brain will not activate the whole system as the valves will not open, the oil will not flow into the bottom chamber and the hydraulic connection to activate the rear suspension will not be realized. In that way, it eliminates the forces coming from the cyclist and can make the riding more efficient on smooth terrain.

Regarding **the location and size of the Brain**, as commented before and seen in *Figure 8*, it is normally attached into the rear wheel hub (precisely in the left side, for not bothering with the gears and the chain system). Proportionally to the wheel, the Brain unit is small and goes unnoticed:

Figure 8. Old version of the Brain, located in the rear wheel hub. Source: Specialized

Actual models of this system, in comparison to the previous image, provide a better small bump sensitivity through a lighter spring and inertia valve design, improving traction in cornering and grip in curves, as well as on climbs. Also, the suspension circuits have been combined seamlessly to ensure that the transition between them is smooth and predictable, increasing the comfort for the rider.

In this project, the modeling of the Brain will be based on one of the models that has this technology from the brand Specialized, the **Specialized EPIC Pro**, that will be shown further in the project (*Section 5*).

3.1. BRAIN SYSTEM FINAL CONCEPTS

Reassuming the key concepts of the Brain, which is purely a mechanical system, it:

- → Solves the loss of pedalling power produced by the shock compression, providing the benefits of both rigid and double suspension bike
- → Acts only when necessary and automatically, without the rider's intervention
- → It can tell the difference between the inputs from the rider and the trail, automatically adjusting the suspension accordingly

4. METHODOLOGY & CONCEPTUALISATION: DYNAMIC SIMULATION

Dynamic simulations have become an essential tool for engineers and designers to understand the dynamic behaviour of complex systems before they are built. These simulations enable virtual design testing and optimization, cutting down on costs and time spent on development while boosting performance and reliability.

ADAMS software, from Hexagon CAE simulation solutions company, is one of the most popular software programs for dynamic simulations, used in the automotive, aerospace, and other industries. It is a multi-body dynamics simulation software that allows the modeling and analysis of mechanical systems. It computes the dynamic behaviour of the system in response to forces, torques, and motions using a potent solver. Before investing in expensive physical prototyping, it helps engineers to quickly evaluate design choices and make judgments under a wide range of operating conditions. Additionally, it offers understanding of how systems behave under various operating settings and can aid in spotting potential design issues before they arise.

Furthermore, its user-friendly interface makes the modeling process simple, allowing engineers to rapidly and simply develop complicated models. It also offers a huge collection of pre-built components that shorten modeling time and enable the import of 3D CAD models from several software programs, including SolidWorks, as it will be the case of the project.

For the purpose of this project, ADAMS will be used to build and simulate a multi-body mountain bike, in its module **ADAMS View Student edition**. The student edition does have some limitations compared to the full version of ADAMS View, and understanding those was basic for approaching the simulation process, as it could become an obstacle for very complex systems. The key limitations are a maximum of 20 parts and 50,000 nodes allowed in the model, which can become a problem for complex systems. In that way, the model will be developed in an efficient but the most simple way possible, not exceeding on redundancies on joints or unnecessary geometries for the purpose of the project.

4.1. DYNAMIC SIMULATIONS OF SUSPENSION SYSTEMS

As already mentioned in previous sections, suspension systems are critical components of many mechanical systems, particularly in automotive and aerospace industries. Dynamic simulation:

- → Can provide engineers with insights into how the system responds to various forces, torques, and motion inputs
- → Can provide results of how it performs under different road conditions, loads, or speeds to optimize the design of the suspension system for improved comfort, stability, and performance. Different scenarios will be simulated in the project to analyse the response of the system
- → Can virtually test and evaluate different design options, with different configurations, such as different types of springs, dampers, linkages, or geometries, reducing the need for costly physical iterations and testing and ensuring its reliability performance in real-world applications.

5. 3D MODELING OF THE MOUNTAIN BIKE

After explaining the main issue of pedalling power loss in mountain bikes, we can proceed to develop a simulation model of a mountain bike to study the Brain application's performance and explore its potential and benefits.

To do so, it is necessary to have a model in CAD (Computer Assisted Design), assimilable by the software that is going to be used for the simulation, in this case MSC Adams View, in its student version. As commented before in *Section 4,* it is important to keep in mind the limitations of the student version provided by the university, such as the restriction to 20 rigid bodies and 50.000 nodes, as well as limitations on the number of joints. This can have a significant impact on the efficiency and accuracy of the simulation when working with the software, as it can bring some critic limitations.

Therefore, the model should be based on simplicity, trying to resemble a real bicycle but without unnecessary geometries or details for the aim of the project, so it is not very laborious to work with, for example, when simply loading the model or at the moment of simulating. We have to keep in mind that an unnecessary complex model will reduce the efficiency of the simulations, increasing the time of calculation and slowing down the study process.

5.1. APPROACHES FOR THE ELECTION OF THE GEOMETRY

The study will focus on the main mechanisms of a mountain bike with both front and rear suspension systems, with a particular emphasis on the interface between the model and the applied loads. To achieve this, we will use Adams software to analyse the complete dynamic behaviour of the system and determine the forces and accelerations acting on the components. Simulating the entire system is crucial to understanding the behaviour of each component and ensuring the robustness of the design.

The development of the model began by considering several options for choosing the right geometry of the system under study. After reviewing relevant literature, several options were identified to be potentially suitable for the study. These include:

1- In this first study *[R7],* the author evaluates the bicycle ride comfort with Adams and comparing it to a mathematical model. The study model in Adams was very simple, representing only the stiffness of the wheels and the front fork:

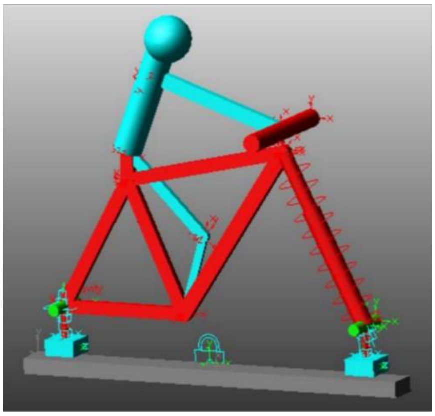


Figure 9. Bicycle model of study. Source: [R7]

2- According to *Carlos Franco Robledo – Bicycle analysis (Ansys-Adams stress)* **[*R8*],** the proposed model is a simplified double suspension bike, on which the principal objectives were those of simulating dynamically the bike to study the stress state approximation of the deformable bicycle frame (working together with Adams and Ansys). No models or technical data were available apart from the resuming slides of the project. We can observe that a real modelization of the person was included in:

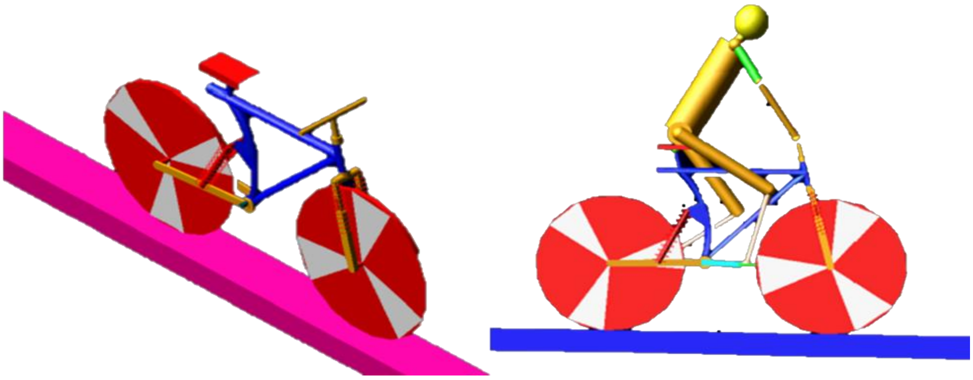


Figure 10. Bicycle model of study. Source: [R8]

3- In this other study, "Modeling and dynamic simulation of mountain bikes – Daniel Estevez Fernandez" *[R9],* the author's main objective is to study the behaviour of the rear suspension of a bicycle for different models and types of double suspensions bicycle's configurations, working together with Simulink and SimMechanics. The chosen geometry is made in 2D and extruded from a Sketch in Solidworks, resulting in the following geometry:

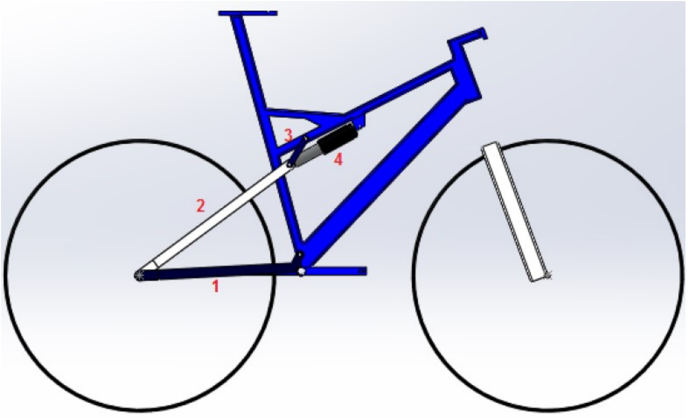


Figure 11. Bicycle model of study. Source: [R9]

4- After carrying out some research, a first simplified model was created in Solidworks to perform initial simulations and gain a better understanding of the software. The first model consisted of a basic frame and wheels, with suspensions added later to observe its behaviour. However, due to the model's limited range of movement, it was decided to make an upgrade of the quality of the model to better represent the actual bike and its movement:

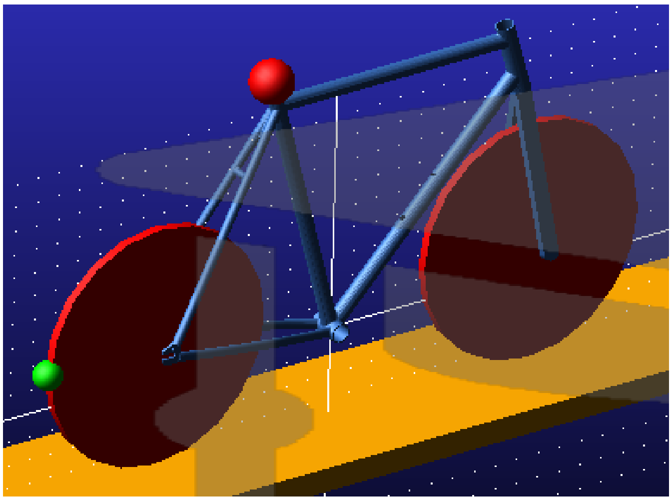


Figure 12. Simplified model of a bicycle. Source: own work

5- Finally, after a thorough analysis of many options, it was considered convenient a more realistic geometry, overall it was given importance on the rear frames attached to the rear suspensions. Be that as it may, it was taken as a reference the previously mentioned Specialized Epic Pro Model. The chosen 3D geometry is from the library GrabCAD (a freely accessible online CAD community), together with some geometries of own creation that will be specified in the next section, to resemble the official model. In the following images it can be seen the official Specialized model and the 3D model recreation used in the model:

Figure 13. Specialized EPIC Pro model. Source: Specialized

Figure 14. 3D model of the Specialized EPIC Pro used in the project.
Source: Grabcad and own creation

5.2. 3D MODEL DESCRIPTION

This section will provide a detailed description of the 3D simulation model. As commented in the previous paragraph, after analysing a big variety of options, it was considered appropriate to use the model that was most reliable to reality (to the reference Specialized EPIC Pro model), because it was prioritized to pay particular attention to the rear frames attached to the rear suspensions. The solution was a 3D geometry of a mountain bike from the online library Grabcad, a freely accessible online CAD community whose models can be used freely, together with some geometries of own creation that will be specified in this section. In the following *Figure 15* it can be seen the 3D model recreation used in the mode in another perspective:

Figure 15. 3D model of the Specialized EPIC Pro used in the project.
Source: Grabcad and own

The model is a basic version of a bicycle and does not include cables, callipers or brake discs, since the study and influence of this parts is not the objective of the project. It has also been considered that the model is symmetrical to avoid balance problems when performing the simulation. In the next sections it will be explained more detailed how the movement of the bike is created.

Given the multitude of rear suspension configurations used in mountain bikes until today, it was considered of vital importance to recreate realistically the mechanism attached to the rear suspension to the study model, because it will be directly connected to the Brain system and we shall try closely replicate the movement of the rear suspension system. In first instance, *Figure 16* provides a more detailed view of the rear suspension configuration from the official model. From this perspective, it can be seen the similarity in *Figure 17* between our 3D model and the actual mountain bike setup:

Figure 16. Rear suspension configuration of the Specialized EPIC Pro model. Source: Specialized

Figure 17. Rear suspension configuration of the simulation model. Source: Grabcad and own

The parts in study that were **personally modelled** are the attachments of the rear suspension to the principal frame of the bike and the rear shock absorber geometries. The absorber geometries connect directly the principal frame and the swing rear frame, so especial attention was paid into it. They are:

- The **black geometry**, which is attached to the principal frame
- The **grey geometry**, consisting of a cylinder+fork, that is the other part of the rear suspension and is attached to the top rear frame

In the next *Figure 18* a closer view of these parts can be seen:

Figure 18. Own creation geometries of the rear suspension. Source: own

In the *Annexes* of this project it will be included the detailed drawings of these parts, as well as the complete model of the mountain bike, to show their actual dimensions.

6. DYNAMIC SIMULATION OF THE MOUNTAIN BIKE

In this section it will be discussed some important aspects of the simulation of the bicycle model in Adams, including from the importing of the CAD to deeper concepts as the correct choice of contact parameters. The **correct simulation of the model was challenging** and took big part of the time dedicated to the project, but it gave better understanding of the model and its behaviour under different conditions. In Adams, if the user does not work with the accurate parameters in the model, even if it is a well-constructed model will not behave realistically.

Remarkable information or particularities of the model are that the rider was not modelled as a 3D geometry person, as it had no function but to add in the model the gravitational and inertial loads, so it was simplified as a simple geometry with the correct mass and inertia properties. Also, in the case of the front suspension, a total of two springs could be considered in both left and right sides of the fork, but it was reduced to one spring with the equivalent properties to simplify the model, which has the exact same behaviours. Every simplification possible, always considering that it has no effects on the results, has to be taken in account as it will avoid increasing the complexity of the model and so, increasing the calculation times, which can be very affected by parameter contacts. For instance, choosing a non-reasonable contact parameters can increase the required time calculation from 30secons to more than one minute, which can be relevant if many simulations have to be executed.

Regarding the **limitations** that had to be faced in Adams, the main challenge was to not reach the maximum number of bodies and nodes in the model. In the introduction of some particular CAD geometries, many nodes had to be used to define them due to its complex surfaces and the necessary geometry tolerances, and the maximum number of nodes was reached, preventing to add other elements such as the future Brain in the model. At that point, there had to be a restructuring of some parts that involved deleted mainly “aesthetic” geometries that had no function in the model

In general terms, to develop the model in Adams the following steps were taken:

1. Importing Geometry:
2. Defining masses and materials
3. Defining Joints:
4. Adding Springs and Dampers:
5. Adding a forces and moments
6. Addition of the mass and inertia rider
7. Terrain
8. Parameter contacts

6.1. IMPORT THE CAD IN ADAMS

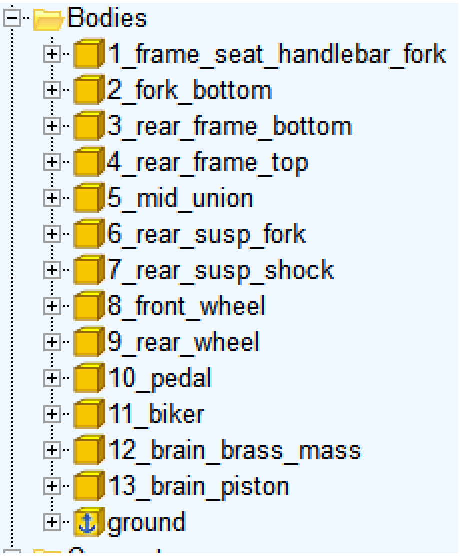
Having chosen the final geometry for the model, which was downloaded from the *Grabcad* library, a first “cleaning process” of the geometry was made, removing the unnecessary parts for the simulation. Some other minor modeling changes were made to the geometry before importing it to Adams. It was imported in Adams with the Parasolid format, which is a versatile choice used in many CAD softwares.

