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Masterproef

Simulation and comparison of automotive shock absorbers

Promotor :
dr. ir. Kris HENRIOULLE

Promotor :
ing. ROMAN CERMK

Jeroen Konings
Proefschrift ingediend tot het behalen van de graad van master in de industriële wetenschappen: elektromechanica

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Abstract English

A suspension system of a vehicle is equipped with a spring, in combination with a shock absorber. The soaring need to enhance the comfort characteristics, and the higher imposed safety requirements have resulted in a rapidly gaining importance of the vehicle suspension system. One of the recent developments to improve the riding comfort is using a semi-active shock absorber Instead of a passive shock absorber. In this master thesis, the effectiveness of an ideal semi-active shock absorber will be analyzed and compared with an ideal passive shock absorber. In order to be able to achieve this goal, simulation software MSC ADAMS is used. The software will use a simulation model of a full-car suspension system to simulate the results. This model is run on three different types of roads: a country road, a city road and with the ISO Lane Change maneuver. Methodologies to analyze the simulation results are introduced, these are the vertical acceleration and normal forces for the city and country road, and lateral acceleration and roll angle for the lane change maneuver. The results show that semi-active shock absorbers, if they are well tuned, can improve the performances compared to the passive shock absorber.

Abstract Dutch

De wielophanging van een voertuig is uitgerust met een veer, in combinatie met een schokdemper. De stijgende nood om de comfortkarakteristieken te verbeteren, en de hogere opgelegde veiligheidseisen hebben tot resultaat dat de wielophanging zeer snel aan belang wint. Een van de recente ontwikkelingen om het rijcomfort te verhogen is door gebruik te maken van semi-actieve schokdempers in plaats van passieve schokdempers. In deze masterthesis, zal de doeltreffendheid van een ideale semi-actieve schokdemper geanalyseerd en vergeleken worden met een ideale passieve. Om dit te bereiken zal de simulatiesoftware MSC ADAMS gebruikt worden. De simulatie software maakt gebruik van een simulatiemodel van een volledig voertuig ophangingssysteem om de resultaten te berekenen. Dit voertuigmodel wordt geanalyseerd op 3 verschillende wegen: een veldweg, een stadsweg en een laanwissel maneuver. Methodes om de simulatieresultaten te analyseren worden vermeld, dit zijn de verticale acceleratie en normaalkrachten voor de veld- en stadsweg, en de rolhoek en laterale acceleratie voor de laanwissel. De resultaten tonen dat een semi-actieve schokdemper, indien ze correct zijn afgesteld, verbeterde prestaties kunnen leveren in vergelijking met een passieve schokdemper.

1. Introduction

1.1. Introduction

Because of my Erasmus program, my master's thesis has been executed for the University of West Bohemia, located in Czech Republic.

1.2. Premise

In all present vehicles, a suspension system is indispensable. In the very beginning, this was a rather simple device. However, as time went by, it got more complicated and more components were added to this system.

At the very beginning, there was actually no such thing as a suspension system for a (motorized) carriage. There was only a rigid connection between the wheels and the body chassis of the vehicle. However, since the vehicles could drive faster and faster, there was a need for a smoother ride. The first vehicle ever build, shown in figure 1, could reach 16km/h and included a spring that smoothed out the ride of the car.



Figure 1: Benz Patent Motor car [1]

After this, different kinds of springs were used in the automotive, such as, among others, leaf springs [2]. Although these springs allowed a vehicle to reach a higher speed without allowing a lot of jolting, there were still disadvantages to these springs: "When springs are made sufficiently stiff to carry the load properly over the small inequalities of ordinary roads, they are too stiff to respond readily to the larger bumps. The result is a shock, or jounce, to the

passengers. When the springs are made lighter and more flexible in order to minimize the larger shocks, the smaller ones have too large an influence, thus keeping the [car] body and its passengers in motion all the time. “ [3] Therefore, damping of the movement of the body is required. This can be accomplished by adding a shock absorber to the vehicle. There are different sorts of shock absorbers, however, the main type of shock absorbers used nowadays is the hydraulic shock absorber.

These hydraulic shock absorbers, also referred to as a ‘passive shock absorber’, offer an improved comfort level and handling of the car, in comparison with the cars without shock absorbers. Although passive shock absorbers are the simplest sort of shock absorbers and they are easy to replace, this type also comes with a major disadvantage. The inability of the system to change its characteristics throughout life is an important flaw. Therefore, a compromise between road holding and comfort will have to be made. This problem is for every vehicle that makes use of this passive shock absorber.

At the same time, considering the magnitude of the automotive industry, it is of the utmost importance for the car manufacturers that the development of the vehicular suspension system is continued. Recent developments have enabled the possibility for online altering these characteristics of the shock absorbers, these developments being the semi-active and fully active shock absorbers.

The semi-active shock absorbers can vary these characteristics, using different techniques including:

- varying the orifice;
- using electrorheological fluids,
- using magnetorheological fluids.

The semi-active shock absorbers can thus alter the characteristics for optimal settings for each type of road, which will improve the road handling ability and comfort level even more. High-end cars are nowadays often equipped with a button which enables the driver to alter the characteristics of the suspension system, or technically the shock absorber. In this research, the basic idea is a button like this one that will be used in the vehicle. Although this button has more functionalities than only altering the shock absorber characteristics, the other functions of the buttons will be left aside.

In the figure 2, a picture of such a button is shown. This button is currently used in the Lexus LS 600h.



Figure 2: Settings button Lexus LS 600h [4]

This button enables to switch between different kinds of shock absorber-settings. By turning the button to the left or the right, the comfortable respectively sport settings are activated. Pushing the button will make the normal settings active.

These different positions for the buttons each invoke a different setting for the shock absorbers, in order to achieve the desired behavior. In the table below, the different settings of shock absorber are linked to the different positions of the button, showed in figure 2.

Table 1: Positions and settings button

Button position	Shock absorber setting
Comfortable	Softest setting
Normal	Middle setting
Sport	Stiffest setting

In short, passive shock absorbers don't allow to alter their characteristics, where semi-active shock absorbers do. Since a passive shock absorber makes use of a universal setup, set by the manufacturer, there is no possibility for the customer to wrongly set the shock absorber. However, this is a possibility for the semi-active shock absorber. Therefore, the performances offered by a semi-active shock absorber depends on the knowledge of the driver to set the appropriate settings for the shock absorbers.

The active shock absorbers can not only vary these characteristics, they can even add energy to the system. However, because of the high price and the immense energy consumption, active suspension systems are not that common yet in the automotive industry.

1.3. Objectives

The objective of this research is to analyze and compare the performances of different kinds of shock absorbers, in order to determine which shock absorber offers the optimal performances for different road conditions. In a first step, the different types of semi-active shock absorbers will be simulated on the different types of road. The semi-active shock absorbers consist of an electrohydraulic, an electrorheological and a magnetorheological shock absorber. The second step includes the simulation of a passive shock absorber on each type of road.

The results of all these simulations will be analyzed to attain a decent view of the difference between the passive and the semi-active shock absorbers. This will be an important analysis, as it will point out if the research, performed so far, has led to an improvement of the road handling and the comfort level.

The initial objective was to do experiments on a real magnetorheological shock absorber in order to obtain the real characteristics of this type of shock absorber. These characteristics would then be used for the simulations. However, since the test rig was not operational, this objective could not be realised.

1.4. Material & Method

MSC ADAMS is the software that will be used to perform the simulations on the different shock absorbers. In order to perform these simulations, a model of a vehicle will be adapted for each of the different shock absorbers. Once these vehicle models are finished, they will be used on different types of roads.

These roads will be chosen in a way that will cover the most of the possible road disturbances available. Some of these roads can be loaded directly from MSC ADAMS, others will be self-programmed.

The simulations will be analyzed and compared, based on different criteria. These criteria are formulated, based on criteria found in the literature. They offer an excellent way of objectively compare the shock absorbers,

2. Literature study

2.1. Introduction

The car industry is one of the biggest industries in the world. Therefore it is of the utmost importance that car manufacturers deliver the highest quality of vehicles that is possible. This implies that every component used in the vehicle must be excellent themselves, including the suspension system of a vehicle.

The suspension system of a vehicle plays a vital role in the global behavior of vehicles. Reimpell and Stoll say: "The vehicle suspension system is responsible for driving comfort and safety as the suspension carries the vehicle-body and transmits all forces between body and road". [5] The suspension system is the part of a vehicle that connects the road with the chassis of the vehicle. "Since the invention of the wheel people have tried to soften the bumps and jolts of the road by fitting a spring of some kind between the axle of the wheel and the main body of the vehicle itself. The springs ("compliances") store energy and have to be prevented from bouncing by "dampers" that turn the spring energy into heat that is blown away. Suspension components have in turn controlled the design of vehicle body structures - and even of wheels and tires." [6] There have been a lot of developments in the automotive sector over the last decades, especially with regards to the suspension systems. However, the main task of a vehicle suspension system has always remained the same: "To support the automotive vehicle, provide directional control during handling maneuvers and provide effective isolation of passengers/payload from on/off road surface disturbances." [7]

The main movements that a vehicle experiences are heave, roll and pitch, as can be seen on figure 3.

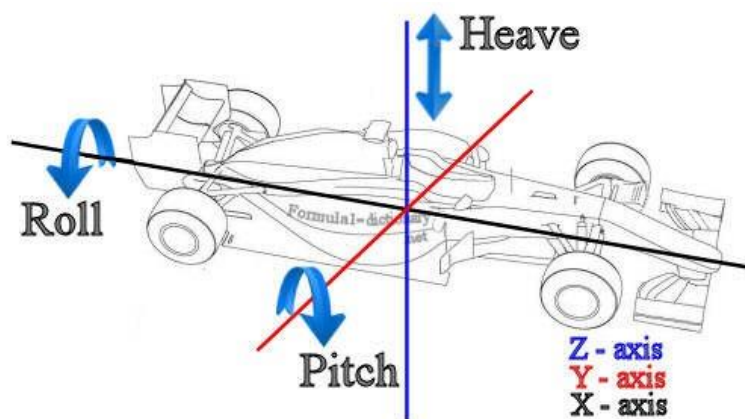


Figure 3: Automotive vehicle's dynamics [8]

The axis's are as follows: The x-axis is in the direction of forwards translation of the vehicle. The y-axis is the lateral movement of the vehicle and the z-axis is the vertical movement of the car. It's important to notice that roll and pitch are rotational movements, whereas heave is a translational movement.

The different movements and how they can occur are as follows: To start with, there is roll: Roll is the rotation around the x-axis and may occur when taking a corner. Next, there is pitch: Pitch is the rotation around the Y-axis and this happens during acceleration and braking. Lastly is heave, this is the translation over the Z-axis and is due to suspension (re)action.

“Vehicle ride comfort is one of the most prominent factors affecting purchase decision and customer satisfaction. Meeting the customer comfort requirements, which is a popular issue, plays an important role in terms of vehicle marketing.” [9] And as stated before, since the automotive market is a major industry, every improvement that can be applied on a vehicle can have very big positive consequences for the manufacturers.

“Even though it seems only normal that the suspension system of a vehicle provides the optimal driving comfort with optimal safety on the road, these two features are hard to optimize at the same time. The reason is that a vehicle requires a soft vehicular suspension in order to provide a good ride comfort. In pursuance of an insensitivity for applied loads, the suspension ought to be stiff. However for a car to have good handling, it necessitates a setting in between stiff and soft. “ [3, p. 235] Figure 4 shows this paradox of ride comfort and vehicle handling.

