CZECH
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IN PRAGUE

Faculty of Mechanical Engineering

Department of Automotive, Combustion Engine and Railway Engineering

VIRTUAL MODEL OF SUSPENSION SYSTEM

BACHELOR'S THESIS
2024

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Program: B2341 Bachelor of mechanical engineering
Specialization: 3901R051 Computer Aided Design
Supervisor: Ing. Lukáš Kazda

BACHELOR‘S THESIS ASSIGNMENT

I. Personal and study details

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Study program: **Bachelor of Mechanical Engineering**

Branch of study: **Computer Aided Design**

II. Bachelor’s thesis details

Bachelor’s thesis title in English:

Virtual model of suspension system

Bachelor’s thesis title in Czech:

Virtuální model zavěšení přední nápravy automobilu

Guidelines:

Choose the type of independent suspension of the front and design a simplified model of the suspension in a scale of 1:2, which will be produced using 3D printing technology.
Create a multibody model of this suspension using the Matlab - Simulink software, which respects the geometry and basic parameters (stiffness, damping..)
Furthermore, create a simple two-mass model (a system of 2 differential equations).
For both models drive over a defined bump and compare the results.

Bibliography / sources:

Name and workplace of bachelor’s thesis supervisor:

Ing. Lukáš Kazda Department of Automotive, Combustion Engine and Railway Engineering FME

Name and workplace of second bachelor’s thesis supervisor or consultant:

Date of bachelor’s thesis assignment: **16.04.2024** Deadline for bachelor thesis submission: **10.07.2024**

Assignment valid until: ______________

Ing. Lukáš Kazda	doc. Ing. Oldřich Vítek, Ph.D.	doc. Ing. Miroslav Španiel, CSc.
Supervisor’s signature	Head of department’s signature	Dean’s signature

III. Assignment receipt

The student acknowledges that the bachelor’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor’s thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt — Student’s signature

Abstract

The purpose of this bachelor's thesis was to conduct a comprehensive study of the double wishbone front suspension using the example of the second generation Audi R8.

The main task was to create a 3D model of this suspension and analyze its behavior in order to compare it with other suspension models used in the automotive industry. In addition to creating a 3D model, the behavior of a quarter car with a given type of suspension was also simulated and compared with simple model of suspension. Moreover, a physical model of the pendant was made on a scale of 1:2, which was printed on a 3D printer. This physical specimen is intended to be used as a teaching aid for students and other interested parties to better understand the principles of suspension operation through a practical example.

The study examined various aspects of the double wishbone front suspension, including its geometry, kinematics and dynamics. Detailed modeling and analysis of the suspension behavior under various conditions, such as different types of roads and speed limits, was carried out. The results of these analyzes helped to better understand the influence of various factors on the behavior of the suspension and highlight the advantages of this type of design compared to others.

The study also highlighted the use of modern technologies such as 3D modeling and 3D printing in education and scientific research. The suspension physics mockup not only serves as a teaching tool, but also as a practical means of demonstrating basic automotive engineering concepts and principles in the real world.

Overall, this work represents a significant contribution to the study of modern vehicle suspensions. It provides a comprehensive understanding of double wishbone front suspension and its benefits, and demonstrates the potential of modern technology to support education and research in the automotive industry.

Keywords

Suspension; Suspension Geometry; Computer-Aided Design; Virtual Modeling; Vehicle Simulation; Simulation Software; Automotive Engineering; 3D printing; Multibody Dynamics Simulation

Declaration

I declare that I wrote this thesis solely by myself with guidance of my supervisor and my colleagues. All information stated in the text of the thesis are my invention except where I state otherwise by reference to the original source.

Prague 2024

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Oleksandr Malkov

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Abbreviations and nomenclature

Table 1: Abbreviations used in the thesis

ABC	All body control	KPO	The kingpin offset
ABS	Acrylonitrile butadiene styrene	LHM	Liquid hydraulic mineral
ADC	Airmatic dual control	LCA	Lower control arm
ATV	All-terrain vehicle	PETG	Polyethylene terephthalate glycol
BJ	Ball joint	PLA	Polylactic acid
CFRP	Carbon Fiber Reinforced Polymers	POS	Position
CTU	Czech Technical University	QTY	Quantity
EM	Electric Motor	SUV	Sports Utility Vehicle
EV	Electric Vehicle	UCA	Upper control arm
PTFE	Polytetrafluorethylen		

Table 2: Latin nomenclature used In the thesis

G	Shear Modulus [MPa]	f	Frequency [Hz]
m	Mass [kg]	k	Stiffness [N/m]
t	Time [s]	b	Damping [Ns/m]
x	Coordinate [m]	F	Force [N]
y	Coordinate [m]	M	Moment [Nm]

1. Introduction and motivation

This bachelor's thesis investigates the geometry, kinematics and dynamics of a car's double wishbone suspension, followed by conceptual development and creation of 3D physical models as a teaching aid for students. Also, in the future, the behavior of this type of suspension will be simulated in the Simscape Multibody program and compared with a simpler two-mass model. Thus, this work will focus on the choice of production technology and scale of individual components, as well as their mutual functional compatibility. For example, a large number of parts will be printed on a 3D printer. For more complex parts that cannot be printed or their printing will affect the functional behavior of a given model, we can choose, for example, a purchase option. Therefore, parts for which there will be specific requirements, such as low adhesion and high strength, will be purchased.

Actually, what a car suspension is? The suspension is a complex engineering system of elements designed to smooth out the impact of impacts on passengers and increase ride comfort. And each component of this system has a unique function, the geometric parameters of which determine the behavior of the car. Suspension is the element that connects the wheel to the supporting system. Almost every road is accompanied by shocks, but thanks to the suspension, the interior remains unchanged. This system provides shock absorption. Even if the road is perfectly smooth, shocks and vibrations still continue. If there are potholes and rocks, this will be felt much more strongly. The pendant is needed to give it an attractive effect. However, the functionality of the design is wider than it seems in the traditional implementation: it also ensures the safety of the machine and maintains controllability.

As far as driving the car on an uneven surface like a road, for instance, the experience is far from comfortable. Aside from the discomfort for the passengers, the maneuverability of the vehicle may be severely affected by the frequent bumps and potholes. This is the very function of a suspension: the means of connection between the wheels and the car body. Moreover, this connection is dynamic: it should be flexible enough to enable the wheel to move up and down freely. It also allows the wheel to make lateral moves either way.

Furthermore, the suspension is approaching car safety. Since the function of the suspension is to dull vibration from road dust and imperfection, it minimizes the possibility of losing control and thus contributes to overall safety in driving a vehicle. This is especially important when driving in difficult weather conditions. Moreover, it affects the stability of the machine during various turns. It ensures the adhesion of car wheels to the road, and, thanks to this, you can freely drive on sharp turns. This element of the car is very important for the driver's and the passengers' safety. Therefore, a car suspension is not a collection of independent parts, but a complete system combining comfort with the safety of movement and driving. Its high-quality work is one of the main conditions for a comfortable and secure trip on the road.

The suspension not only protects the car, but also reduces pressure, making it softer and more comfortable, and also absorbs vibrations and shocks from road unevenness and other external factors. Otherwise, even a completely good road made from the outside could be felt, and the driver would certainly feel changes in vibration. This is what stabilizes the car body. [7]

The qualities of the suspensions vary, but the basic functions are universal for any model:

- mitigation of physical impacts on transport
- maintaining the desired direction of the wheels, ensuring precise steering
- vehicle stabilization while driving, roll limitation

The role of a vehicle suspension

The suspension design of a vehicle must take into account several factors in order to ensure safety, comfort, and handling:

- Ride quality and handling. The suspension system must effectively adapt to uneven road surfaces, allowing the wheels to maintain optimal contact with the road. This minimizes vibrations transmitted to the vehicle body, providing a smooth ride at different speeds and road conditions.
- Steering service. Maintaining constant wheel alignment is necessary to maintain stability and control when maneuvering and turning. This significantly reduces the likelihood of losing control of the vehicle.
- Vibration isolation. The suspension system must provide effective protection against high-frequency vibrations that may occur when driving on uneven or bumpy roads. This will help reduce the noise level inside the car and provide a more comfortable journey for passengers.
- Structural strength. The suspension structure must be strong enough to withstand all the loads placed on it while the vehicle is moving. This includes both vertical loads and lateral forces that may occur during cornering or heavy braking. [3]

How the suspension works

Systems vary, but they consist of basic elements:

- Shock absorbers are vital components of a suspension system. Their main function is to absorb shocks and vibrations that occur on uneven roads. This provides passengers with a smooth and comfortable ride while preventing fatigue. Shock absorbers also help stabilize the vehicle's body during maneuvers such as turning, braking, and driving over uneven terrain.
- Shock absorber struts serve to reliably hold springs and shock absorbers in their intended positions, thereby imparting rigidity and stability to the car body. They also play a critical role in distributing wheel loads onto the body and ensuring optimal weight distribution throughout the vehicle.

- Tie rods and steering mechanisms play a critical role in transmitting the movements of the steering wheel to the wheels, allowing for precise and responsive vehicle control.
- Stabilisers, also known as anti-roll bars, are specifically designed to minimize body lean when cornering. This improves vehicle stability and handling, especially at high speeds or in difficult driving conditions.
- Ball joints and control arms provide the vital connection between the wheels and the vehicle body. They allow the wheels to smoothly overcome road irregularities with minimal resistance and optimal stability.

Defining wheel position

Since the suspension system plays a key role in controlling the position of the road wheels, it is necessary to understand the terms and wheel placement. The placement of the wheels in relation to the road and the vehicle's suspension itself is critical and usually determines suspension flex and seat control. The following sections will look at parameters related to wheel position and their effect on vehicle handling. A detailed understanding of these concepts will allow you to effectively analyze and adjust suspension performance to achieve the best results in handling and ride comfort. [1]

Camber angle

This parameter determines the angle between the wheel plane and the vertical line. A positive value indicates the wheel is tilted outward from the vehicle (Figure 1).

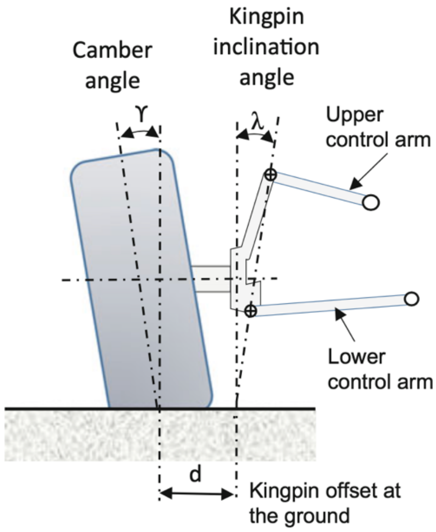

Figure 1 Position of positive camber wheels [10]

Camber affects various aspects, including vehicle load and cornering behavior. Slight positive camber promotes even tire wear and reduces rolling resistance. However, many cars, especially passenger cars, often have negative camber even when unloaded. The range of values for the front axle typically ranges from zero to minus one degree twenty minutes (Figure 2). [10]

Negative camber increases tire lateral grip during cornering and improves handling through the effect of camber drag, which is dependent on tire characteristics.

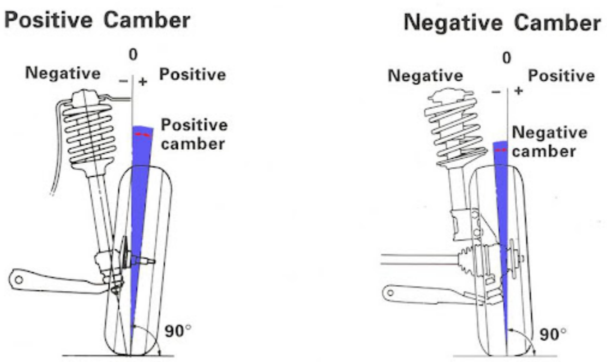

Figure 2 Positive and negative camber [10]

The disadvantage of independent suspension is the tilt of the wheels relative to the car body when turning, which leads to an increase in negative camber of the inner wheels and positive camber of the outer wheels (Figure 3). [1]

The outer wheels try to go beyond the turn, which leads to a decrease in the level of controllability. It is important to note that the change in camber (relative to the road) is the result of a combination of changes caused by suspension movement (compression inward, expansion outward) and changes due to body roll. [10]

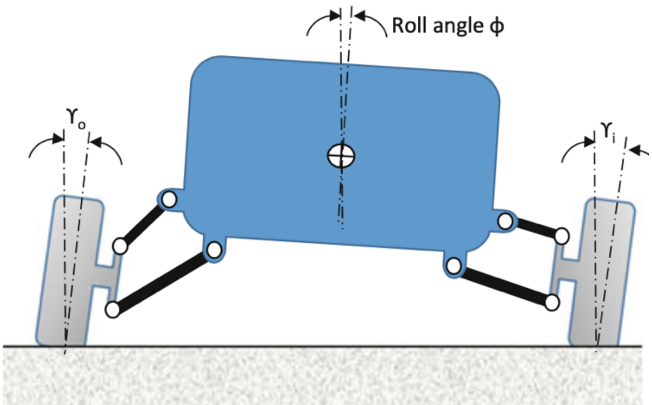

Figure 3 Camber angles when turning left using independent suspension [7]

Kingpin offset

Kingpin offset (KPO) is the distance between the center of the tire contact patch and the point of intersection of the kingpin axis with the ground plane (indicated by the letter "d" in Figure 1), which is considered positive when the intersection point is inside the wheel.

In practice, the KPO value can vary from small positive to small negative values. For a given suspension system, you can change the KPO value by changing the tire width. Increasing KPO results in improved steering response. However, the disadvantage is that the offset creates a torque lever, which causes longitudinal forces in the tire contact patch, generated when braking or hitting a bump or pothole, to be transmitted through the steering mechanism to the steering wheel. [10]

Thus, the consequences of the kingpin displacement are as follows:

- Braking stability (external brakes). In a diagonal split braking system, a negative KPO value can help neutralize the effect of missteering. A similar effect occurs with split wheel braking, where one wheel locks, or with unbalanced front brakes. When braking during a turn, negative RPM causes the outer wheels toe in, creating a tendency to oversteer. For internal brakes, the deciding factor is the hub offset (see below).
- Return: A positive increase in KPO improves performance by increasing lift as the steering angle increases.
- Steering Effort: A positive or negative KPO value is generally expected to reduce static steering effort by allowing the tire to roll on the road surface for a certain period of time, thereby reducing tire abrasion. However, in practice the effect is negligible even at large KPO values.
- Torque Management: With a conventional non-biased differential that distributes torque evenly to each shaft, high torque values can cause the steering to bind if one wheel loses traction. [6]

Kingpin offset at the hub

The kingpin offset on the hub is defined as the horizontal distance from the kingpin axis to the intersection of the hub axis and the tire centerline (Figure 1). If the centerline of the tire lies outside the kingpin axis at the center of the hub, then the hub offset is considered positive.

Castor angle

The castor angle is the inclination of the kingpin axis, which is projected into the longitudinal plane, initially through the center of the wheel. It is considered positive in the direction (Figure 4). The castor angle creates a self-leveling torque for the non-drive wheels. The value of the angle depends on the deflection of the suspension and, for steered wheels, affects the camber angle depending on the angle of rotation of the steering wheel. [1]

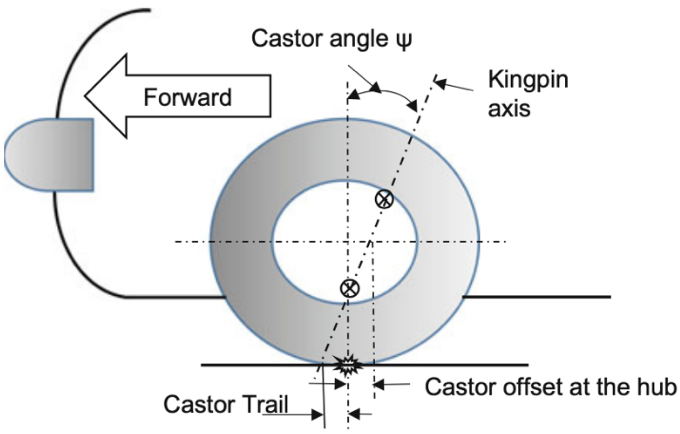

Figure 4 Determination of caster angle and castor trace [10]

The influence of the caster angle is manifested as follows:

- Worn tires and beads. Changes in camber caused by tire wear can lead to bead wear, especially at high locking angles. This means that as the vehicle is driven, tire wear may be uneven, causing additional wear on suspension components, especially when the steering wheel is turned excessively.
- Steering Response: Positive steering angle creates negative camber on the outside wheel, which improves steering response. This means that when you turn the steering wheel, the outer wheel tilts slightly inward, which improves traction and increases the vehicle's cornering stability. [2]

The castor trail

The castor trail, also known as the mechanical mark, is defined as the distance from the point where the king pin axis intersects the ground to the center of the tire contact patch (Figure 4). This setting affects the amount of self-leveling torque, which in turn affects the vehicle's ability to self-level after a turn. Some front-wheel drive vehicles experience increased self-levelling torque when cornering due to traction and lateral forces.

This can lead to undesirable consequences such as excessive steering, especially on rough roads, which can make the vehicle difficult to control. [1]

The impact of castor residue on the behaviour of a car can be as follows:

- Braking stability: During braking, the caster angle typically decreases, which reduces the wheel footprint and can reduce braking stability. Thus, a vehicle with a higher track level can provide better braking stability.
- Return: A car with more tire support usually has stronger steering return.
- Straight-line stability: Increasing the wheel space improves straight-line stability of the car.
- Steering Effort: The effect of steering wheel wake on steering effort depends on driving speed and circumstances. In general, a vehicle with more steering wheel support may require more steering effort, especially at high speeds or under strong lateral accelerations.

Castor offset at the hub

The roller offset in the hub is defined as the longitudinal distance from the vertical center line passing through the center of the wheel to the intersection of the longitudinal axis passing through the center of the wheel and the axis of the king pin. This parameter is considered positive when it is in front of the center of the wheel. Using negative offset reduces the mechanical impact and self-centering force felt on the steering wheel.

Toe-in/Toe-out

This is the difference between the front and rear distance separating the center plane of a pair of wheels (given at static ground clearance and measured to the inner wheel rims).

Toe-in occurs when the center planes of the wheels converge toward the front of the vehicle (Figure 5).

Braking and rolling resistance forces often cause toe-in effects, while traction forces (especially in front-wheel drive vehicles) act in the opposite direction. This leads to the front wheels coming off both the unknown and driven front axles. [10]

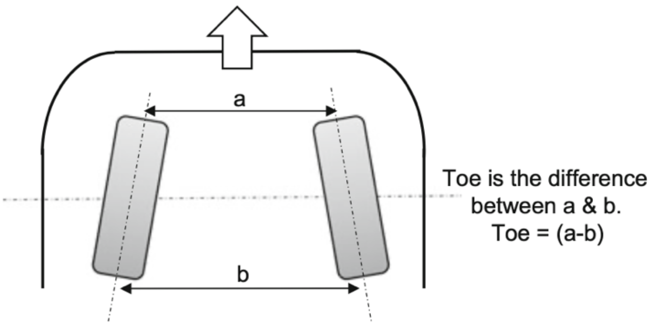

Figure 5 Toe-in definition (plan view) [10]

In the case of front-wheel drive cars, this is necessary to ensure driving stability, especially when the driver suddenly releases the gas pedal. With independent front suspension, body roll can change toe-in and therefore steering roll.

2. Types of suspension elements

Coil springs

The main task of coil springs (Figure 6) is to support the weight of the vehicle and shocks from the road surface, and maintain proper ground clearance. City passenger cars are equipped with standard medium-hard springs.