6.2. DEFINING MASSES and MATERIALS

When importing a CAD model into Adams, the software does not generate a centre of mass of the part automatically but only a kind of Markers called PSMAR (that relate only the geometry location, not any mass or inertia properties), for which an error will halt if a simulation is executed. In order to use the part in the simulation, it is necessary to assign the correct material, and is then when the software is able to calculate the mass properties of the part, including its centre of mass. It is remarkable to say that Adams uses the density and volume of each component to automatically calculate the inertia properties of the parts, which is a very useful resource from the software. It is of big importance of having a well-defined the centre of mass as it is used to calculate displacements, velocities, accelerations, forces, torques and other parameters of the part. There is fully customizability for imposing as well a particular mass or inertia properties, as well as the material density.

After assigning the correct materials to every part in the model, the **bike's weight was determined to be 9.3kg** including the wheels, which is a perfectly realistic value as mountain bikes vary from 9-12kg, and it was an indicator that they correctly defined. Special attention was dedicated to the densities of the materials chosen, as the inertia properties would be calculated automatically.

The system was close to reach the 20 limit parts, so some geometries that had a **fixed joint between them** (there were no relative movements between them) were put together under the same part, being the final parts:



Bodies
- 1_frame_seat_handlebar_fork
- 2_fork_bottom
- 3_rear_frame_bottom
- 4_rear_frame_top
- 5_mid_union
- 6_rear_susp_fork
- 7_rear_susp_shock
- 8_front_wheel
- 9_rear_wheel
- 10_pedal
- 11_biker
- 12_brain_brass_mass
- 13_brain_piston
- ground

Figure 19. Final parts of the system, including the future Brain. Source: own

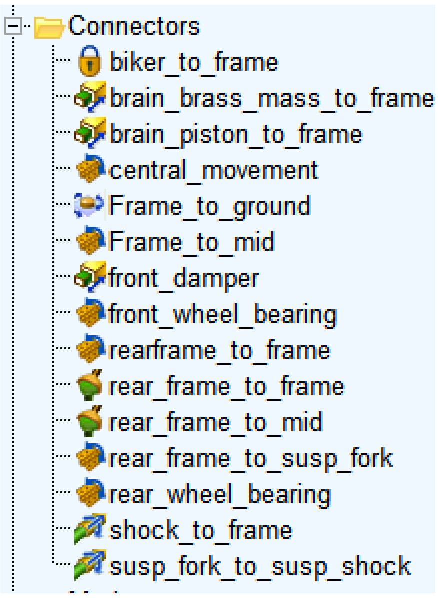
An example is part_1=frame_seat_handlebar_fork, that the same part includes all these four geometries. This efficient way to "save unnecessary parts" is useful but has the inconvenient that only one material can be used for the whole part. Without entering in too many details, the procedure followed so it was not an inconvenient to the mass and inertia properties, was taking into account the total masses of these bodies and generating a new material with a new density that could resemble the global properties of mass and inertia. In a normal version of Adams (not the student version) this procedure would have been necessary, as there is no limitation on the number of parts used.

6.3. DEFINING JOINTS

The following step is to connect the components and establish relations between them using joints, which basically will define how the components can move relatively to each other. The number of the joints used in the model can increase considerably the complexity of understanding of itself. Therefore, its definition has to be executed very precisely, as one single not-well-defined joint can result in completely erroneous results, even if the rest of the model is well-defined.

Important information about it, is that in the use of 3D models for 2D movements like in the case of the project, there has to be considered the appearance of movement redundancies, which can be critical in terms of properly defining the model. An analytical study should be conducted to identify which joints may produce problems and determine which other types of joints can be used to resolve them (tip: verifying the model can help giving this information).

Without entering into much detail about it, the joints defined in the model are seen in *Figure 20*, where there are joints of different types, such as: fixed, translational, rotational, in_plane



Connectors
- biker_to_frame
- brain_brass_mass_to_frame
- brain_piston_to_frame
- central_movement
- Frame_to_ground
- Frame_to_mid
- front_damper
- front_wheel_bearing
- rearframe_to_frame
- rear_frame_to_frame
- rear_frame_to_mid
- rear_frame_to_susp_fork
- rear_wheel_bearing
- shock_to_frame
- susp_fork_to_susp_shock

Figure 20. Final joints of the system, including the future Brain. Source: own

6.4. ADDING SPRING-DAMPERS

As the main purpose of the project is to study the Brain rear suspension, it is critical to properly define the spring-damper elements (and its parameters) that will be equivalent to the suspensions. Many time of the project was dedicated to the research of reference values of stiffness and damping for the suspensions, therefore it has been considered relevant to dedicate this section to it.

Reading in literature:

- The author in *[R13]* assumes values of stiffness-damping of (6.74 N/mm-0.186N*s/mm) and (47N/mm-1.10N*s/mm) for the front and rear suspension, respectively.
- On the other side, in *[R7]* the author gives a value of 29.8N/mm for the front fork stiffness.

- In [*R18]* the author does not give a front stiffness value, but quantifies the front damping as 0.975N*s/mm, and the rear stiffness as 73.9N/mm.
- The author in [*R19]* considers the values of the front suspension parameters of 73.6N/mm and 0.0078N*s/mm.
- Finally, a very useful resource was considered to ask to people that worked or had worked with bike suspensions. Specialists in the topic, considered reasonable values ranges of [5-30] N/mm for the front stiffness and between [40-90] N/mm for the rear stiffness.

Be that as it may, and seeing the high variability of the ranges studied, it was considered convenient to start simulations with a value inside a particular range, and precise later an exact value seeing the behaviour and the displacements of the simulations of the model. The chosen ranges were:

- Front suspension: stiffness [5-30] N/mm and damping [0.05-0.5] N*s7mm/mm
- Rear suspensions: stiffness [40-100] N/mm and damping [0.1-1] N*s

The precise and accurate values of this will be determined in *Section 6.10.1.3-SAG.*

6.5. ADDING FORCES AND MOMENTS

Many attention was given to this section, because choosing properly the forces and moments that will act into the model will be a critical parameter for getting the most real and desired results. The forces present in the model, apart from the vertical gravity, are:

- Aerodynamic resistance force
- Spring forces
- “Finecorsa” force (limit switch)
- “Coppia motrice” (driving torque) and pedalling force
- Extra vertical forces on the pedalier

6.5.1. AERODYNAMIC RESISTANCE FORCE (DRAG)

Adding drag forces in a dynamic simulation model is important because it helps to obtain a more accurate prediction of the system behaviour. Drag is a force that opposes the motion of an object through a fluid, such as air or water. In systems such as vehicles, airplanes and other structures can be very relevant as it is a force that affects the speed, direction and stability of the motion. Drag force has been defined like:

$$F_{drag} = 0.5 \cdot \rho \cdot C_x \cdot A_{frontale} \cdot v_{body}^2$$

This force will be function of the velocity, and therefore not constant during the simulation, being the other variables constant:

- ρ is density of the fluid, in this case, the air
- C_x is the drag coefficient, which depends on the shape and orientation of the object (it has been assumed as 0.6
- $A_{frontale}$ is the projected area of the object, perpendicular to the direction of motion. It has been calculated and it is shown below.
- v_{body}^2 is the velocity of the object relative to the fluid (will change during the simulation, as it is an instantaneous variable).

The frontal area has been calculated projecting approximately the rider's and bike's area in a frontal plane:

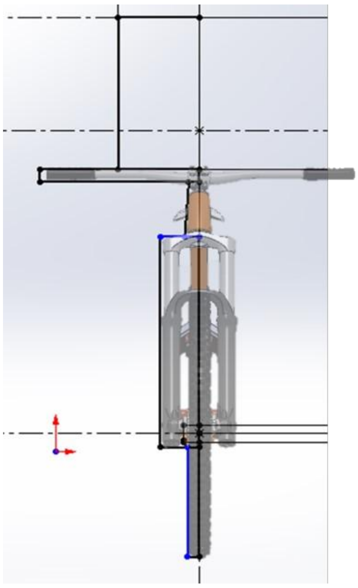


Figure 21. Projected area of the bike and the rider. Source: own

The total value calculated for this area is approximately $A_{frontale} = 0.5$ m^2 (it has also been added the projected area of the rider's legs and the pedals), noting that this value can vary a lot depending on many factors such as the position of the rider.

6.5.2. SPRING FORCES

As commented in previous sections, in the system it has been introduced a spring/damper element in each suspension to modelate the behaviour of the suspension. This is a useful resource from Adams, but due to the final scope of the project, in which the stiffness of the spring will have to be changed depending on the Brain's measures, it cannot be used as this stiffness or damping coefficient are constant variables, or at maximum defined by a Spline.

The solution to that is to introduce a force in Adams that represents the exact behaviour of the spring, in which we will have more freedom to apply functions in the future and "play" for rigidizing and disrigidizing the spring depending on the Brain. Be that as it may, the spring element has been disactivated from the model and the equivalent forces have been introduced.

Following the basic definition of the spring:

$$F_{spring} = -K \cdot x - c \cdot v$$

In Adams it has been introduced as the following formula, paying attention to the initial length of the spring and the chosen parameters, as well as the functions to represent the deformation and velocity deformation of the spring:

*-75.0 * [(DM(MARKER_437,MARKER_438)-136.0413907174)] - 0.75 * VR(MARKER_437,MARKER_438)*

Where *DM* returns the magnitude of the translational displacement from one coordinate system object to another and *VR* returns the radial (relative) velocity to one coordinate system marker from another, being 75N/mm the stiffness of the spring, 0.75N*s/mm the damping of the spring and 136mm the adjustment of the initial length of the spring.

6.5.3. "FINECORSA" FORCE (LIMIT SWITCH)

An important requirement in the bicycle suspensions is that they have a displacement or travel limit. The suspension can compress up to an specific distance, but not further than that. If more force is applied to the spring once it has reached the travel distance, the spring is able to transmit forces but not to compress more.

Defining this travel limit in Adams was not an easy task in Adams, but after some research, it was finally found a function called **BISTOP,** which is a gap function with this functionality. Special attention was given to the parameters of the function. This is the example of the rear suspension travel limit, where it has been stablished a maximum possible compression of 50mm and traction of 10mm:

BISTOP[DZ(MARKER_358,MARKER_359,MARKER_359), VZ(MARKER_358,MARKER_359,MARKER_359) , -10.0, 50.0, 10000, 1.5, 10, 0.1]

6.5.4. "COPPIA MOTRICE" (DRIVING TORQUE) AND PEDALLING FORCE

Together with the **pedalling force**, the **driving torque** is a key parameter in the simulation, which can bring to many different results. To explain clearly the concepts about the driving torque:

- → It is the rotational torque created by the application of the pedalling force, which is applied to the pedals by the cyclist's legs to turn the chain and propel the bike forward.
- → It is calculated as the product of the force applied to the pedal and the distance from the pedal to the centre of the bike's crankset (or pedalier). It is important to clarify that the force is applied to both pedals.
- → The driving torque is an important factor in determining the speed and acceleration of the bike, as well as the **overall power output of the cyclist**, which will be one of the most important measures in our simulations.
- → This torque **is not constant**, as it varies to 0 from a maximum value. The pedals produce torque at different moments between them, being only the pedal that is moving down the one who realizes the torque (the they switch roles between the pedals). This means the torque that the pedals produce is alternately created between the left and right side of the bike. Regarding the value:
  - o It is at the highest value when the pedals are at 3 o'clock position and 9 o'clock position respectively (both horizontal), as the force is applied vertically downwards and there is "the maximum distance" between force and pedal crank.
  - o Alternatively, the torque is at its lowest value when both the pedals are vertical, or at the 12 and 6 o'clock positions, as the distance is the smallest.
  - o In resume, the torque is at its maximum and minimum value twice per pedal revolution. To represent that, and only keeping the positives values of the torque, it has been introduced in the simulation like:

Driving torque = -(2*200*175)**ABS(sin(360.0d * time*(Biker_rpm/60)))*

Where:

- The product *(2*200*175)* is the amplitude of the torque. 2 for both pedals, 200N is the force applied from the pedalling and 175mm is the length of the pedal crank.

- *Biker_rpm* is the number of RPM that a cyclist produces during the pedallings, or also understood like the frequency of the pedalling. It depends on lots of factors, as for example speed, terrain inclination, type of bike…etc. But as a general rule, average riders can hold up to 60-90rpm, while professionals can reach 100-110rpm. The value used in the model will be 90rpm, which is a skilled average rider.

Making reference to the mentioned **pedalling force**:

- → The amount of force that a cyclist can generate while pedalling depends on several factors: body weight, level of training, resistance of the bike, etc. So it is difficult to specify in one number.
- → Professionals cyclists can produce up to 600-700N of pedalling force in a high-intensity race. But average cyclists can generate a force around 200-400N. In this way different values of the pedalling force will be studied will be studied the simulations.

6.5.5. EXTRA VERTICAL FORCES ON THE PEDALIER

A force variable that will also be introduced in the model are the **vertical forces on the pedalier.** These are different from the pedalling forces, as they are an **additional contribution to the effort that the cyclist makes while pedalling**. To clarify:

- These forces are not from the cyclist's muscular action. They are generated mainly from the movements of the rider, in situations such as sprinting or an up-hill, where an extra effort is made by the rider in the pedalling.
- They can also be considered from the friction in the bottom bracket bearings or the possible elastic deformation of the bike frame.
- They can affect the efficiency and comfort of the rider.
- These forces can increase significantly in situations of high efforts from the rider's side, such a sprinting situation or climbing steep hills.

These forces are considered important for the model due to this last reason, its increasing value in situations like sprinting, which we will want to evaluate with the Brain. Reading in literature, like in *[R16],* it is difficult to quantify them numerically, but an average acceptable range is about the 10-20% of the rider's weight. In the case of the model, where the rider will be 75kg, this means these forces can be up to 75-150N value. As the driving torque, they have been represented as:

100**ABS(sin(360.0d * time*(Biker_rpm/60)))*

6.6. ADDITION OF THE BIKER MASS AND INERTIA

The last necessary boundary condition is the cyclist's own weight. In this case, as the fully modelling of the rider is not important for the aim of the project, it has been decided to apply a simplified spheric mass in the key place where a cyclist would be in real life, adding the correct inertias of the rider. It is important to highlight that in a simulation like in this project, it is not necessary to model the real geometry of the rider, as it does not add any further information than the correct mass and its inertia properties in our dynamic simulation do. In that way, we are simplifying the model but having the same dynamic behaviour, not overloading it of unnecessary geometries that can decrease the efficiency of our study.