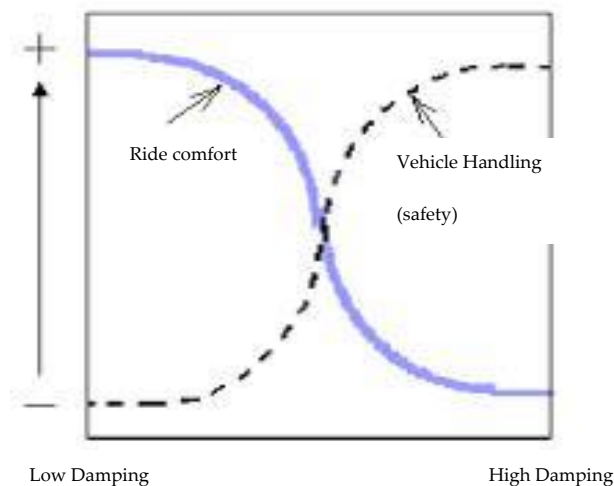


Figure 4: Passive Suspension Design Compromise [10]

As said earlier, the road surface disturbances induce vibrations in a vehicle. “The source of these vibrations is investigated into two categories: internal vibrations and external vibrations. Internal vibrations are induced by tires, powertrain, and engine, whereas external

vibrations are induced by the forces coming from the road. The road- and engine-induced vibrations are the major sources of NVH (noise, vibration, and harshness) problems in ride comfort evaluation.” [9] In this paper however the vibration due to the engine (mounting) and powertrain are left aside, as they can’t be significantly reduced through suspension optimization.

2.2. Components suspension system

First, I will shortly explain what the components are of a regular suspension system of a vehicle. Thereafter I will explain the main topic, namely shock absorbers.

“Two springs, four stops, two shock absorbers and one anti-roll bar usually control the springing of a pair of road wheels, the limitation of spring travel and the reduction of body roll inclination for each wheel-station on passenger cars and light commercial vehicles.” [5]

“Springs are the energy storage unit of the suspension system, the amount of energy that they store depends on the sort of spring and on the displacement of the spring. The springs that are predominantly used in the automotive sector are the air-and gas-filled springs and steel springs.” [5, p. 340]

2.2.1. Springs

I will briefly explain the different kinds of springs, as it is not the main topic of this thesis.

2.2.1.1. *Air-and gas-filled springs*

The air-and gas-filled springs are usually reserved for use in the high-end car models, the main reason these springs are not used in the low-end and mid-end cars is because of the high price tag of this system. However, this system offers also an important advantage: Using this system it is possible to maintain the same driving height, regardless of the load that has to be supported by the suspension system.

2.2.1.2. Steel springs

The group of steel springs consist of leaf springs, coil springs and torsion bars.

1.1.1.1.1. Leaf springs

One of the first springs used in vehicles are the leaf springs. These springs are made of several layers of thin, long and small pieces of flexible steel or sometimes also composite material. These layers are then put on top of each other. When there are multiple leaves, the length of the leaf increases with every additional leaf. The different leaves are then formed into an arc form, where the axle is located at the center of the arc. A problem however is the poor control over the friction between the leaves. These kind of leaves are widely used for solid axles. (i.e.: rear axle of pick-up truck or trailer). Figure 5 shows a typical leaf spring.



Figure 5: Leaf spring [11]

1.1.1.1.2. Coil springs

These springs are common to use in the present suspension systems. It consists of a metal, formed in a helical shape. When a coil spring is compressed, there will be energy stored inside the spring in order to decompress after the compression. The force needed to compress (or extend) the spring is equal to:

$$F = k * X$$

In this equation, F is the force required to change the spring's length. X is the distance the spring shortened or lengthened by and k is a characteristic of the spring, the stiffness of the spring to be more precise. If a coil spring is installed in a vehicle, the spring will find itself in

a steady-state as a result of the static load of the vehicle. The spring will compress and extend around this steady state.



Figure 6: Coil spring [12]

1.1.1.1.3. Torsion bar

This system basically consist of a metal bar, connected at one end to the chassis of a vehicle, and on the other end to the wheel. The energy will be stored by applying torque on the bar. In order to be able to apply any torsion on the bar, it is necessary that the munt to the wheel is perpendicular to the torsion bar. Furthermore, the mounting with the wheel has to have an off-set with regards to the torsion bar. An important advantage of the torsion bar is that the behavior can be slightly altered by adjusting the spindle. (this is the connection of the torsion bar with the lower control arm)



Figure 7: Torsion bar [13]

2.2.2. Antiroll-bar

“An antiroll-bar is also an option to install on the suspension system of your car, at least it is if the objective is to reduce the body roll (and improve the cornering abilities of the car) since it isn't a spring nor a shock absorber. The middle section of the "U" is attached crossways on the car body on pivoting rubber mounts, its bent ends joined to the suspension. In this way, lever forces occurring on one side act to balance the opposite side. Anti-roll bars improve tracking, and thus the handling of a vehicle. At the same time, they also reduce body roll. The improved tracking makes cornering even safer and more comfortable.” [14]

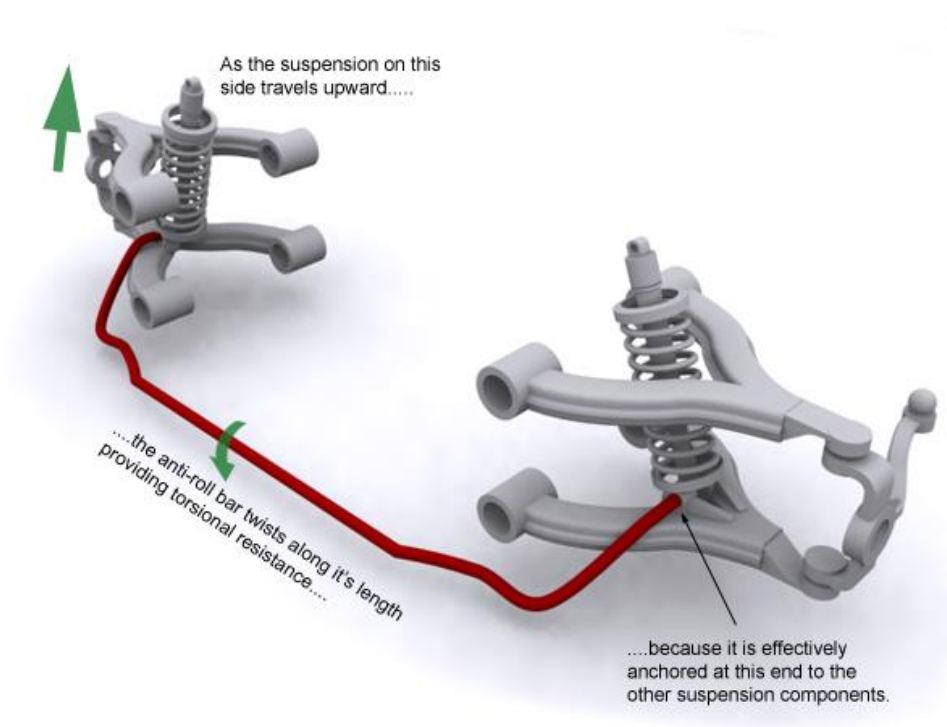


Figure 8: Antiroll bar [15]

However, a suspension system consists of more than springs alone. If there were only springs in a car, the energy will only be dissipated by continuous movement of the spring. This results in a ride that isn't comfortable. In order to eliminate this undesirable behavior, shock absorbers will be fitted on a vehicle.

2.3. Shock absorbers

First of all, shock absorbers do not support the total weight of the car. Their main task is to control the spring movement. They achieve this by converting the kinetic energy from the springs into thermal energy, which is dissipated through the hydraulic fluid. Unlike springs, shock absorbers are dependent of the speed of movement of the rod inside the cylinder. The higher the speed, the more resistance the rod will encounter. Besides controlling the movement of the spring, the shock absorber also ensures that the wheels stay in contact with the road. The top of the shock absorber is fitted to the chassis, the other end of the absorber is connected to the wheel.

2.3.1. Passive shock absorbers

The most commonly used passive shock absorber is the twin tube low pressure gas shock absorber. A second type is the mono tube high pressure gas shock absorber. Important to know is that, although they are gas pressured shocks, they are not completely filled with gas. The piston still resides in a hydraulic fluid. At the bottom of the cylinder, for the mono tube shock absorber, is a floating cylinder, which separates the hydraulic fluid in the cylinder from the gas chamber. The twin tube shock absorber has a reservoir of gas in the outer cylinder.

The main function of both absorbers is the same. Once a bump has been hit, the rod will move down and the fluid will be compressed. This compression will logically induce a higher pressure on one side of the rod, which in turn invokes a movement of the fluid from the high pressure side to the lower pressure side through the orifices. However, since the structure of both the shocks is different, the remainder of the movement of the shock absorbers is different. Therefore, the mono tube and twin tube shock absorber will be explained in more detail.

2.3.1.1. *Mono tube high pressure gas shock absorber*

Mono tubes offer a high dampening ability and good heat dissipation, therefore, these shock absorbers are used in the racing industry, for example: Formula 1. Because of the high pressure gas at the bottom of the cylinder, the seals must be of high quality and the inner surface of the cylinder must be polished for a good surface quality. An important advantage of the high pressured gas is the high reduction of cavitation of the hydraulic fluid.



Figure 9: Mono tube shock absorber [16]

Figure 9 shows a mono tube gas pressure shock absorber, the different components are:

1. gas reservoir,
2. separating piston,
3. oil reservoir,
4. operating piston,
5. piston rod,
6. piston rod guide,
7. working cylinder,
8. Teflon ® Seal for piston rod,
9. adjusting unit.

2.3.1.2. Twin tube low pressure gas shock absorber

The twin tube low pressure shock absorber is composed of two tubes. An inner tube where the cylinder moves coaxial and an outer tube. As the piston moves down, the hydraulic fluid below the piston will be pressurized. Because the piston rod moves down, there will be less volume for the hydraulic fluid. This 'excess' of hydraulic fluid will flow to the second tube, where it will compress the gas.

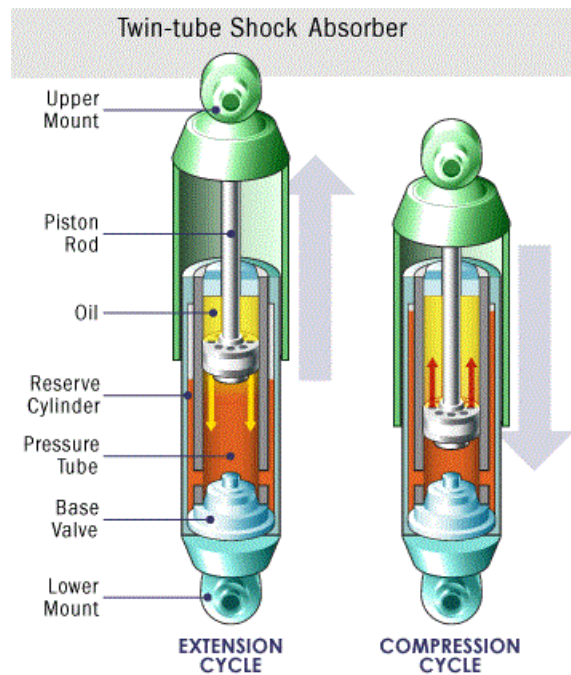


Figure 10: Twin tube shock absorber [17]

However, the shock absorbers mentioned above are passive shock absorbers in the sense that they all have the same characteristics throughout their life (if the wear of the components and the degradation of the oil fluid is excluded). This attribute of passive shock absorbers is also the biggest disadvantage. Once they have been set for use, they will behave the same for every kind of excitation. In other words, compromises have to be made when using passive shock absorbers.

Furthermore, as mentioned before in figure 4, a compromise will have to be made for safety and comfort. Because a passive shock absorber can't alter its characteristics, the compromise will be made after which it is impossible to change this.

2.3.2. Semi-active shock absorbers

However, everything said above about passive shock absorbers isn't applicable for semi-active shock absorbers.

Swevers J. [18] shows that

“comfort and road handling of a passenger car can be improved by replacing its passive suspension by a controlled semi-active suspension. Comfort and road handling performance of a passenger car are mainly determined by the damping

characteristic of the shock absorbers. Being able to change the damping characteristic depending on the kind of road the car is driving on can improve the behavior of the car. “

“When compared with the fully active system, the semi-active suspension system requires less energy, is cheaper, the simplest in design, and provides other competitive performances when compared to passive systems.” [19]

The difference between passive and semi active shock absorbers can easily be shown by next figure, these figure are a ‘quarter-car model’ representation of a suspension system. This means it only applies to one wheel of a car. Because this applies to only one wheel of a car, the only degree of freedom this model has is heave (vertical translation). Figure 11 shows this representation for a passive shock absorber.