Figure 6 Coil spring [7]

Reinforced springs with high rigidity are elements of the rear suspension of the car. They are actively installed on cars that have significant weight loads on the rear axle. These are trucks, cars with trailers. Some cars may be equipped with springs with a variable rod section - with variable stiffness. Thanks to them, the car easily adapts to any driving situation.

Most coil springs are made in kilns from spring and torsion steel rods. When deformed, the material is able to return to its original position. Springs are made from round rods. They can be barrel-shaped, conical, cylindrical. The springs are made from carbon fiber for racing cars.

Torsion bars

Torsion bars (Figure 7) are flexible metal rods of circular cross-section that have splined joints at the ends. They cope well with rotational loads and provide an elastic connection between the wheel and the body while the car is moving. [9]

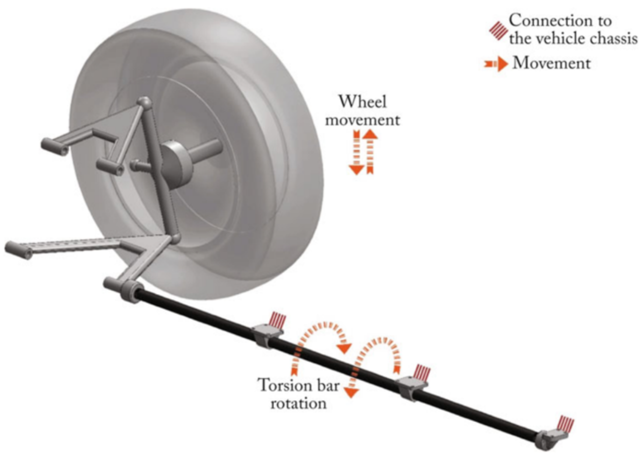

Figure 7 Torsion bar [7]

These suspension elements are most often installed on the independent suspensions of multi-wheel vehicles. They are attached at one end to the body and at the other to the lever, which ensures effective traction of the wheels with the road and improves vehicle handling.

Torsion bars are common front suspension components on framed SUVs and vans such as Mercedes-Benz, Iveco and Renault..

Leaf springs

Leaf springs (Figure 8) are elastic elements of a car's suspension, made of metal, that effectively transfer the load from the body to the wheels or tracks. They can be single-leaf or multi-leaf, depending on the design and suspension requirements. These suspension components are one of the earliest types of resilient components and were originally used on both cars and trucks.

Figure 8 Leaf spring [7]

Nowadays, leaf springs are most often installed on commercial vehicles, especially heavy-duty trucks and construction equipment with dual rear axles. Although some passenger car manufacturers are abandoning the use of springs in favor of other types of suspension due to some disadvantages such as high friction and rough ride on smooth surfaces, for heavy trucks springs remain the most reliable solution. They ensure that the truck body is held at a given height and ensure traffic safety. [7]

Some manufacturers are introducing new technologies to improve the performance of leaf springs, such as using a graphite coating to reduce friction or shot peening the material. This allows us to maintain the advantages of leaf springs and make them more modern and efficient. [10]

Electromagnetic

Modern manufacturers are always coming up with new technical solutions to increase vehicle durability and maximise comfort levels as part of their ongoing efforts to perfect and upgrade their products. The car's distinctive electromagnetic suspension (Figure 9) was one of the creative design solutions. It is primarily utilised in prototype cars at present moment; it has not yet gone into commercial production.

Technically speaking, an automobile's electromagnetic suspension is a sophisticated system consisting of a unique strut for every wheel. The strut is meant to provide the highest level of smoothness for the vehicle, it replaces the traditional spring and shock absorber and is controlled by an electronic unit. [6]

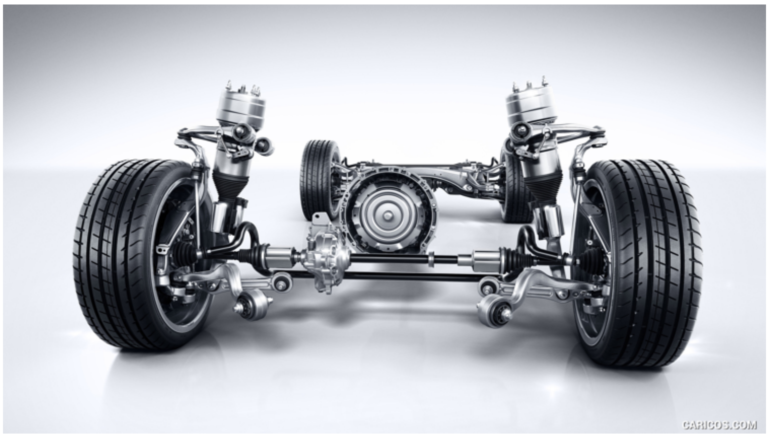

Figure 9 Electromagnetic suspension [17]

The main difference between magnetic suspension and its analogues is that the former works without the need to use springs, stabilizers, torsion bars, shock absorbers and other components required by their traditional predecessors and found in the vast majority of modern car designs.

In this case, the functions of these parts are performed either by solenoid valves or by the so-called magnetic rheological fluid. To be fair, some modern suspensions still have springs and shock absorbers installed in case the automation unit malfunctions and the car needs to move.

The following must be noted while discussing the benefits of magnetic suspension: responsiveness (no other suspension type can deliver such speed). Exceptionally smooth ride that makes the vehicle seem to float on the road and prevents passengers from feeling even the slightest flaws in the pavement. Maximum safety when driving at any speed and in any weather. Potentially, there is just one drawback: the structure's exorbitant expense.

Since electromagnetic suspension is far more expensive than comparable systems of other kinds, car designers hardly ever use this kind of solution.

Hydraulic

In hydraulic suspension (Figure 10), instead of shock absorbers, hydraulic struts or hydraulic compensators with a very large working stroke are used. Special balls or hydrospheres are screwed onto the upper end of each rack, acting as springs. They are also called "buli". They are designed extremely simply: the cavity inside the sphere is divided into two parts by an elastic membrane, on one side the sphere is filled with nitrogen (pressure from 35 to 60 atmospheres), and on the other side the membrane is supported by special oil (LHM or LHM+) of a caustic green color.

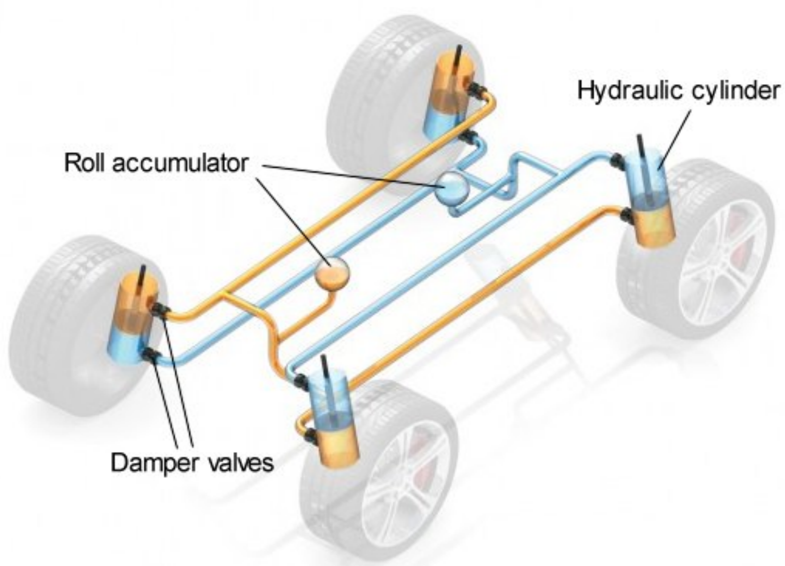

Figure 10 Hydraulic suspension system [18]

As we know, the vehicle's ground clearance decreases as it is loaded. To prevent this, self-leveling rear suspension systems can be used. Compared to air suspension, hydraulic suspension is more reliable. For example, the Mercedes ABC "Active Body Control" hydraulic suspension has a service life of about 400000 km, and the Mercedes ADC "Airmatik Dual Control" air suspension has a service life of about 150000 km. The suspension works on a principle similar to the pneumatic system. Once again, the elastic component differentiates the pendants from each other. Mercedes drives using hydraulic pistons. [28]

The hydraulic system uses a special fluid, untimely replacement of which can lead to insufficient lubrication of the pump and its increased wear, after which it will not be able to create sufficient pressure to lift the car. Valve blocks also fail, causing the car to lower after the engine is turned off. Repairing hydraulic suspension is expensive, since many of its components cannot be repaired.

Pneumatic

Pneumatic - air suspension (Figure 11) is a device that ensures the accuracy of the spatial position of the body due to cylinders into which air is pumped under high pressure. It is compressed air that is the main factor in understanding how air suspension works. [6]

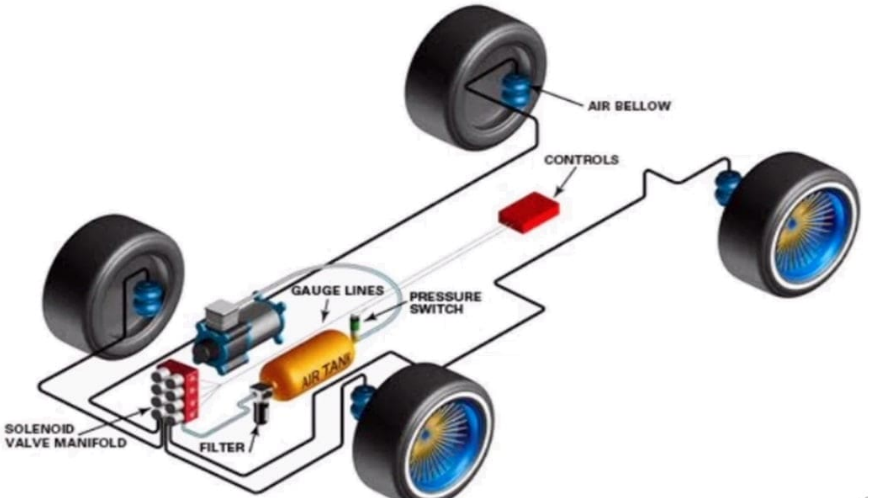

Figure 11 Air suspension system [16]

It absorbs the energy generated when passing obstacles and absorbs it, thereby ensuring the comfort of passengers and the driver, as well as eliminating excessive physical impact on metal elements that can cause destruction and deformation.

To more fully understand the advantages and design features of the unit, it is not enough to say what an air suspension is, it is necessary to identify the main functions, which look like this:

- Adapts the ride height automatically based on the vehicle's load capacity
- Manually establishing and choosing the best parameters based on the circumstances of the trip
- Automatically adjusted ground clearance based on speed

Understanding the design of air suspension, which consists of various important components, is essential to mastering its operation. The key element consists of unique cushions or cylinders made of durable elastomer. Since these cushions are air-filled, you can change the height and firmness of the suspension to suit your needs. The suspension becomes more adaptable and tunable when these balloons replace conventional springs or leaf springs. [8]

Air suspension also includes other components, such as control arms or shock absorbers, that can be integrated with the cylinders to ensure optimal system performance. Depending on the specific model and design of the vehicle, these elements can be combined in different ways to provide maximum comfort and controllability of the vehicle.

3. Types of suspensions relative to kinematics

The market for suspension types in the automotive sector is so diverse because manufacturers are constantly looking for new ideas and technological solutions. They work hard to create suspensions with many additional features in addition to the basic functions of effective damping and handling.

Nowadays, car suspensions must be small, reliable, inexpensive, easy to install and maintain. The times when choosing a car only by engine, body and gearbox are long gone. These days, the suspension of all types of vehicles - from city cars to SUVs and trucks - needs to be tuned depending on the vehicle's intended use and road conditions. [9]

There is no universal solution that would be suitable for all types of vehicles, but for each of them it is possible to select the optimal suspension that combines the necessary characteristics and functionality. Manufacturers will continue to develop and improve different types of suspensions to meet the needs of different markets and operating conditions.

MacPherson suspension

MacPherson suspension (Figure 12) is one of the most common types of car. In this article we will learn what a MacPherson suspension is, its main pros and cons, and also consider the diagram and design of this suspension.

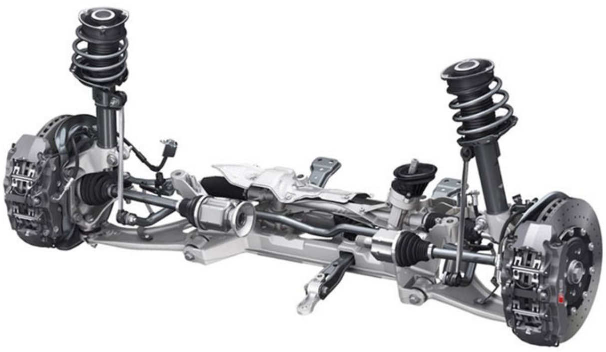

Figure 12 MacPherson suspension [14]

The main structural element of the suspension is the shock absorber strut, which is why it is also called a “swinging candle”. "Candle suspension" is mainly used for the front wheels. The rear-wheel drive version in English-speaking countries is called "Chapman Suspension" is named after the Lotus engineer who designed it. [9]

The use of MacPherson suspension made it possible to place the engine and gearbox transversely in the engine compartment and led to its widespread use in the modern front-wheel drive automobile industry. The kinematics of the MacPherson suspension can be seen in the Figure 13. The main load-bearing element of the suspension is the subframe. It is attached to the car body using silent blocks. The use of rubber-metal supports reduces noise and vibration transmission to the body. The subframe serves as the basis for mounting the steering gear, wishbone supports and anti-roll bar.

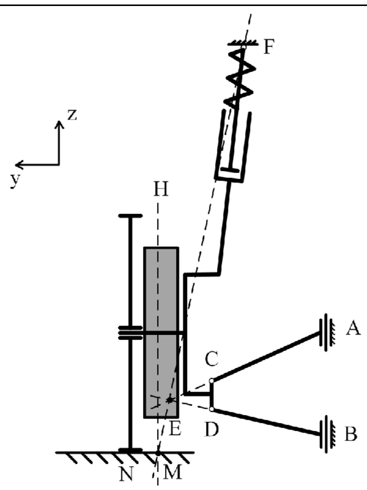

Figure 13 MacPherson kinematics [7]

The transverse arms of the right and left wheels are attached to the subframe on both sides using rubber bushings. The levers are double fastened, which gives the structure rigidity in the longitudinal direction. A steering knuckle is attached to the other end of the wishbone through a ball joint. The steering knuckle is attached to the steering rod by means of a swivel joint, allowing the wheel to turn. The upper part of the steering knuckle is attached to the shock absorber strut, and the lower part is connected to the wishbone. It also houses the brake caliper and bearing assembly. [9]

Double wishbone suspension

This type of suspension is characterized by the presence of two separate arms: an upper and a lower one, which are connected to the wheel and the frame or body of the car. Each of these levers plays a role in ensuring the vehicle's stability and controllability. The upper arm is usually attached to the car body or frame at the top of the wheel tube, and the lower arm is attached to the wheel at the bottom. [1]

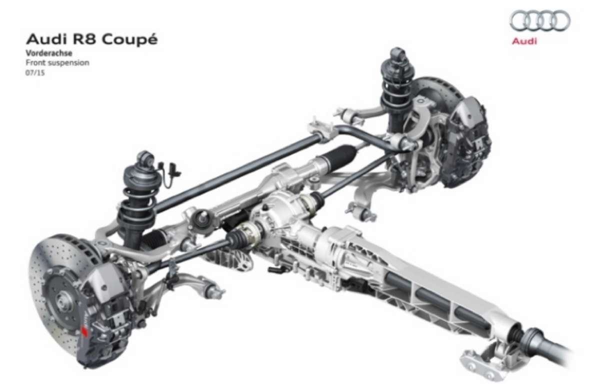

Figure 14 Double wishbone suspension [14]

This design solution allows the suspension to better adapt to road irregularities and more accurately control the movement of the wheel, which, in turn, provides improved handling and stability of the vehicle on the road (Figure 14). The double wishbone suspension works by minimizing unwanted lateral wheel movement when driving over rough roads, resulting in a smoother, more stable ride. [7]

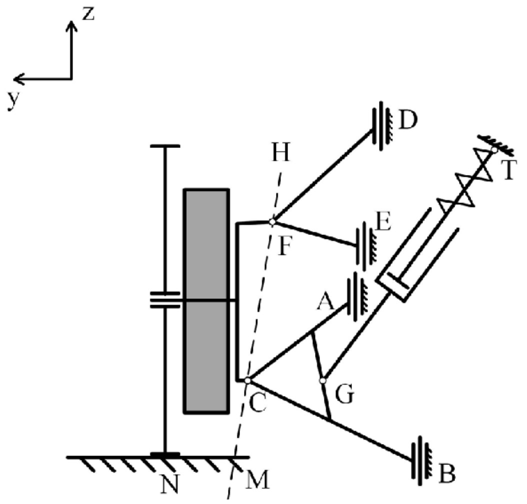

Figure 15 Double wishbone kinematics [27]

In passenger cars, this type of suspension is usually used in models with a higher level of comfort and handling, as it provides a smoother and more stable ride. Double wishbone suspension is also often used in sports and racing cars due to its ability to provide precise handling and excellent stability at high speeds. The kinematics of the double wishbone suspension can be seen in the Figure 15.

Multi-link suspension

Multi-link suspension, or Multilink (Figure 16), is a development of the double-wishbone independent suspension of a passenger car. Unlike the standard version, the guide elements are not single V-shaped arms, but separate parts that independent of each other. Their number usually varies from three to five elements, it all depends on the manufacturer. [5]

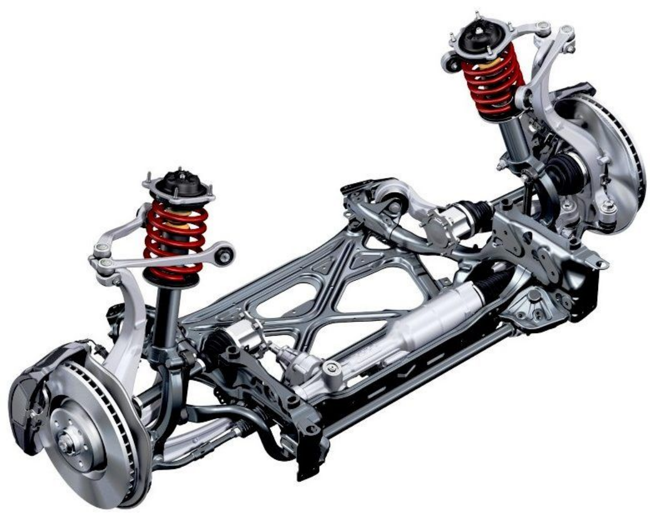

Figure 16 Multi-link suspension [14]

During manufacturing, the design features of the remaining suspension elements and their interaction are taken into account. The Multilink design gives the hub assembly additional mounting points and increased mobility, which significantly improves ride quality and overall vehicle handling.