Searching in literature, several approaches were taken into account for deciding where to define the **rider's centre of mass**:

1. The first of them was according to a biomechanical study carried out by the *Ergocycling Iberica Institute [R11],* in which the weight of the rider is distributed between the bicycle seat and the handlebar. In this article, the seat supports 60% of the total weight of the cyclist and the handlebars the remaining 40%. Therefore, considering the average weight of an adult man at 75 kg, the distribution would consist of:
    a. 60% x 75kg = 45kg of weight applied as a punctual mass in the seat
    b. 40% x 75kg = 30kg of weight applied as a punctual mass in the handlebar

2. The second approach, and the one that is going to be used in the project to modelize the rider of the bicycle, is to determine the approximate position of the centre of mass of a bicycle rider when is in seated position, as the author does in *[R13] Simulation and Control of a Suspension Semi-Active: Case of a Downhill Bike, Aguilera-Cortes & others*. This method, is equivalent to the first approach because, as it can be seen in *Figure 22*, the centre of mass of the rider is slightly moved towards the seat respect to the handlebar. In that way, getting as the origin reference the contact point of the rear wheel of the bike, the centre of mass is located in CM=(0.378, 1.196) meters, taking in account that the Z-coordinate is 0, due to our model will be working in the XY-plane. We can contrast the similitude of the dimensions with the *Figure 22* and our model, seeing that the distance between the contact points of the wheels in our model is 1.2m (very close to the 1.135m in the picture):

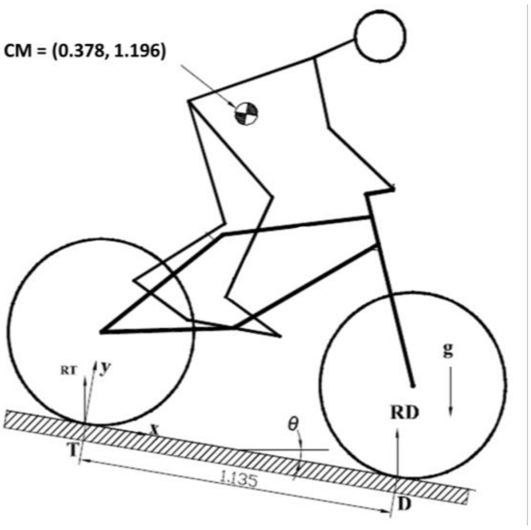


Figure 22.Schematic location of the centre of mass of the rider. Source: [R13]

In order to define the **inertial characteristics of the rider**, following the information given by the author in *[R17],* where an approximate number of 2500 people was measured, it has been considered the rider to be in a standing position, for which the inertias are:

- → I_{xx}=1.05e7 [kg x mm^2], being X the axis of movement
- → I_{yy}=9.7e5 [kg x mm^2], being Y the vertical axis from the ground
- → I_{zz}=1.12e7 [kg x mm^2], being Z the perpendicular axis to the XY-plane

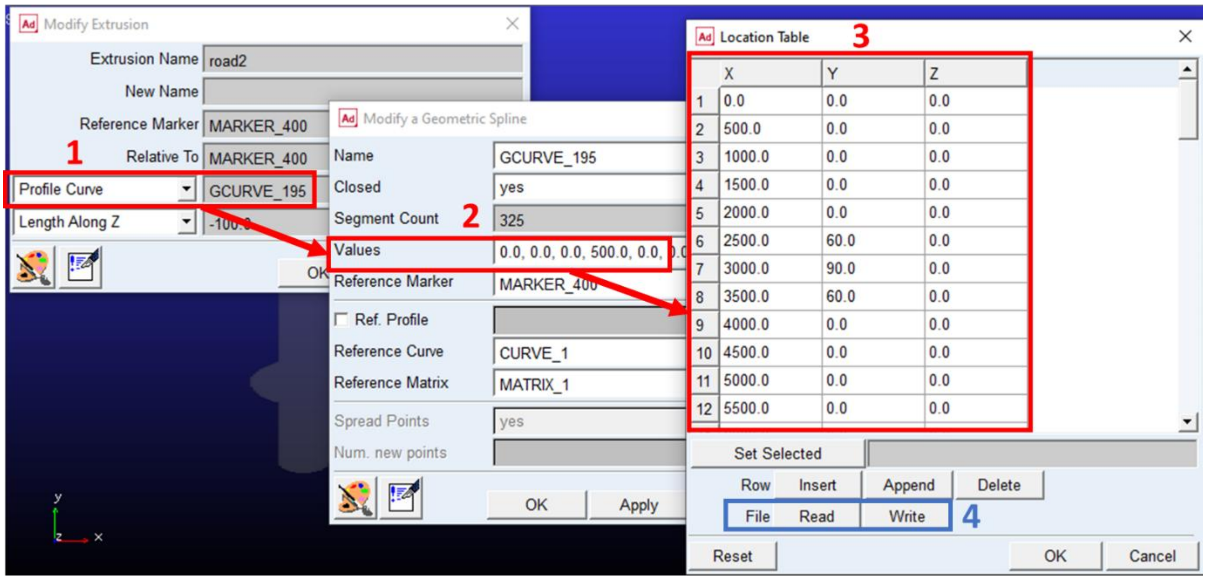
In that way, in the simulation both rider and bike will be like in *Figure 23*, where the rider is represented by the read sphere with the correct values of mass and inertia, and will be fixed to the frame of the bike:

Figure 23. Body and bike modeling in Adams. Source: own

6.7. TERRAIN

In the study case of the simulations, we want to test the suspensions of the bike against different type of terrains. We want the terrain to be totally customizable, in order to be changed easily to be able to carry out simulations with different shapes of terrains. To do so, the most effective way to simulate it is by an extrudable Rigid body (a profile which you can choose how deep to extrude in the Z-axis afterwards). The contour of this RigidBody will be defined by the an element called Spline, which are curves that are used to interpolate or approximate a set of data point. This data point will be defined by the user. In our case, the simulations will start by defining some totally smooth terrain, and the we will add bumps along the terrain. As it is totally customizable, the height and frequency of the bumps are totally up to the user's preference. In *Figure24* we can see the command RigidBody: Extrusion, and in *Figure 25* the process inside the menu of the extrusion. We will mark the profile will be defined by a curve, and then inside the curve we will choose the values. These values can be changed on the "Location table" by hand, or they can be imported as a .txt file from an external application:

Figure 24. Adams command of RigidBody/Extrusion. Source: own



Extrusion Name: road2
New Name:
Reference Marker: MARKER_400
Relative To: MARKER_400
Profile Curve: GCURVE_195
Length Along Z: -100.0

Name: GCURVE_195
Closed: yes
Segment Count: 325
Values: 0.0, 0.0, 0.0, 500.0, 0.0,
Reference Marker: MARKER_400
☐ Ref. Profile
Reference Curve: CURVE_1
Reference Matrix: MATRIX_1
Spread Points: yes
Num. new points:

	X	Y	Z
1	0.0	0.0	0.0
2	500.0	0.0	0.0
3	1000.0	0.0	0.0
4	1500.0	0.0	0.0
5	2000.0	0.0	0.0
6	2500.0	60.0	0.0
7	3000.0	90.0	0.0
8	3500.0	60.0	0.0
9	4000.0	0.0	0.0
10	4500.0	0.0	0.0
11	5000.0	0.0	0.0
12	5500.0	0.0	0.0

Figure 25. Process of customizing the Spline inside the Extrusion element menu. Source: own

To have an idea, in *Figure 25* we can see there is a bump created between the length 2500 and 3500mm of the terrain, that first elevates up to 60mm, reaches 90mm and goes down to 60mm and 0mm afterwards. That easy, is how we can create all the bumps we want, being more or less steep or "aggressive" to take for the suspensions.

It is remarkable to say that this Rigidbody has been included in the "ground_part", as this way, it does not count as a Part and we do not use of the available 20 parts available in Adams. As it belongs to the "ground_part", it will be fixed in space without the need of putting any restriction to it.

6.8. DEFINING PARAMETER CONTACTS

In Adams View, and while doing a dynamic simulation in general, defining the contact parameters properly is crucial because it directly affects the accuracy and reliability of the simulation results. These parameters determine the behaviour and interaction between two or more bodies in the simulation, such as friction, stiffness, damping, and collision response.

In this section, special attention will be given to these parameters, as **they were the initial reason for many troubles at the beginning of the simulations in the project**, and a lot of research time was spent to understand them. While defining the contact parameters:

- If they are not defined correctly, the simulation may produce incorrect results, such as unrealistic deformations or movements of the objects. In the initial simulations with the model, this was the reason why the system was not behaving well (there was extreme bouncing of the wheels it some occasions after passing over a bump). After much time spent on solving this, much more attention was paid into it.
- A correct definition can help to prevent numerical instability or convergence issues during the simulation, making it run more efficiently. And of course, it is essential for obtaining accurate and reliable simulation results in Adams view, and helps to ensure that the simulation behaves as realistically as possible.

In Adams, inside the contact forces, we can distinguish between **normal** and **friction** forces. As a general concept, contacts can be modelled as forces with 0 value when there is no penetration between the geometries and positive value there is penetration.

6.8.1. NORMAL FORCES

There are two types of predeterminate **normal** forces:

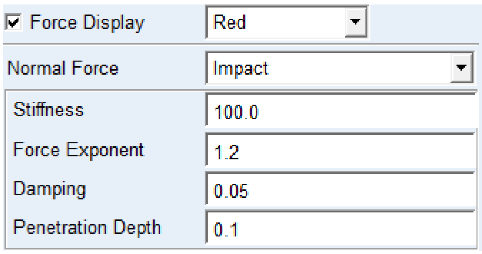
- → Restitution based: instantaneous impact modelling. Less effective numerically and computationally. Only used when there is no information about the other type of contact.
- → Impact based: continuous impact modelling. It is better numerically and results in faster simulations. It is assumed that contact elements are spring-damper elements that generate impact forces depending on the penetration between the geometry. It is based on the following formula, that includes a Hertz term and a damping:

$$F_n = kg^e + step(g,0,0,d_{max},c_{max})\dot{g}$$

Where:

- k is the stiffness
- g the gap function
- e is the force exponent
- c_{max} is the maximum damping coefficient at d_{max}
- $\dot{g}$ is the penetration velocity at the contact point.

The following values were used in Adams:



☑ Force Display: Red
Normal Force: Impact
Stiffness: 100.0
Force Exponent: 1.2
Damping: 0.05
Penetration Depth: 0.1

Figure 26. Values used in the model for the contact normal force. Source: own

It is essential to understand that, with this contact and the correct election of the parameters, **we are modeling the deformation of our tyre when in contact with the ground**. We are using the *Impact base model*, in which the elements in contact are assumed to be spring-damper elements. This approach represents the theoretical modeling of a deformable tire in contact with the ground. Although it is also possible to model the tire as **deformable solids**, some trials showed that this exponentially increased the calculation time and did not add extra results.

The **contact stiffness value** between a bike tire and a terrain can vary depending on the specific tire design, tire pressure, and terrain conditions. However, as a general guideline, the contact stiffness value for a bike tire on a typical road surface can range from 100 to 1000 N/m. According to several studies:

- → For example, a study published in the Journal of Sound and Vibration [R14] reported contact stiffness values ranging from 186 to 488 N/m for a 26-inch mountain bike tire on a smooth concrete surface.

- → Another study published in the Proceedings of the Institution of Mechanical Engineers *[R15]* reported contact stiffness values ranging from 100 to 550 N/m for road bike tire on a smooth asphalt surface.

As well as the **contact damping coefficient**, that can vary in a range of 0.01-0.05 Ns/mm. It has been chosen a high value of **0.05 Ns/mm** for not inducing too many vibrations in the contact.

For the other two parameters:

- → **Force exponent**: is used to define the nonlinear behaviour of the contact force as a function of the penetration depth. It determines how quickly the contact force increases as the penetration depth increases. A higher force exponent results in a stiffer contact response, while a lower force exponent results in a softer contact response. It is typically set to a value between 1.5 and 2.5, for which is chosen the value 1.5 (as we want a softer contact response).
- → **Penetration depth**: represents the distance that the two surfaces penetrate each other when in contact, and it affects the contact force calculation. The penetration depth can be set to a value that corresponds to the expected deformation of the surfaces in contact. As it depends on the specific application, a reasonable number has been set as 0.1mm (as higher values induced many vibrations on the contact).

6.8.2. FRICTION FORCES

The **friction** model used in the simulation is the **Coulomb** model, in which the user indicates a static and dynamic friction coefficient, as well as the values V_s and V_d, the stiction and friction transition velocity (where μ_s and μ_d are attained). Seeing it in the graphic:

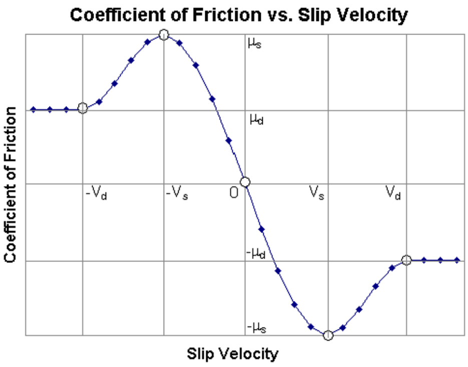
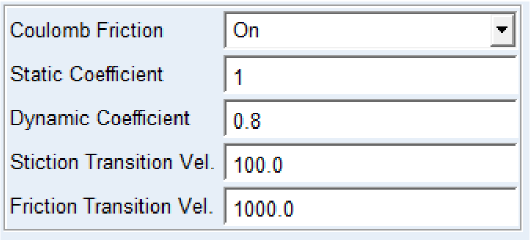


Figure 27. Representation of the Coulomb model. Source: Adams Help [R12].

Basing those values on general ranges commonly used in the tire-terrain interaction simulation, it is assumable to suppose the following ranges, noting that these values can be affected by many different factors:

- → μ_s = [0.8-1.2]
- → μ_d = [0.6-1.0]
- → V_s = [100-1000] mm/s
- → V_d = [800-1200] mm/s

And so, the values used in the model for the contact in both front and rear tyre with the terrain are:



Coulomb Friction	On
Static Coefficient	1
Dynamic Coefficient	0.8
Stiction Transition Vel.	100.0
Friction Transition Vel.	1000.0

Figure 28. Values used in the model for the friction contact force. Source: own

6.9. INITIAL CONDITIONS

In dynamic simulations, sometimes it is necessary to impose initial velocity conditions to the parts that move independently from each other**,** to ensure the good behaviour of the model. The decision to apply these conditions or not will depend particularly on the system and the simulation that is being performed.

In the case of the model, it was noted that when working with the Brain (where the spring is nearly totally rigid), the convergence of the calculus was much faster with just giving little velocities in the independent moving parts. In that way, angular velocities of 1deg/s were given to both and front wheels, and a linear velocity of 1mm/s to the frame of the bike in the moving direction of the bike.

6.10. FIRST SIMULATIONS

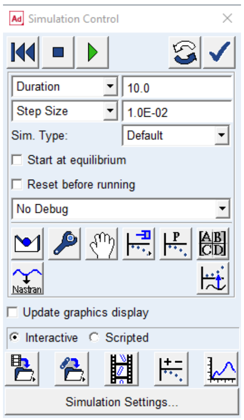
Once the model is correctly defined in Adams, we can proceed to carry on with the simulations. As commented in the previous sections, the main future scope of the simulations is to see the benefits of the Brain suspension. In this section, **simulations of suspensions without the Brain** will be carried to see how the model behaves in first instance and if all the parameters are correctly defined. In some cases, this was a process of trial/error in which several options and critical parameters were tested before of having the expected results, as the contact parameters that where refined this way.

<u>Assumptions</u>: before starting seeing some results, it is important to note the simplifications or assumptions made in the simulations. The main simplifcation are:

1. The whole **model will move in the XY-plane**, in other words, it will be a 2D movement. This was made with a Planar joint in the centre of mass of the principal frame of the bike. It is remarkable to say that some parts do have components of force or displacements in the Z-axis, but negligible comparted to the values in the XY-plane. This is because of the chosen joints of the model, which some of them have the degree of freedom to move in the Z-axis. They were chosen this way to remove the redundancies (as it is a 3D model that moves in 2D) and reduce computational complexity.
2. The **rider has been geometrically simplified**, adding its inertial properties, and **is fixed to the principal frame of the bike** (the rider's position and centre of mass do not change with respect to the frame of the bicycle). However, the pedalling forces made by the rider are included in the model. Other studies incorporate in their simulations rider movements that can affect the distribution of inertia properties and the centre of mass, but as this was not a primary objective of the current project, it was not included.

<u>**Type of simulation**</u>: it was valuated the most appropriate method for conducting the simulations. In Adams View, there are two ways:

1. **Interactive simulations**: quick and effective way to simulate. It will be the method used along the simulations, as it is the most effective way of simulation if there is no need of disconnecting or breaking joints (as well as adding or putting Motions and other elements) in the middle of the simulation. It is remarkable to comment that the user can choose the Duration and the Step size of the simulation (recommendable 0.01), and it is permitted the used of sensors:


Simulation Control

Duration: 10.0
Step Size: 1.0E-02
Sim. Type: Default
☐ Start at equilibrium
☐ Reset before running
No Debug
☐ Update graphics display
● Interactive ○ Scripted

Figure 29. Interactive simulation panel in Adams. Source: own

2. **Script-base simulations**: it allows greater control and flexibility over the simulation process, and can be used to automate repetitive tasks or complex situations. As such actions were not required, it was decided to use the *Interactive simulation*.

In the course of the simulations, **sensors** will be used to get particular data of action times. In the following sections it will be explained when and why. Simulations are carried out stablishing as a general rule time=10 seconds and a Steps_size=0.01. It will be studied with different terrain configurations, in which different parameters will be studied.

The **terrain scenarios** that are studied in the simulation are:

1. <u>Terrain 1</u>: smooth large terrain, that will be used for calculating all the initial results and refine some parameters, as well as a first scenario for the Brain.
2. <u>Terrain 2</u>: large terrain with different areas, with smooth and bumpy parts, to see the behaviour of the Brain in those conditions.

6.10.1. MEASURES

While simulating with Adams, one of the most potential features of the software is the big amount of parameters that can be measured. It is important to pay attention on measuring the correct variable and in the coordinates that we want (global or relative). When having decided which will be the final variables to measure, they will be calculated and stored in every simulation to be able to compare different curves in the Postprocess desk afterwards. In this case, the most interesting Measures that will be seen along the document will be:

a. Time to reach the end of the terrain
b. Velocities in the bike
c. Spring: deformation and forces

d. Pedalling power required by the rider to go along certain distance
e. Comfort, in terms of accelerations
f. Contact forces

6.10.1.1 NORMAL FORCES

Looking at the contact normal forces of the model, we can proceed to get some conclusions. The normal forces will be located in the contact points of the front and rear tyre with the terrain, assimilating a **punctual contact**. In reality, the contact between a tyre and the terrain is not just a single point of contact, but an **area of contact of small dimensions** (due to the deformability of the tyre). However, in many engineering applications it is assumed that this area of contact can be approximated as a single point for practical purposes, such as in vehicle dynamics analysis or tire design. This simplification is made possible by assuming that the tyre's contact patch behaves as a point contact, as the contact area can also vary depending on factors such as the tyre pressure, the terrain surface, and the load on the tyre.