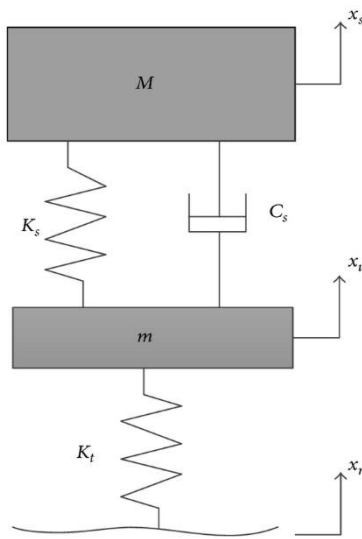


Figure 11: A passive quarter-car model [20]

Figure 12 shows this representation for a semi-active shock absorber.

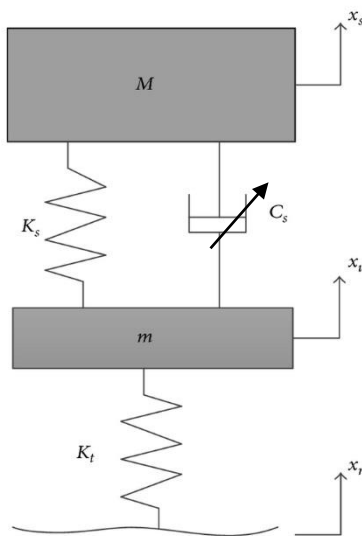


Figure 12: A semi-active quarter-car model [20]

In this picture:

M = Sprung weight

M = Unsprung weight

K_t = representation of tire

K_s = representation of spring

C_d = representation of shock absorber

The sprung weight that is displayed represents the weight of the car, or $1/4^{\text{th}}$ of the weight in this quarter-car model. The weight of the car is supported by spring, hence the name 'sprung weight'. The unsprung weight consists of the weight of the wheel and all the components of the suspension system that logically are not supported by the spring. Reduction of the unsprung weight of a car may also help to improve the handling of the car, since the springs and shock absorbers will have to exercise a smaller force in order to maintain proper contact with the road surface.

The spring K_t represents the flexible properties of the wheel. The spring K_s is the spring used in the suspension system. The damper C_s is the shock absorber of the suspension system. As shown by figure 11 (quarter car model), the passive model has a static damper. Whereas the semi-active model has a varying damping constant, as shown in figure 12. This is the main difference between the two types of shock absorbers. There are multiple ways of achieving a varying damping characteristics, although the main techniques used nowadays are:

- electrohydraulic shock absorbers,
- electrorheological shock absorbers,
- magnetorheological shock absorbers.

2.3.2.1. *Electrohydraulic shock absorber*

These are principally the same as the passive shock absorbers. The only difference is that the valve in the piston can be changed, in order to control and vary the flow through the valve. This allows to alter the behavior of the damper. "The required mechanical motion makes this slow-responding." [21] Figure 13 shows the schematic representation of an electrohydraulic shock absorber.

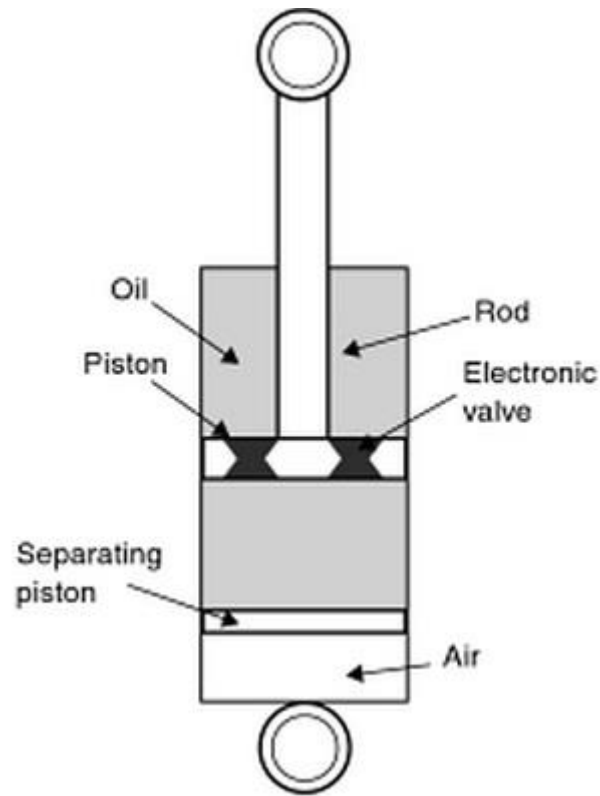


Figure 13: Schematic representation of an electrohydraulic shock absorber [22]

2.3.2.2. Electrorheological shock absorber

Secondly there are the electrorheological shock absorbers. They make use of one type of the so-called smart fluids. “The electrorheological fluid are made from suspension of an insulating base fluid and particles on the order of $0.1\text{-}100\text{ }\mu\text{m}$ in size. The volume fraction is between 20% - 60%.” [23]

“The electrorheological effect, termed *Winslow* effect after the discoverer, arises from the difference in the dielectric constants of the fluid and particles. In the presence of an electric field, the particles, due to an induced dipole moment, may form chains along the field lines. “ [22] This principle is shown in figure 14.

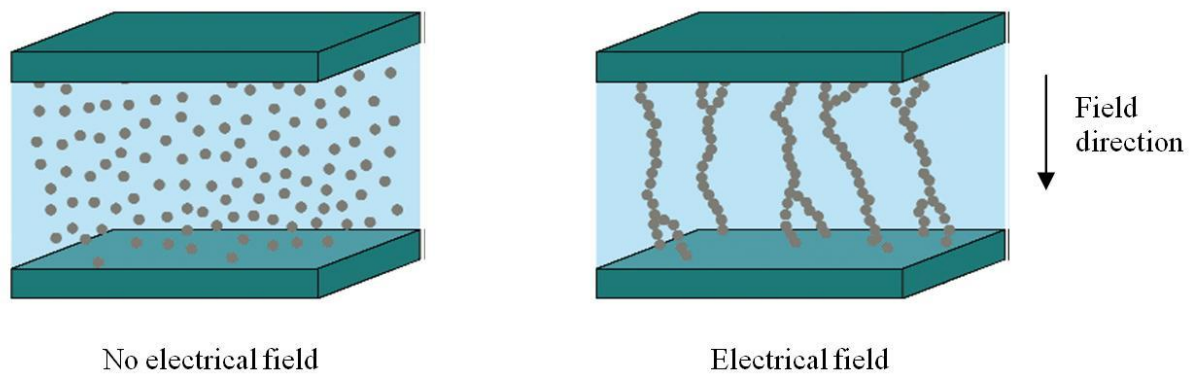


Figure 14: Electrorheological effect [24]

“The stiffness of the ER shock absorber can be altered by applying a voltage between electrodes, this will affect the ability of the fluid to flow. The structure of an electrorheological shock absorber can be seen on the figure below. The ER shock absorber can be regarded as an “electric capacitor”; the external body is an anode and the piston is a cathode. The electric field appears in the space between the piston and the body. In order to obtain the necessary forces, the surface of the piston is relatively large.” [22]. The structure of an electrorheological shock absorber is shown in figure 15.

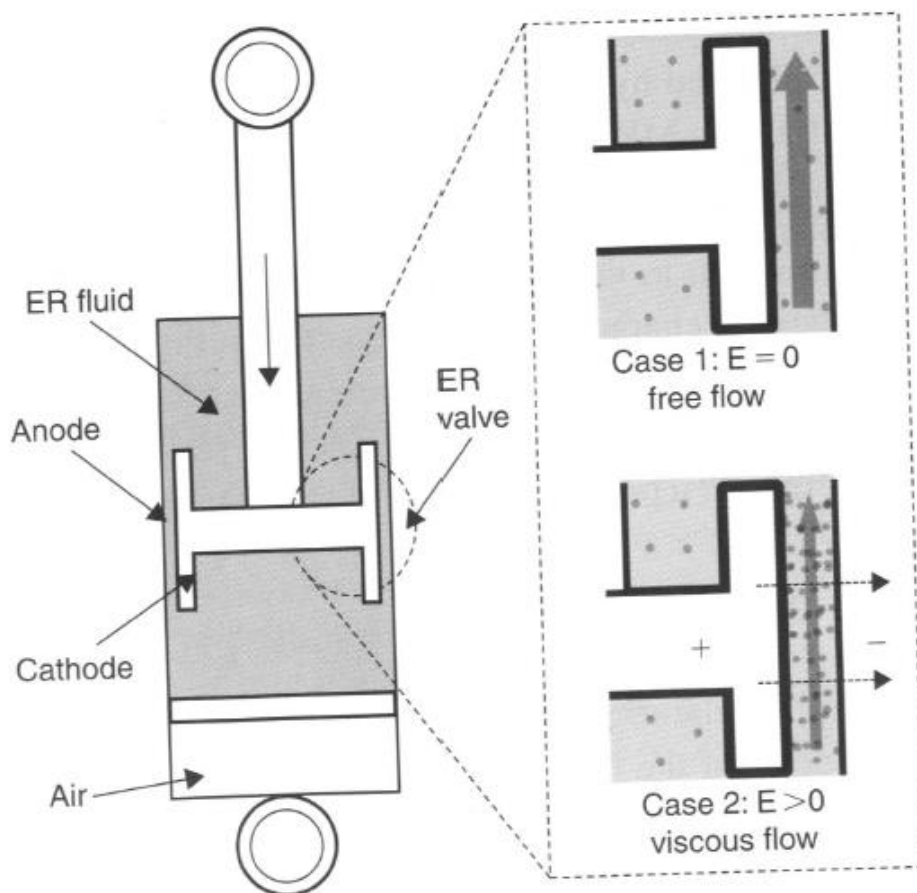


Figure 15: Schematic representation of an electrorheological shock absorber [22]

2.3.2.3. Magnetorheological shock absorber

Last of the semi-active shock absorbers are the magnetorheological shock absorbers. These are most common to be used in present cars because of their high yield strength “(10 times higher than electrorheological)”. [23, p. 321] In order to sufficiently understand the working of a MR- shock absorber, it is important to know the magnetorheological fluid used in these shock absorbers.

“A magnetorheological fluid is a suspension containing micron sized particles made of magnetic material, often soft iron. The carrier liquid is mixture of oil, usually a silicon oil. The size of the particles may differ from 2 to 20 μm , with a volume concentration of the particles between 10-40 vol%.

$$\lambda = \frac{\mu_0 \chi_p^2 H^2 V}{12 k_B T}$$

In this formula, to calculate the coupling constant between particles, the symbols are as follow:

μ_0 = permittivity of vacuum

χ_p = susceptibility of particle material

H = magnetic field strength

V = volume of magnetic particles

k_B = Boltzmann's constant

T = absolute temperature

Important to notice about this formula is the fact that if a magnetic field $H = 0 \frac{A}{m}$ is applied, the interparticle interaction will almost go to zero. The only magnetic force left will be the remanence force, although it's negligible in comparison to those in the fields. This implies that, in the region of zero field conditions, the suspension shows as a Newtonian behavior. In other words, the viscosity of the fluid will be only determined by the viscosity of the carrier fluid and the volume fraction of the suspended material.

However, when a magnetic field is applied, the interparticle interactions will become no longer negligible. Even more, due to the interactions, large chains and complex structures will be formed. These chains and structures will determine the viscous behavior of magnetorheological suspensions.” [23] The suspension's behavior when a magnetic field is applied is closer to the Bingham type behavior than it is to the Newtonian behavior.” [25] “A problem of magnetorheological fluids, is the settlement and separation over time of the solid phase. This problem can however be overcome by adding additives to the fluid.” [23]

In figure 16 the difference is shown between no magnetic field and when a magnetic field is applied.