The multi-link suspension can be installed on both the front and rear axles of the car. In this design, the upper and lower arms act independently of each other and are attached to the body on one side and to the wheel hub on the other. [3]

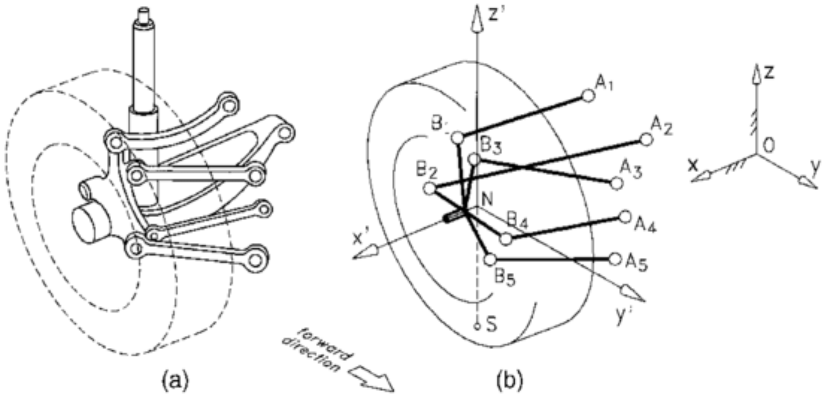

Figure 17 Multi-link kinematics [7]

The main advantage of such a suspension is that the wheel hub has the ability to change its position in the horizontal plane. This improves comfort on uneven roads and improves vehicle stability when cornering. [9]

The kinematics of the double wishbone suspension can be seen in the Figure 17.

The disadvantages of using a multi-link front suspension in the form of an increase in the cost of the car and expensive repairs are justified only in the production of expensive cars. Additional levers of a complex design with ball joints increase the cost of the entire suspension structure. It is also necessary to provide for a complex structure of interaction between elements that have greater mobility, especially when turning the wheel. In this regard, the front suspension of the “Multilink” type is not used in most passenger cars, in the production of which the main criteria remain low price, reliability and maintainability.

The multi-link suspension can be installed on one- and all-wheel drive vehicles. Currently, it is widely used in the production of both passenger cars and crossovers. The Multilink suspension improves the car's handling and also provides better grip on the road surface. [5]

Solid axle

This type of suspension is widely used in various classes of cars, including "A" and "C" classes, as well as in other market segments. This design usually includes elements that allow each wheel to move independently, but they remain connected to each other by certain elements, such as a beam or wishbone.

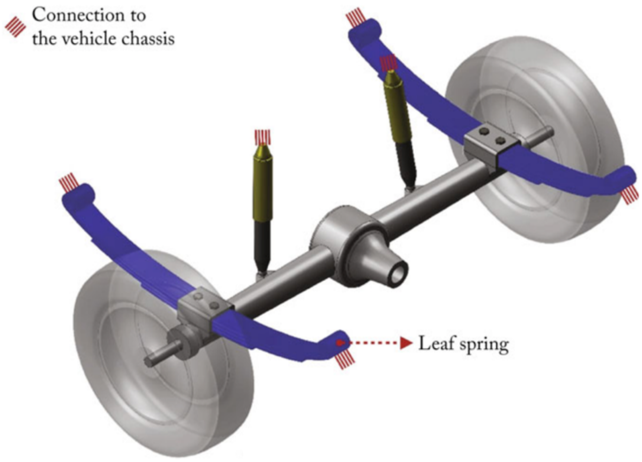

Figure 18 Solid axle with leaf springs [7]

Drive axles, sometimes called "live" axles, are part of a vehicle's drivetrain. In them, solid axles (Figure 18) carry the drive wheels and differential, transferring torque from the engine to the wheels to provide propulsion. This design allows the drive wheels to be controlled and provides drive on one or both axles of the vehicle. [7]

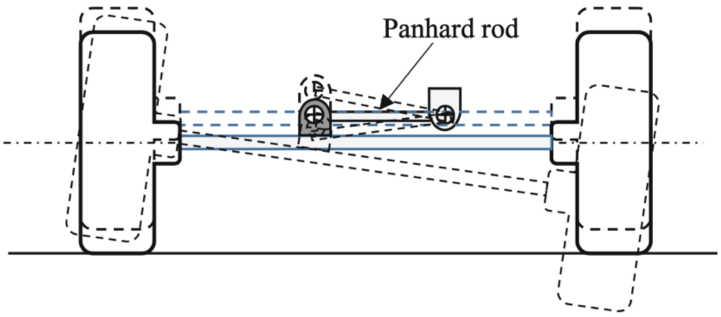

Figure 19 Mechanism showing axle lift or rock [7]

Non-driving axles, often known as "dead" axles, are a design where a solid beam simply connects two non-driving wheels that can be steered. These axles do not take part in transmitting torque from the engine to the wheels.

Although solid axles are rarely used on modern passenger cars due to their limitations, they are common in trucks and commercial vehicles, as well as many SUVs. This is due to their simplicity compared to more complex independent suspension systems. They typically minimize wheel camber (except for minor camber caused by differential tire deflection on the inside and outside wheels), and wheel alignment is easily adjusted to promote even tire wear.

In the design of vehicles, various methods of attaching continuous axles using dependent suspension systems are used. In this context, only the basic types and their associated principles are discussed. [11]

The Hotchkiss arrangement (Figure 19) is the most popular way to mount a solid driving axle. It is a simple and effective suspension system that provides proper wheel alignment with the fewest amount of parts. Its simplicity is owing to the leaf spring's qualities, which are flexible vertically yet relatively inflexible transversely and longitudinally.

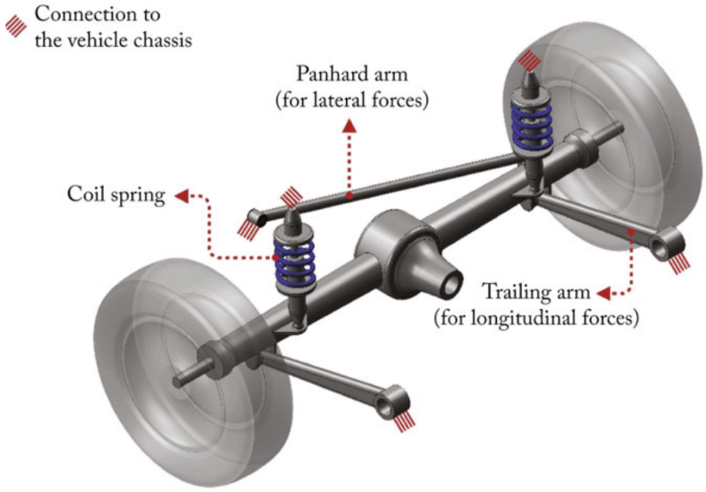

Figure 20 Solid axle with Panhard arm and coil spring [7]

Over time, advancements in leaf springs have overcome the issues of friction between leaves. Currently, the most common structures are single-leafed and cone-shaped. However, due to insufficient spring stiffness, which is required to provide acceptable driving characteristics, single leaf springs are typically unable to withstand lateral loads as well as driving and braking torques on modern vehicles.

In such circumstances, Panhard arms (Figure 20) are used as supplementary reinforcing elements. These Panhard arms restrict lateral movement to the chassis and prevent spring wrap (when a spring forms an “S” shape owing to torque on the wheels), which can cause wheel hop. [10]

This balances comfort and handling, making independent suspension an appealing option for a wide range of cars. Rigid axles are used in a wide range of vehicles, including passenger cars, crossovers, SUVs, and even commercial vehicles. It is commonly utilised in both front and rear-wheel drive vehicles, as well as some all-wheel drive variants.

In passenger cars, this form of suspension can be used on both the front and rear axles. It offers a comfortable and stable driving experience, making it ideal for daily use in cities and on highways. In crossovers and SUVs, it also enables the vehicle to cope successfully with diverse types of roads and uneven terrain, resulting in excellent cross-country capability and handling. Some commercial vehicles, such as vans and trucks, can also use independent suspension to provide a comfortable ride and good load capacity.

Thus, this type of suspension is used in a wide range of vehicles, providing a balance between comfort, handling and maneuverability in various operating conditions.

De-Dion suspension

The De Dion suspension system (Figure 21) is a compromise that combines the benefits of a rigid beam with independent suspension. It is used exclusively for the drive axle of a vehicle.

Figure 21 De-Dion suspension [9]

This dependent type of suspension system was created by Albert De Dion, in which the wheels are connected by a single cross element. However, this system is distinct from other forms of dependent suspension. The primary benefit of this design is that it helps equally distribute the vehicle's weight, as a result getting greater handling and ride comfort. [12]

When using suspension on land vehicles, the terms"unsprung " and "sprung weight" are used. The first includes all automobile parts except wheels and their components (brakes, rims and tires). The higher the mass of the sprung components, the more comfortable and stable the vehicle's movement. The forces applied to the vehicle by the unsprung components must be balanced by the sprung mass. The kinematics of the De-Dion suspension can be seen in the Figure 22. [10]

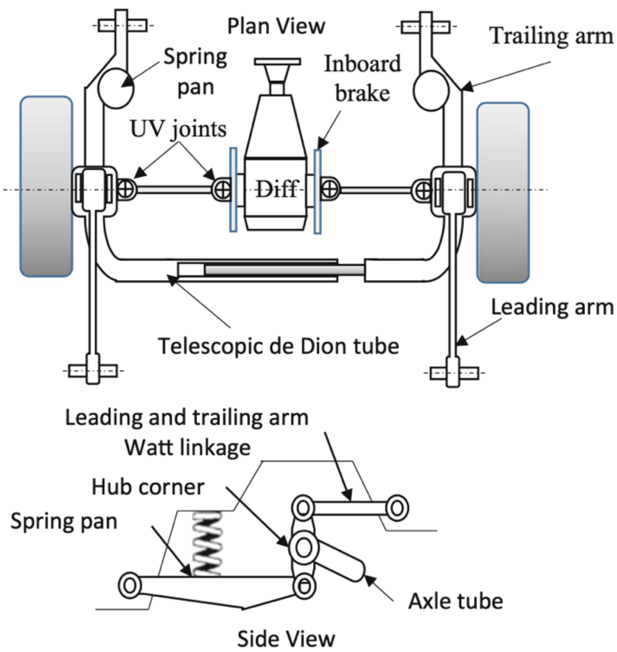

Figure 22 De Dion suspension system [7]

All of the De Dion's suspension components are suspended, making it relatively heavy and uncomfortable to ride. Perhaps in the nineteenth century, when these conceptions were still hazy, the inventors were influenced by their own thoughts. The primary purpose of the De Dion suspension was to reduce unsuspended mass and transfer it to the automobile body. This purpose is accomplished by connecting the main drive to the vehicle body.

The drive transmits power to the wheels via two axles, each having two joints. In this approach, the suspension maintains the relationship between the wheels while keeping the unsuspended mass to a minimum.

The De Dion suspension system has advantages and faults, yet it is still used today. Many current automobiles use it as the foundation for their suspensions, incorporating new technologies and materials to improve handling and comfort. [11]

Torsion beam

Torsion beam suspension (Figure 23) includes one rigid axle that connects the right and left wheels of the car. The operation of such a suspension system follows a certain pattern: when one wheel (for example, the left one) plunges into a hole, the other wheel (the right one) rises up, and vice versa. Typically, this axle is connected to the car body using two elastic elements known as springs.

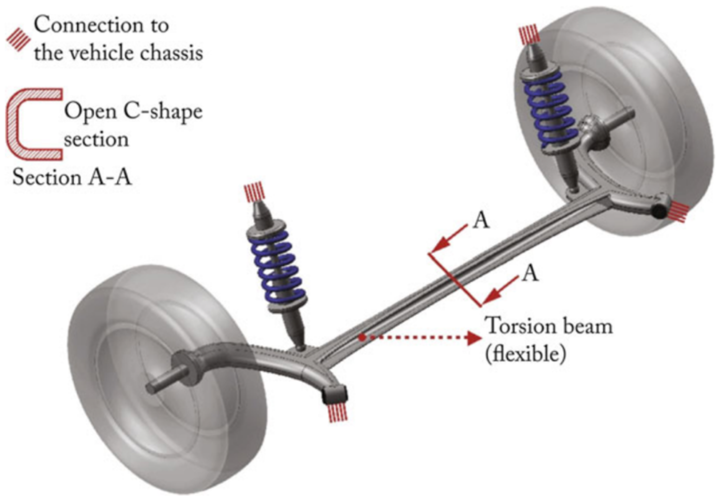

Figure 23 Torsion beam [7]

This concept is simple to apply and offers a strong connection. When one side of the car crosses an uneven road, the entire vehicle tilts in that direction. Because this suspension is built on a solid beam, passengers may feel acute shocks and vibrations when driving.

This style of suspension has been utilised in a variety of cars and vehicles, both historically and currently. It is widely utilised in the rear suspension of many rear-wheel drive vehicles, as well as certain front-wheel drive vehicles, particularly those where the cost-performance ratio is critical. The kinematics of the torsion beam suspension can be seen in the Figure 24. [12]

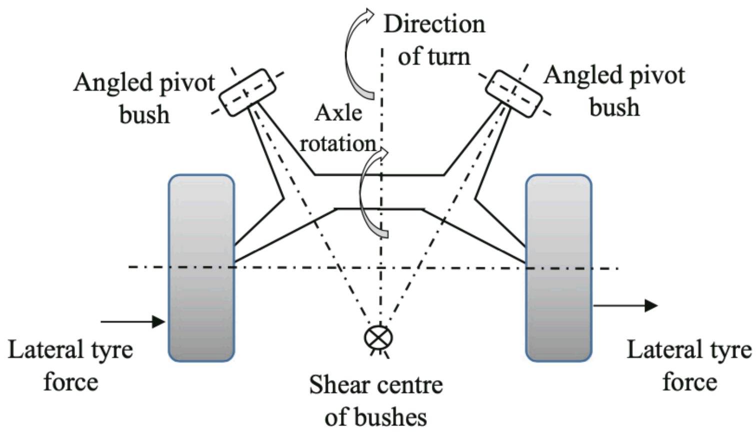

Figure 24 Torsion beam kinematics [7]

In rear-wheel drive cars, dependent suspension is often used because of its simplicity and reliability. It provides sufficient levels of handling and comfort, making it a popular choice for cars aimed at everyday use.

Variable suspension can also be used in some commercial vehicles such as trucks and vans, where it can provide the required load capacity and strength at a relatively low cost.

However, as technology advances and the desire to improve handling and comfort, dependent suspension often gives way to more modern and efficient suspension systems such as independent suspension. [10]

4. Double wishbone suspension

The Double wishbone suspension (Figure 25) has two independent arms ("A" shaped arms) for each wheel, forming a "double cherry". The levers are attached to the car's frame or body by ball joints or hinges. The lower arm is attached to the wheel via a vertical hinge or ball joint, whereas the upper arm is often attached to the body via a horizontal hinge or ball joint. This enables for unfettered vertical movement of the wheel. [4]

Figure 25 Double wishbone suspension example [14]

Application

- High-end and sports automobiles commonly use double wishbone suspension for better handling, stability, and comfort.
- In race vehicles enables for customised angles and exact geometry, resulting in optimal track performance.

Operating principle while driving:

- Spring compression: When a car moves on an uneven road and a wheel hits an obstacle, the suspension springs are compressed. At this time, the upper and lower arms of the suspension rotate relative to each other, allowing the wheel to maintain contact with the road and absorb shock.
- Controllability and stability: The geometry of the arms ensures stable vertical movement of the wheel, minimizing body tilt when cornering. This improves the vehicle's handling as the wheels remain more perpendicular to the road during cornering, providing better traction and stability.
- Tilt compensation: During a turn, the vehicle may lean in the direction of the turn. The suspension geometry compensates for this lean, keeping the wheels in a more upright position for increased stability and improved handling.
- Depreciation: In addition, that suspension usually includes shock absorbers and springs. Shock absorbers soften shock and vibration, while springs maintain optimal load levels and prevent excessive compression or expansion of the suspension. [11]

Additional features:

- Geometry tuning to optimise suspension performance based on vehicle design and driver/engineer preferences.
- The triangular arm shape enhances wheel movement precision and position control.
- The Double Wishbone suspension design ensures even load distribution between wheels, improving traction and tyre wear.

Advantages:

- The Double Wishbone suspension offers superior handling and stability due to its arm design and adjustable angles.
- Effective Shock Absorption: Double cherry design optimises shock absorbers and springs, reducing vibration.
- Vertical wheel motion reduces body lean while cornering, resulting in increased stability and predictability.
- Double Wishbone suspension is ideal for cars that require excellent handling, stability, and comfort. However, its intricate design and setup requirements may be disadvantageous for certain models and operating conditions. [3]

Disadvantages:

- Higher production and maintenance expenses compared to other pendant styles.
- Design requires more space under the car, which may be a drawback for smaller vehicles.
- Inexperienced owners and mechanics may struggle to tune and adjust this type of suspension due to the need for specialised equipment.

Examples of cars with Double wishbone suspension:

- BMW 5 Series
- Subaru WRX STI
- Porsche 911
- Mercedes-Benz S-Class
- Honda Civic Type R

Summary

The Double Wishbone suspension geometry creates optimal conditions for vertical wheel movement, which results in improved vehicle handling and stability. In addition, it provides comfortable and stable movement on various road surfaces and operating conditions. When the car is moving on an uneven road, when the wheel hits an obstacle, the geometry of the Double Wishbone levers allows the suspension to effectively compress and absorb impacts. This ensures even distribution of the load on the wheels and prevents unnecessary body tilt when cornering, which in turn improves the vehicle's handling and stability.

The triangular arm configuration allows for more precise wheel movement and improved control over wheel position. This allows the driver to feel confident and predictable in the behavior of the car on the road.

In addition, the Double Wishbone suspension also promotes even tire wear and more effective traction, which improves safety and overall ride quality. These characteristics make it a popular choice for sports and performance vehicles where high standards of handling, comfort and performance are required.

5. The basic principle of simulation in the Simscape program

Simscape uses physical modeling principles to model dynamic systems. The basic principle on which Simscape is based is the nodal variable method.

The nodal variable principle in Simscape is a system modeling technique in which the system is represented as a network of nodes or components. These nodes are connected through physical ports, each of which represents a physical variable such as voltage, current, or mechanical force.

It is important to understand that components in Simscape do not simply “connect” with each other, but form a network through which flows of physical quantities flow. For example, if you have an electrical circuit, then each element of that circuit (source, resistor, load) will be connected through electrical ports through which electrical current flows. Likewise, mechanical components will be connected through mechanical ports to transmit mechanical force or motion.

When modeling, Simscape uses "node variable" algorithms to solve a system of equations that describe the physical interactions within that network of nodes. These equations describe conservation laws and physical laws that determine the behavior of a system over time. For example, for an electrical circuit this may be Ohm's law, and for a mechanical system it may be Newton's law.

Simscape benefits

Physically based approach

Simscape offers a physically based approach to system modeling. This means that during reating models, the actual physical characteristics and interactions of system components are taken into account.

This approach allows the program to calculate the dynamics of the system over time and predict its behavior under various input conditions. The user can create complex multiphysics models by algorithmically connecting components through their ports and analyzing the interactions between them. In this way, Simscape provides more physically based and accurate simulation results for a variety of systems.

Integration with MATLAB and Simulink

Simscape is fully integrated with the MATLAB software package and the Simulink simulation environment.

Users can use the full power of MATLAB to analyze simulation results. This includes the ability to conduct various computational and statistical analyses, construct graphs and diagrams, and develop control algorithms and systems.

A Simscape simulation can be part of a larger simulation and control system developed in Simulink. This provides the user with the flexibility to integrate Simscape models into larger projects.

Multiphysics systems

Simscape provides the ability to model systems that span multiple physical domains. For example, you can create a model that combines electrical, mechanical and hydraulic components into one system. This allows you to analyze the interactions between different domains and evaluate their impact on the overall system.

This approach is especially useful in the design and optimization of systems, where it is important to take into account all aspects and interactions between various physical phenomena. Simscape provides a convenient tool for creating and analyzing such multiphysics systems.

These advantages make Simscape a powerful tool for designing, analyzing, and optimizing a variety of physical systems. It allows users to create high-fidelity models, integrate them into a wide range of projects in MATLAB and Simulink, and analyze interactions between different physical domains to achieve optimal solutions.

6. 3D printing

What is 3D printing?