Making a simple mechanical calculation of the static equilibrium of the bike in contact with the floor:

- → Total mass of the system: 84.3kg (equal to weight of the rider and the bike, which are 75 and 9.3kg respectively)
- → Coordinates of the centre of mass of the system: (40.72 , 732.43, 0) mm
- → So we can calculate the distances between the tyres and the centre of mass, as it can be seen in *Figure 30*:

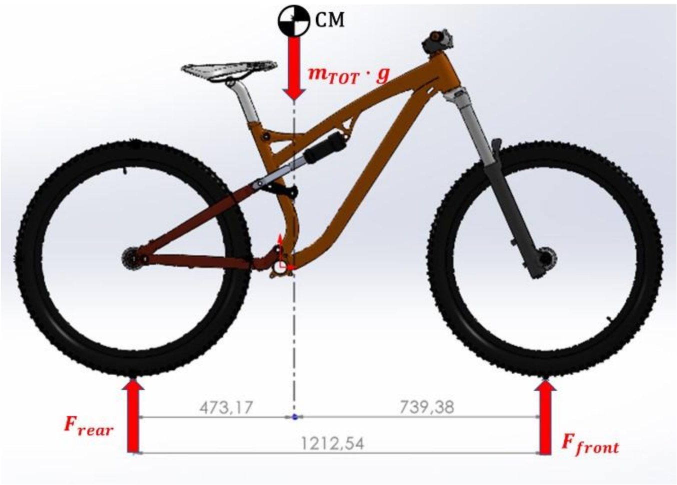


Figure 30. Force diagram of the vertical contact forces

Imposing the static equilibrium of forces and moments:

$$\sum F_v = 0 \qquad \rightarrow \qquad m_{tot} \cdot g = F_{front} + F_{rear}$$

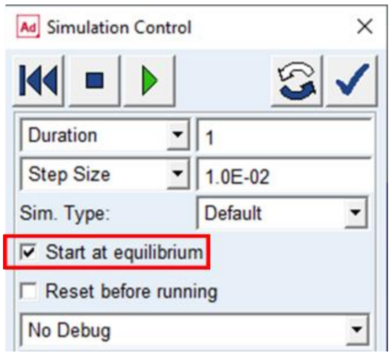
$$\sum M_{ext}(A) = 0 \qquad \rightarrow \qquad m_{tot} \cdot g \cdot (d_{rear}) = F_{front} \cdot (d_{rear} + d_{front})$$

With which we can calculate the forces (easy scenario, 2 unknown variables, 2 equations):

$$\boldsymbol{F_{front}} = m_{tot} \cdot g \cdot \frac{d_{rear}}{d_{rear} + d_{front}} = m_{tot} \cdot g \cdot \frac{0.47317}{1.21254} = \mathbf{322.71}\boldsymbol{N}$$

$$\boldsymbol{F_{rear}} = m_{tot} \cdot g - F_{front} = \mathbf{504.3N}$$

In order to do this in Adams, a short time calculation has been performed with the "Start at equilibrium" option enabled. By doing so, the user sets the initial position and orientation of the model in an equilibrium state at time=0, where all the forces and torques acting on the system are balanced and the system is not moving (stationary). This ensure that no pedalling torque or external forces other than the weight force of the mass and the reaction forces in the tires are applied. Then, the contact forces can be checked at time=0, as shown in *Figure 31*:



Duration: 1
Step Size: 1.0E-02
Sim. Type: Default
☑ Start at equilibrium
☐ Reset before running
No Debug

Figure 31. Start at equilibrium option in Adams. Source: own

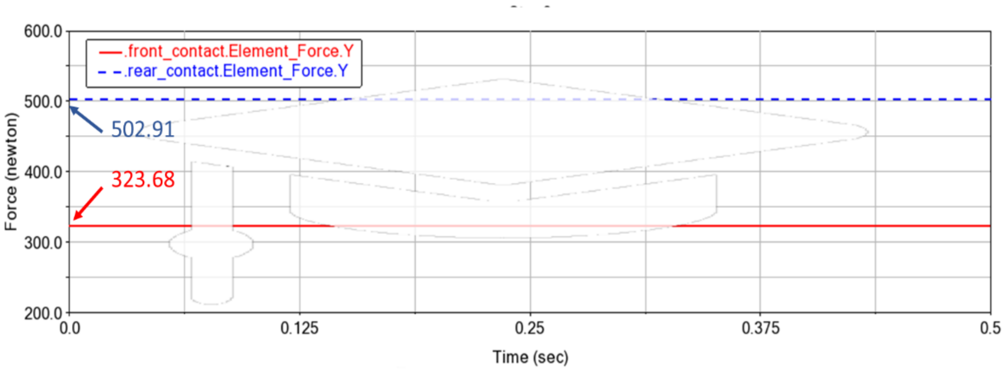


Figure 32. Front and rear static contact forces in Adams. Source: own

Comparing both values, it can be seen that they contrast with those calculated manually previously, with a maximum dispersion of 0.5% which is totally acceptable and means the system calculates properly the static equilibrium:

	front contact force [N]	rear contact force [N]
Manually	322.71	504.3
Adams	323.68	502.91
Relative error [%]	0.5 %	0.3 %

Table 1. Values of the rear and font contact forces analytically and with Adams calculated

This static force does not provide direct information about the accelerations experienced by the cyclist, but is only an indirect indicator of the loads acting on the bike, and it is clear to think the distribution of these forces will vary along the simulation, due to weight distribution or the simple fact that the wheels can get lost of contact in some points.

Tip: the total mas and centre of mass of the system were calculated using the option *Tools/Agregate Mass* in Adams, in which the user can select the parts to taking into account for it, and it was selected the whole model.

6.10.1.2 G-FORCES

In the study of each particular terrain, the **normal accelerations forces measured in G** (G-forces experienced on the mountain bike) will be studied:

- Contact normal forces. It is important to note that the measured contact forces are not necessarily equal to the accelerations experienced by the cyclist, as they can be attenuated or amplified through the bicycle components before they reach the cyclist.
- The references values for those can vary depending on factors such as speed and height of the bump:
  - A comfortable ride has accelerations smaller than 1G until the range of 1G-1.5G. Accelerations of 2G are considered uncomfortable and even painful to people.
  - In cases of high speed and a large bump can easily exceed 2-3 Gs (this means the rider experience a force of 2-3times their body weight in the opposite direction of gravity), being able to arrive to 4-5G.
- **Average force / static force**: Dividing the average contact force in a test by the static force that you measure gives the fraction of the total force that is due to the static load. The static load refers to the force exerted while the bike and the cyclist are at rest, only due to the weight of the cyclist and the bike. The resulting fraction can provide useful information about the additional dynamic load being exerted on the system due to acceleration and other external forces. High value means that the tire has good grip and can maintain traction on the ground, while low coefficient means the tire is more likely to lose traction.

G-forces can be physically demanding and may lead to discomfort and even injury if the rider is not prepared for it. In terms of security, for that it is very important a proper body position and balance on the riding.

Another common measure is the **acceleration of the centre of mass of the rider**, in particular the WBCII (Whole Body Comfort Index), which evaluates the cyclist’s comfort. It is defined as the square root of the sum of the squares of the accelerations in the three axes (x, y, z) of the centre of gravity. Factors that contribute to this comfort are contact forces with the bike and the ground.

6.10.1.3 SAG

With this same simulation where no torque or external forces are applied, we can also check the SAG (pre-compression in the suspensions because of the rider’s weight). This was a key step for **defining precisely the stiffness in our suspensions:**

- → As mentioned in Section 6.4, the literature indicates the spring stiffness for both front and rear suspensions can vary in a wide range, depending on several factors.
- → One key factor is the rider’s preferences and characteristics. Front and rear suspensions are customizable for the rider and how soft/hard wants the suspensions, and this has an impact on the SAG. Therefore, adjusting the stiffness of the suspension is a common way to adjust the SAG.

Starting with a value of stiffness inside the range considered in *Section 6.4*, the SAG was calculated, but either in the front or the rear suspension it was in the desired value of 25-30%. Iterating for different values, the stiffness was adjusted (always inside the range) until the correct value of SAG was achieved, for which the final stiffnesses that will be used in the simulation are:

	Front suspension		Rear suspension
	equivalent	single	
Stiffness [N/mm]	**20**	**10**	**75**
Travel limit [mm]	100		52.5
Spring static deformation	27.1		13.5
SAG [%]	27.1 %		25.7 %

Table 2. Final election of the suspensions stiffnesses depending on SAG

Note that in the case of the front suspension, in Adams we work with the equivalent spring of 10N/mm (which is equivalent to say we work with 2 equal springs of 20N/mm in parallel).

6.10.1.4 SPRING LEVERAGE RATIOS

With the initial simulations, the spring leverage ratios of the suspension have been assessed. While talking about **spring leverage ratios**:

- It refers to the ratio between the wheel travel and the amount of compression or extension in the spring that is used in a suspension system. In easy words, it is the measure that tells how much the suspension compresses or extends for a given amount of movement in the wheel.
- It is an important parameter to take into account in the suspensions, as an appropriate value is important for optimizing the performance of a bike's suspension system for different types of terrain and riding styles.
- Regarding the meaning of its values:
  - A high leverage ratio means that the wheel will travel further than the spring compresses or extends, resulting in a softer ride, but with less resistance to pedalling or braking forces.
  - A low leverage ratio means that the wheel will not travel as much, resulting in a firmer ride, but with more resistance to pedalling or braking forces.
- The typical general values for mountain bike suspensions are between 1.5 and 3 for rear suspensions, and between 1.0 and 2.0 for front suspensions, although again, these ranges can vary depending on the suspension system design.

In the simulation, as seen in the *Figure 33*, the values are 1.1 and 2 for the front and rear suspension, respectively. It is important to remind that virtual compression limits (travel limits) have been added to both suspensions, which are 100mm for the front and 52.5mm for the rear suspension:

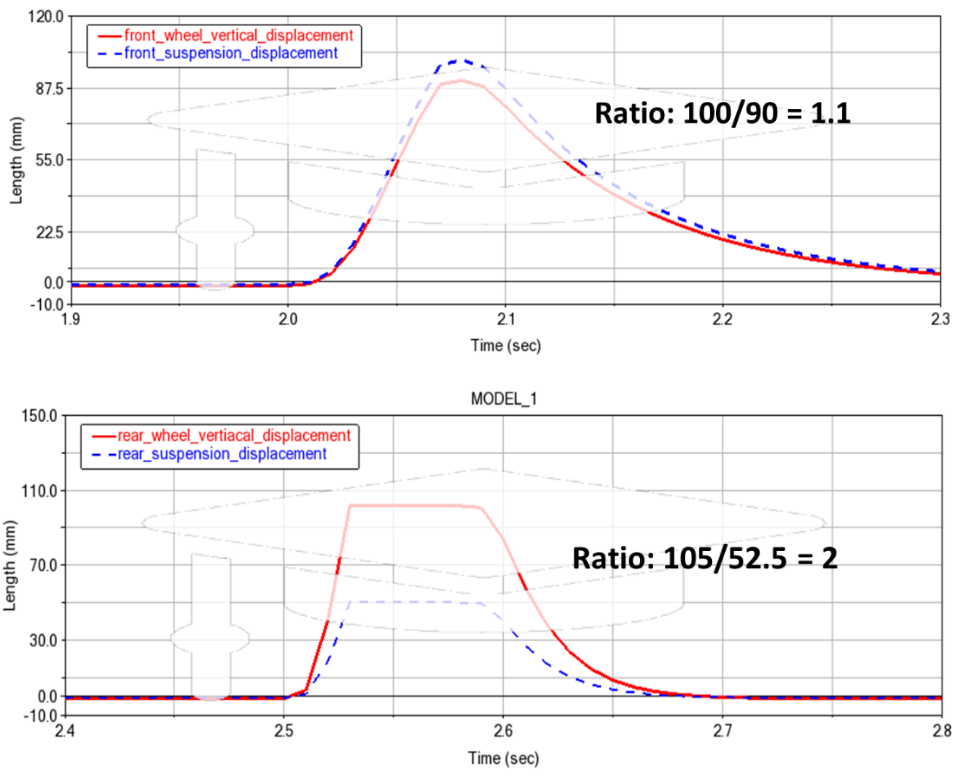


Figure 33. Spring ratios for both front and rear suspensions. Source: own

It is also important to highlight the trajectories of both front and rear suspension. In *Figure 34*, it has been represented in the software the trace mark of its relative trajectories, as a black line. In the case of the front suspensions it is straight line, as the joint between the fork system is purely a translational joint. In the case of the rear suspensions, the trajectory is an arc of circumference, as it can be practically assumed the articulation (rear_frame – frame) to be the instant centre of rotation:

Figure 34. Trajectories of both front and rear suspensions. Source: own

7. BRAIN APPLICATION IN MOUNTAIN BIKES

7.1. BRAIN 3D MODELING. APPROACH. SIMPLIFICATIONS (to finish)

Once the model with normal suspensions has been functionally modelized, it is time for deciding how to model the Brain system in the model. As it has been cited few times, the Brain acts like a “mechanic sensor”, relying only on a mechanical system, that includes a valve system with a fluid, oil, to activate and disactivate the rear suspension.

The **complete real modelation of the Brain**, including the physical dispositive itself, the valves and the fluid (the oil), was considered far beyond the objectives of this project, due to Adams cannot modelate a fluid in the simulation. It was evaluated to work together with a software like Matlab to modelate the behaviour of the fluid and introduce it in the system with a diagram block, but again, it was considered far beyond the project’s objectives.

The **solution** to that, was studying **which aspect of the Brain will be important for the application of the mode**l → it will be purely its functionality or “philosophy” as mechanical sensor.

A physical model of the system was created to resemble the dimensions of the actual system, as shown in *Figure 35*. No additional elements, such as valve models or oil, were included in order to prevent the system from becoming unnecessarily complex and to keep the simulations as streamlined as possible, while still providing accurate results:

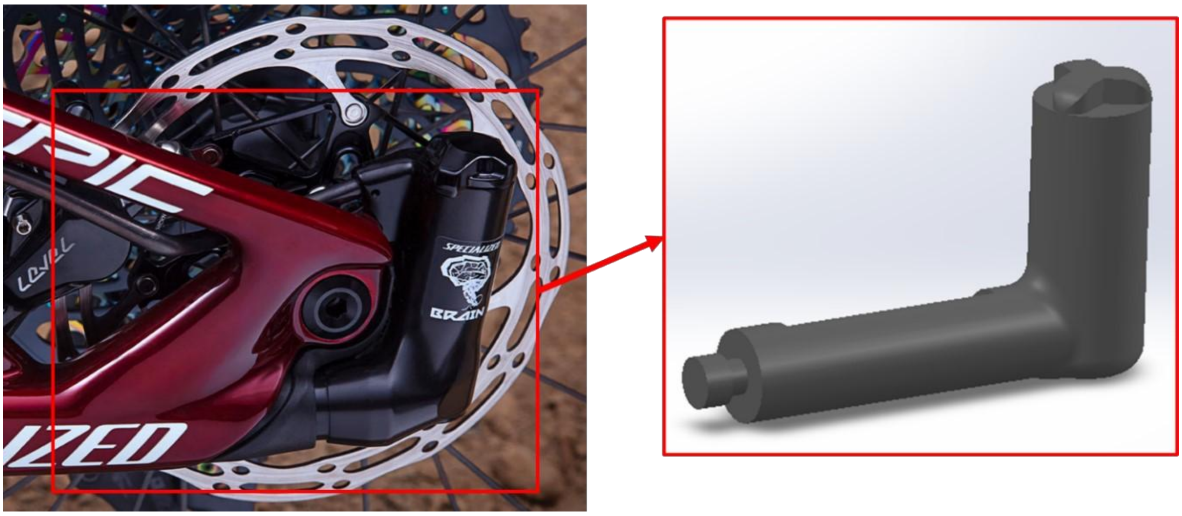


Figure 35. Real model of the Brain system and its 3D modelling for the simulation. Source: own

To appreciate the movements of the components inside the Brain in the simulations, such as the Brain brass mass and the piston, a section cut has been created in the Brain, as in the original picture seen in ***Figure 36***. In the picture below, it can be seen the real system with the section, and the modelled system attached into the bike:

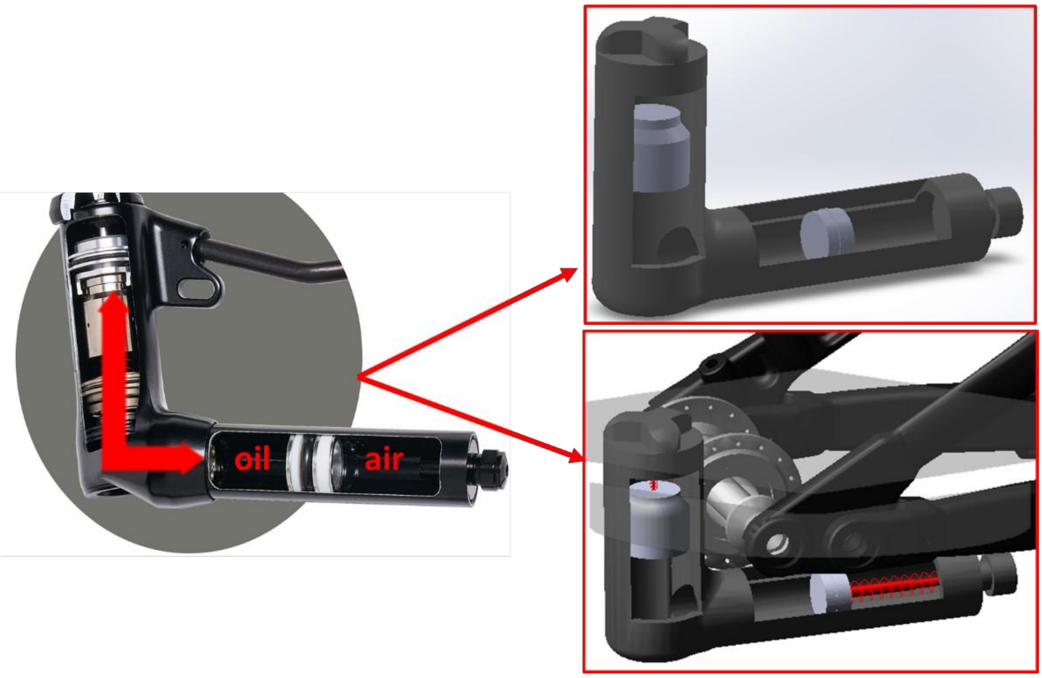


Figure 36. Real model of the sectioned Brain system, its 3D modelling and is location in the mountain bike model, attached to the rear wheel hub. Source: Specialized and own

The **attachment to the bik**e will be made "virtually" with a Fixed joint between the Brain and the rear frame of bicycle, as modeling the real attachment adds no extra information to the simulations. In the real model, this dispositive follows the movement of the rear wheel hub and is attached to the rear frame, which is the behaviour imposed in Adams.

It is important to note that the **hydraulic connection** with the valves will not be physically modelized, because there is no need of modeling this hydraulic connection physically, but with a sensor condition that will be added in the simulation (explained in the next Section 7.2).

In the end of the project, in ***Annexes***, where will be the detailed planes of these geometries.

7.2. APPLICATION IN MOUNTAIN BIKES SIMULATIONS

Once the modelization of the Brain has been introduced in the model, the next step to follow was to think how it would interact with the system of the bike, permitting to rigidize or disrigidize the rear spring. To do so:

- The Brain brass mass has a translational relative joint with the Brain "cover" or external part, so it can move vertically relatively to it.
- The **separation distance** of these two parts will be the key measure for the Brain. It is going to be called "*brain_sensor*":
  - When this value is below a particular number, the initial value with the static bike, it means the **Brain has not been activated**, no bump has been encountered for the rear wheel and therefore the rear suspension acts like a rigid one (as there is no need of the suspension to act).
  - At the moment the rear wheel goes over a bump, this value becomes bigger (admitting a certain tolerance or sensitivity to it) and will activate the Brain, permitting the rear suspension to act like a normal one.

When applying the Brain technology, in the process of **rigidizing the spring in the simulation**, that is the scenario where the bike goes through smooth terrains and does not encounter any bump or obstacle that activates the Brain, two approaches were considered:

1. The first one was consider **changing the cylindrical joint** between the rear fork suspension and the rear shock absorber **for a fixed one** every time the Brain was activated. This involves changes in the model's joints definition, which can only be approach with Scripts, and after some trials was not consider the most efficient way to do it.
2. The second one, and the one used in the simulation, was to **put a very high value of stiffness in the spring force**, so that it would act like an **almost rigid spring**. After trying different values of the rigid spring stiffness:
    a. It was observed that very high values difficulted a lot the convergence of the calculus
    b. After some iterations, a value for the rigid stiffness of 600N/mm was considered to be adequate. It is x8 times stiffer than the normal rear suspension, that is 75N/mm (600/75=8). This ratio was perfectly acceptable for considering the spring as rigid, although very little oscillations will be seen in the spring. In the worst scenario, in the normal suspension there is a deformation of almost 17mm against the 0.6mm for the rigid spring, which is totally acceptable.

To execute this second approach, different ways were tried, like using:

1. **SPLINES** for the spring forces
2. The **function IF**
3. The **function STEP**.

After trying the three ways, it was seen that the function IF could cause discontinuities in the derivatives of the function evaluation, and the integrator to decrease the time step size or fail, giving as well high peaks of accelerations. In that way, the function STEP was the one used for the scope of the Brain:

STEP(.Step2.brain_sensor, 30, .Step2.brain_spring_force, 35, .Step2.suspension_force)

Where *brain_spring_force* and *suspension_force* were the Measures equivalent to the spring force, while being almost rigid and the normal value of the rear suspension:

-600.0(DM(MARKER_435,MARKER_436)-136.0413907174)- 2.5*VR(MARKER_435,MARKER_436)*

-75.0(DM(MARKER_435,MARKER_436)-136.0413907174)-0.75*VR(MARKER_435,MARKER_436)*

That way, in the whole simulation the system will be evaluating the value of brain_sensor and depending on the result, if its <30mm it will take the first spring force (spring almost rigid) and if it is >35mm it will take the normal spring stiffness and damping. The difference between 30 and 35 was given to the system to take a softer changing of stiffness, as if it was very abrupt, peak forces could be observed in the system.

7.3. RESULTS: COMPARTISON WITH NORMAL SUSPENSIONS

In this section of the project, it will be **compared the viability of Brain suspensions with normal suspensions, and it is perhaps the most critical part of the entire study**.

By analysing the benefits of using Brain suspensions compared to conventional suspensions, it can be seen the potential advantages of this innovative technology. The expected results of the analysis may vary, but as a previous anticipation:

- → Brain suspensions will **outperform conventional suspensions in terms of pedalling power required from the rider**.
- → Due to the pedalling, spring deformations should be seen along the riding in smooth terrains with the normal suspensions, while with the Brain, this oscillations should not exist or be very small. In normal suspensions, this would be traduced in a reduction of the pedalling efficiency.
- → However, in terms of comfort or acceleration it is not clear the direction it will take.

Starting with the simulations, different scenarios of terrains will be used, and also with different simulation conditions, with different forces applied into the system.

Some times, if the system is complex or there are many inputs in the simulation, it is recommendable to **not activate the *Start at equilibrium*** option, as it can increase considerably the calculation time. In that case, an initial short simulation time will be dedicated to the system to stabilize, and will not be used as relevant data for the results (the first steps of the simulation will be “cut out” for studying the results). This approach was used in all the simulations, as in the case of the Brain, in the beginning the spring has a very high value of stiffness, and that induced particularities in the system. It is also remarkable to note that, as accelerations will be studied, in the it has been used the integrator ***GSTIFF*** with formulation ***SI2*** as solver settings, which is a better approach for the study of accelerations. After studying the results for different values of **error tolerance**, it was chosen an **error of *1e-2*** instead of *1e-3*, as it involves faster simulations with nearly the exact same results.

7.3.1. TERRAIN 1: SMOOTH TERRAIN

This is going to be the main scenario for understanding in first instance the benefits of the Brain. It will be basically a smooth road without any perturbation or bump on it, so there are no external effects that can difficult the basic comprehension of the Brain.

To make a complete comparative of the parameters that can have an influence on the behaviour of the Brain, it has been studied a comparation between the Brain and the normal suspensions combining pedalling forces of 100-200-300N and vertical forces in the pedalier of 0-100-200N, to see the direct relation of those parameters in the model.

The simulation with the different forces will always follow the same procedure:

- The bike will be accelerated until the maximum speed possible, where it will arrive into stationary conditions where the pedalling force and the aerodynamic force are equilibrated, oscillating through a value of maximum speed (this is because the pedalling is not constant, but goes from 0 to a maximum value). The time value of reaching the maximum speed will be calculated in every case.

- In all cases, the system will be simulated until 25 seconds. This was done in order to have two differentiate parts: the start and the max speed section. For studying the power given for the rider, 3 data will be collected to study if the Brain is more beneficial in one section or another:
    - In the start section, from 0 seconds until it reaches the maximum velocity
    - The maximum speed section, from the moment the maximum speed is stablished until the end of the simulation, 25 seconds
    - Total, from 0 seconds until reaching the 25 seconds

Many outputs were studied, being the most important the ones shown in the following images. In order not to add excessive number of graphics in the document, it will be shown an example of the curves measures for one case, of the Brain system with Pedalling=200N and Fvertical=100N, and the rest will be summarised in comparative tables:

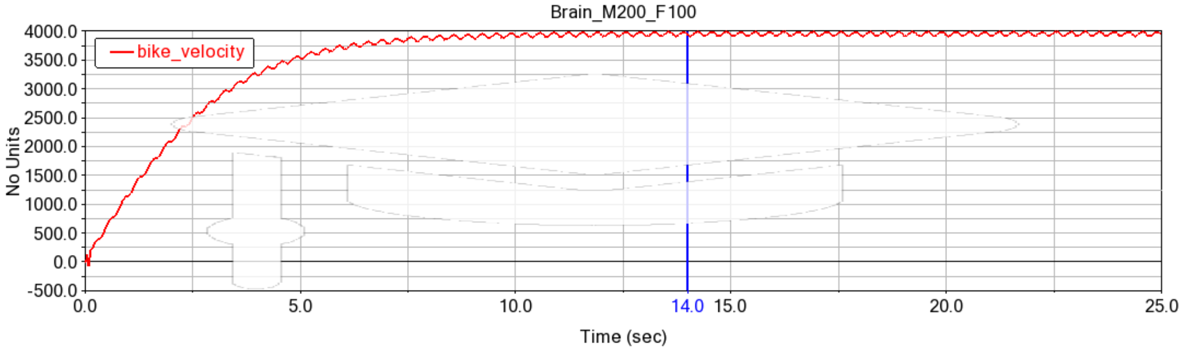


Figure 37. Velocity of the bike, case of Fpedalling=200N and Fvertical=100N. Stabilization velocity reached at 14 seconds. Source: own

Referring to *Figure 37*, where the bicycle velocity is plotted, it can be observed that the bike increases steeply in the beginning of the simulation and starts to stabilize when being closer to the maximum value, but always with an oscillational behaviour, as commented, because the pedalling is not constant. Finally, when reaching stationary conditions in which the force of pedalling (transmitted as the driving torque) is in equilibrium with the aerodynamic resistance force, the bike oscillates over an approximate value of 4000mm/s.

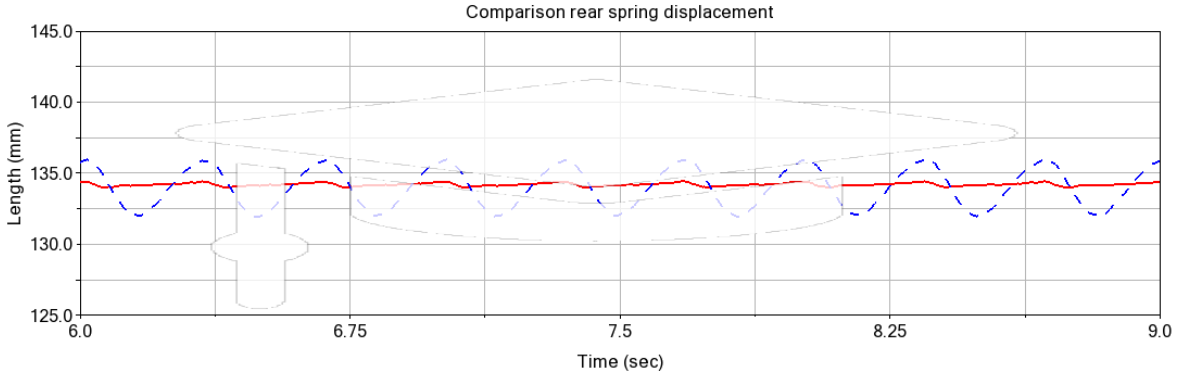


Figure 38. Comparison of the rear spring displacement in the case of Fpedalling=200N and Fvertical=100N. In red, the Brain system. In blue, the normal suspension system. Source: own

In *Figure 38*, it can be studied how the Brain system has a very small displacement of the rear spring (near to 0.5mm), as it has been “rigidized” if there is not any output from the terrain that activates the suspension. In the case of the rear suspensions, the spring displacement is about 4.1mm.

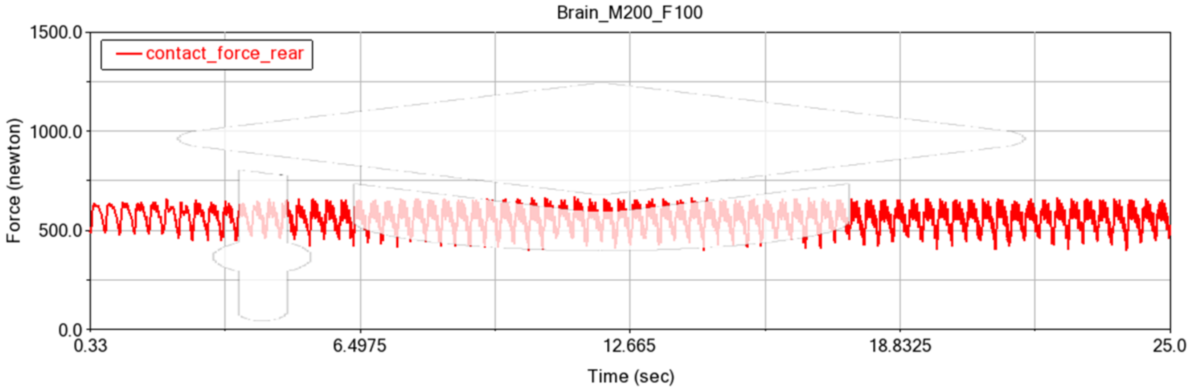


Figure 39. Contact force in the rear wheel. Average value of 558N (x1.12 the static value of 502.91N). Source: own

It is important to comment that the tyre geometry can have a crucial role in the shape of this graphic. The geometry of the tyre used in the model has the so called patterns that are designed to provide grid and traction on different surfaces. In the case of the model, these tyres have a stiffness defined with the contact but they are not deformable, so the software identifies “little obstacles” in contact with the ground, that can cause peaks in the normal forces. Nevertheless, these peaks are small and have not been considered relevant. One solution would have been used a simple cylindrical geometry

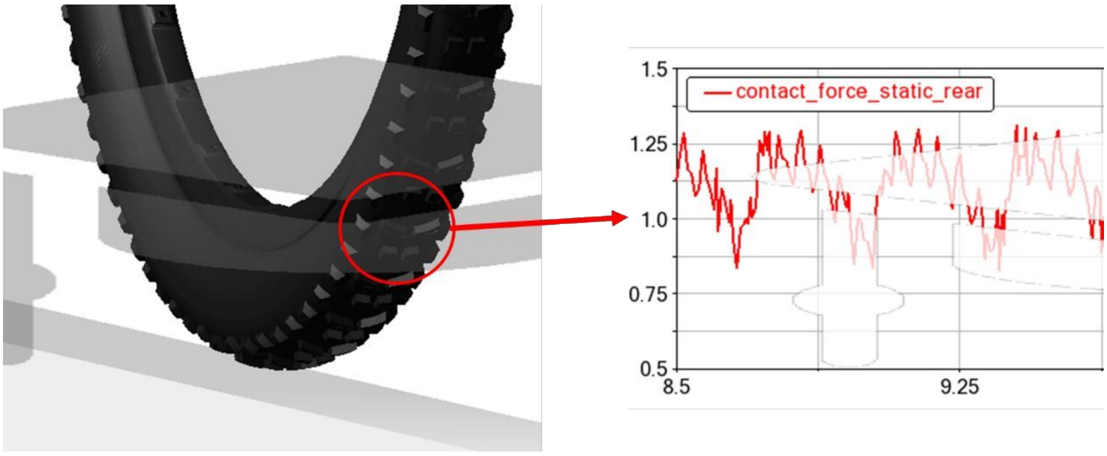


Figure 40. Representation of the tyre patterns and the curve associated to the rear contact force with the ground, divided by the static value of the rear contact force, to see the fraction of the force due to the static force.