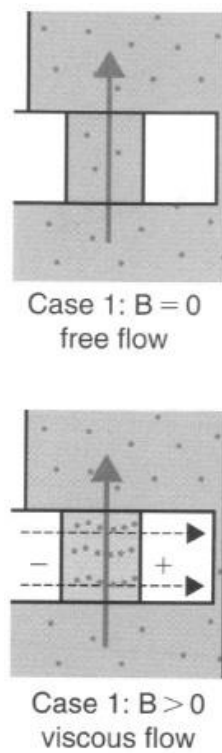


Figure 16: Magnetorheological effect [22]

The structure of a magnetorheological shock absorber is displayed in figure 17. The magnetic coil in the cylinder is clearly visible. It is that coil that provides a magnetic field in the magnetorheological fluid.

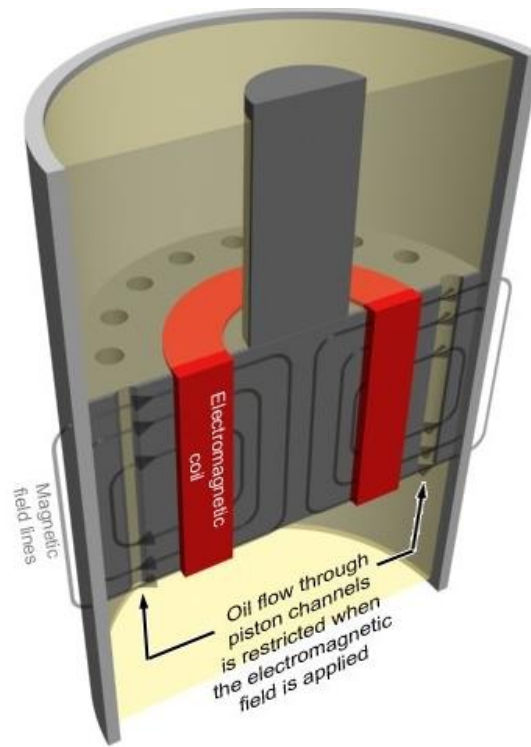


Figure 17: Structure magnetorheological shock absorber [26]

“The main difference between ER and MR fluids is that MR fluids require large currents but low voltages, whereas ER fluids require low currents but high voltages. The main advantage of using MR fluids is that the required electrical voltages can be generated directly from the car’s own electric system without the need for invertors.” [27]

2.3.3. Active shock absorbers

Besides the passive and the semi-active shock absorbers, there are also active shock absorbers. The key difference between active shock absorbers and semi-active-/passive shock absorbers is the ability to add energy to the system, whereas passive and semi-active shock absorbers can only dissipate energy. Figure 18 shows the quarter car model for a suspension system with an active shock absorber. Both the spring and the shock absorber are replaced by 1 actuator which controls the movement of the sprung weight.

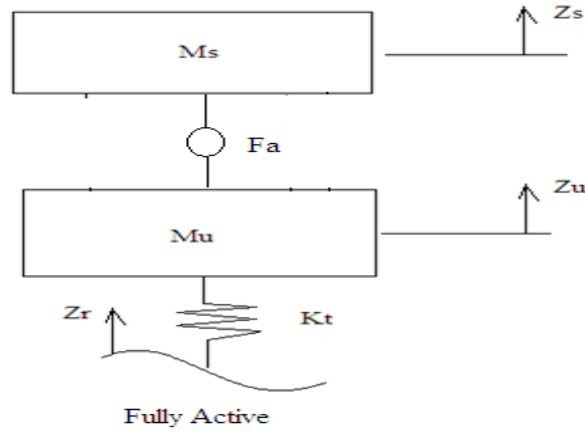


Figure 18: A fully active quarter-car model

As shown in figure 18, the difference is clearly visible between a semi-active shock absorber (figure 12) and an active shock absorber. Figure 19 shows the force-velocity diagram, and the area's where the different types can be active.

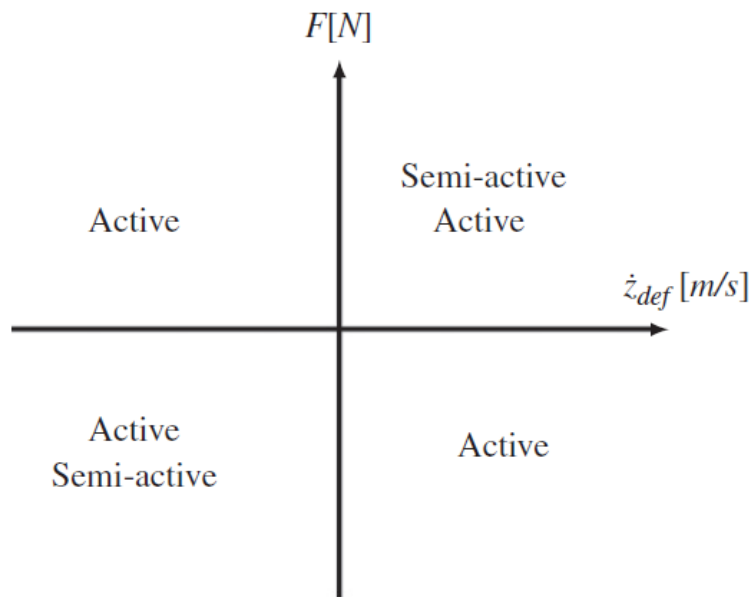


Figure 19: Active versus semi-active force/deflection speed [28]

The right side of the Y-axis represents compression of the shock absorber, whereas the left side represents lengthening of the shock absorber. For the right top quarter, the shock absorber is compressed and the spring will apply a force on the shock absorber in order to retain the steady state length. This means the shock absorber will only dissipate the energy of the spring, the same goes for the left bottom quarter. However, for the right bottom corner, the shock absorber will be compressed and the shock absorber will compress the

spring even more. Because it will add energy to the system, the left top and right bottom quarters are only available for active shock absorbers.

Furthermore, the performances of active shock absorbers are far better in comparison with the performances of the passive and semi-active shock absorbers. These outstanding performances brought the active suspension in the Formula 1, however active suspension got banned because of the high cornering speeds which are possible because of this suspension. A serious drawback for these superb performances are however a high energy consumption and a high price for this system.

“Further improvement of the performance of an active shock suspension can be acquired if a preview of the upcoming road would be available” [29]. By knowledge of the road ahead of the car, the settings of the suspension can be altered in order to maintain the optimal performances in terms of both road holding and comfort.

4. Software

MSC ADAMS, created by one of the oldest software firms in the world: MSC Software, is an acronym for “Automated Dynamic Analysis of Mechanical Systems”. This software package is, according to MSC Software, the world's most widely used Multibody Dynamics (MBD) software. It assists engineers to perform studies, in order to attain useful information. These studies can include the distribution of different forces in an assembly, or acquiring a representation of the moving parts in an assembly. It is obvious that this software can be very important for testing prototypes before this prototype is actually produced. This can reduce the cost of developing a new product by a considerable amount. This software package is also used by world-renowned car companies, for example: Bugatti, the official racing team of Volvo (Polestar), Leyland Trucks Ltd., Scania and many more. [30]

5. The vehicle model

Adams features a predefined-vehicle model (which can be seen on figure 20), this vehicle model can be used to learn how to properly work with the program. This car however can also be used for the simulations that have to be performed for this research, since the predefined vehicle model behaves as a normal car.

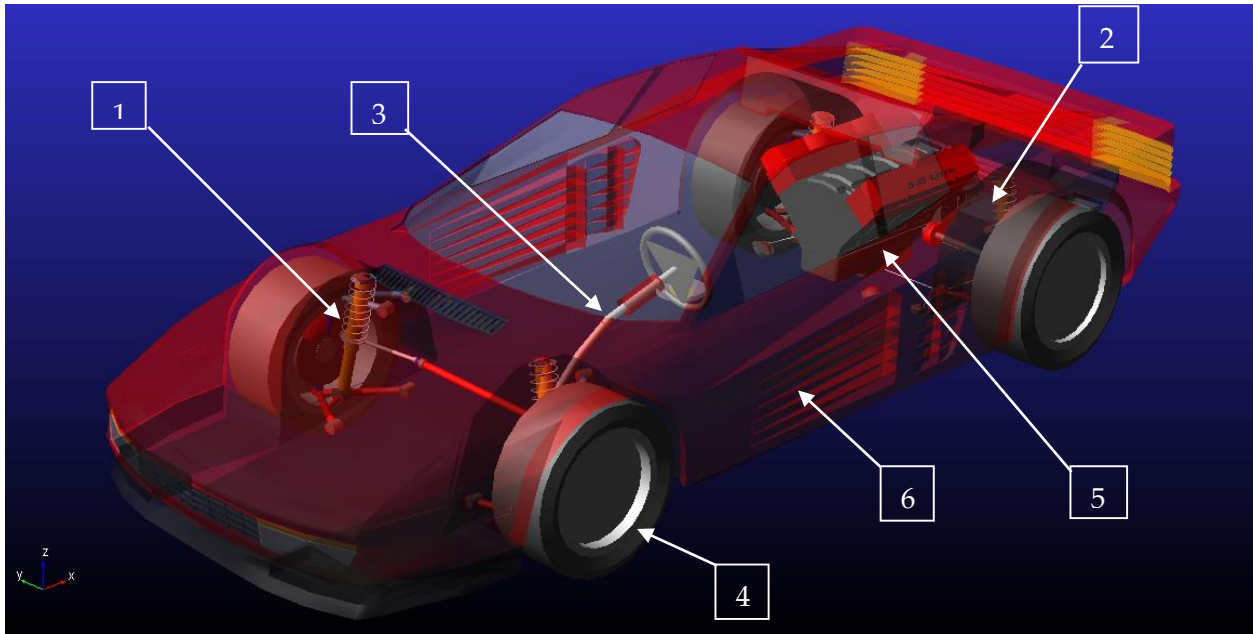


Figure 20: Vehicle model

As you can see from figure 20, the components that are included in this model are:

- the front suspension (1),
- the rear suspension (2),
- the steering (3),
- the tires (4),
- the powertrain (5),
- the body (6).

In other words, all the components required for the simulation of the behavior of the vehicle are present in this representation. All parts except of the tires, springs and shock absorbers are rigid parts. Even though, this model allows us to make realistic simulations that can be directly interpreted without having to adjust the final results.

Since we are investigating the influence of different shock absorbers on the behavior of the vehicle, the only characteristic that has to be changed is the one of the shock absorber of the car. The characteristics of the shock absorber will be altered, by the means of the force-

velocity diagram. This will change the behavior of the car, allowing the car to behave as a car which has semi-active shock absorbers installed.

5.1. Characteristics

In order to properly compare all the different kinds of shock absorbers, data from all the types of shock absorbers is required. In literature, ideal characteristics can be found for passive, electrohydraulic, electrorheological and magnetorheological shock absorbers. Because all the characteristics are ideal, they are highly suitable for comparing the best possible performances of the different shock absorbers.

5.1.1. Ideal passive shock absorber

In figure 21 shows the ideal characteristic of a passive shock absorber.

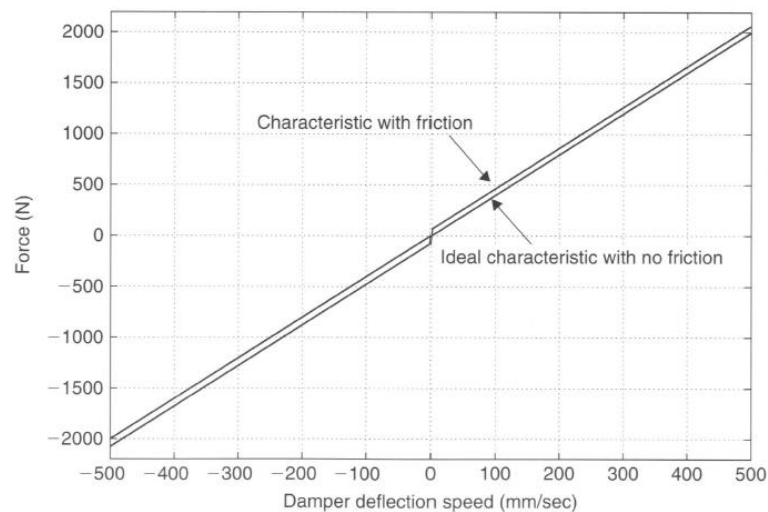


Figure 21: Ideal linear passive characteristic of hydraulic shock absorber [22]

The higher the deflection speed of the shock absorber, the higher the force is. Which is the normal behavior, expected for a shock absorber with a varying orifice. The characteristic with no friction will be used in the simulations.