3D printing (Figure 26), also known as additive manufacturing, is the process of creating three-dimensional objects from digital models. Unlike traditional methods, which remove material from blanks, printing creates objects by adding material layer by layer from a digital model. This method allows you to create complex geometric shapes and unique products.

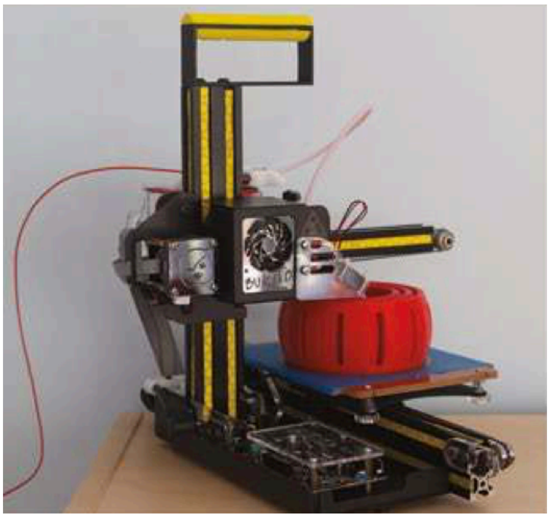

Figure 26 Example of printing [19]

In this project, it was chosen as the main method for producing components. This choice is due to several factors. First, it allows you to create parts with highly complex geometric shapes that may be difficult or impossible to reproduce using traditional machining methods such as milling or turning. This is especially important if the project contains parts with unique shapes or internal cavities. [19]

Benefits of 3D printing:

One of the most significant benefits of 3D printing is its ability to generate parts with minimal waste. This means that printing allows you to swiftly change designs and scale production based on demand. There is no need to develop new tools or equipment with each update. Traditional machining procedures, such as milling, can produce enormous volumes of chips, causing significant material loss. In the case of 3D printing, waste is often restricted to the support structures that hold the model together while printing. These structures can be optimised by lowering their number or modifying their shape, resulting in significant material and production cost reductions.

Another important aspect is its ability to achieve high precision parts. While the 3D printing process may not provide the same precision as CNC machining, with proper printer setup and calibration, very accurate results can be achieved. For most projects that do not require extreme precision, 3D printing results are quite satisfactory.

The 3D printing process uses only the material needed to create the object. This reduces waste and makes the process more environmentally friendly. [13]

Materials

There are various sorts of materials used in 3D printing, each with its own set of properties, benefits, and uses. Here are some of the most popular 3D printing materials:

- Plastic (PLA, ABS and PETG).
- Flexible materials (TPU - thermoplastic polyurethane).
- Metals (stainless steel, aluminum).
- Polymer composites (ASA - acrylonitrile styrene acrylate).
- Ceramics (slate ceramics).

Plastic is one of the most popular and commonly used materials for 3D printing. Plastic is available in a variety of varieties for 3D printing, each with its own set of properties and advantages. Here are some of the primary reasons behind plastic's popularity in 3D printing:

Polylactide (PLA)

PLA is a bioplastic derived from plant sources such as corn, potatoes, and sugar cane. This makes it a more environmentally friendly alternative to petroleum-based polymers.

It is recommended to print at temperatures ranging from 190 to 220 °C. Lower temperatures will provide greater precision, whilst higher temperatures may improve layer adhesion. Heating the platform is rarely necessary, but if it is, the temperature is typically between 50 and 60 °C. [13]

Advantages:

- Easy to print and has low cooling shrinkage, making it a good choice for beginners.
- Doesn’t require special heating of the printing chamber.
- It has a pleasant sweetish smell when printing.
- Biodegradable: Can be degraded in the environment by bacteria.

Application:

Well suited for creating prototypes, packaging parts, toys, decorative items and other load-bearing and non-functional objects.

Acrylonitrile butadiene styrene (ABS)

ABS is a durable and impact-resistant plastic that is widely used in industry. To successfully print ABS, it is advisable to have a heated print chamber, as it has a high shrinkage and can warp when cooled quickly.

It is recommended to print at temperatures between 230 and 250 °C. This helps to avoid deformation and ensure good adhesion between layers. This ensures good adhesion between layers and high-quality output. It is recommended to heat the platform to 80-110 °C to prevent deformation and ensure good adhesion. [19]

Advantages:

- ABS is more durable and temperature resistant than PLA.
- Resistant to oils, grease and solvents.
- Suitable for further processing: easy to process, e.g. by sanding or gluing.

Application:

Automotive parts, functional prototypes, engineering parts, household products.

Polyethylene terephthalate glycol (PETG)

PETG combines the advantages of PLA and ABS, is highly durable and resistant to moisture and chemicals. It is recommended to print PETG on a heated platform (about 70-80 °C) and a closed printing chamber to prevent bubbles and deformation. Print temperatures are between 230 and 250 °C.

Advantages:

- Durable and durable material with good resistance to chemicals and mechanical stress.
- Allows you to create transparent parts.
- Higher melting point compared to PLA, making it suitable for applications requiring high heat resistance. [19]

Application:

Bottles, containers, transparent parts, mechanical parts.

Main stages of the 3D printing principle

- Digital Model: The process starts with producing or obtaining a digital model of the object. This model can be built with specialised 3D modelling software or with existing models.
- Preparing the model: After creating the model, it is prepared for printing. This process entails dividing the model into layers, specifying printing parameters, and developing supporting structures.
- Printing: The printer deposits or extrudes the material layer by layer according to a digital model. Each layer hardens to form a physical model of the object.

7. Design of double wishbone 3D model

To begin with, it is necessary to clearly define the purpose of creating this training model. This will allow us to understand in which parts of the model we should closely adhere to the design of a real car suspension, and where parts can be simplified to make production easier. The car of the second generation Audi R8 (Figure 27) was taken as a basis. The main purpose of this scaled-down 3D model suspension based on the Audi R8 gen 2 suspension (Figure 28) is to increase awareness of the key design elements of the double wishbone front suspension that are important to vehicle handling. This model (Figure 29) should also demonstrate overall suspension kinematics using specific geometry and principles. An example of wheel hub placing in this 3D printed model can be seen in the Figure 30.

Figure 27 Audi R8 gen 2 [14]

To achieve this goal, some systems, such as the braking system and all-wheel drive, can be significantly simplified. For example, the detail of the braking system may be reduced because it is not the main functional element of the training model. It is important to focus on the elements that are directly related to wheel handling and suspension to ensure a proper understanding of how these systems work. Simple methods such as manually lifting the brake disc or other relevant model components can be used to demonstrate the shock absorber properties of this type of damping. This will allow to clearly show the principle of operation of the suspension without the need to use complex mechanisms. It is also necessary to take into account the design and production concept of each part of the model. This includes analysis of the time, cost and feasibility of different technologies.

Optimizing part production is key to ensuring model efficiency and availability. It is important to choose materials that will make the model light and easy to transport. This is especially important for educational purposes, where models will be moved between classrooms quite often or used in various student demonstrations. Some components of the model require special attention to strength and rigidity. For example, an element such as a frame on which the entire model is attached must be rigid enough to withstand loads and ensure the reliability of the entire structure.

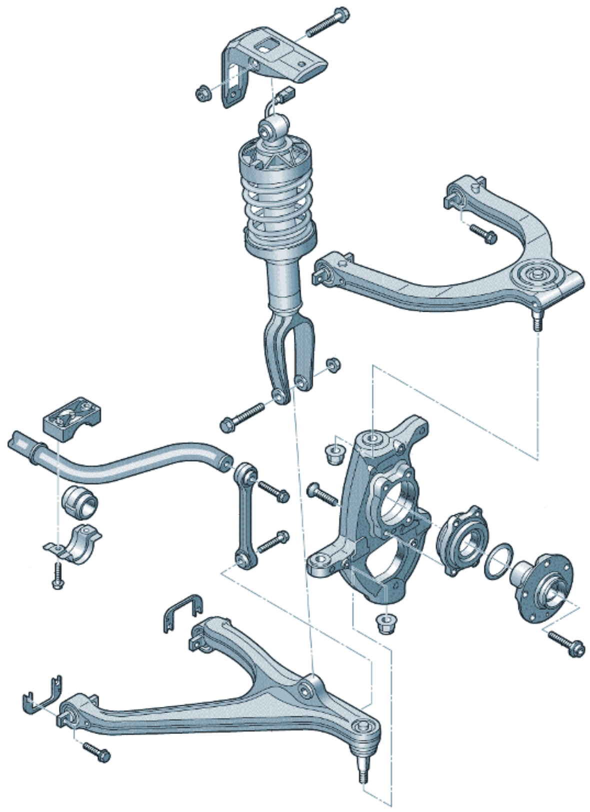

Figure 28 Audi R8 gen 2 suspension [14]

At the same time, other elements can be made of lighter materials, which will reduce the overall weight of the model and simplify its transportation and use. An important aspect is also the ability to quickly and easily replace individual parts of the model. This is especially true in educational environments where models may be subject to frequent use. The ability to quickly replace parts without the need to completely disassemble the model significantly increases its convenience and durability.

A list of all elements used in this 3D model can be seen in the Table 3. Therefore, when designing and producing a given vehicle suspension training model, many factors must be considered, including the purpose and functionality of the model, the materials used to make it, and whether it can be made easier without sacrificing key features. Such an integrated approach will create an effective and visual teaching model that will be useful primarily for students in the field of automotive engineering.

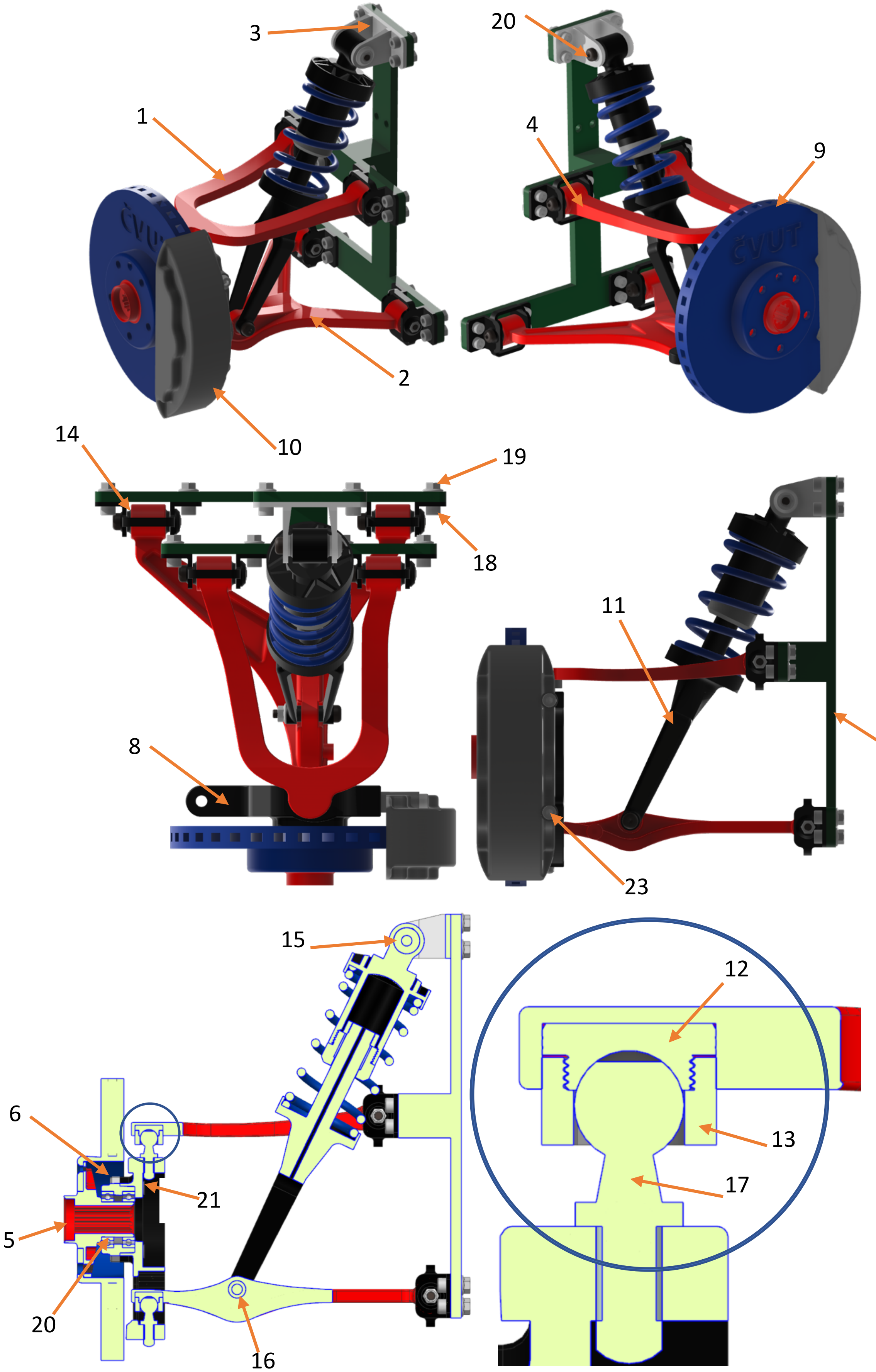

Figure 29 Double wishbone 3d model

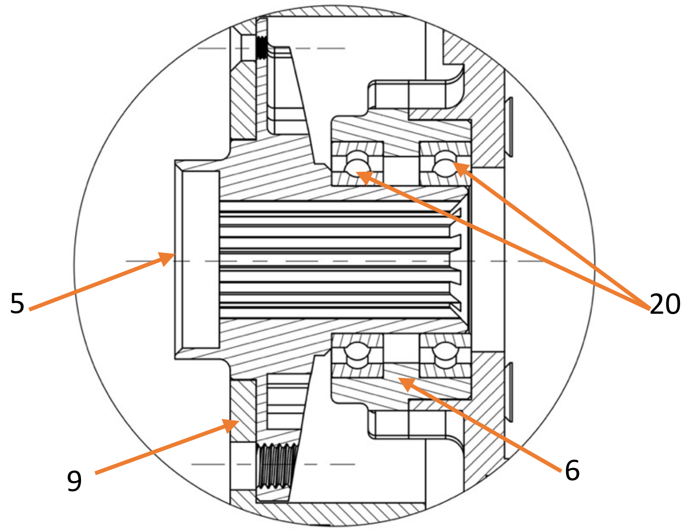

Figure 30 Wheel hub placing

Table of content		
POS.	QTY.	Part name
1	1	Upper control arm
2	1	Lower control arm
3	1	Shock absorber mount bracket
4	4	Control arm mount bracket
5	1	Wheel hub
6	1	Wheel bearing cover
7	1	Frame
8	1	Knuckle
9	1	Brake disk
10	1	Brake caliper with pads
11	1	Shock absorber
12	2	Upper ball stud cover
13	2	Lower ball stud cover
14	4	Control arm bushing
15	1	Rear end bushing
16	1	Front end bushing
17	2	Ball stud with threaded stud DIN71803
18	27	Hexagon Socket Head Cap Screw DIN912 - M5x12
19	27	Hexagon Nut DIN934 - M5
20	6	Shoulder Screw ISO7379 - 6x25
21	4	Hexagon socket countersunk head screw DIN7991 A2
22	2	Stainless steel deep groove ball bearing with integral sealing SKF W 61804-2RS1
23	2	Hexagon Socket Head Cap Screw DIN912 - M5x25

Table 3 Elements of the double wishbone suspension 3d model

Wheel hub

Wheel hubs (Figure 31) are critical components of automobile suspension, providing a reliable connection between the wheels and the suspension knuckle. Their functional purpose is to act as a link, transferring loads from the wheels to the suspension and back. This means that the hubs not only support the weight of the car, but also ensure the rotation of the wheels, and also transmit the forces generated during movement from the wheel to the suspension and inversely.

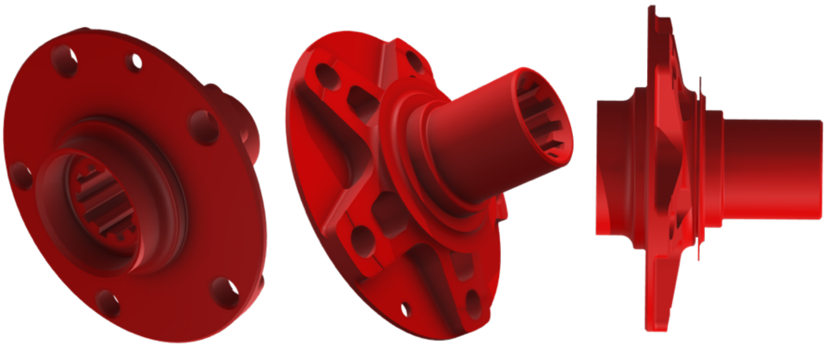

Figure 31 Original wheel hub model

In practice, hubs perform several important functions. First, they secure the wheel to the vehicle using bolts or nuts. This ensures a secure connection and prevents the wheels from coming loose while driving. In addition, the hubs have internal bearings that allow the wheels to rotate freely around their axle, ensuring smooth vehicle movement.

Another important function of hubs is to withstand the various loads and forces that occur when the vehicle is moving. This includes vertical forces created by the weight of the vehicle and passengers, as well as horizontal forces created by acceleration, braking and cornering. It is important that the hubs are strong and reliable enough to withstand these loads without deformation or damage, ensuring the safety and drivability of the vehicle.

Thus, hubs play a key role in the reliability, safety and performance of automobile wheels, making them an integral part of the vehicle structure.

In the process of modeling the wheel hub for educational use, I made many changes to improve its suitability for 3D printing. These changes were designed to make the process of creating this part more efficient and speed it up. These included optimizing geometry and eliminating unnecessary geometric complexity, resulting in shorter print times and less material usage (Figure 32).

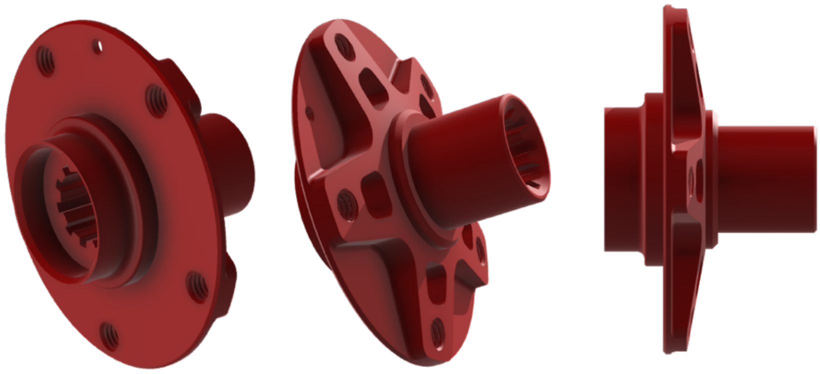

Figure 32 Final wheel hub model

Despite these changes, all hub mounting points remain unchanged. This was done to ensure compatibility with existing components and maintain the functionality of the hub. In this way, I was able to improve the process of creating a part without making significant changes to its design and characteristics.

Wheel bearing assembly

Wheel bearings play a critical role in ensuring safe and efficient driving. The purpose of wheel bearings is to reduce friction when a car's wheels rotate. This helps the wheels turn more easily, reducing stress on the shaft and transmission system. When wheel bearings wear out, friction in these components increases and they become susceptible to damage while driving. Wheel bearings require lubrication to function properly. Bearings that are not properly lubricated can rust or rub against each other during use, significantly shortening their lifespan. In cars, ball and roller bearings are most often used as wheel bearings. Ball bearings tend to last longer because the ring in which they are located is sealed, making it difficult for contaminants such as dirt and dust to enter the chamber and destroy the lubricant inside. Because annular housing roller bearings are typically not sealed, their lubricant becomes more easily contaminated, but they are also easier to access and service.