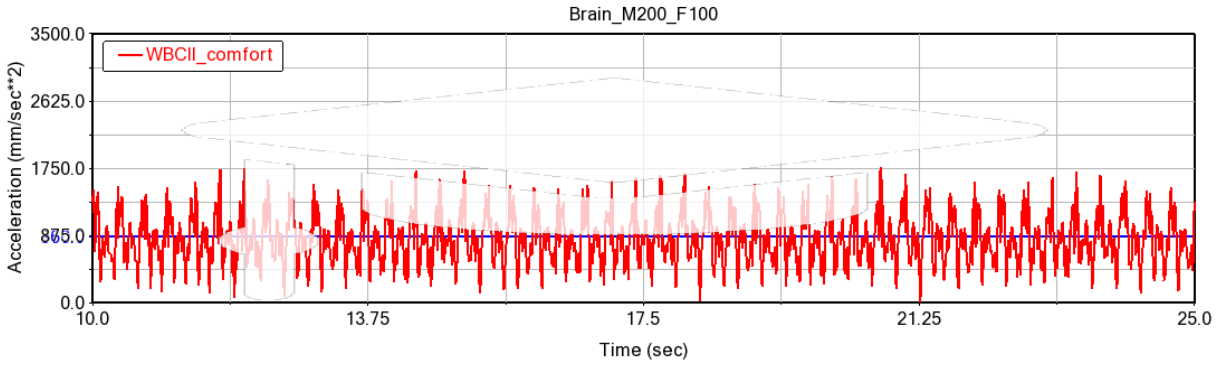


Figure 41. WBCII parameter of comfort. Average value of 0.86G, inside comfort standards. Source: own.

By the measure seen in *Figure 41*, the comfort of the rider will be studied, following the canons of WBCII explained in previous sections.

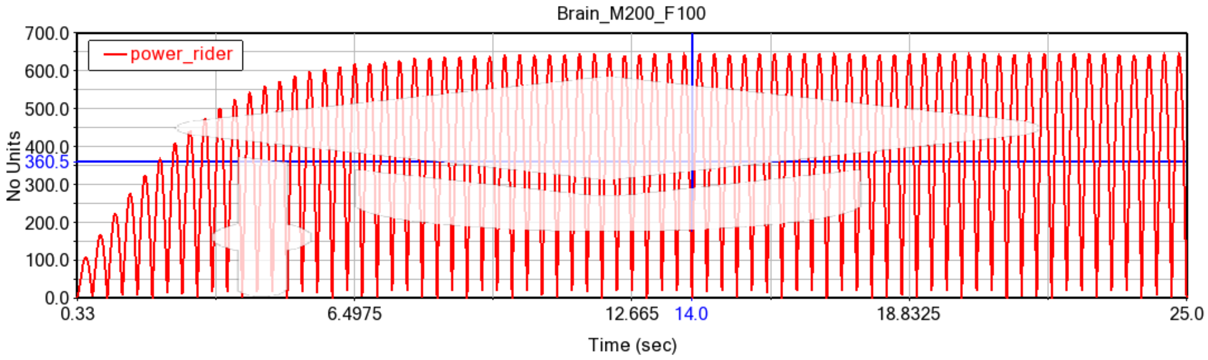
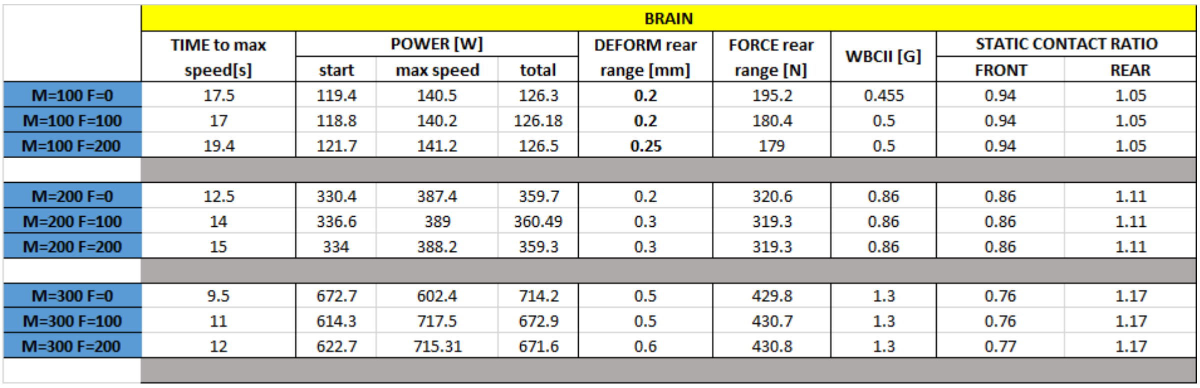


Figure 42. Power of the pedalling exerted by the rider. Source: own

In *Figure 42*, it is represented the **pedalling power exerted by the rider**. It will be one of the most important parameters to study in the whole simulations. To clarify:

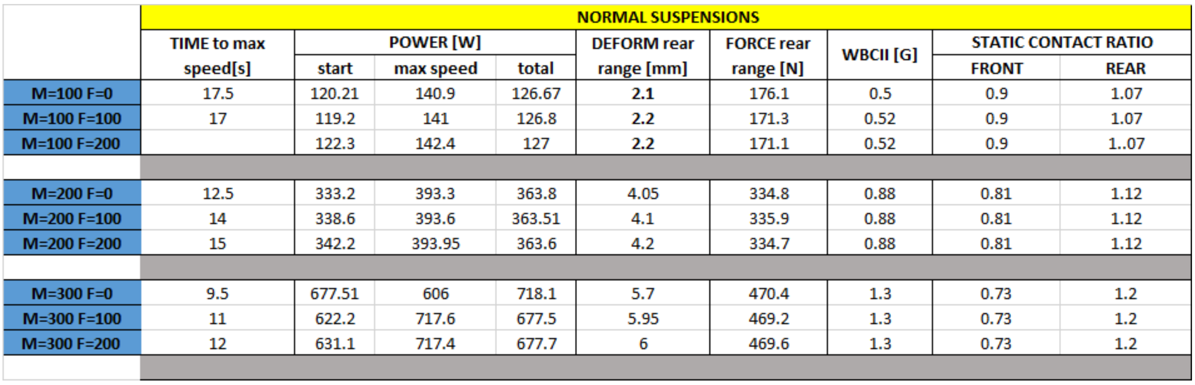
- Launching the simulation with the same values of Fpedalling and Fvertical, but with or without the Brain system, will allow to compare directly the benefits of it.
- It can be seen in the graphic that the power is sectionized in two parts in the X-value at 14 seconds, which is considered the point where the maximum speed of the bicycle is reached.
- Therefore, three outputs of power will be extracted from the graphic: from 0 to 14s, from 14s to 25s and the overall, from 0 to 25s.
- The average power for the whole simulation is 360.5W, as referenced in the graphic.
- Power differences between the Brain and the normal suspensions will be calculated to see the benefits of the Brain.

All the study cases are summarized in the following tables:



	BRAIN								
	TIME to max speed[s]	POWER [W]			DEFORM rear range [mm]	FORCE rear range [N]	WBCII [G]	STATIC CONTACT RATIO	
		start	max speed	total				FRONT	REAR
M=100 F=0	17.5	119.4	140.5	126.3	**0.2**	195.2	0.455	0.94	1.05
M=100 F=100	17	118.8	140.2	126.18	**0.2**	180.4	0.5	0.94	1.05
M=100 F=200	19.4	121.7	141.2	126.5	**0.25**	179	0.5	0.94	1.05
M=200 F=0	12.5	330.4	387.4	359.7	0.2	320.6	0.86	0.86	1.11
M=200 F=100	14	336.6	389	360.49	0.3	319.3	0.86	0.86	1.11
M=200 F=200	15	334	388.2	359.3	0.3	319.3	0.86	0.86	1.11
M=300 F=0	9.5	672.7	602.4	714.2	0.5	429.8	1.3	0.76	1.17
M=300 F=100	11	614.3	717.5	672.9	0.5	430.7	1.3	0.76	1.17
M=300 F=200	12	622.7	715.31	671.6	0.6	430.8	1.3	0.77	1.17

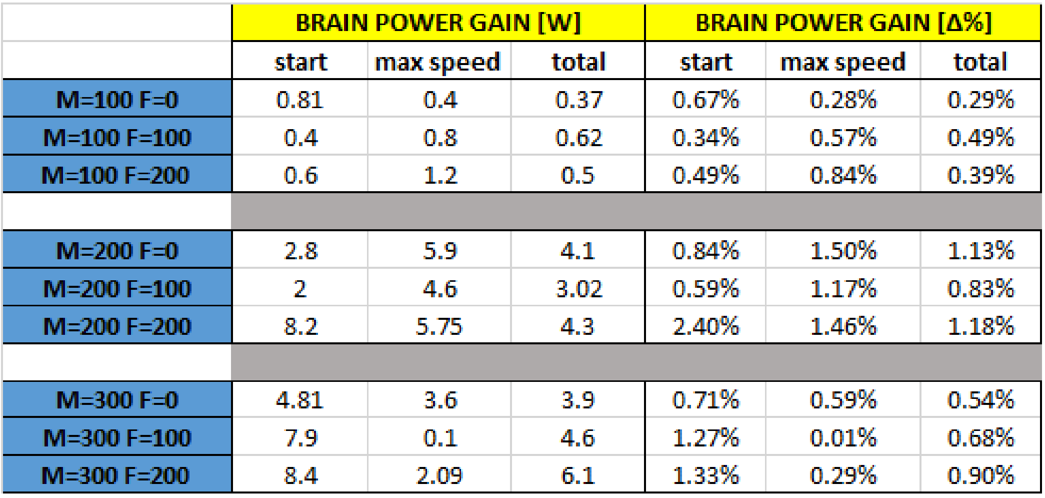
Table 3. Brain study cases. Source: own



	NORMAL SUSPENSIONS								
	TIME to max speed[s]	POWER [W]			DEFORM rear range [mm]	FORCE rear range [N]	WBCII [G]	STATIC CONTACT RATIO	
		start	max speed	total				FRONT	REAR
M=100 F=0	17.5	120.21	140.9	126.67	**2.1**	176.1	0.5	0.9	1.07
M=100 F=100	17	119.2	141	126.8	**2.2**	171.3	0.52	0.9	1.07
M=100 F=200		122.3	142.4	127	**2.2**	171.1	0.52	0.9	1..07
M=200 F=0	12.5	333.2	393.3	363.8	4.05	334.8	0.88	0.81	1.12
M=200 F=100	14	338.6	393.6	363.51	4.1	335.9	0.88	0.81	1.12
M=200 F=200	15	342.2	393.95	363.6	4.2	334.7	0.88	0.81	1.12
M=300 F=0	9.5	677.51	606	718.1	5.7	470.4	1.3	0.73	1.2
M=300 F=100	11	622.2	717.6	677.5	5.95	469.2	1.3	0.73	1.2
M=300 F=200	12	631.1	717.4	677.7	6	469.6	1.3	0.73	1.2

Table 4. Normal suspensions study cases. Source: own

To clarify, the variable "time to max speed" is the time to get into the stationary conditions. Reassuming the difference on the power exerted for the rider to reach the end of the terrain:



	BRAIN POWER GAIN [W]			BRAIN POWER GAIN [Δ%]		
	start	max speed	total	start	max speed	total
M=100 F=0	0.81	0.4	0.37	0.67%	0.28%	0.29%
M=100 F=100	0.4	0.8	0.62	0.34%	0.57%	0.49%
M=100 F=200	0.6	1.2	0.5	0.49%	0.84%	0.39%
M=200 F=0	2.8	5.9	4.1	0.84%	1.50%	1.13%
M=200 F=100	2	4.6	3.02	0.59%	1.17%	0.83%
M=200 F=200	8.2	5.75	4.3	2.40%	1.46%	1.18%
M=300 F=0	4.81	3.6	3.9	0.71%	0.59%	0.54%
M=300 F=100	7.9	0.1	4.6	1.27%	0.01%	0.68%
M=300 F=200	8.4	2.09	6.1	1.33%	0.29%	0.90%

Table 5. Comparative table of the gain in terms of power of the Brain technology, in the different study cases, terrain 1

In conclusion, analysing the different measured variables the simulations show that, with respect to:

- **The pedalling power exerted from the cyclist**, the Brain technology **does provide benefits with respect to the normal suspensions**:
    - → In all cases, with no exception, the power that is required to the rider to cycle 25seconds in a smooth terrain is smaller with the Brain.
    - → The difference values do not have a large magnitude, being the maximum a total of 8.4W in the extreme case of M=300 (pedalling force 300N) and F=200 (vertical force 200N), which represents a 2.4% the total power exerted in that start section.
    - → In a general line, the higher the pedalling force, the more beneficial is the Brain, as it can be seen the power gain is much higher in the cases of M=200 and M=300.
    - o Focusing on the different sections, the start or the maximum speed section, no relevant conclusions could be taken. In some force scenarios, the Brain gains more power in the start and other in the maximum speed section. Nevertheless, in all sections, including the global one, the Brain is beneficial.
    - o Regarding the vertical force in the pedalier, no clear conclusions can be taken.
- Regarding the **deformation of the rear spring**, it can be observed that in the Brain this value is almost zero, while for the normal suspensions it oscillated between 2-6mm, increasing with the value of the pedalling force. It is a logic statement as more pedalling forces involve higher amplitude of the driving torque and therefore higher induced oscillations in the rear spring.
- No relevant conclusions could be made about the **WBII comfort variable and the static contact loads ratio**, as there were no relevant differences between the simulations. The comfort acceleration was always <1 or very close to it, which is inside the comfort ranges.

7.3.2. TERRAIN 2: SMOOTH AND BUMPY TERRAIN

Once the Brain suspensions have been tested in a smooth terrain, it was essential to study its behaviour in a bumpy terrain. To do so, bumps of 30-40-60mm height have been created in Adams along a large terrain of 60meters:

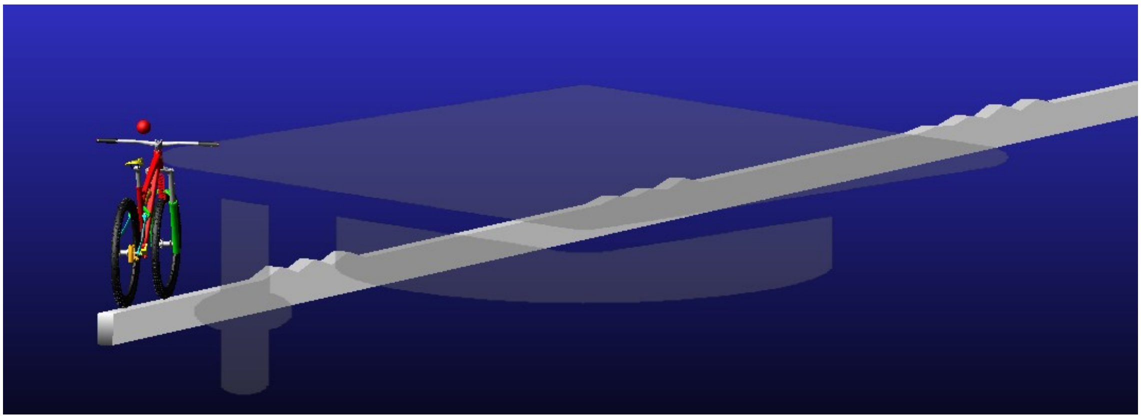


Figure 43. Perspective of the model with part of the bumpy terrain. Source: own

Simulations in this scenario have been executed without the action of the vertical force associated to the rider's movements, but with different values of pedalling forces have been studied, from 100 to 300N, to arrive until the end of the 60 meters. The pedalling force and the comfort have been the main parameters measured in this case. In the following *Figure 44 and 45*, it can be seen the bicycle going through some bumps and the compression of the spring, which proves the correct behaviour of the Brain system, and the behaviour of the bike's velocity against the obstacles of the terrain for a pedalling force of 100N:

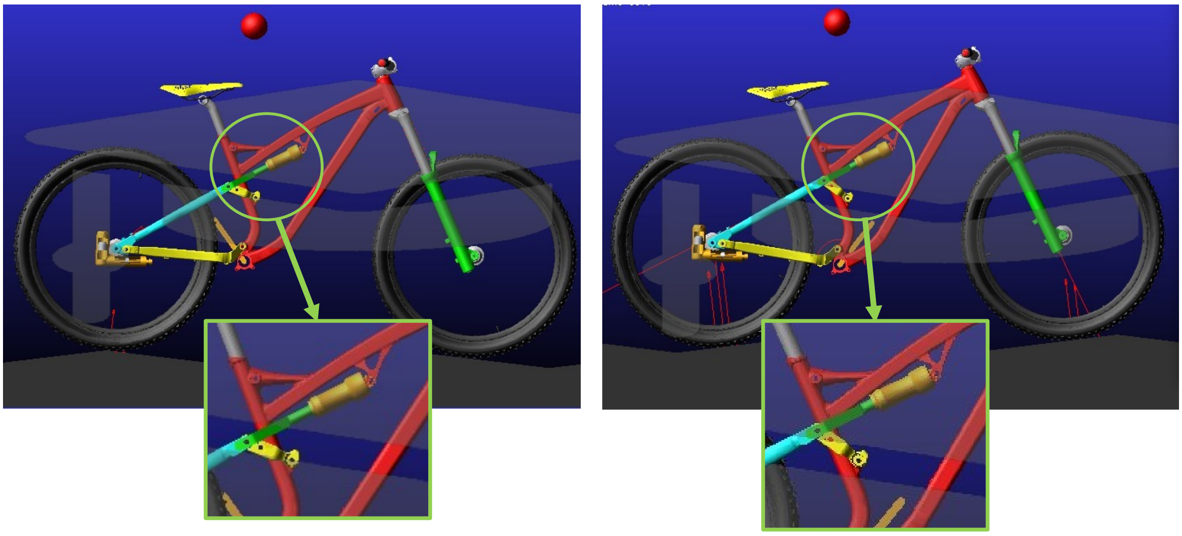


Figure 44. Bicycle model before and after encountering the bump, where it can be appreciated the compression of the rear spring. Source: own

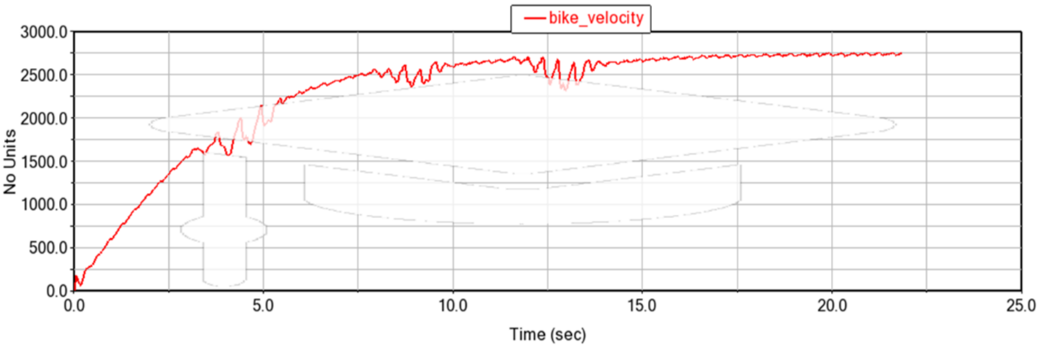


Figure 45. Velocity of the bike in the terrain scenario. Source: own

The results are summarized in this table:

	BRAIN			NORMAL SUSPENSIONS		
	TIME [s]	POWER [W] total	WBCII [G]	TIME [s]	POWER [W] total	WBCII [G]
M=100	21.65	120.7	1.5	21.84	119.3	1.3
M=150	17.54	222.12	1.81	18	221.5	2.3
M=200	15.15	339.12	2.1	15.58	347.5	3
M=250	13.5	479.1	2.5	13.9	489.7	3.5
M=300	12.31	639	2.9	12.55	659.3	3.7

Table 6. Summarized results of the simulations for different driving torques or pedalling forces.

	BRAIN GAIN [W]	BRAIN GAIN [Δ%]
M=100	-1.4	-1.17%
M=150	-0.62	-0.28%
M=200	8.38	2.41%
M=250	10.6	2.16%
M=300	20.3	3.08%

Table 7. Comparative table of the gain in terms of power of the Brain technology, in the different study cases, terrain 2

The results show that:

- **Regarding the time**, with higher pedalling forces the bicycle arrives sooner to the end of the 60 meters terrain, as more power will be exerted from the rider. The case of the Brain is always quicker than the normal suspensions, but in all cases less than 0.5 seconds.
- Talking about the **pedalling power exerted by the rider** to arrive to the end of the terrain, for small pedalling forces such as 100N and 150N, which involve smaller velocities on the bike, there are no relevant differences with the Brain and the normal suspensions, being even the normal suspensions a bit more beneficial. Over a value of 200N in the pedalling force, which involves higher velocities in the bike, the Brain is more beneficial than the suspensions, with gains of 8-10-20W (which represent a maximum total of the 3% of the power exerted to go through the terrain in that configuration). These last differences may be due some acceleration peaks that have been noticed in the case of the suspensions. The presence of peaks in the power output graph may be explained by the interaction between the suspension and the high pedalling force. In situations where the suspension is active and the rider is applying high pedalling force, the loss of traction before jumping over a bump is increased due to the suspension's movement. As a result, the impact upon landing is greater, requiring more power to accelerate the bike again
- Regarding the **comfort index**, comparatively, the Brain has always smaller values than the normal suspensions.

It has to be clarified that many different configurations of terrains were simulated, in which the purpose was to obtain logical results without too many particularities of accelerations or loss of traction, and that the results may be highly affected but the type of terrain.

8. APPLICATION: OFF-ROAD MOTORCYCLES

One of the secondary objectives of the project was to study other possible applications of the Brain suspension system, such is the case of off-road motorcycles, where the suspensions play a crucial role in the performance, comfort and stability while riding in challenging terrains.

Due to limitation within the project's timeframe, simulations in Adams have not been executed for the case of off-road motorcycles, as the dynamics of a motorcycle differs to a large extent from the bicycles' one. Nevertheless, it has been considered appropriate to provide some context about these suspension systems, which can be used in future studies for those interested in this area.

8.1. SUSPENSION STATE OF ART: OFF-ROAD MOTORCYLES

Following the guidelines of bicycles suspensions, motorbike suspensions typically involve the use of specialized components such as forks and shock absorbers to absorb and dampen forces and vibrations from uneven terrain, impacts, and other external sources. These components work together to isolate the rider from the obstructions of the terrain, allowing for smoother handling, improved traction, and enhanced performance.

Giving a quick review to these components:

- **Forks**: forks are the front suspension components that attach to the front wheel of the motorcycle. They typically consist of two telescopic tubes that slide within each other and contain springs and dampers. The springs absorb and store energy from impacts, while the dampers control the rate at which the forks compress and rebound, providing damping or resistance to the movement. This helps to absorb forces from the terrain and maintain contact between the front wheel and the ground, allowing the motorcycle to maintain traction, stability, and control. Dampers in fork suspensions typically contain oil, as it is an excellent medium to control the motion of the fork.
- **Shock Absorbers**: shock absorbers are the rear suspension components that connect the rear wheel to the motorcycle's frame. They are responsible for absorbing and dissipating forces from the rear wheel, providing damping to control the motion of the rear suspension. They are typically hydraulic or gas-operated, and they work in conjunction with the forks to provide a balanced suspension system that can absorb impacts, vibrations, and forces from the terrain.
- **Linkages**: linkages are mechanical components that connect the suspension system components, such as the forks and shock absorbers, to the motorcycle's frame and swingarm. They are used in some suspension configurations, such as the linkage-based suspension system, to provide progressive and controlled suspension movement. Linkages can vary in design and complexity depending on the specific suspension configuration, but they play a critical role in optimizing the suspension performance, providing stability, traction, and control.
- **Other components**: In addition to the other components motorcycle suspension systems may also include other components such as bushings, bearings, seals, and springs. These components work together to provide smooth movement, minimize friction, and optimize the suspension performance in various off-road conditions.

8.2. COMPARISON WITH BICYCLE SUSPENSIONS

In comparison to bicycles, off-road motorcycles experience significantly higher magnitudes of loads, accelerations, and speeds, as well as more aggressive braking forces. Motorbikes are heavier, faster, and capable of higher levels of acceleration and braking, which puts greater demands on the suspension system. Additionally, motorbikes **do not rely on pedalling force**, and their movement is dependent only on the engine power, having significantly higher RPM than bicycles. This fundamental difference in propulsion adds new challenges to the design and performance of motorbike suspensions, taking in account careful considerations for the suspension design and performance, and for an optimal and safe ride.

Off-road motorcycles often employ different types of suspension configurations to meet the specific requirements of off-road riding. These configurations vary in their design, complexity, and performance characteristics, and manufacturers often use a combination of different configurations to achieve the desired performance, featuring as well adjustable suspensions that allow the rider to tune the suspension to its preferred settings. Some common configurations are briefly explained:

1. Telescopic Fork System: commonly used in motocross, enduro, and other off-road motorcycles. It consists of a pair of telescopic forks that are attached to the front wheel and provide vertical movement, containing springs and dampers to absorb and dampen forces from the terrain, allowing the front wheel to move up and down independently of the frame. They are relatively simple in design and offer good performance in terms of handling, stability, and control.
2. Rear Mono-Shock System (mono shock system): commonly used in off-road motorcycles where the rear wheel encounters significant impacts and requires independent movement. It uses a single shock absorber to connect the rear wheel to the frame. This configuration allows for more precise control of the rear suspension, as the shock absorber can be fine-tuned to provide optimal performance. These systems offer better traction, improved stability, and enhanced handling, particularly in challenging off-road conditions.
3. Twin Shock System (dual shock system): commonly used in older or vintage off-road motorcycles, and they can still be found in some modern off-road motorcycles that prioritize a classic or retro aesthetic. It uses two shock absorbers, one on each side of the motorcycle, to connect the rear wheel to the frame. This configuration provides a simpler design compared to the mono-shock system, but may offer slightly less performance in terms of handling and control.
4. Linkage-Based Suspension System: commonly used in high-performance off-road motorcycles, such as those used in professional racing or extreme off-road competitions. It uses a linkage mechanism to connect the suspension components, typically the shock absorber, to the frame and the swingarm. This configuration allows for a more progressive and controlled suspension movement, providing better traction, stability, and control in challenging off-road conditions.
5. Air Suspension System: are commonly used in high-end off-road motorcycles where the rider's preferences and riding conditions can be easily adjusted. It uses air as the medium for damping and absorbing forces from the terrain. These systems utilize air chambers or air springs in combination with dampers to provide adjustable and tuneable suspension performance. Air suspension systems are known for their

versatility and ability to provide a smooth and controlled ride in various off-road conditions.

8.3. POSSIBLE APPLICATION OF BRAIN

As commented along the project, the main particularity of the Brain suspension is that it is a “mechanical sensor” or a purely mechanical system without any kind of electronic control system. On modern motorbikes, control suspension systems often rely on electronics to provide advanced features such as automatic adjustment of the suspension settings based on the instantaneous riding conditions, but it is possible to have a purely mechanical system:

- **Mechanical-based** suspensions are determined by the physical characteristics of the components (such as stiffens, compression, rebound rates and geometries). Some riders prefer these kind of systems for its greater simplicity and predictability, as it allows to tune the performance of their suspension to their specific needs and riding style.
- **Electronic-based** systems, as commented, they can offer a wider range of benefits in comparison to mechanical systems. Adjustable damping, active suspensions and rider height adjustments are some examples of these systems. However, they can also increase the complexity of the system, requiring of specialized training and equipment to repair, as well as increasing the cost maintenance

In conclusion, when evaluating the application of the Brain in these kind of vehicles, **it is possible**, but it is necessary to determine which areas the system would provide the greatest benefit, as in comparison to bicycles, motorbikes have higher chain forces due to the action-reaction between the transmission gears attached to the wheel and the frame and there is no existence of the pedalling force. One example is the **Öhlins TTX Flow shock absorber**, a mechanical suspension example that adjusts the damping based on both the speed and terrain, allowing the suspension to be more responsive to small bumps and providing better traction on rough terrain, without the need of electronic components.

Overall, while the specific and same technology of the Brain suspension may not be suitable for off-road motorcycles, determining the greatest benefits of the Brain, it is possible to design a similar system that is specific to motorbikes and does not require any electronics to regulate the stiffness of the rear suspension.

9. CONCLUSIONS

9.1. SINTESI OF THE RESULTS

The simulations carried out in this thesis using Adams View have provided valuable results of the application of the Brain technology in mountain bikes, under different terrains and loads. By testing various configurations and parameters, it was possible to observe some differences in performance to normal rear suspensions.

It should be noted that the Brain does not "add extra power into the system", but prevents a certain amount of energy loss caused by pedal-induced oscillations in the rear suspension of a typical suspension rear system. To summarize the results obtained, it has been observed that:

- → In smooth terrains, in all cases of force combinations, the Brain improved the loss of pedalling power with respect the normal suspensions, requiring less pedalling power to the rider (for conditions such as the same pedalling frequency and time simulated).
- → The gain of the Brain with respect the normal suspensions is only a small fraction of the total pedalling power exerted by the rider in those same conditions, representing between 0.3-2.5% of the total power. As mentioned in literature and discussed in *Section 2.3.4*, in previous studies the authors considered this loss could range from 1-2%, which contrasts with the obtained results.
- → In general, the higher the pedalling force, the more beneficial the Brain system is.

No definitive conclusions were obtained whether the Brain technology is more beneficial during the starting/accelerating phase or when the bike has reached its maximum speed.

9.2. THESIS CONTRIBUTIONS, LIMITATIONS and FUTURE PROSPECS

Once the project is finished, a final evaluation of the proposed objectives must be made. Broadly speaking, the initial objectives have been successfully achieved:

- ✓ The Brain system has been studied and analysed
- ✓ A functional mountain bike model, which is geometrically similar to the real model and considerably realistic in terms of its behaviour, has been developed in Adams
- ✓ The modeled behaviour of the Brain technology has been incorporated into the model to allow for a comparison of its potential benefits, in comparison to traditional suspension systems.
- ✓ The application has been done in a customizable way, with the possibility to easily change conditions such as the terrain or the loads, as it has been explained along the project.

On the other hand, regarding the secondary objectives of the project of studying another application of the Brain system, such as with off-road motorcycles, it has been given some context about these system's suspensions and argued about the possibility of its real application. Due to limitation within the project's timeframe and the complexity of its application, simulations in Adams have not been executed, but some context was provided for future studies.

Personally, I have been able to develop my skills with the software ADAMS, which is a very powerful tool for dynamic simulation that I had not previously used before starting this project. The process has required significant amount of time and effort, as many problems have arisen in the modelling and characterization of the mode in ADAMS, but with dedication, I have been able to solve them. It has been proved that the user needs to be accurate in the simulations for them to work in an effective and realistic way, as some not well defined parameters con interfere with the whole behaviour of the model.