5.1.2. Ideal electrohydraulic shock absorber

In figure 22 displays the ideal characteristic of an electrohydraulic shock absorber.

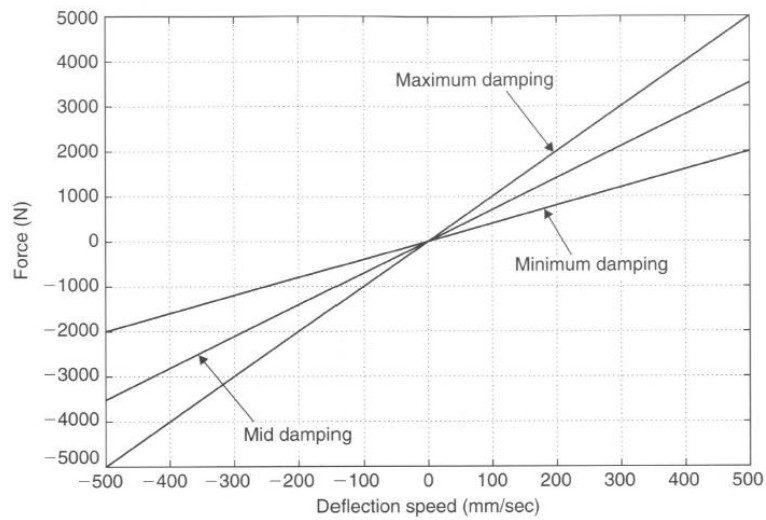


Figure 22: Ideal damping characteristic of an electrohydraulic shock absorber [22]

Since an electrohydraulic shock absorber is nothing more than a passive shock absorber with an adjustable orifice, the characteristic of this shock absorber is very similar to the one of a passive shock absorber. However, because of the varying orifice, it is possible to reduce the orifice which will make it more difficult for the fluid to flow through. This will result in a graph that is steeper. Every linear graph, between maximum damping and minimum damping, can be attained by altering the orifice.

5.1.3. Ideal electrorheological shock absorber

The figure below displays the ideal characteristic of an electrorheological shock absorber.

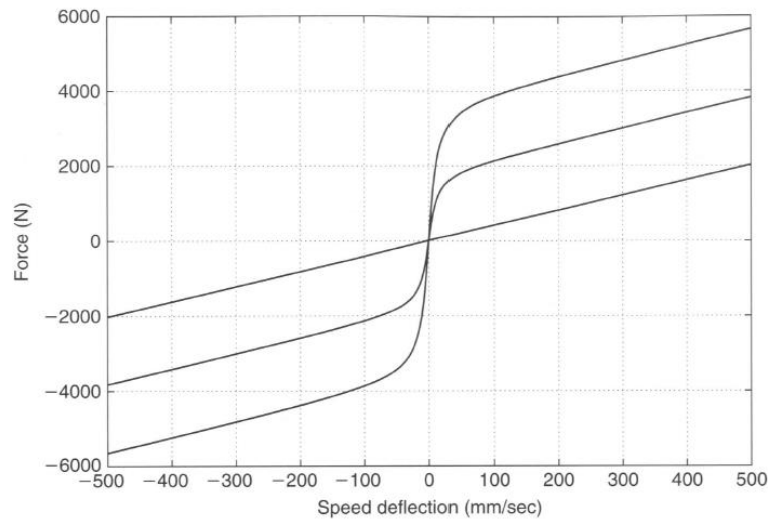


Figure 23: Ideal damping characteristics of an electrorheological shock absorber [22]

When there is no current applied, there will also be no electrical field. This ensures the electrorheological fluid to flow almost free through the orifice. Even though electrorheological fluids contain small particles, it will behave as a normal fluid when there is no electric field. This behavior results in a passive-like characteristic for the 'no electric field state', in other words the linear function. When a current is applied, the characteristic will change as can be seen on figure 23. It is possible to attain characteristics in between the maximum and minimum value, by altering the electric field.

5.1.4. Ideal magnetorheological shock absorber

The figure below shows the ideal characteristic of a magnetorheological shock absorber.

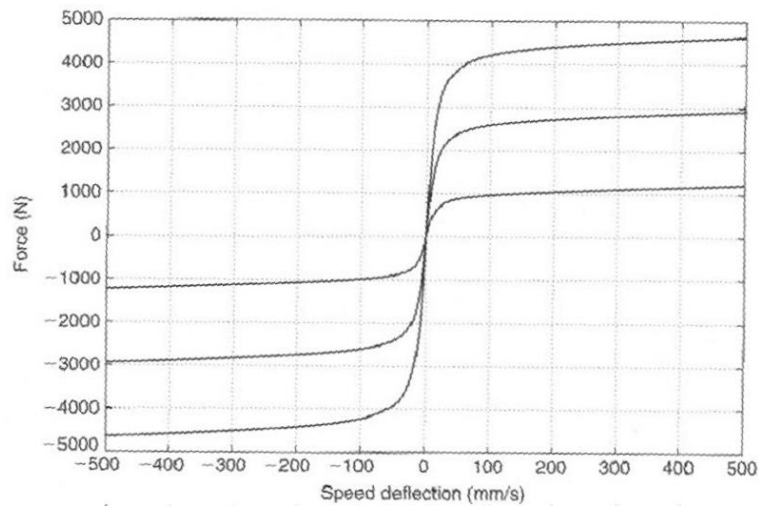


Figure 24: Ideal damping characteristic of a magnetorheological shock absorber [22]

There are only 3 graphs given, however it is possible to achieve any graph in between maximum damping and minimum damping. This can be accomplished by varying the current that is applied on the magnetic coil. The higher the current that flows through the magnetic coil, the stronger the magnetic field will be. This has a direct impact on the viscosity of the fluid, more specifically the viscosity will rise with an increasing current, which in turn induces a higher force. Note that, when no current is applied on the magnetic coil, the shock absorber characteristic is not linear. This is because of the magnetic particles in the carrier fluid.

5.1.5. Approximation characteristic shock absorber

The shock absorbers, as they are used in all sorts of vehicles, show a behavior that is not identical to the characteristics shown before. These real characteristics present some irregularities in comparison with the ideal characteristics. In figure 25, a real damping characteristic is given for a magnetorheological shock absorber.

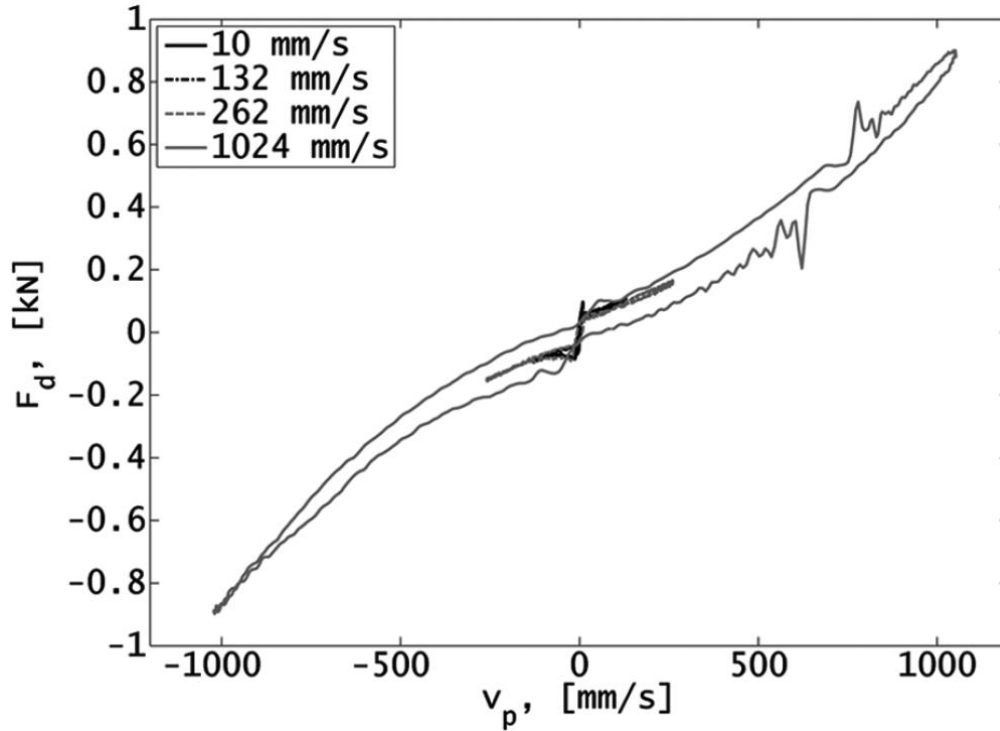


Figure 25: Real damping characteristic of a magnetorheological shock absorber with the low setting applied [31]

Since it is not possible to apply these irregularities in MSC ADAMS, because the software can only handle one curve, the function used in MSC ADAMS will have to be ideal damping characteristics of shock absorbers.

5.2. Applying characteristics

In order to get the predefined vehicle to behave like a vehicle with magnetorheological shock absorbers, the characteristics of the shock absorbers have to be changed in MSC ADAMS. The next figure shows the graph of the ideal magnetorheological shock absorber with high settings applied, imported into MSC ADAMS.

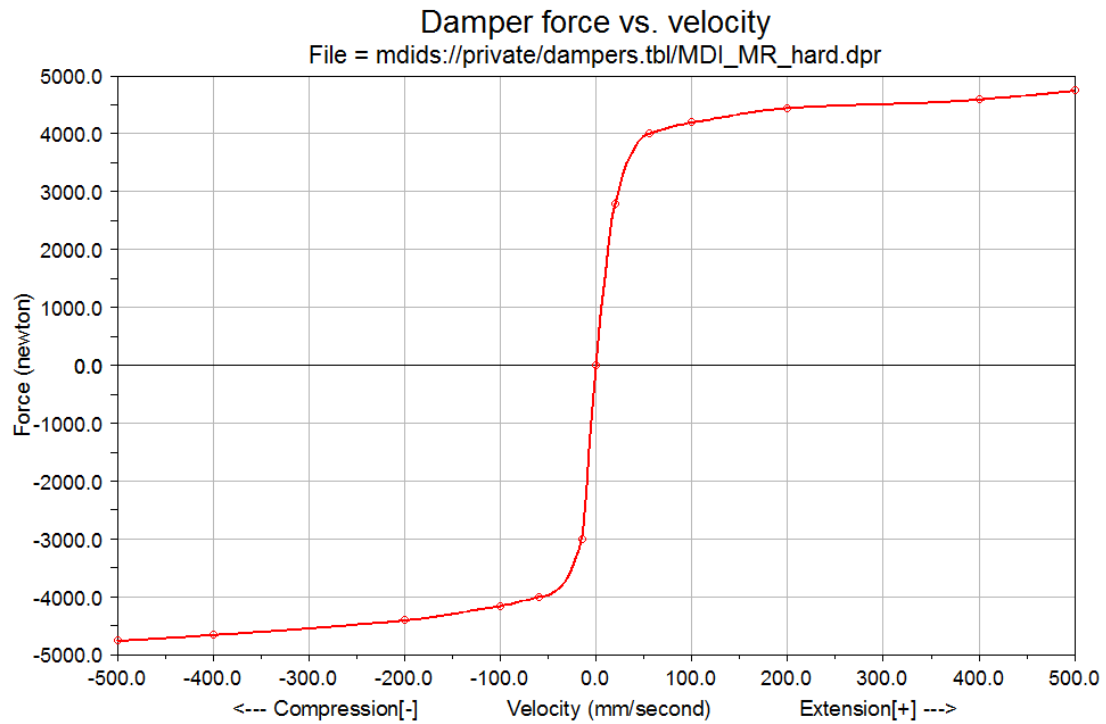


Figure 26: Approximation of real damping characteristic of magnetorheological shock absorber

6. The road model

Only a car isn't enough to perform the required simulations. Another necessity is a road for the car to be driven on. For this research, 3 roads will be used in the simulations. With these 3 roads, the aim is to cover as much road conditions as possible. The chosen roads are:

- a country road,
- the ISO Lane change maneuver,
- a city road.