The wheel bearing assembly (Figure 33) consists of a wheel bearing cover (Figure 34), which is attached to the knuckle using 4x screws, as well as bearings, which are placed in two recesses on the wheel bearing cover on both sides.

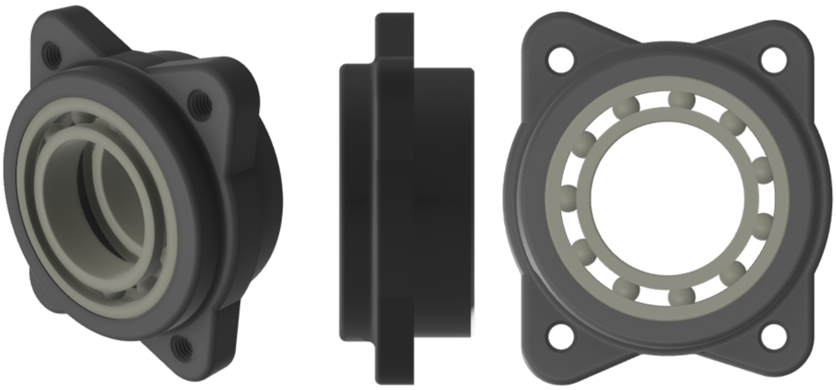

Figure 33 Wheel bearing assembly model

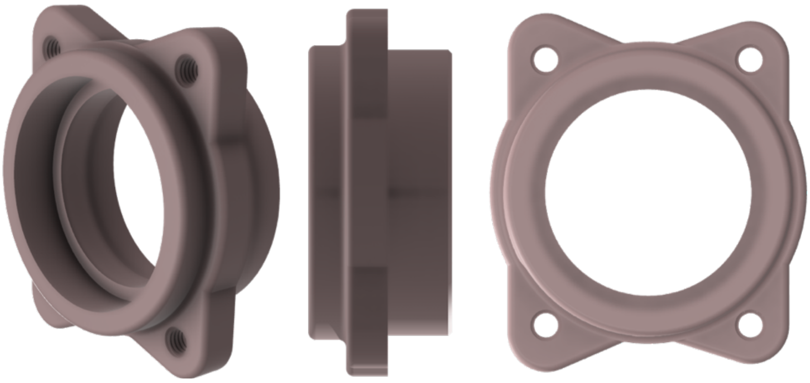

Figure 34 Wheel bearing cover model

The purchased parts were 4x Countersunk head screw M4X20 DIN 7991 A2 (Figure 35) and 2x SKF W 61804-2RS1 bearings (Figure 36). The main dimensions of countersunk screws can be seen in Table 4.

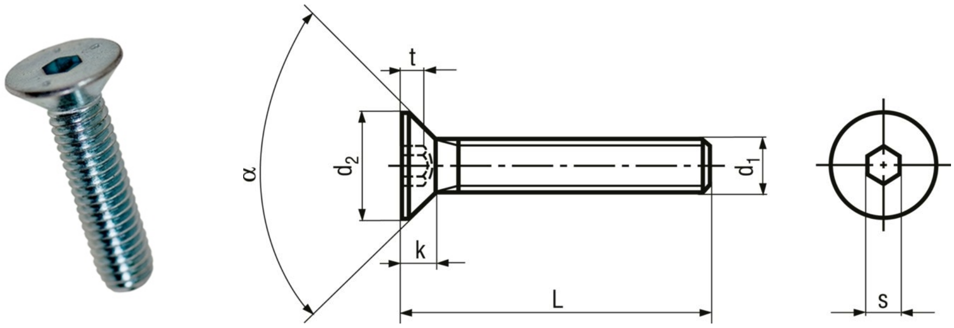

Figure 35 Countersunk head screw M4X20 DIN 7991 A2 [20]

d1	d2 max.	k max.	s	t	α	L
M3	6	1.7	2	1.2	90º	20

Table 4 Countersunk head screw main dimensions

The original suspension model used roller bearings, but in this model I used ball bearings. The main argument for using them was the price, since roller bearings are more expensive and can withstand heavier loads, which we do not need to use at all in educational purposes.

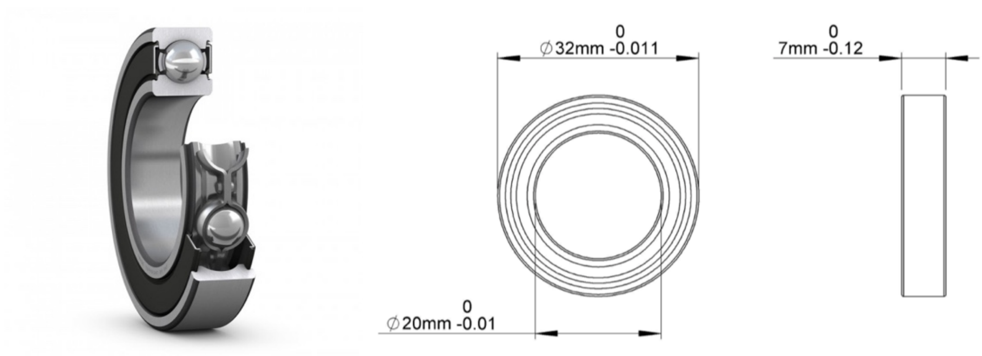

Figure 36 SKF W 61804-2RS1 [21]

Upper and lower control arm

A control arm is a part of a car's suspension that connects the wheel to the chassis and provides the vehicle's handling. The suspension arm consists of several parts: a lever, a ball joint and a silent block.

The job of the suspension arm is to hold the wheel in a vertical plane and provide the necessary suspension stiffness. As the car moves, the wheel is constantly exposed to impacts and bumps on the road, and the suspension arm plays an important role in absorbing these impacts and maintaining the stability of the car.

The upper arm connects the chassis to the top of the wheel and plays an important role in maintaining suspension rigidity. It is shaped like the letter 'A' and is attached to the car body from above, and to the wheel from below. The upper is usually used in combination with the lower control arm to provide full suspension rigidity.

The lower arm connects the vehicle's chassis to the bottom of the wheel. It is also shaped like the letter 'A', but is located at the bottom and is attached to the car chassis using bushings. The lower suspension arm can be spherical or with a ball joint.

UCA and LCA option 1

As we can see (Figure 37 and Figure 38), there is a hole in the UCA and LCA, which is intended for installing a ball joint into it, which is fixed with a locking ring on the underside of the arms. Since this part was created in size 1:1 and there is no suitable ball joint for this diameter, I remade this model to fit with the new ball joint.

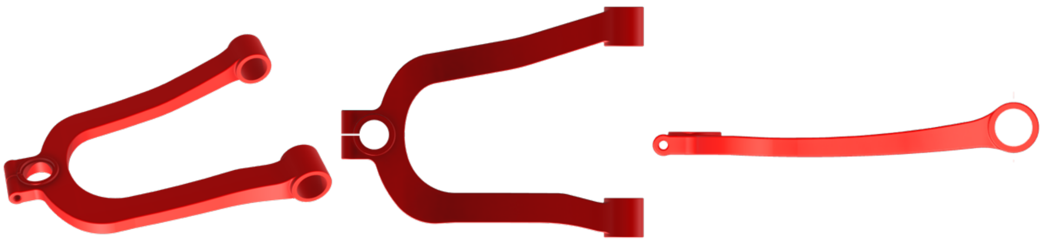

Figure 37 The original model of upper control arm

Figure 38 The original model of the lower control arm

UCA and LCA option 2

The main change to this geometry is the use of the lower inner surface of the arms as one of the working surfaces for the ball stud (Figure 39), meaning that the arm is also half of the ball stud cover.

The main disadvantage of this configuration is that if the internal working surface for the ball stud is damaged, the entire arm will have to be redone which will entail significant financial and time costs.

Figure 39 The lower and upper control arms (option 2)

UCA and LCA option 3

In this type of model (Figure 40 and Figure 41), the geometry and method of fastening the ball joint were radically changed. Now the arms is not half of the inner working surface for the ball stud. Instead, a recess appeared in the control arms into which a ball joints is installed, the functionality of which does not depend on the geometry of the control arms.

The advantage of this design is faster production using 3D printing.

Figure 40 Final version of upper control arm model

Figure 41 Final version of the lower control arm model

Knuckle

The steering knuckle (Figure 42) is an integral part of the vehicle's steering system and plays a key role in transmitting steering wheel movements to the front wheels. It consists of wheel hubs that connect to suspension and steering components. However, in addition to this function, the steering knuckle is also crucial for the safety and stability of the vehicle's front suspension.

Figure 42 Knuckle original model

To ensure proper operation, the steering knuckle must be well machined, have an accurate radius and a perfectly machined surface. Traditionally, such components are made from wrought iron or forged steel.

However, due to the current trend towards weight reduction, an increasing number of cars are equipped with aluminum steering knuckles.

In addition to transmitting steering wheel movements, the steering knuckle also plays a role in maintaining correct wheel geometry and optimizing vehicle control. Its design must be strong enough to withstand the stress of cornering and driving on rough roads. It is also important that the steering knuckle is properly balanced to prevent vibration and ensure smooth vehicle movement.

Since this suspension model will be used exclusively for educational purposes, during the design of the steering knuckle, a number of geometric changes were made to facilitate the formation and production of a physical 3D model (Figure 43) of this vehicle suspension element. The original steering knuckle has a geometry that is heavy enough to reproduce on a 3D printer, which would make it difficult for us to print it and also significantly increase production time and cost.

Figure 43 Knuckle final model

Frame

The frame is a connecting and supporting system (skeleton), which is the basis for attaching suspension parts.

Frame option 1

At first the idea was to make a frame out of metal. The model itself consisted of metal elements, which subsequently had to be connected by a permanent connection using welding (Figure 44).

This option much stronger and could withstand heavier loads. But since this model of the front suspension of the car is only a practical demonstration that will be used for educational purposes to improve the knowledge of students, this was not necessary.

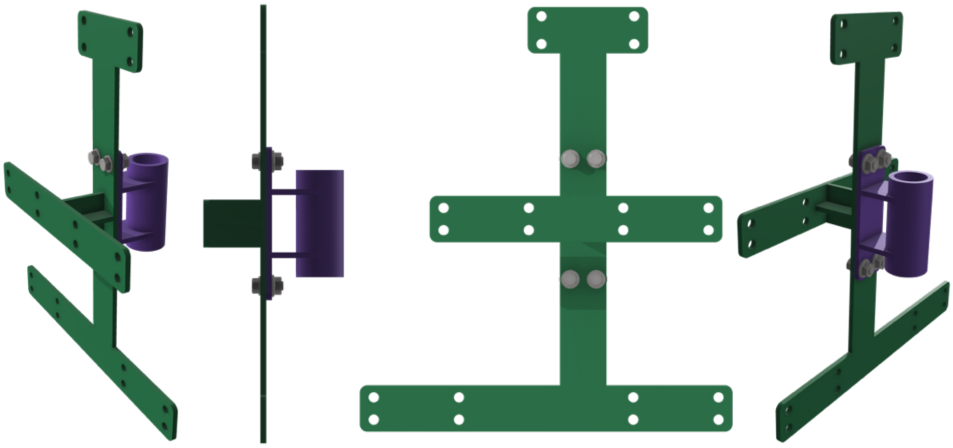

Figure 44 Original model of the frame

Frame option 2

This version of the frame is a completely solid model made of plastic using 3D printing (Figure 45). This option is much cheaper to produce than its previous version (laserized metal parts connected by welding), and is also lighter, which gives us the opportunity to manipulate with it using less energy.

Also, much less financial resources are spent on the production of this model, which is a very important factor.

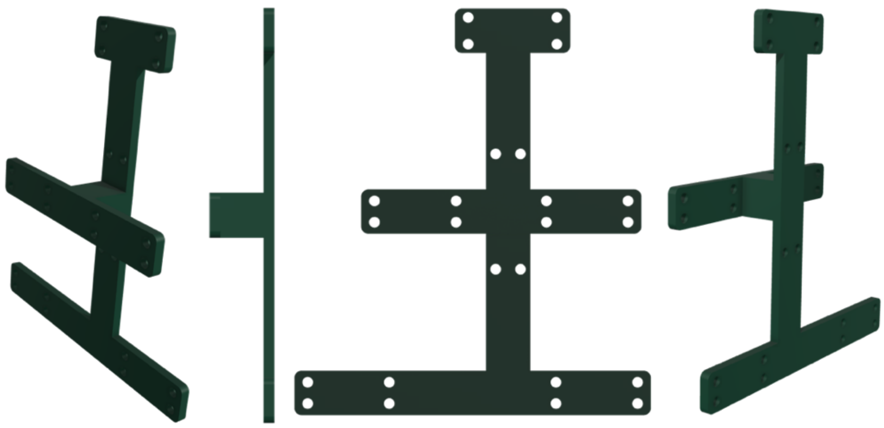

Figure 45 The final model of the frame

Bushings (silentblocks)

According to their design, silentblocks belong to non-separable rubber-metal hinges. This is one of the types of hinges in which the mutual movement of parts is ensured by the elasticity of rubber, without slipping.

This design does not require lubrication and maintenance throughout its entire service life. In silentblocks, the elastic part is connected to the inner and outer rings by vulcanization or using glue. To make an elastic layer, rubber, polyurethane and other polymer materials are used. There is constant debate among car enthusiasts about which silentblocks are better.

On the one hand, rubber has decent performance characteristics and an affordable price. Contrariwise, despite the high price, the service life of polyurethane silentblocks is an order of magnitude longer, which allows you to save on service station fees. The main purpose of silentblocks is to absorb vibrations. Due to their design features, they are able to perceive and withstand axial, radial and angular loads.

Since this suspension model serves only educational purposes and does not tolerate virtually any vibrations during manipulation, the use of rubber silent blocks would be inappropriate due to their cost and also manipulation with them. If purchased silent blocks were used, it would be problematic to work with them (the connection would be difficult to disassemble and reassemble due to the adhesion of these materials to each other).

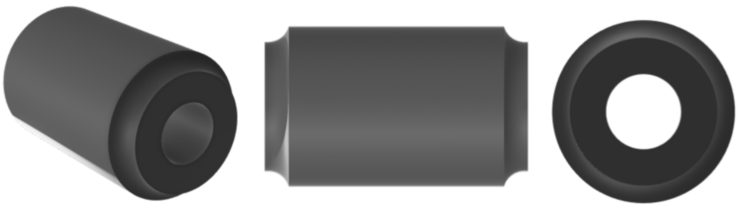

Figure 46 Bushing example model

Due to all the disadvantages of using purchased parts, it was decided to make silent blocks ourselves - using 3D printing from plastic (Figure 46). This connection is more disassembly and collective, since two identical materials that used in the model parts.

Mount brackets

In technology, brackets are used to secure components and parts of automobiles, as well as devices, mainly on vertical planes. The brackets, like other elements of this project, were 3D printed using plastic.

To attach the arms, was used 6x shoulder screw 6-M5X25 ISO 7379 12.9 as purchased parts (Figure 47). Main dimensions of shoulder screws can be seen in Table 5.

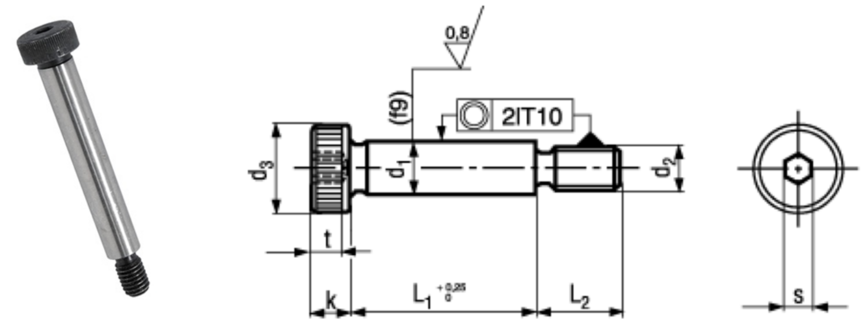

Figure 47 Shoulder Screw ISO 7379 [22]

d1	d1 min.	d1 max.	d2	L2	d3	k max.	t min.	s	L1
6	5.96	5.99	M5	9.5	10	4.5	2.4	3	8

Table 5 Shoulder screw main dimensions

Ball joint

When I started developing a 1:1 scale model and then reduced it to half its size, I encountered serious difficulties in finding a suitable ball joint. Starting with the idea of using ball joints from ATVs, which initially seemed more suitable due to their compactness compared to car ones, I soon realized that even these did not meet my requirements. As a result, I decided to develop my own ball joints, relying on my engineering and design skills.

The process of creating the ball joints for my model was long and meticulous. I conducted a series of studies and experiments to determine the best design and material for these connections. Using modern methods and technology, I made several prototypes, each time improving the design and functionality.

During the engineering process, I took into account factors such as material strength, wear resistance, compatibility with other vehicle components, and ensuring smooth suspension operation.

Several ball joint designs were tested and analysed before I was able to select the optimal design. This process required extensive testing for strength, reliability and performance under a variety of operating conditions.

Ball joint option 1

In this design I used a common contact surface for both of the connection arms (Figure 49) and the lower ball joint cover (Figure 50). I decided to use an off-the-shelf part as the ball stud rather than 3D print it out of plastic. This is due to the fact that the finished part provides higher friction and durability compared to the plastic version.

As the purchased part was used steel M6 ball stud DIN71803 (Figure 48). The main dimensions of the ball joint can be seen in Table 6.

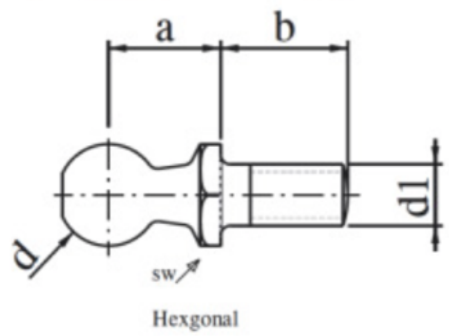

Figure 48 DIN 71803 [23]

Code	Size	d	d1	a	b	sw	Mass (kg)
H2	10M6	10	M6	11	12.5	10	0.0087

Table 6 Ball joint main dimensions

Given that this model is primarily intended for training and education, it was important that it must be durable and have quickly replaceable elements. In this context, the use of off-the-shelf parts has become the best option as it ensures reliability and ease of maintenance.

Figure 49 Upper part of the ball stud cover on UCA and LCA (option 1)

In addition, a completely plastic connection would create additional difficulties during installation and repair. The goal was to make the model for education, and using reliable materials and components helped achieve this goal.

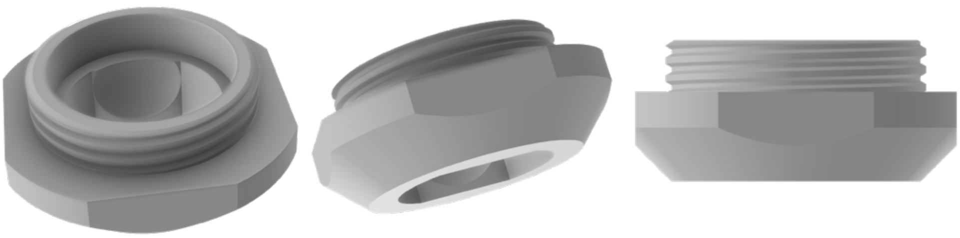

Figure 50 Lower part of the ball stud cover (option 1)

Ball joint option 2

In this version of the ball joint, I moved away from using the joint contact surface of the connection arm. This decision was made by me based on the fact that if the ball joint was damaged, the connection arm itself would have to be redone, which would not be effective in terms of time and material resources. Considering that creating a complex element such as a connection arm using 3D printing takes a significant amount of time, using a joint contact surface would not be justified.