Looking to **inspire future works**, this project is opened to future and more complex improvements to be incorporated into the work, such as:

- Perfectionate the simulations adding extra variables or conditions, which include not only bumps but steep and down-hill terrain, to evaluate the behaviour of the Brain in those configurations. Control rotational systems might be necessary if difficulties are brought to the stabilization of the model
- Introduction of more complex elements like the chain and the real pedals, for which we would have to introduce new modelizations of gears and belts.
- Study in simulation terms the application of the Brain in off-road motorbikes

10. LIST OF FIGURES

11. BIBLIOGRAPHY

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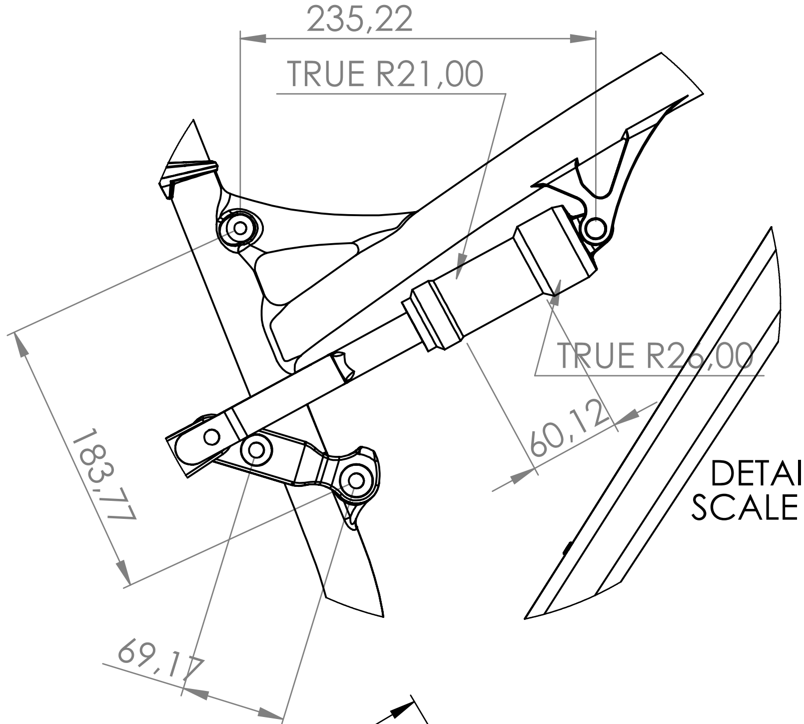

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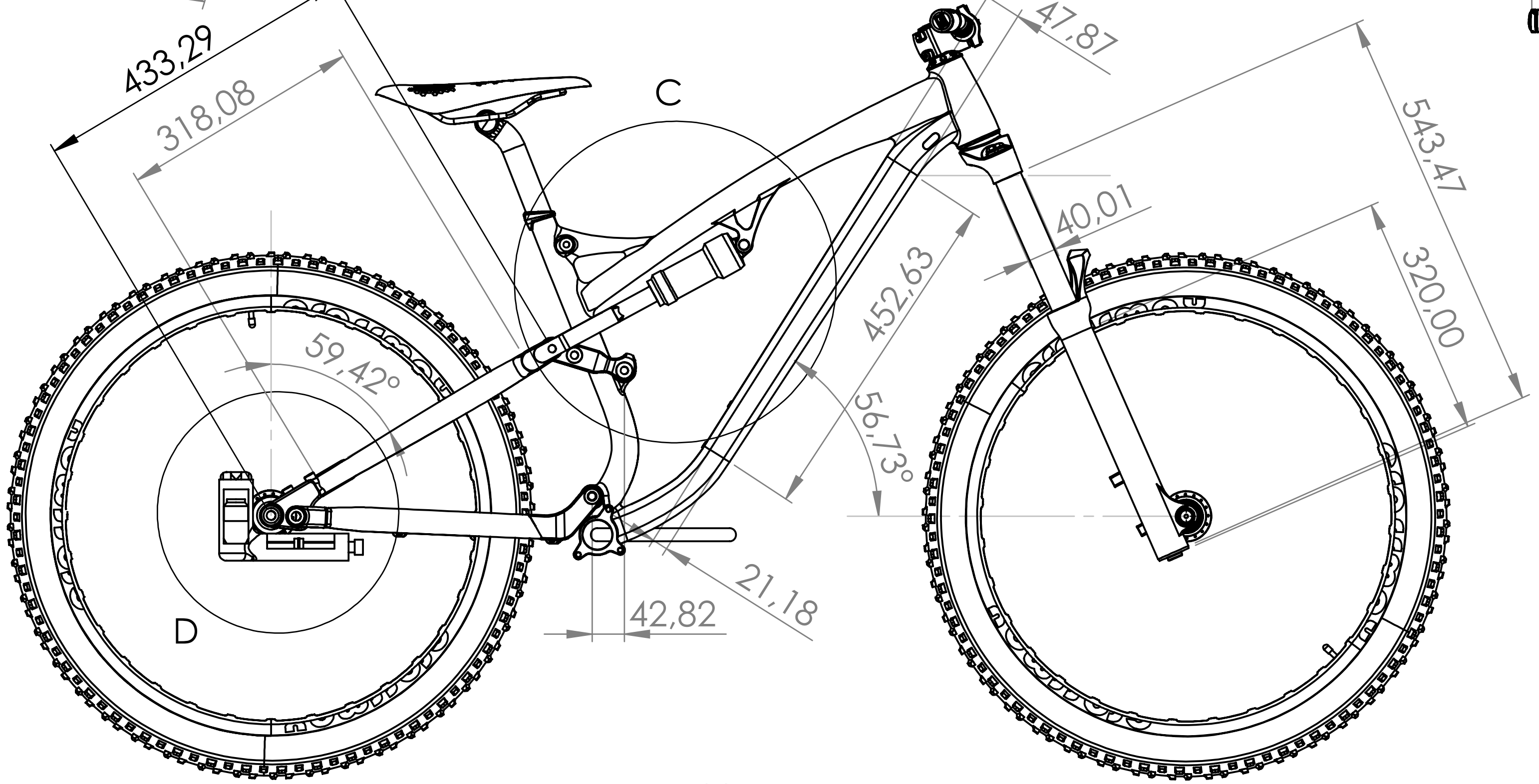

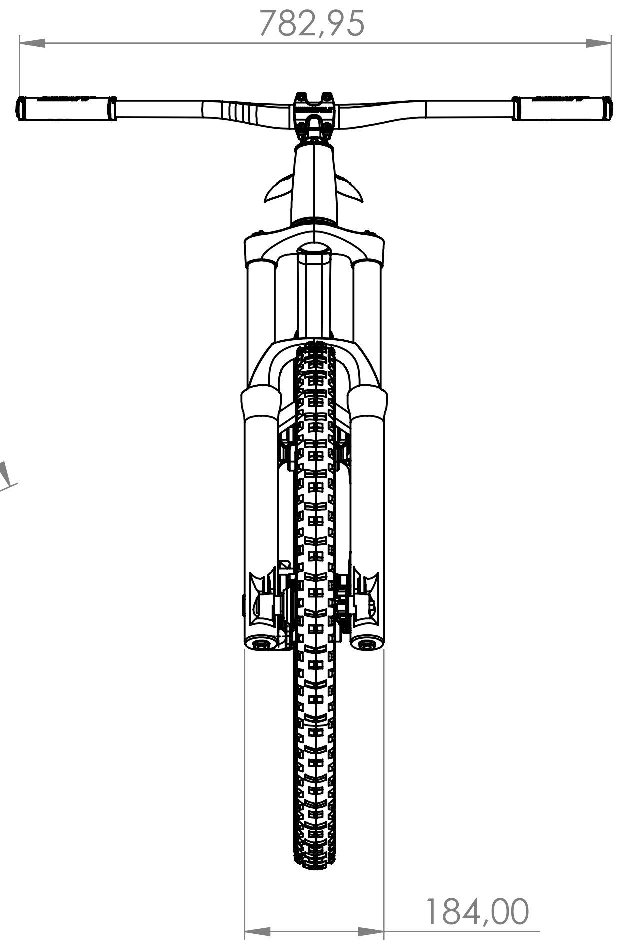

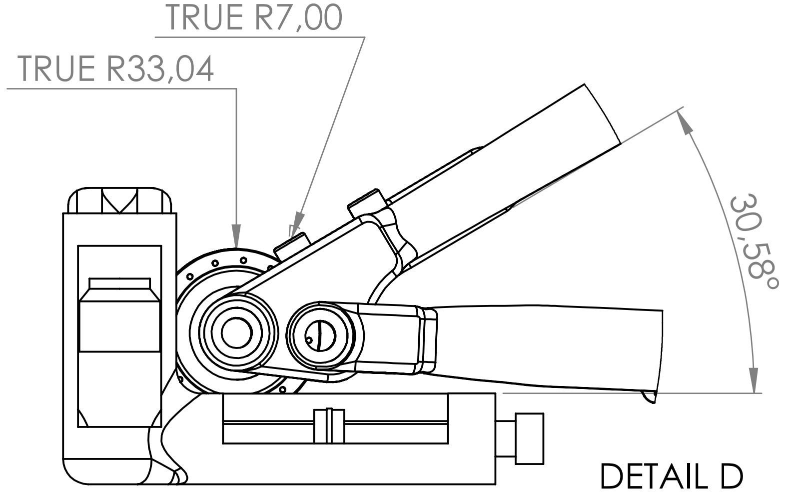

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JORDI URCOLA PEYA

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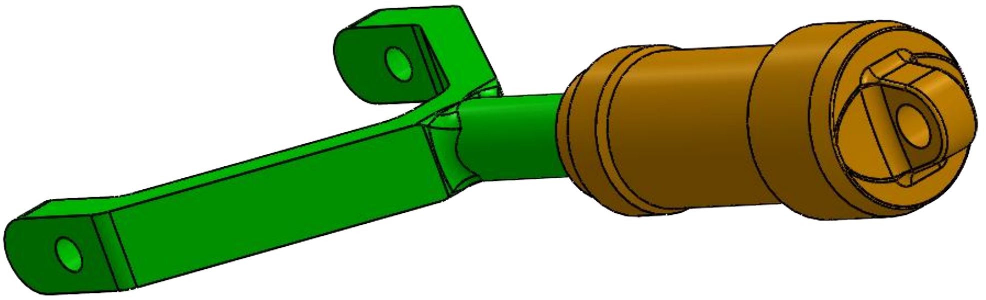

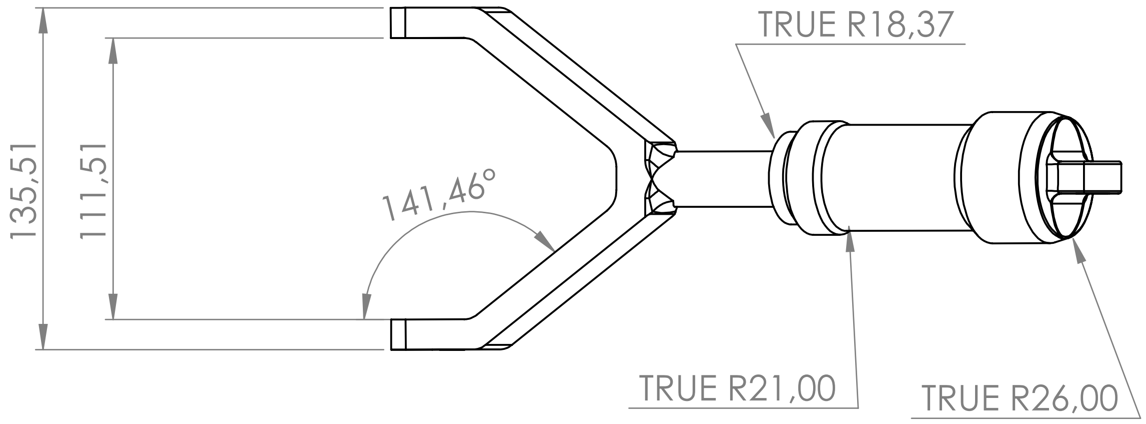

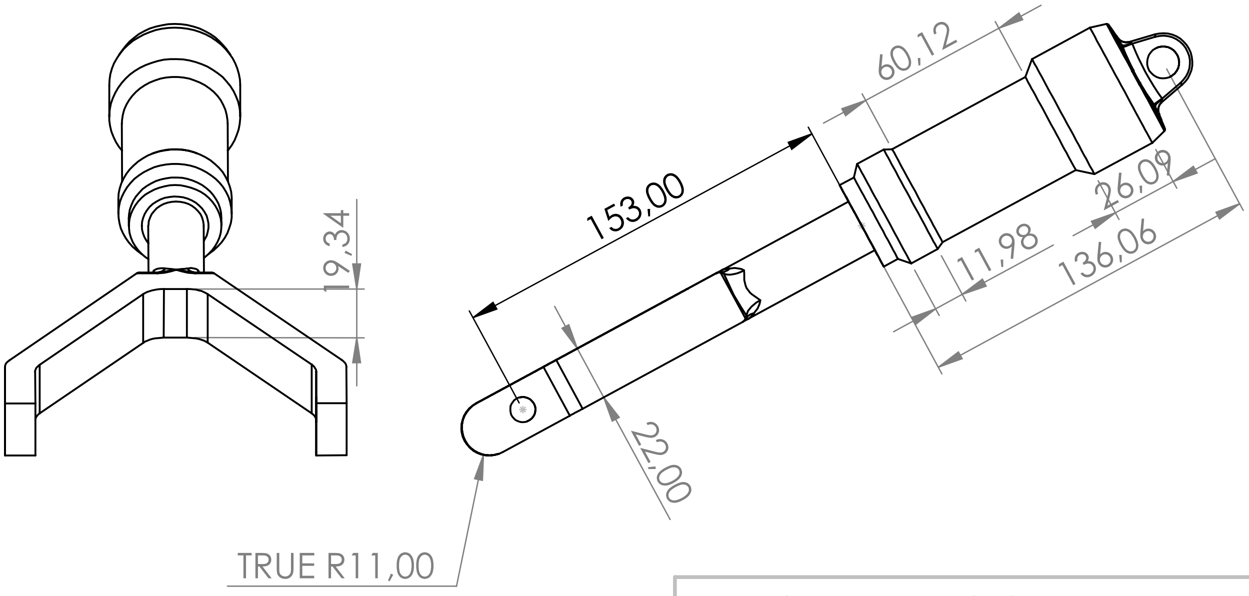

JORDI URCOLA PEYA

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Brain mountain bike rear suspensions

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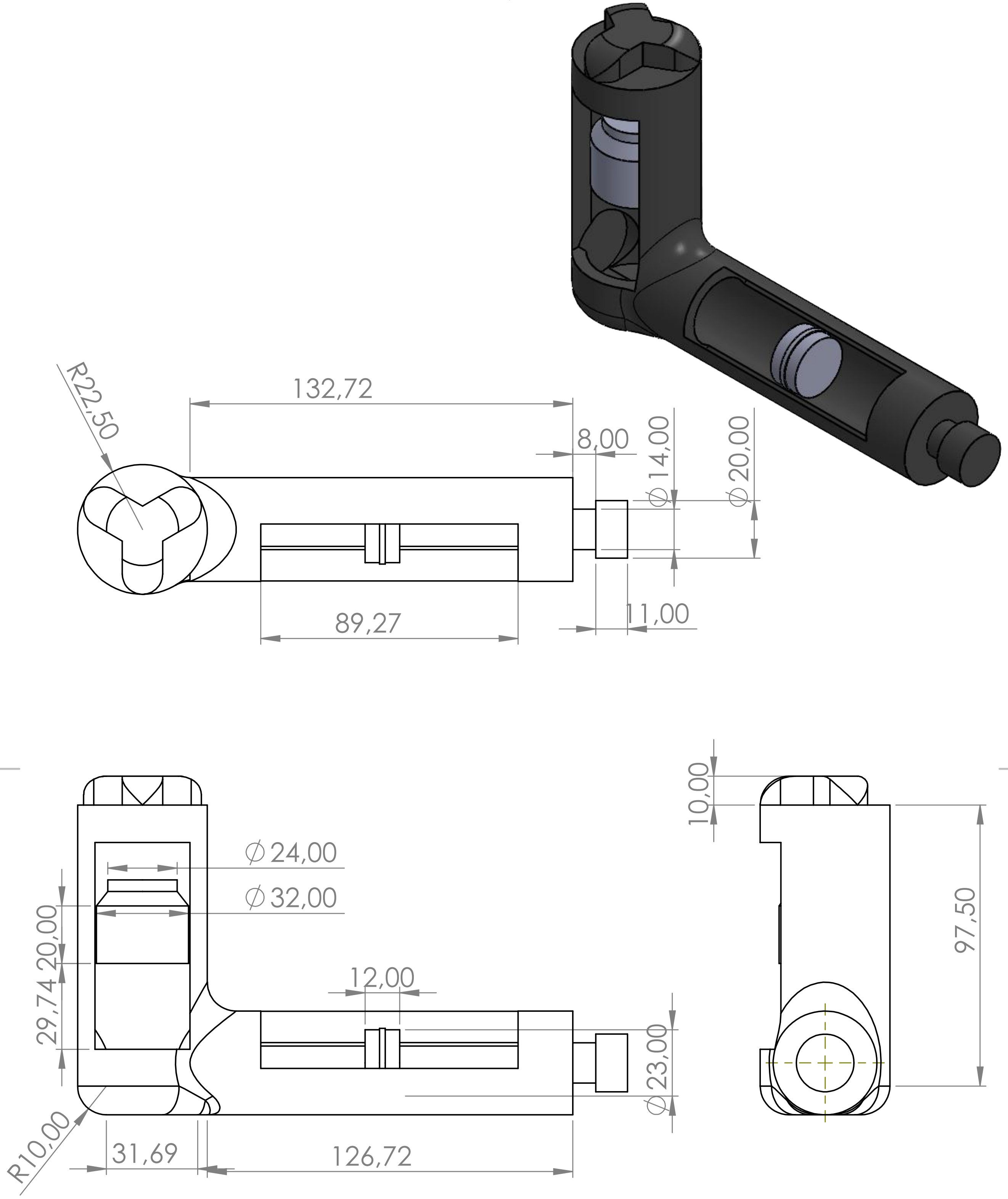

JORDI URCOLA PEYA

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