6.1. Country road

This road is a predefined road in MSC Adams. It consists of a straight road, with a very uneven road surface. The need for a vehicle to have excellent performances on off-road surfaces might not be the principal goal for the present car manufacturers, definitely not for personal vehicles, since we have smooth roads wherever you want to go. However, for the occasionally off-road situations a certain level of comfort has to be achieved.

In the figure below, an example for a typical country road with an uneven road surface is shown.



Figure 27: A country road [32]

6.2. ISO Lane Change

The second road is the ISO Lane Change. “The double lane-change maneuver is used to identify vehicle dynamics. The target is to analyze and determine the road-holding ability and handling characteristics of a vehicle, with the procedure applicable to vehicles with a gross vehicle mass of up to 3,500kg. The severe double lane-change maneuver is a dynamic process rapidly driving a vehicle from its initial lane to another lane in parallel, and back to the initial lane, without exceeding lane boundaries. The scenario provides feedback about the overall driving behavior of the tested car.” [33] The ISO in the name of this maneuver, indicates this maneuver being included in the International Organization for Standardization, ISO 3888.

Furthermore, if this test is executed with a human driver it is possible that the results may show deviating results. “The results of the ISO lane change test depend heavily on the skills of the test driver. The fact that the entire system of car and driver will be assessed in the test, it is very difficult to gain objective results of the test.” [34]. This is an important reason, why the simulation of this maneuver is a good alternative with results that can be evaluated objectively.

The figure below shows the test setup for an ISO Lane change.

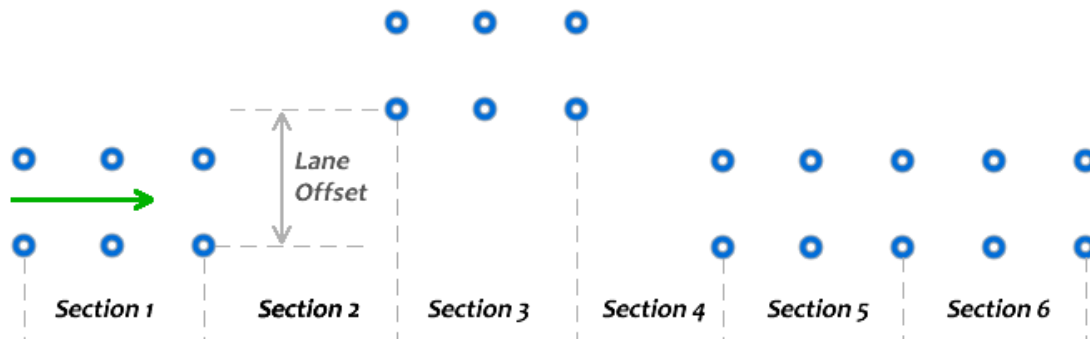


Figure 28: Test track dimensions [35]

The blue circles are the cones where the car has to drive through. The lane offset amounts 3.5 meters.

“Although the moose-test may be more famous as a safety test for vehicles, the ISO lane change and the moose test are very similar to each other. In fact, the double lane change is nothing more than an upgrade from the moose test. The aim of this new test was to define the criteria for a lane change test to ensure that the results were reproducible, demonstrable and also comprehensible to consumers. Thus, the working group (including representatives of the seven German car manufacturers, the insurance sector, the Automobile Club, independent scientists and representatives of test organizations and motoring journalist)

created the VDA (Verband der Automobilindustrie) test. The requirement level of the VDA lane change test had to be at least as demanding in all phases as the “moose avoidance test.” [36].

6.3. City road

The third and last road setup that is going to be used for simulations is a flat road with obstacles along the way. With this road, the objective is to simulate road excitations as can be encountered on an average secondary road. Because there isn't a road predefined in MSC Adams that includes all these obstacles, this road is self-made using the road builder option in Adams.

These obstacles consist of:

- a speed bump,
- a pothole in the road,
- a short object on the road.

6.3.1. Speed bump

The dimensions are based on the data of speed bumps defined by the regulation of the speed bumps in a Belgian royal decree [37]. The dimension of the speed bump are shown in the next figure:

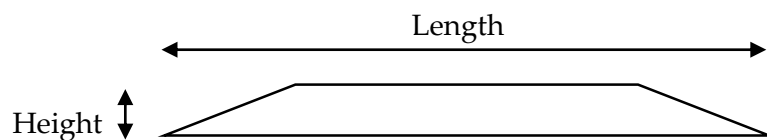


Figure 29: Schematic representation of speed bump

Length = 4,8 meters

Height = 8 centimeters

6.3.2. Pothole

The next obstacle that can be encountered when driving over a secondary road are potholes. In Belgium, these potholes are becoming a serious problem. “The amount of reports of potholes in the road increased sevenfold in 1 year time.” [38] Although this article deals about this phenomenon happening in Belgium, this is applicable to every country with severe winters where there is a need to salt the roads. The figures below shows a pothole as will be used in the simulation and the dimensions used for the pothole.



Figure 30: Potholes in road [38]

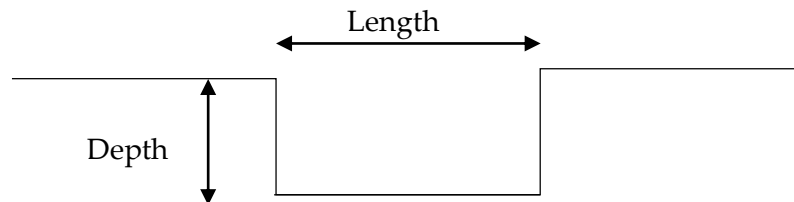


Figure 31: Schematic representation of pothole

Length = 0,5 meters

Depth = 5 centimeters

In the simulation road, there is another kind of pothole included. Namely a pothole for both wheels. An example of this obstacle is for example a road that is badly damaged by salt, as shown in figure 30. Or when there are road works, as shown in figure 32.



Figure 32: Road works

6.3.3. Object on road

The last object is a temporarily raise of the road surface. These objects can be a broad variety of objects, ranging from garbage over lost cargo of trucks to a dozen other possibilities. Another common example for this object are the short speed bumps, as shown in the next figure.



Figure 33: Short object on road

In the figure below, you can see how this road disturbance will be approximated.

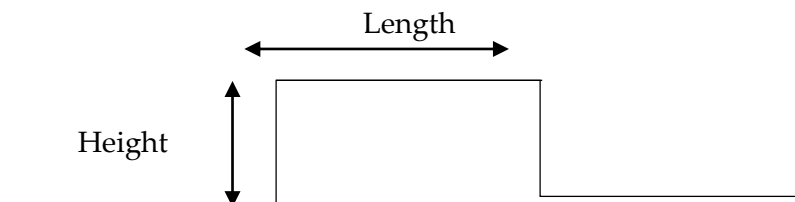


Figure 34: Schematic representation of short object

Length = 15 centimeters

Height = 5 centimeters

The road, with all the different kinds of disturbances implemented, can be seen on the figure below.

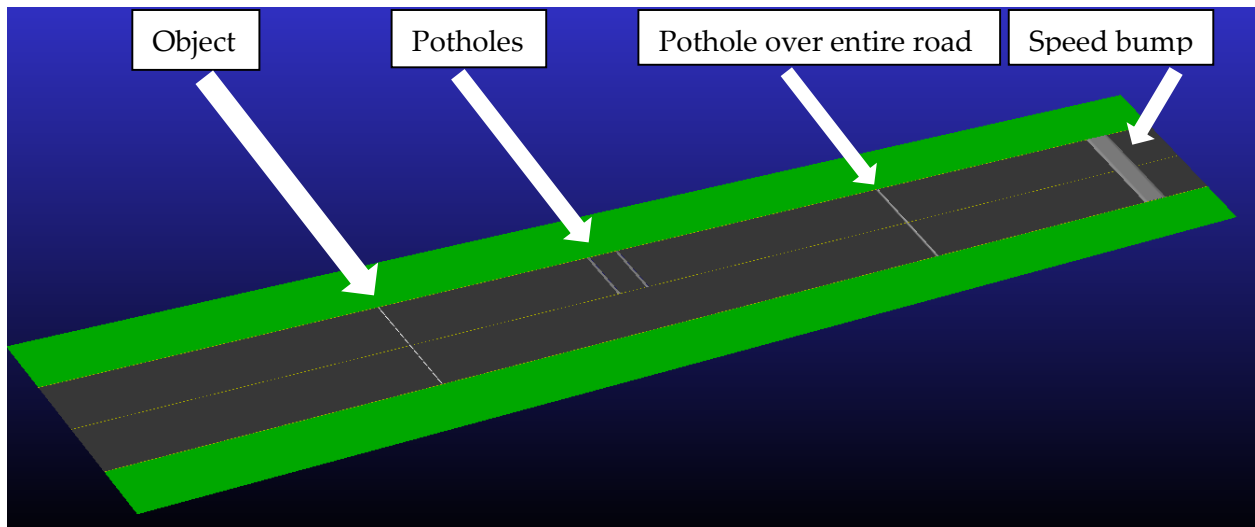


Figure 35: Road model modelled in MSC ADAMS

In the table below, the distances are given for the different objects as well as the total length of the road. In order for the vehicle to reach a steady state after an object, a safety zone of 50 meters is invoked.

Table 2: Positions objects on road

	DISTANCE FROM START
SPEEDBUMP	10 m
POTHOLE ENTIRE ROAD	60 m
POTHOLE 1	110 m
POTHOLE 2	115 m
OBJECT	150 m

7. Settings for simulations

7.1. Country road

This is a road without any turns, so a straight-line maintain test will be applied for this simulation. Straight-line test implies that the steering angle of the car is locked. A maintain test is a test that will be executed while the car drives a predetermined constant velocity. The velocity of the car is set on 30 km/h. This is a realistic speed to drive over a country road

7.2. ISO Lane Change

As it is a predefined test where the car can't maintain a straight road, we will use the function 'Course event' in MSC Adams to perform this simulation.

The vehicle speed has to be larger than 60 km/h throughout the run [36], although some other sources maintain a minimum speed of 80 km/h [39], [40]. However, normally the speed should be raised until the car fails to finish the maneuver without hitting any cones. Since this is not visible in the simulation, there will be only 1 speed used: 80 km/hr.

7.3. City road

This is a road is, just like the country road, a straight road, so a straight-line maintain test will be applied for this simulation. As been said earlier, a straight-line test implies that the steering angle of the car is locked while the car drives a predetermined constant velocity.

Since the objects on this road can be encountered on a secondary road, where generally a lower speed limit applies, a speed of 50 km/h is chosen. When a driver notices an object, it is realistic to assume that he will brake and slow down the vehicle to pass the object. However, the worst case scenario is considered for the simulation thus the test will be executed at a speed of 50 km/hr.

8. Criteria for simulations

With the aforementioned vehicle and roads, the simulation can be performed without any problems. However, these simulations are useless without an appropriate and objective method to analyze all the obtained results. The different analyzing methods are shortly discussed in this chapter.

8.1. Comfort

One of the criteria for these simulations is logically the comfort of the driver, as it is one of the main functions of the suspension system.

To begin with, it is important to state that the comfort of a driver depends on several conditions. There are the environmental conditions (i.e.: temperature, weather, ...) and the general state of the driver himself, however it is impossible for the shock absorber to alter these conditions. Thus they will be left aside.