I have developed a design that involves nesting a separate ball joint cover into a recess created in the arm. This approach allows the ball joint to be completely disassembled, which is especially useful for educational purposes for students. The ball stud cover consists of two parts – upper (Figure 51) and lower (Figure 52). The internal contact surface of the lower part of the cover is designed so that the ball pin has a slight pre-tension and does not fall out of the cover when it is manipulated. The upper and lower parts of the cover are using a threaded connection, ensuring ease of manipulation.

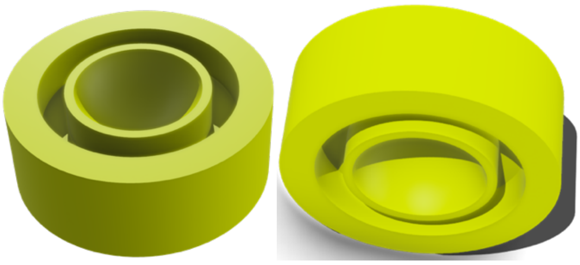

Figure 51 Upper part of the ball stud cover (option 2)

The ball stud cover itself is attached to the connection arm using an interference fit, with the outer diameter of the cap being slightly larger than the diameter of the recess in the arm. This connection allows for fastening without the use of additional connection elements and glue.

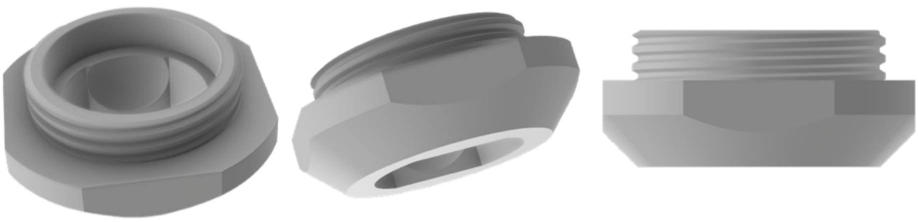

Figure 52 Lower part of the ball stud cover (option 2)

Ball joint option 3

The final variant of ball joint was designed with minor changes to the lower and upper parts of the cover geometry to simplify the design and improve the 3D printing process.

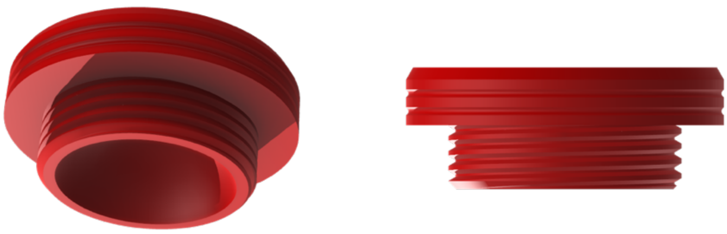

Figure 53 Upper ball stud cover final model

The connection of the body itself with the connection arm remains unchanged (the ball stud cover is inserted into the recess of the arm). Simplifying the geometry allows us to speed up 3D printing and not have an impact on the technical characteristics of this part.

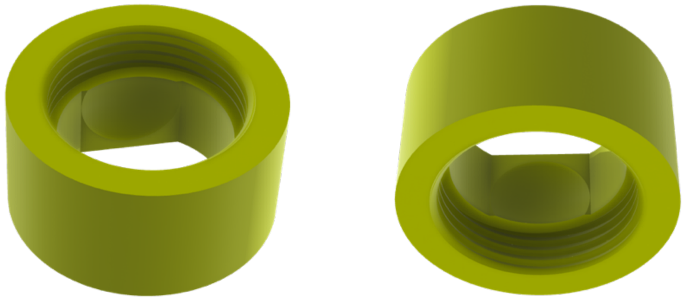

Figure 54 Lower ball stud cover final model

As we can see, the position of the threaded connection has been changed (the internal thread is now on the lower ball stud cover (Figure 54), and the external thread is now on the upper ball stud cover (Figure 53)). An example of a ball joint in the upper control arm can be seen in the Figure 55.

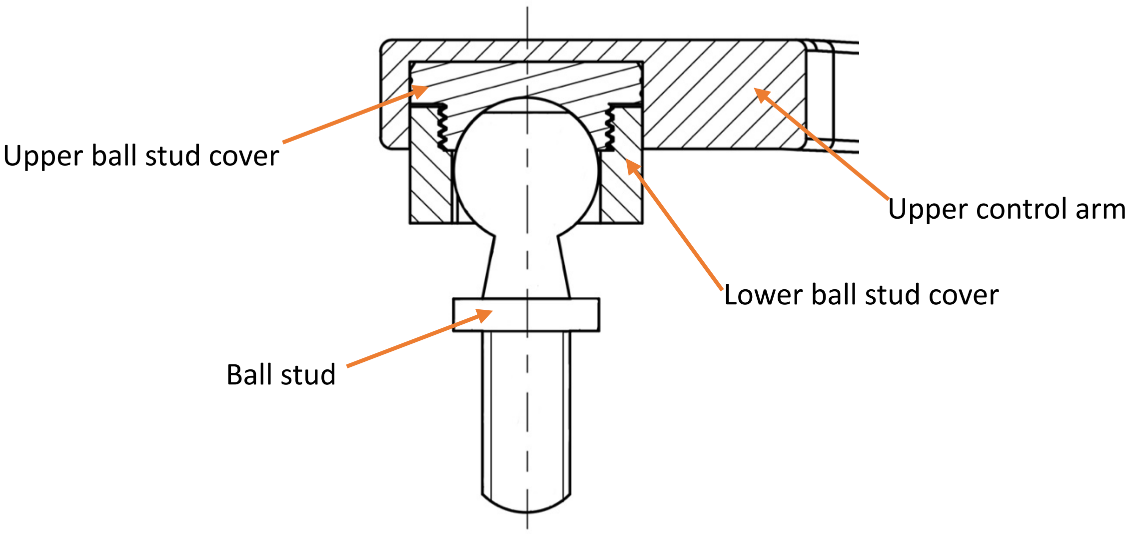

Figure 55 Example of placing a ball stud in the UCA

These adaptations have made the manufacturing process more efficient and cost-effective, which is especially important in the resource- and time-constrained environments that characterize prototype development and research.

Brake disk

Brake discs play a significant role in the braking system as they are the ones that come into contact with the pads, creating the friction that causes a car or any other vehicle to slow down to the point of failure stop. In the original car model, on the basis of which this physical 3D model of the front suspension Audi R8 gen 2 is made, is used carbon-ceramic brake discs (Figure 56). They have lighter weight, high wear resistance and high thermal conductivity and heat resistance compared to conventional iron brake discs. Also, this car model is a sports car, and ventilated brake discs are used here. Ventilated discs are lightweight, modern and reliable brake rotors for cars of various classes. In such disks, the central part is a separate element and looks somewhat different than in ordinary ones.

Figure 56 Audi R8 gen 2 carbon-ceramic brake disk [14]

The wheels spin, the blades capture air and release hot, exhausted air. It is due to this that it is possible to reduce the heating of the discs, the pads associated with them and consequently, the entire brake system. This advantage was appreciated by fans of sports cars, as well as simply by those who demand the maximum from their brakes. On the track and on the street, in slushy off-road conditions, they eliminate the problem of brake overheating. They consist of two plates, inside of which there are blades. This design allows air to circulate freely in the space between the blades.

Since this brake disc is composite, it would be quite problematic to produce a 3D model in a 1:2 size. To achieve this, a number of changes were made to the 3D model (Figure 57), which allowed us to simplify the design and reduce the cost of production of this element.

The idea of using the university name on the brake disk was implemented by the supervisor of this bachelor's thesis.

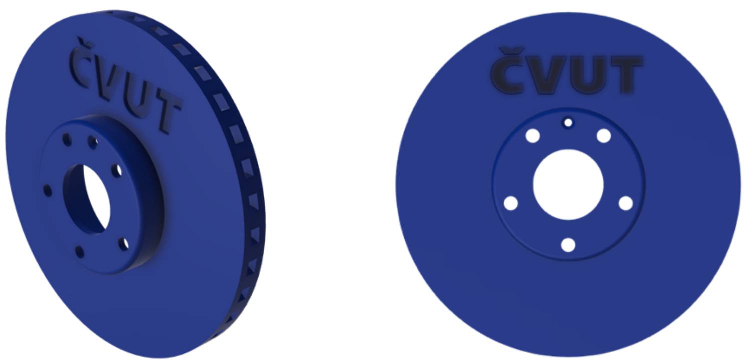

Figure 57 Brake disk final model

Brake caliper with pads

The caliper is one of the key elements of the braking system, which helps the car slow down effectively during braking. Its task is to ensure that the pads are pressed against the brake disc and thereby stop the car.

Also, the caliper is responsible for the performance of the car, as well as for the safety of the driver and passengers. During the development of the 3D model of the brake caliper, I made significant changes to its geometry in order to facilitate the 3D printing process.

These changes were significant because they were expected to greatly simplify the production process for the part. As part of this modification, I also decided to integrate the brake pads and caliper into one unit (Figure 58). This mods will not affect its functionality in any way and will significantly reduce the 3D printing time.

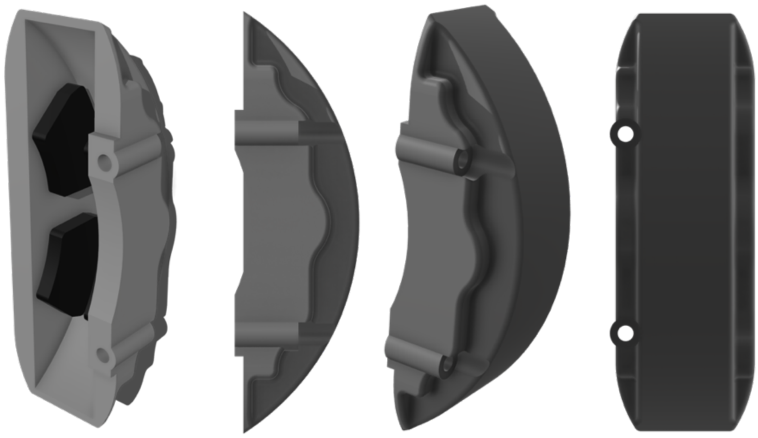

Figure 58 Brake caliper with pads

The caliper mounting points remain unchanged to maintain compatibility with other brake system components and provide stable mounting as required by design.

Suspension shock absorber

A shock absorber (Figure 59) is a damping element of a suspension. Its main task is to dampen resonant vibrations in the suspension, that is, it makes sure that the car does not sway on elastic elements (coil springs, leaf springs) for too long, and the wheels do not lose contact with the road for a long time, bouncing above the road like a ball.

Figure 59 Shock absorber [14]

All these effects are dangerous due to loss of vehicle controllability. The shock absorber works faster on compression and slower on rebound. It reduces the speed of expansion of the elastic element and extinguishes its excess energy, helping the suspension elements to return to their original position as quickly as possible after hitting an uneven road.

Thus, the shock absorber is one of the most important parts that ensure safety when driving a car. In the original model, this shock absorber has a very big advantage - it has variable stiffness and rebound. These settings allow for better traction when driving aggressively on the track, allowing for faster cornering speeds.

When creating this shock absorber model (Figure 60), a large number of changes were made, since this model is solely a teaching aid and does not claim to be 100% similar to the original shock absorber model.

Figure 60 Shock absorber model

The parts that make up the physical 3D model of the shock absorber can be seen in the Figure 61. A list of all elements used in this shock absorber can be seen in the Table 7.

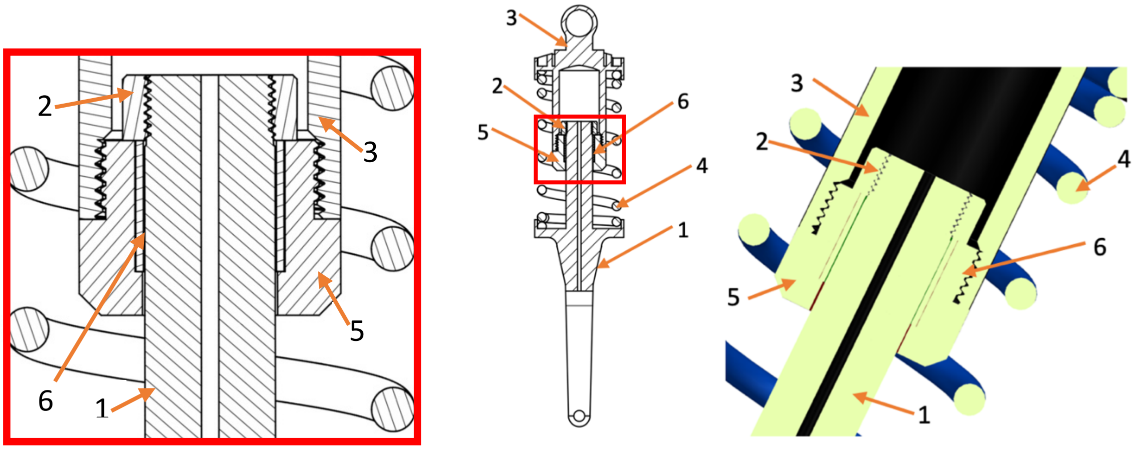

Figure 61 Shock absorber assembly

Table of content		
POS.	QTY.	Part name
1	1	Pushing rod with front end
2	1	Piston
3	1	Rear end
4	1	Coil spring
5	1	Bolt
6	1	Sliding sleeve PTFE EGB1515-E40-Z

Table 7 Shock absorber assembly elements

Pushing rod with front end

This part is a moving element in the suspension shock absorber assembly (Figure 61). The piston (Figure 63) is attached to this pushing rod (Figure 62) via a threaded connection. The rod with front end moves into the sliding sleeve (Figure 67), which in turn is attached to the bolt also via threads.

Figure 62 Pushing rod with front end model

All elements are 3D printed from plastic except for the sliding sleeve, since this part is purchased to improve mobility.

Piston

Piston (Figure 63) is a connecting element in the shock absorber assembly, which connects the pushing rod with the front end (Figure 62) by thread size M15x1 and does not allow it to go beyond the shock absorber by performing linear movements in this assembly.

Figure 63 Piston model

Rear end

This element in the shock absorber assembly is a housing into which a bolt, pushing rod with front end, valve and coil spring are installed. The movement of the pushing rod in this 3D model is limited by the planes of the rear end part, as well as by the plane of the bolt on which the valve rests, thereby limiting the movement of the pushing rod with front end.

Also, in this rear end part (Figure 64) you can see an eye in which a silent block is installed, which connects the shock absorber assembly to the frame using a bolted connection.

Figure 64 Rear end 3D model

Coil spring

A coil spring is an elastic suspension element that softens shocks and shocks from driving on uneven roads. After hitting an obstacle, the wheel lifts off the ground and becomes uncontrollable.

The purpose of the spring is to return it to its place as quickly as possible, but after hitting the road the wheel bounces back, and the softer the spring, the more it can compress and absorb more energy. Since this energy is consumed very slowly, the vibrations do not die out for a long time, fueled by new shocks from road irregularities.

To solve this problem, a shock absorber comes to the rescue, which is designed to quickly dampen wheel vibrations by converting vibrations of the body and suspension into heat.

In order to correctly select the parameters for making the 3d printing coil spring (Figure 65), certain calculations were made based on the force that can be produced by hand when lifting the wheel of a given physical 3D model. Final data we can see the in the Table 8.

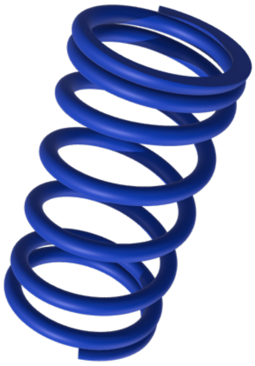

Figure 65 3D printed coil spring

$$s' = \frac{s \cdot \cos\alpha \cdot L}{a}\ [m]$$

$$k_{virt} = \frac{F}{s' \cdot 10^{-3}}\ [N/m]$$

$$k_{real} = k_{virt} \cdot \left(\frac{L}{a} \cdot \cos\alpha\right)^2\ [N/m]$$

$$L_{min} = L_0 - s\ [m]$$

$$n_{max} = \frac{L_{min}}{s}\ [-]$$

$$k = \frac{G \cdot d^4}{8 \cdot D^3 \cdot n} \cdot 10^3\ [N/m]$$

Force on wheel	F	20	N
Spring stroke	s	28.5	mm
Wheel stroke	s'	43.6	mm
Wheel suspension stiffness	k_{virt}	458	N/m
Attachment to the frame - attachment to the shock absorber	a	110	mm
Attachment to the frame - wheel	L	190	mm
Turning the shock absorber	α	29.67	°
Required spring stiffness	k_{real}	1074	N/m

Shear modulus	G	1375	MPa
Wire diameter	d	5	mm
Spring diameter	D	42	mm
Unloaded spring length	L_{max}	95	mm
Preload spring length	L_0	88.5	mm
Compressed spring length	L_{min}	60	mm
Maximum number of threads	n_{max}	12	-
Number of active threads	n	5	-
Suggested stiffness	k	290	N/m

Table 8 3D printed coil spring main dimensions

Bolt

Bolt is a load-bearing part into which the sliding sleeve is installed. The bolt (Figure 66) is connected together with the pushing rod by means of a threaded connection, where the external thread M26x1.5 is on the bolt.

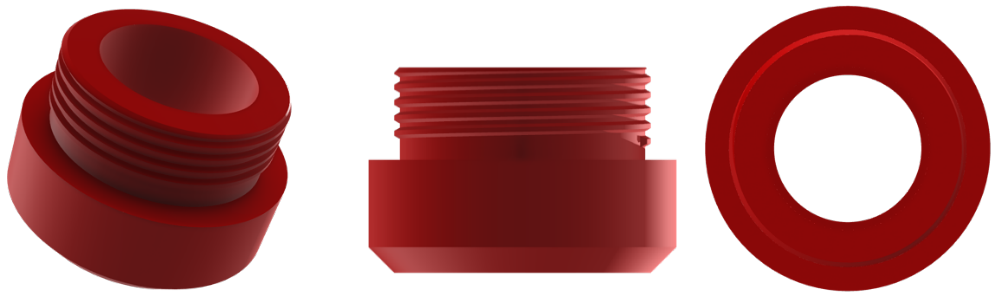

Figure 66 The bolt model

Sliding sleeve

Sliding sleeve (Figure 67) is used as an element to reduce friction between the bolt and the pushing rod. These elements are made using 3D printing, which means creating a part by laying layers of molten plastic on top of each other.

Figure 67 Sliding sleeve

Without the use of sleeve, it would be quite problematic and financially costly to achieve minimal backlash and smooth movement of these parts among themselves.

The purchased part EGB1515-E40-Z (Figure 68) was used as a sleeve. Thanks to this element made of PTFE (Polytetrafluorethylen), it was possible to achieve the expected friction parameters. The main dimensions of the ball joint can be seen in Table 9.

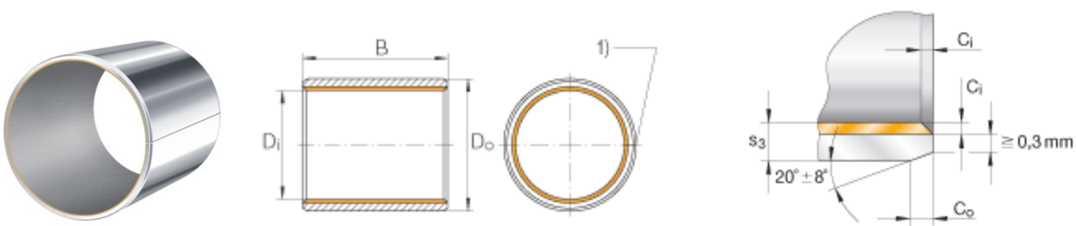

Figure 68 Sliding sleeve PTFE EGB1515-E40-Z [24]

D_o	D_i	B	$C_{i\,max}$	$C_{i\,min}$	C_o	s_3	m
15	17	15	0.6	0.1	0.6	1	5.7

Table 9 Sliding sleeve main dimensions

8. Matlab simulation

In this part we will look at designing a model in the Matlab Simscape Multibody program for further comparison of the results with a simple two-mass model built in the Matlab Simulink program.

Simscape Multibody

It is a simulation environment for 3D mechanical systems such as robots, vehicle suspensions, construction equipment, and aircraft landing gear. Multibody systems are modeled using blocks that describe bodies, joints, constraints, force elements, and sensors. Simscape Multibody formulates and solves the equations of motion for an entire mechanical system. Automatically generated 3D animation allows you to visualize the dynamics of the system. Simscape Multibody helps to design control systems and test system-level performance.

Basic principle of modeling

Solver configuration is an important element in this system, with the help of which parameters are set for the numerical solution of equations that describe this physical system. Bodies are our 3D models created either in this program or in a third-party 3D modeling program and transferred to Simscape. Bodies connect to other bodies using joints. To connect them, is needed to put coordinate systems on our 3D models, the axes of which will later be connected. An important aspect at this stage is the correct placement of these coordinate systems. Incorrect placement will result in errors, as well as incorrect operation of the entire system simulation. Forces and torques are used to create external forces and moments acting on our model. Constraints add restrictions on the movement of certain components of the entire model. To obtain results and further study them, sensors are used, which transmit the parameters of the value being studied to plots. Example of creating a dynamic model in this program can be seen in the Figure 69.

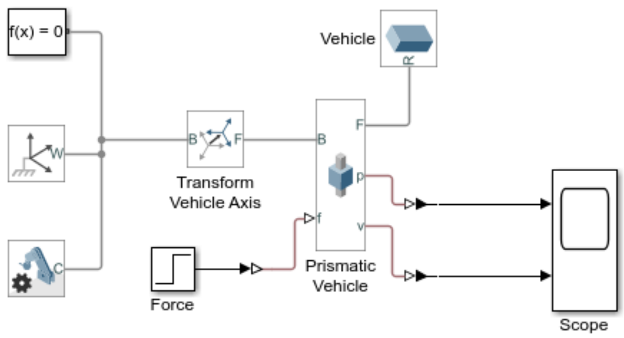

Figure 69 Example of creating model in the Simscape Multibody [25]

The main parameters required for the simulation are:

- Initial conditions (position of bodies in space, influence of external forces)
- Masses of data objects
- Connecting objects correctly using coordinate systems
- Correct shock absorber parameters
- Start and stop time of simulation

Simulink

Simulink is a graphical interface for creating block diagrams that represent physical systems based on signal flows and mathematical equations. In this program, models are created using blocks, where each block is a specific mathematical operation or logical function. This interface also requires differential equations to describe the dynamics of the system. The main difference from Simscape is the inability to use a 3D model and dynamic simulation. Simscape allows the use of physical connections, which in Simulink is represented only by signal streams. Example of creating a model in this program can be seen in the Figure 70. [15]

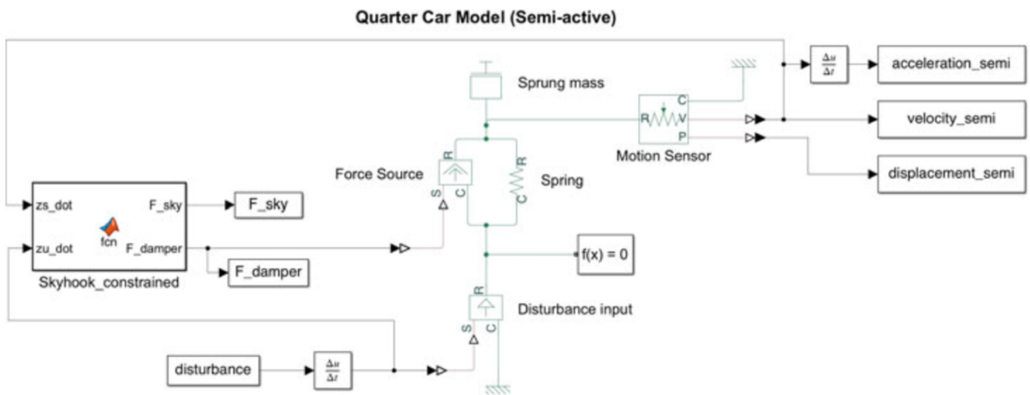

Figure 70 Example of creating model in the Simulink

The main parameters required for the simulation are:

- Step Size - defining the step for integration
- Initial conditions of the system, such as initial velocity and position
- Block Parameters - parameters of individual blocks

To carry out simulation in Simulink and Simscape Multibody programs, it is necessary to calculate the shock absorber parameters, such as coil spring stiffness and damping which will subsequently be translated into coefficients that will be used for simulations. For coil spring stiffness, two calculations will be made, which will be based on the mass of the car and the main parameters of the spring.

Calculations will also be made regarding the position of the shock absorber, since the Simscape Multibody program uses not only its basic parameters, but also its geometry, as well as its position in space. While Simulink only uses its parameters.

Basic spring and damper parameters required for simulation

Ideal coil spring stiffness calculation

In this part, calculations are made based on the force, which we calculate using the mass of the car and the distribution of mass between the axles of the car.

Force to one front wheel

$$F = \frac{(m_u + m_p) \cdot g \cdot (1 - 0{,}594)}{2} = \frac{(300 + 1645) \cdot 9{,}81 \cdot (1 - 0.594)}{2} = 5667\ [N]$$

Stiffness for a vertical coil spring

$$k_{vert} = \frac{F}{u} = \frac{5667}{115} = 49{,}28\ [N \cdot mm^{-1}]$$

Ideal stiffness conversion for an obliquely oriented coil spring

$$\alpha = \operatorname{arctg}\left(\frac{231.9}{407.1}\right) = 29.67\ [°]$$

$$k_{real} = \frac{k_{vert}}{\cos(\alpha)} = \frac{49{,}28}{\cos(29.67°)} = 56.83\ [N \cdot mm^{-1}]$$

Real coil spring stiffness calculation

In this part, calculations are made based on the main parameters of the coil spring, which are more realistic for further simulation.

Coil spring main parameters for the real stiffness calculation:

$$\varnothing d = 12\ [mm]$$

$$\varnothing D = 96\ [mm]$$

$$n = 5\ [°]$$

$$G = 7.93 \cdot 10^4\ [MPa]$$

Actual coil spring stiffness

$$k_{real} = \frac{G \cdot d^4}{8 \cdot n \cdot D^3} = \frac{7.93 \cdot 10^4 \cdot 12^4}{8 \cdot 5 \cdot 96^3} = 46{,}50\ [N \cdot mm^{-1}]$$

Vertical coil spring stiffness of a real spring

$$k_{vert} = \frac{k_{real}}{\cos(\alpha)} = k_{real} \cdot \cos(\alpha) = 46.50 \cdot \cos(29.67°) = 40.40\ [N \cdot mm^{-1}]$$

Comparison of ideal and real coil springs stiffness

In the Table 10 we can see that the ideal spring stiffness parameters obtained based on calculations through the mass of the car on the front axle are higher than the stiffness parameters obtained based on calculations made from the main parameters of the coil spring used in the Audi R8 gen 2 car.

Coil spring	Ideal $[N \cdot mm^{-1}]$	Real $[N \cdot mm^{-1}]$
Oblique stiffness	56.83	46.50
Vertical stiffness	49.28	40.403

Table 10 Comparison of ideal and real springs

Newton-Euler equations

Using the Newton-Euler equation, which describes the dual-mass damper spring system of an ¼ of the car (Figure 71), we will calculate the frequency, with the help of which we will later compute the critical damping. Next, working out the necessary damping coefficient from the critical damping, so that can give this parameter to the ¼ car model.

$$m_2 \cdot \ddot{x}_2 = -k_{12}(x_2 - x_1) - b_{12}(\dot{x}_2 - \dot{x}_1)$$
$$m_1 \cdot \ddot{x}_1 = -k_{10}(x_1 - y) + k_{12}(x_2 - x_1) + b_{12}(\dot{x}_2 - \dot{x}_1)$$

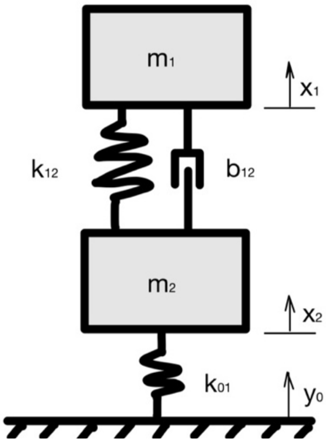

Figure 71 Dual-mass damper spring system

Inherent frequency

$\det(K - \lambda M) = 0$
$\lambda_1 = 14522{,}50\ [s^{-2}]$
$\lambda_2 = 109{,}50\ [s^{-2}]$

$$\Omega_1 = \sqrt{\lambda_1} = \sqrt{14522{,}50} = 120.51\ [s^{-2}]$$
$$\Omega_2 = \sqrt{\lambda_2} = \sqrt{109{,}50} = 10.46\ [s^{-2}]$$
$$f_1 = \frac{\Omega_1}{2\pi} = \frac{120{,}51}{2\pi} = 19.18\ [Hz]$$
$$f_2 = \frac{\Omega_2}{2\pi} = \frac{10{,}46}{2\pi} = 1.66\ [Hz]$$

Critical damping

$$b_{kr} = 2 \cdot m_2 \cdot \Omega_2 = 2 \cdot 488.60 \cdot 10.46 = 10221.5\ [N \cdot s \cdot m^{-1}]$$

Appropriate damping constant for a quarter model with vertical absorber position

$$b_{12} = \frac{2 \cdot m_2 \cdot f_2}{n} \cdot \ln\left(\frac{x(t)}{x(t + n \cdot T)}\right) = \frac{2 \cdot 488.6 \cdot 1.66}{3} \cdot \ln(1000) = 3735\ [N \cdot s \cdot m^{-1}]$$

Damping constant for real shock absorber position

$$b_{real} = \frac{b_{12}}{\cos(\alpha)} = \frac{3735}{\cos(29.67°)} = 4298.58\ [N \cdot s \cdot m^{-1}]$$

As an obstacle that our model passes through, was chosen a speed bump that can be seen in the Figure 72 . This object is intended for a speed of up to 10 km/h. The same speed was used throughout the simulation of crossing the bump.

Figure 72 Speed bump

Its dimensions are: 500x470x75 mm. Due to our simulation, we are only interested in the height and width of the speed bump. The assumption in this simulation is that the car moves perpendicular to our object. To compare the behavior of these models, a simulation of driving through a higher obstacle measuring 500x300x150 mm at a speed of 35 km/h was also carried out.

These simulations do not take into account the denting of the speed bump, we assume that the material from which it is made is ideal and does not bend under the influence of the weight of the car. The simulations occur as follows: the model moves at a speed of 10 km/h (35km/h) and at the same speed crosses the limiter - speed bump (obstacle), after which the speed remains unchanged, without acceleration.

In the Figure 73 we can see a simulation model, which was made in the Simulink program. The road along with the speed bump is represented using a 1-D Lookup Table. This block allows us to set up our input signal as a road coordinator depending on the time we got from our speed of 10 km/h and in another simulation 35 km/h. This signal is then converted by the Ideal Force Source block. This block is an ideal force source that generates a force proportional to the input physical signal. We can also see two masses. The mass 1 is the mass of the car with some suspension elements, and the mass 2 is the rotating masses, which is represented by the wheel, wheel hub and the brake disk.

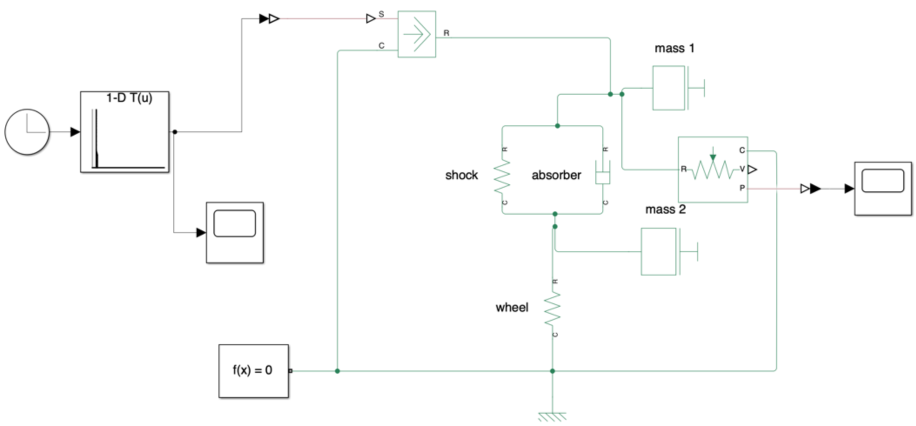

Figure 73 Simulink suspension model

When designing a model in the Simscape Multibody program, there are no such difficulties as converting masses into two components, as well as converting the geometry of the roadway into a function that depends on time. Here everything is built on the geometry of the bodies. The main thing is to correctly compare the bodies with each other and correctly set the initial conditions. All elements of this model are fastened by connecting the coordinate systems of each 3D element to each other, this can be seen in the Figure 74 and Figure 75.

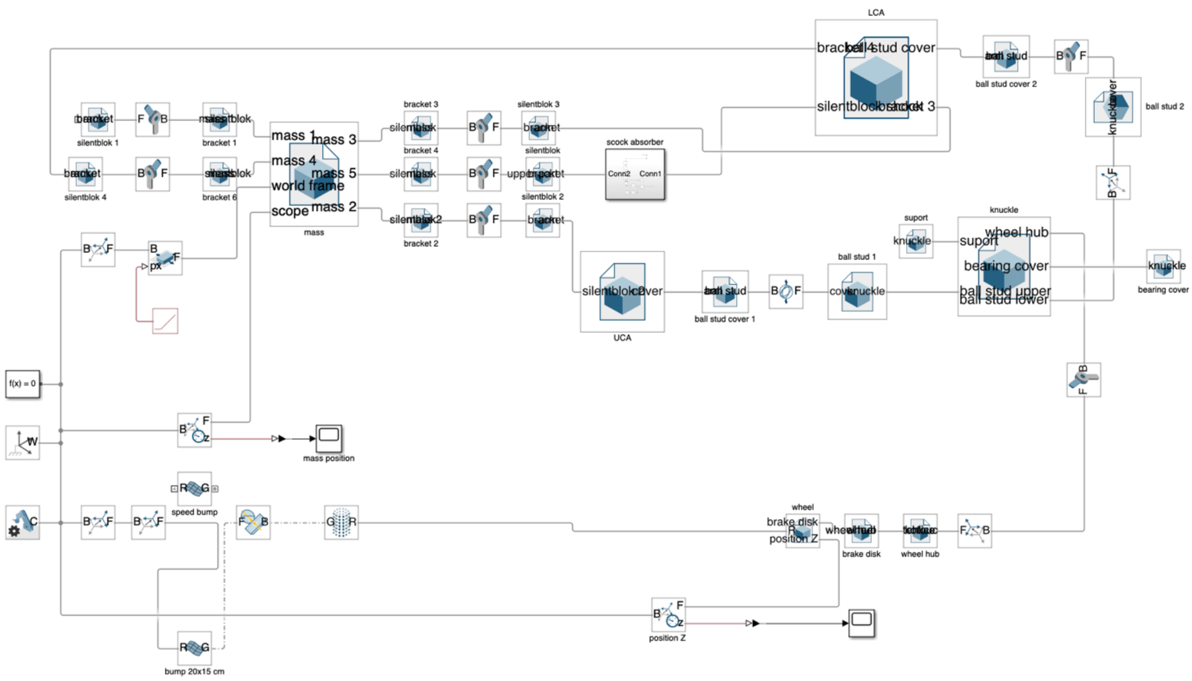

Figure 74 Fastening model elements using coordinate systems.

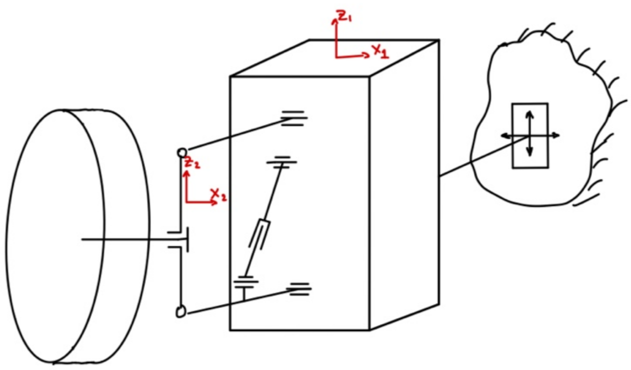

Figure 75 Fastening between elements in Simscape Multibody

In this model, the knuckle movement is carried out using a ball joint, where rotation along the Z_2 axis is limited, since this 3D model does not provide a steering rod to control the direction of movement. Z_1 – Z axis on the body, that represent car structure.

The geometry of the road surface is represented here using coordinates X, Y, Z. Since our speed bump does not represent right angles, we need to set the coordinates of the points quite accurately and close to each other so that the simulation occurs correctly and there are no sudden jumps in height. The suspension 3D model with the road surface can be seen in the Figure 76.

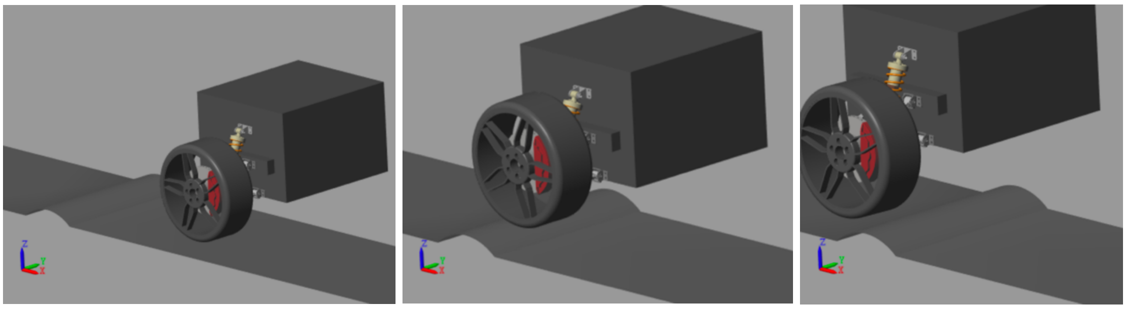

Figure 76 Simscape Multibody geometry model

After all the models are built, the same initial conditions are set, such as the position of the model in space and the initial speed, we can begin to simulate the behavior of these models. The simulation results can be seen in the Figure 77 and Figure 78.