Then there are the conditions, on which the shock absorbers have a considerably effect. This is mainly achieved by controlling the vibrations, induced by an irregular road surface. The objective for optimal comfort is [19], [22]:

$$\min \ddot{z}(t) = \min z(t)$$

In other words, we have to minimize the vertical acceleration as well as the vertical displacement of the body chassis.

8.2. Road holding

The second main function of the suspension system is maintaining contact with the road, since it has an important influence on the safety [19]. Needless to say, this will also be analyzed and it will be done by the means of the force applied on the road, by the wheels. When the vehicle starts the simulation on an even road, the weight of the car will be distributed over the 4 wheels. However due to road disturbances and irregularities this force will vary, ranging from 0 N to maximum. 0 N equals no force, or in other words, the wheels don't make any contact with the road. The maximum is an extreme, when all the other 3 tires

have lost contact with the ground, and this weight multiplied with the vertical acceleration of the vehicle chassis.

8.3. Roll angle

The roll angle is, as mentioned in the literature study, the rotation around the longitudinal (X) axis. It mainly acts when cornering with the vehicle. This roll angle invokes a movement of the center of mass of the car. When cornering, the center of gravity will shift to the outside of the turn, due to the centrifugal force. This will compress the shock absorber on the outside and will lengthen the shock absorber on the inside.

8.4. Lateral acceleration

“During the maneuver the vehicle might even roll over because of the high lateral acceleration involved which occasionally happens with the vehicles with relatively higher center of gravity. The maneuver generally demonstrates the agility and capabilities of the vehicle in lateral dynamics.” [41]. Since the vehicle in our simulations is a sports car, it doesn’t have a high center of gravity, as can be seen in figure 20. Therefore the chances for the vehicle to roll over are minimal. Nevertheless it still is important to measure the lateral acceleration.

Although all these parameters are important, not all of them are necessary for each road type. For the country road and city road is analyzing the roll angle meaningless, since these roads are straight. Furthermore, since the ISO lane change is executed on a flat road, the vertical acceleration of the car will not be analyzed. In the table below, the criteria that will be analyzed are shown for every type of road:

Table 3: Criteria for different types of road

<i>Road Types</i>	<i>Method</i>
<i>Country road</i>	Comfort
	Road handling
<i>ISO Lane Change maneuver</i>	Lateral acceleration
	Roll angle
<i>City road</i>	Comfort
	Road handling

9. Simulation on country road

The first simulation that will be executed, makes use of the country road. As this road has a highly uneven road surface, it is more than realistic to assume that a driver will only use the low settings and the middle settings. However, since it is possible to use the high setting on this road, the high setting will also be simulated for the semi-active shock absorbers.

9.1. Ideal electrohydraulic shock absorber

In the table below, the simulation results for the ideal electrohydraulic shock absorber is given:

Table 4: Simulation results electrohydraulic shock absorber on country road

	Electrohydraulic shock absorber		Electrohydraulic shock absorber		Electrohydraulic shock absorber	
	Low setting		Middle setting		High setting	
	Normal force	Vertical acceleration	Normal force	Vertical acceleration	Normal force	Vertical acceleration
	[N]	[$9.81 \frac{m}{s^2}$]	[N]	[$9.81 \frac{m}{s^2}$]	[N]	[$9.81 \frac{m}{s^2}$]
Minimum	1904	-0,261	1527	-0,334	1377	-0,396
Maximum	4449	0,208	4540	0,216	4474	0,236
Average	3160		3160		3161	
RMS	3181	0,076	3186	0,084	3193	0,095

First of all, it is quite clear that the normal force exerted on the road surface are similar for the 3 kinds of settings, with almost identical average values. Even though, the higher the chosen setting, the lower the minimum value of normal force will become. This will lead to inferior grip of the tire.

However, it is different for the vertical acceleration. Both the RMS value and the total amplitude will become larger when a higher setting is applied on the shock absorber. Therefore, the comfort will be lower for a higher setting.

9.2. Ideal electrorheological shock absorber

In table 5, the simulation results for the ideal electrorheological shock absorber is shown:

Table 5: Simulation results electrorheological shock absorber on country road

	Electrorheological shock absorber		Electrorheological shock absorber		Electrorheological shock absorber	
	Low setting		Middle setting		High setting	
	Normal force	Vertical acceleration	Normal force	Vertical acceleration	Normal force	Vertical acceleration
	[N]	[$9.81 \frac{m}{s^2}$]	[N]	[$9.81 \frac{m}{s^2}$]	[N]	[$9.81 \frac{m}{s^2}$]
Minimum	1904	-0,261	993	-0,470	276	-0,610
Maximum	4449	0,208	4914	0,343	5916	0,519
Average	3160		3166		3173	
RMS	3181	0,076	3243	0,153	3308	0,211

The higher the applied setting, the lower the minimum normal force will become. This of course will lead to a lowered grip on the road surface. The average normal force exerted on the road surface is however insignificant different.

The vertical acceleration shows the same trend as explained for the electrohydraulic shock absorber on the country road. However, the difference between the RMS value of the low setting and high setting is much bigger, which automatically invokes that the comfort of the high setting electrorheological shock absorber will be inferior to the one of the electrohydraulic shock absorber. In figure 36, the graphs of the vertical acceleration for the 3 types of settings are shown for the electrorheological shock absorber.

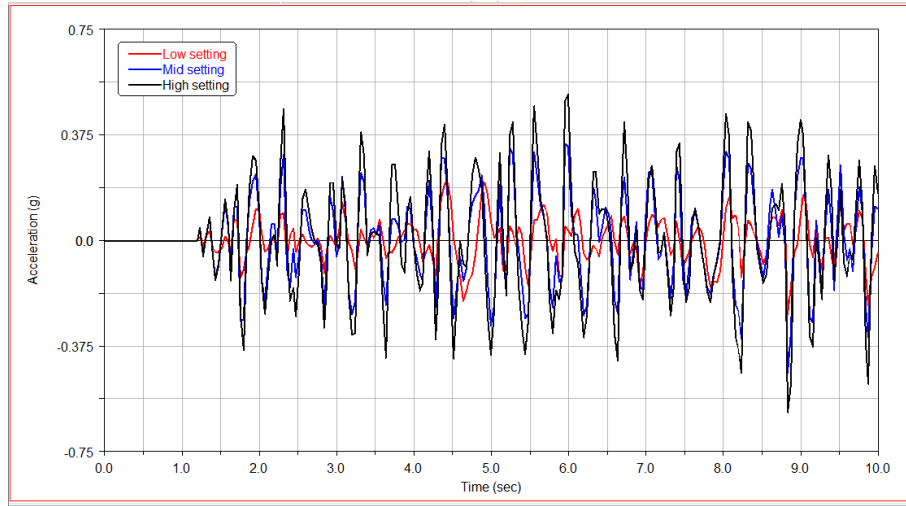


Figure 36: Vertical acceleration for different settings of electrorheological shock absorber on country road

This graph clearly shows the bigger amplitude of the vertical acceleration for the high setting.

9.3. Ideal magnetorheological shock absorber

In table 6, the simulation results for the ideal magnetorheological shock absorber is shown:

Table 6: Simulation results magnetorheological shock absorber on country road

	Magnetorheological shock absorber Low setting		Magnetorheological shock absorber Middle setting		Magnetorheological shock absorber High setting	
	Normal force	Vertical acceleration	Normal force	Vertical acceleration	Normal force	Vertical acceleration
	[N]	$[9.81 \frac{m}{s^2}]$	[N]	$[9.81 \frac{m}{s^2}]$	[N]	$[9.81 \frac{m}{s^2}]$
Minimum	1619	-0,30	829	-0,48	188	-0,656
Maximum	4496	0,217	5093	0,41	6078	0,574
Average	3162		3171		3169	
RMS	3197	0,095	3269	0,175	3316	0,221

The higher the applied setting, the lower the minimum normal force will become. This of course will lead to a lowered grip on the road surface. However, the average force exerted will remain almost the same for the different settings.

The vertical acceleration shows the same trend as explained for the electrohydraulic and electrorheological shock absorber on the country road. The gradient of the curves of the vertical acceleration will resemble very highly on the curves, shown in figure 36.

9.4. Ideal passive shock absorber

In table 7, the simulation results for the ideal passive shock absorber is shown:

Table 7: Simulation results passive shock absorber on country road

	Passive shock absorber	
	Normal force	Vertical acceleration
	[N]	[$9.81 \frac{m}{s^2}$]
Minimum	1904	-0,261
Maximum	4449	0,208
Average	3160	
RMS	3181	0,076

9.5. Conclusion country road

The results of these simulation on a highly uneven road first of all clearly show that the lower settings clearly offer an improved comfort, compared to the higher settings for each type of shock absorber. This was expected, as a softer suspension will result in a more smooth drive.

Figure 37 shows the RMS value of the vertical acceleration for the different types of semi-active shock absorber and passive shock absorber.

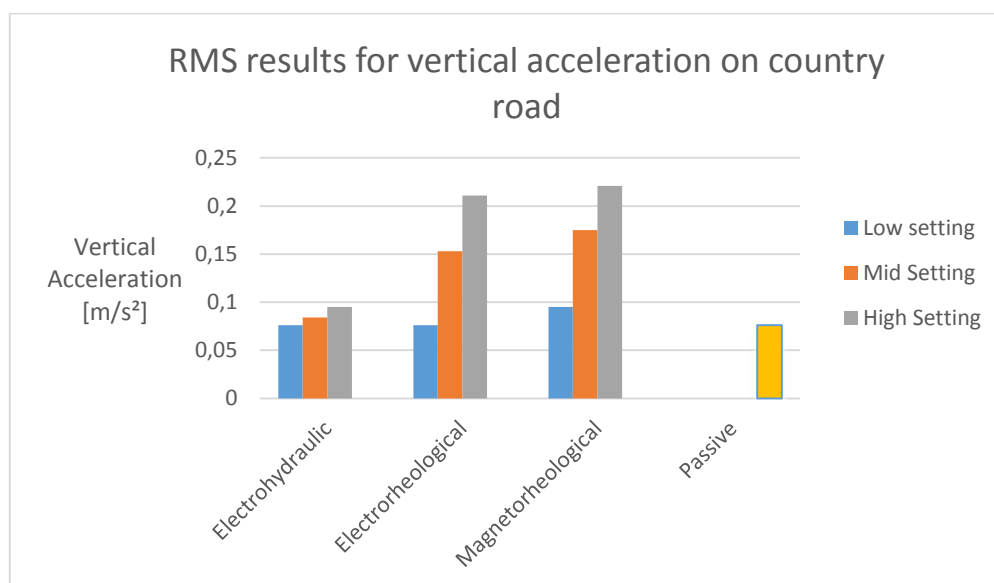


Figure 37: RMS results for vertical acceleration on country road

When we compare the different types of semi-active shock absorbers with the passive shock absorber. The low settings will result in a similar value for the vertical acceleration in comparison with the passive shock absorber. However, the higher the applied settings for the shock absorber are, the higher the RMS value will be. The normal forces are almost the same for the different types of shock absorber. For this country road the electrohydraulic provides the best comfort.

These results show that for the country road, semi-active shock absorbers are able to provide the same level of comfort for the persons inside the vehicle as a passive shock absorber. However, it is quite clear from figure 37 that whenever we apply wrong settings (i.e. not the low settings) to the semi-active shock absorber, the level of comfort can become even worse than the passive shock absorber.

10. Simulation on city road

The second simulation that will be executed, makes use of the city road. This road has some disturbances, and will therefore not be driven with a high speed. So the low and middle settings are more likely to be used by the driver. However, since it is possible to use the high setting on this road, the high setting will also be simulated for the semi-active shock absorbers.