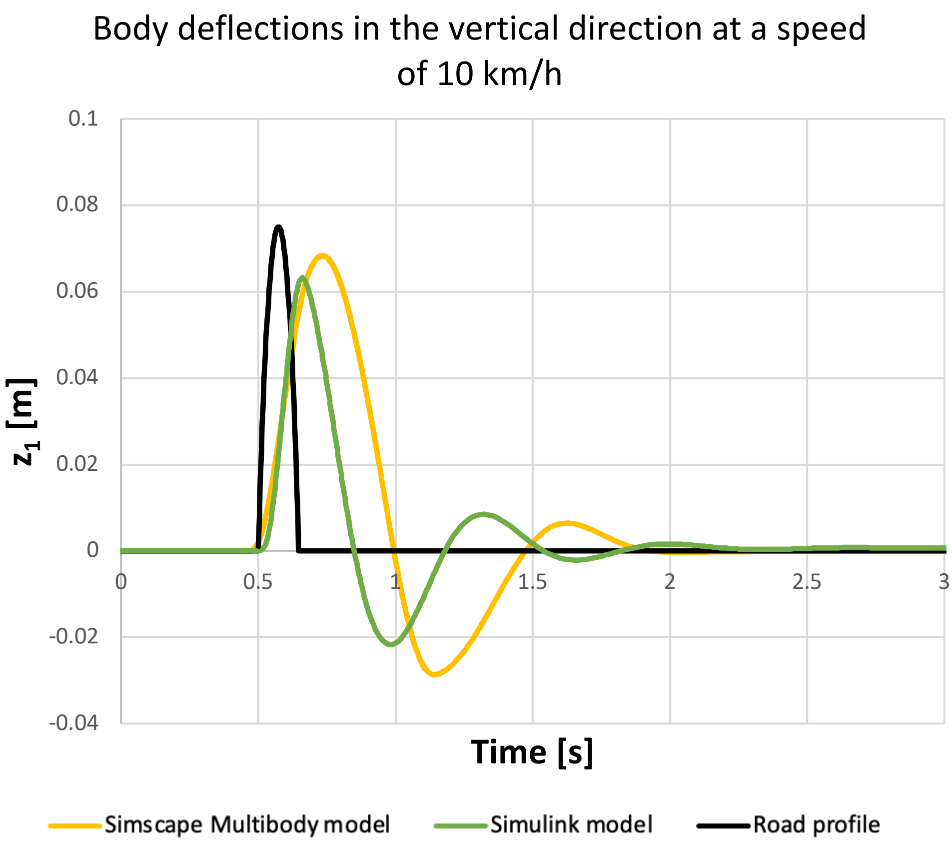

Figure 77 Body deflections in the vertical direction at a speed of 10 km/h

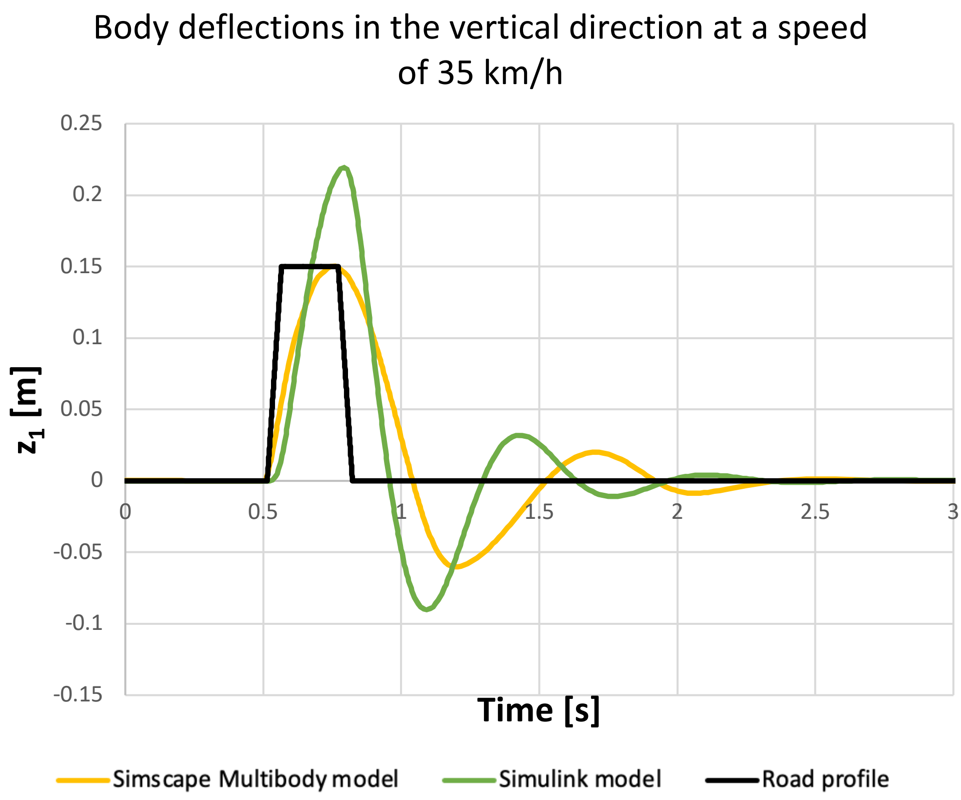

Figure 78 Body deflections in the vertical direction at a speed of 35 km/h

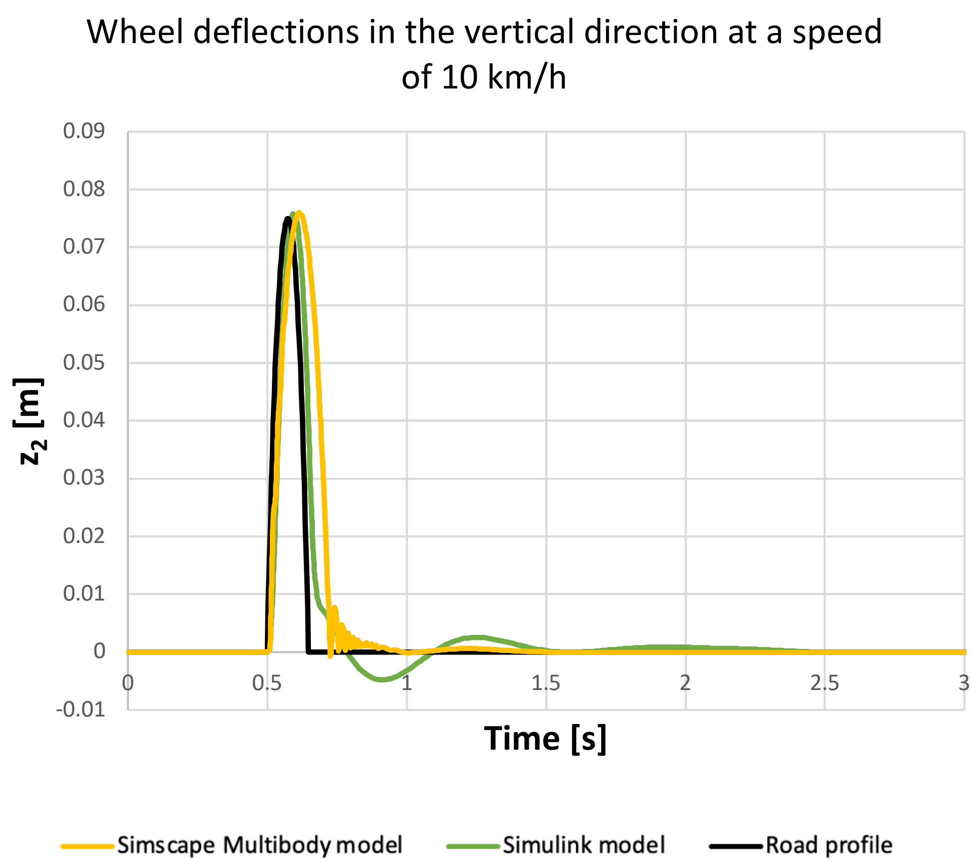

Figure 79 Wheel deflections in the vertical direction at a speed of 10 km/h

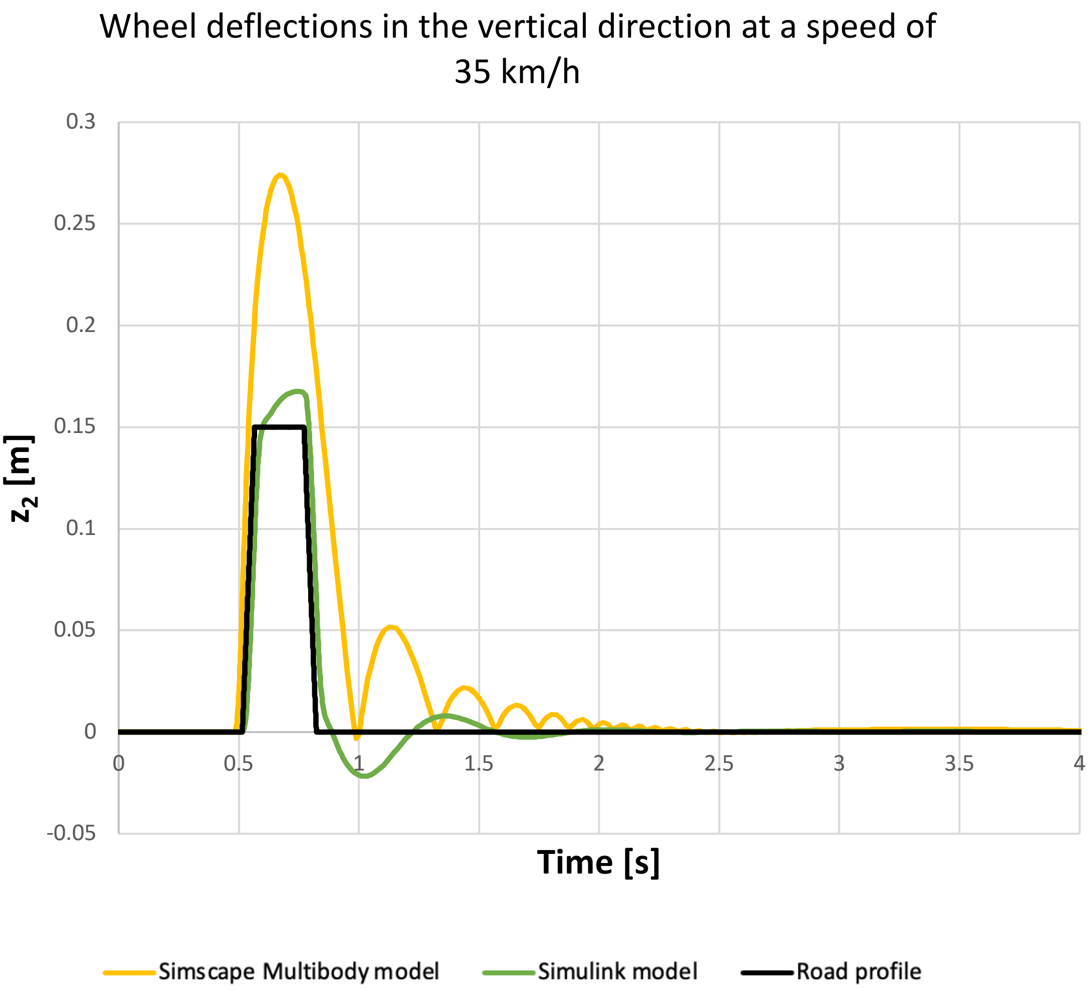

Figure 80 Wheel deflections in the vertical direction at a speed of 35 km/h

From the Figure 77 and Figure 78 we can see that the car in front of and behind the obstacle travels along an ideal road surface at a constant speed. Then, at the time of 0.5 seconds, a speed bump appears and the effect on the models begins. The black line on the graph shows the speed bump. The green line on the graph shows a model made in the Simulink program, the yellow line - in the Simscape Multibody program.

From the Simscape graph of the model, we can see that the position of our car does not change that much when comparing it with the position of the model made in Simulink.

In the Figure 77, that represent vertical deflection on the speed of 10 km/h we can see, that the Simscape model, after passing through an obstacle, stabilizes in a time of 1.91 seconds, however, the Simulink model stabilizes in a time of 2.82 seconds. Also, from this figure can be seen that when driving through an obstacle, the body of the car in the Simscape model reached a height of 0.066 m relative to the initial position, while the Simulink model reached a value of as much as 0.061 m.

In the Figure 78, that represent vertical deflection on the speed of 35 km/h we can see, that the Simscape model, after passing through an obstacle, stabilizes in a time of 2.51 seconds, but the Simulink model stabilizes in a time of 3.62 seconds. Regarding the vertical movement, we can see that the Simscape model has risen by 0.14 m relative to the original position, but the Simulink model has risen by 0.21 m.

This is due to the fact that the Simulink model does not use suspension geometry, but only uses the parameters of the shock absorber and the masses of the bodies that are located on top of each other. This is the biggest factor influencing the stabilization of this model after driving through an obstacle. An important factor is also the recalculation of the parameters of the shock absorber for its vertical location.

In the Figure 79 and Figure 80 we can see graphs of the position of the wheel relative to the initial position depending on the height of the unevenness and the speed of movement of our model. In the Figure 79 we see that at a low speed of 10 km/h the wheel rises by only 0.073 meters in the case of the Simscape model and 0.075 meters in the case of Simulink. The Simscape model stabilizes at around 1.82 seconds and Simulink at 2.73 seconds.

Due to the Figure 80 we see that the position of the wheel of our model created in Simscape at a moving speed of 35 km/h is 0.272 meters, but the position of the wheel in Simulink is 0.162 meters. The Simscape model stabilizes at around 2.5 seconds and Simulink at 2.27 seconds.

From these simulations we can conclude that suspension geometry plays a significant role in the vehicle's road behavior as well as its comfort during use. These differences in positions are due to the geometry of the module itself, since in the case of Simscape our two masses lie on top of each other.

9. Conclusion

The result of this work is a physical 3D model of the front suspension of the car, based on a study of the double wishbone suspension type. Firstly, a 3D model was made stand on the real dimensions of the front suspension Audi R8 gen 2 in a 1:1 ratio. After that the model was already reduced to size 1:2. Next, a significant simplification was made of some design elements of this model that did not affect its functionality, which subsequently greatly simplified its 3D printing and reduced production costs. For parts requiring the necessary strength, stricter geometry and specific requirements, a decision was made to purchase standardized elements.

The function of this physical 3D model is, first of all, to familiarize with the geometry of this type of damping, providing general concepts about its structure, elements and kinematics.

This model is also functional, which is important for the concept of the principle of its operation. The functionality of the model is demonstrated by the example of moving the brake disc and turning the steering knuckle.

This work also examined a comparison of the behavior of a model uses geometry with a simplified two-mass model. To compare the behavior of these models, simulation was carried out in the Simulink and Simscape Multibody programs provided by Matlab. The simulation results clearly show how the suspension geometry influences the vehicle's position in space under the same road conditions.

In the course of creating this work, I became better and more familiar with the types and concepts of car front suspensions. I also became acquainted with the creation of physical 3D models by 3D printing them using different types of plastic and creating suspension models to simulate its behavior.

10. List of pictures

11. List of tables

References

[1] Suspension geometry and computation John C. Dixon 2009

[2] SAE International Journal of Passenger Cars - Mechanical Systems ISSN: 1946-3995, e-ISSN: 1946-4002

[3] JAZAR, RezaN. Vehicle Dynamics: Theory and Applications. 2008. ISBN978-0-387-74244-1

[4] BUDYNAS, Richard G., NISBETT, J. Keith, SHIGLEY, J. Edward. Shigley's mechanical engineering design. 10th edition. New York, NY: McGraw-Hill Education, 2015. ISBN 0073398209

[5] Linear and Nonlinear Kinematic Design of Multilink Suspension ISSN: 2770-3460, e-ISSN: 2770-3479

[6] Road Preview Control for Active Suspension System ISSN: 2380-2162, e-ISSN: 2380-2170

[7] Car Suspension and Handling Bastow, Donald; Howard, Geoffrey; Whitehead, John P.

[8] Vehicle Suspension System Technology and Design Avesta Goodarzi Yukun Lu Amir Khajepour Sekond edition, 2022. ISSN: 2576-8107

[9] Road Vehicle Suspensions, Wolfgang Matschinsky, 1997. ISBN: 978-1-860-58202-8

[10] Automotive Chassis Engineering, School of Mechanical Engineering, University of Leeds, Leeds, UK, David C. Barton & John D. Fieldhouse, 2018

[11] Drivetrain and Suspension Systems, Pankl Racing Systems AG, Kapfenberg, Austria Michael Trzesniowski 2023

[12] The automotive chassis Volume 2: System design Giancarlo Genta, Lorenzo Morello

[13] 3D Printing Stephanie Torta; Jonathan Torta; Mercury learning and information Dulles, Virginia, Boston, Massachusetts

[14] Audi OEM Part catalogue [online] Available from: https://audi.oempartsonline.com/v-2015-audi-r8--base--4-2l-v8-gas/suspension--suspension-components

[15] SUSPENSION SYSTEM IN AUTOMOBILE SYSTEM; ANNA SMERINGAIOVA, IMRICH VOJTKO, BARBARA LESKOVA [online]; Technical university of Kosice, Faculty of Manufacturing Technologies, Presov, Slovak Republic

[16] Construction of air Suspension System [online] Available from: https://themechanicalengineering.com/air-suspension-system/#google_vignette

[17] GREEN PROPULSION REGENERATIVE ELECTROMAGNETIC SUSPENSION SYSTEM (GPRESS) [online] Available from: https://research.utm.my/ciam/project/proton1/

[18] Offering better handling through hydraulics [online] Available from: https://www.caranddriver.com/features/a15123918/the-anti-anti-roll-bar-tennecos-kinetic-suspension-explained-feature/

[19] Mastering 3D Printing Joan Horvath [online] Available from: https://it.dru.ac.th/o-bookcs/pdfs/09.pdf

[20] Countersunk head screw M4X20 DIN 7991 A2 [online] Available from: https://www.briol.cz/cs/p-49-sroub-imbus-zapustna-hlava-din-7991?v=566_43_568_98_388&c=9424.01&gad_source=1&gclid=Cj0KCQjw0_WyBhDMARIsAL1Vz8s1Z9KlVdPuhTVcaPnsaQ-ggVjQbtDJmjYUD1vXfeBXxcSSJQgaUkYaAgw-EALw_wcB

[21] Stainless Steel Deep Groove Ball Bearings W 61804-2RS1 [online] Available from: https://www.lily-bearing.com/products/w-61804-2rs1/

[22] Shoulder Screw ISO 7379 [online] Available from: https://www.briol.cz/cs/p-129-sroub-licovany-s-valcovou-hlavou-a-vnitrnim-sestihranem-iso-7379?v=17_42_544_97_388&c=12783.01&gad_source=1&gclid=Cj0KCQjw0_WyBhDMARIsAL1Vz8tAMNslxn5ROOfUFdJmPwMaT89e5I6CuOEj_0nDy6iUyCQf_jmvczAaAvAuEALw_wcB

[23] Ball Studs (Hexagonal spanner surface) Din 71803 [online] Available from: https://www.agmticaret.com/products/ball-studs-din-71803

[24] Sliding sleeve PTFE EGB1515-E40-Z [online] Available from: https://www.industrial.cz/egb1515-e40-z--kluzne-pouzdro-bezudrzbove-kompozit-ptfe-detail-W010000101.aspx

[25] Model and simulate multibody mechanical systems [online] Available from: https://www.mathworks.com/products/simscape-multibody.html

[26] Audi media center Audi R8 Coupe illustration [online] Available from: https://www.audi-mediacenter.com/de/fotos/detail/audi-r8-21572

[27] The structure diagram of a double wishbone suspension [online] Available from: https://www.researchgate.net/figure/The-structure-schematic-diagram-of-a-double-wishbone-suspension_fig2_326024230

[28] What is the Benefit of Mercedes-Benz AIRMATIC® Suspension? [online] Available from: https://www.mbontario.com/mercedes-benz-airmatic-suspension-benefits/

[29] Speed bump [online] Available from: https://www.denios.cz/zpomalovaci-prah-vnitrni-cerny-vyska-75-mm-prejezd-do-10-km-h-165398/165398?exclude_vat=0&gad_source=1&gclid=Cj0KCQjwsPCyBhD4ARIsAPaaRf2VrPJFIk71S8MdbZf5Ub1BLa9DDe-VBmjex8cKvfzenpm86m9VxN8aAgF0EALw_wcB