10.1. Ideal electrohydraulic shock absorber

In the table below, the simulation results for the ideal electrohydraulic shock absorber is shown:

Table 8: Simulation results electrohydraulic shock absorber on city road

	Electrohydraulic shock absorber Low setting		Electrohydraulic shock absorber Middle setting		Electrohydraulic shock absorber High setting	
	Normal force	Vertical acceleration	Normal force	Vertical acceleration	Normal force	Vertical acceleration
	[N]	$[9.81 \frac{m}{s^2}]$	[N]	$[9.81 \frac{m}{s^2}]$	[N]	$[9.81 \frac{m}{s^2}]$
Minimum	0	-0,59	0	-0,82	0	-0,90
Maximum	21346	1,18	18421	1,48	9968	2,19
Average	3179		3169		3151	
RMS	3336	0,11	3282	0,13	3197	0,17

It is obvious that the average normal force exerted on the road surface are similar for the 3 kinds of settings. Furthermore, all 3 settings for the shock absorbers have a minimum of 0 Newton. However, since there are objects with a vertical edge at the end or the beginning, it is very normal that the vehicle loses contact with the road surface, even if this loss of contact will only last a fraction of a second.

For the vertical acceleration, it is different however. The RMS value becomes bigger when a higher setting is applied on the shock absorber. The maximal amplitude will also become higher. Therefore, the comfort will be lower for a higher setting.

10.2. Ideal electrorheological shock absorber

In the table below, the simulation results for the ideal electrorheological shock absorber is given:

Table 9: Simulation results electrorheological shock absorber on city road

	Electrorheological shock absorber		Electrorheological shock absorber		Electrorheological shock absorber	
	Low setting		Middle setting		High setting	
	Normal force	Vertical acceleration	Normal force	Vertical acceleration	Normal force	Vertical acceleration
	[N]	$[9.81 \frac{m}{s^2}]$	[N]	$[9.81 \frac{m}{s^2}]$	[N]	$[9.81 \frac{m}{s^2}]$
Minimum	0	-0,59	0	-0,98	0	-0,83
Maximum	21346	1,18	17204	1,23	8485	1,64
Average	3179		3172		3163	
RMS	3336	0,11	3283	0,13	3215	0,16

The average normal force exerted on the road surface are similar for the 3 kinds of settings. Furthermore, all 3 settings for the shock absorbers has a minimum of 0 Newton. However, since there are objects with a vertical edge, it is only normal that the vehicle loses contact with the road surface, even if this loss of contact will only last a split-second.

For the vertical acceleration, it is different however. The RMS value becomes bigger when a higher setting is applied on the shock absorber. The maximal amplitude will also become higher. Therefore, the comfort will be lower for a higher setting.

Figure 38 shows the vertical acceleration for the different settings.

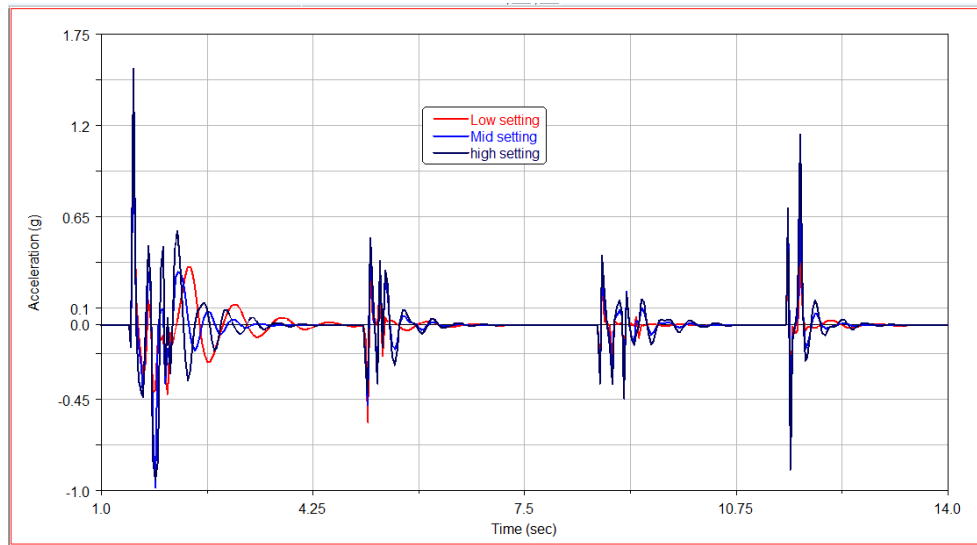


Figure 38: Vertical accelerations for different settings of electrorheological shock absorber

This figure shows that the amplitude of vertical acceleration is lower for the low settings.

This figure however also shows that the higher the chosen setting is, the faster the movement of the vehicle chassis will be damped. Around the mark of 4.25 seconds on figure 38, the high and mid setting are already damped whereas the low settings is still oscillating.

10.3. Ideal magnetorheological shock absorber

In table 10, the simulation results for the ideal magnetorheological shock absorber is given:

Table 10: Simulation results magnetorheological shock absorber on city road

	Magnetorheological shock absorber		Magnetorheological shock absorber		Magnetorheological shock absorber	
	Low setting		Middle setting		High setting	
	Normal force	Vertical acceleration	Normal force	Vertical acceleration	Normal force	Vertical acceleration
	[N]	$[9.81 \frac{m}{s^2}]$	[N]	$[9.81 \frac{m}{s^2}]$	[N]	$[9.81 \frac{m}{s^2}]$
Minimum	0	-0,4865	0	-0,73	0	-0,91
Maximum	22297	0,8279	17651	1,046	7314	1,12
Average	3181		3180		3154	
RMS	3360	0,09	3295	0,11	3197	0,14

First of all, it is quite clear that the average normal force exerted on the road surface are similar for the 3 kinds of settings. Furthermore, all 3 settings for the shock absorbers have a minimum of 0 Newton. However, since there are objects with a vertical edge, it is only normal that the vehicle loses contact with the road surface, even if this loss of contact will only last a fraction of a second.

For the vertical acceleration, it is different however. The RMS value becomes bigger when a higher setting is applied on the shock absorber. The maximal amplitude will also become higher. Therefore, the comfort will be lower for a higher setting.

10.4. Ideal passive shock absorber

In table 11, the simulation results for the ideal passive shock absorber is shown:

Table 11: Simulation results passive shock absorber on city road

	Passive shock absorber	
	Normal force	Vertical acceleration
	[N]	[$9.81 \frac{m}{s^2}$]
Minimum	0	-0,59
Maximum	21346	1,18
Average	3179	
RMS	3336	0,11

10.5. Conclusion city road

Figure 39 shows the RMS value of the vertical acceleration for the different types of semi-active shock absorber and passive shock absorber on the city road:

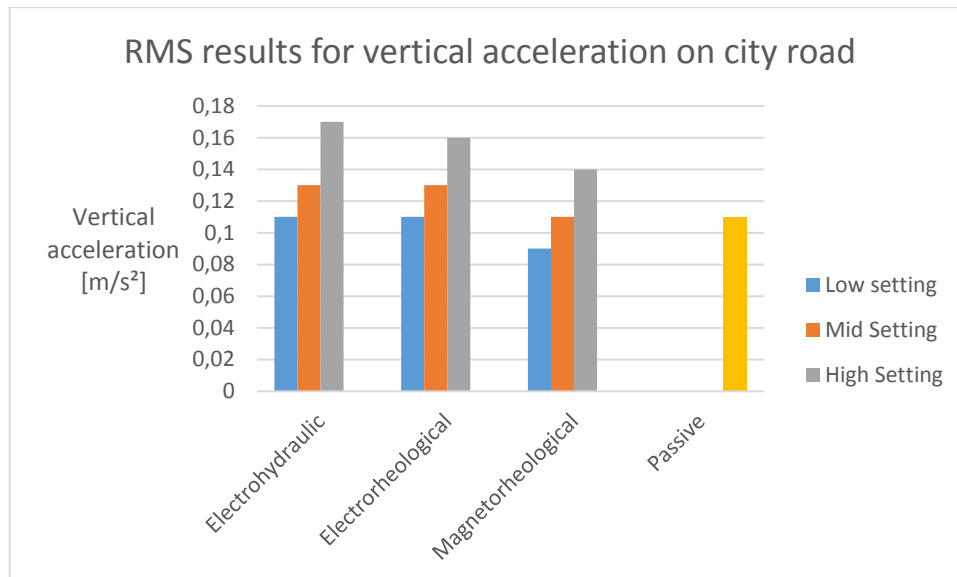


Figure 39: RMS results for vertical acceleration on city road

As this test is to analyze the comfort, the low setting will provide the best comfort for the people inside the vehicle.

When we compare the different types of semi-active shock absorbers with the passive shock absorber. The low settings will result in a similar or lower value for the vertical acceleration in comparison with the passive shock absorber. However, the higher the applied settings for the shock absorber are, the higher the RMS value will be. Therefore, the level of comfort will become inferior to the level of comfort of a passive shock absorber when a higher setting will be applied. The normal forces are almost the same for the different types of shock absorber.

These results show that for the country road, semi-active shock absorbers are able to provide the same, if not better, level of comfort for the persons inside the vehicle as a passive shock absorber. However, it is quite clear from figure 39 that whenever we apply wrong settings (i.e. not the low settings) to the semi-active shock absorber, the level of comfort can become even worse than the passive shock absorber.

11. ISO Lane Change simulation

The last simulation that will be executed, makes use of the ISO Lane change maneuver. For this simulation, the vehicle will perform an emergency lane change maneuver. As the speed is at least 80km/h, the high setting is more likely to be used by the driver. However, since simulations allow to make unreal events happen without any damage, the low and mid setting will also be simulated.

11.1. Ideal electrohydraulic shock absorber

In table 12, the simulation results for the ideal electrohydraulic shock absorber is shown:

Table 12: Simulation results electrohydraulic shock absorber on ISO Lane change maneuver

	Electrohydraulic shock absorber		Electrohydraulic shock absorber		Electrohydraulic shock absorber	
	Low setting		Mid setting		High setting	
	Lateral acceleration [$9.81 \frac{m}{s^2}$]	Roll angle [°]	Lateral acceleration [$9.81 \frac{m}{s^2}$]	Roll angle [°]	Lateral acceleration [$9.81 \frac{m}{s^2}$]	Roll angle [°]
Minimum	-0,79	-2,75	-0,79	-2,70	-0,78	-2.64
Maximum	0,86	3,07	0,86	3,02	0,86	2,94
RMS	0,31	1,11	0,31	1,07	0,31	1,04

The lateral acceleration is for the minimum as well as the maximum as well as the RMS value almost identical for the 3 types of setting for the shock absorber. The difference in lateral acceleration is negligible for the 3 settings.

For the roll angle, there is a difference between the results of the different settings. Although this difference between the high and low settings is not that significant, with a RMS value for the roll angle which is 6 % lower for the high setting, compared to the low setting.

11.2. Ideal electrorheological shock absorber

In the table below, the simulation results for the ideal electrorheological shock absorber is given:

Table 13: Simulation results electrorheological shock absorber on ISO Lane change maneuver

	Electrorheological shock absorber		Electrorheological shock absorber		Electrorheological shock absorber	
	Low setting		Mid setting		High setting	
	Lateral acceleration [$9.81 \frac{m}{s^2}$]	Roll angle [°]	Lateral acceleration [$9.81 \frac{m}{s^2}$]	Roll angle [°]	Lateral acceleration [$9.81 \frac{m}{s^2}$]	Roll angle [°]
Minimum	-0,79	-2,75	-0,78	-1,43	-0,78	-1,06
Maximum	0,86	3,07	0,86	1,77	0,97	1,29
RMS	0,31	1,11	0,30	0,59	0,30	0,37

The lateral acceleration is almost identical for the 3 different settings, with only minor differences for the RMS value and the minimum value. The maximum value for the high setting is however 10% higher than the maximum value of the other settings.

For the roll angle, the difference becomes however very significant. The amplitude of the roll angle for the low settings more than doubles the amount of amplitude of the high setting. The RMS value for the low setting almost triples, compared to the high setting. The middle setting offers a roll angle in between the low and high setting.

Figure 40 shows the roll angle for the different settings of the electrorheological shock absorber:

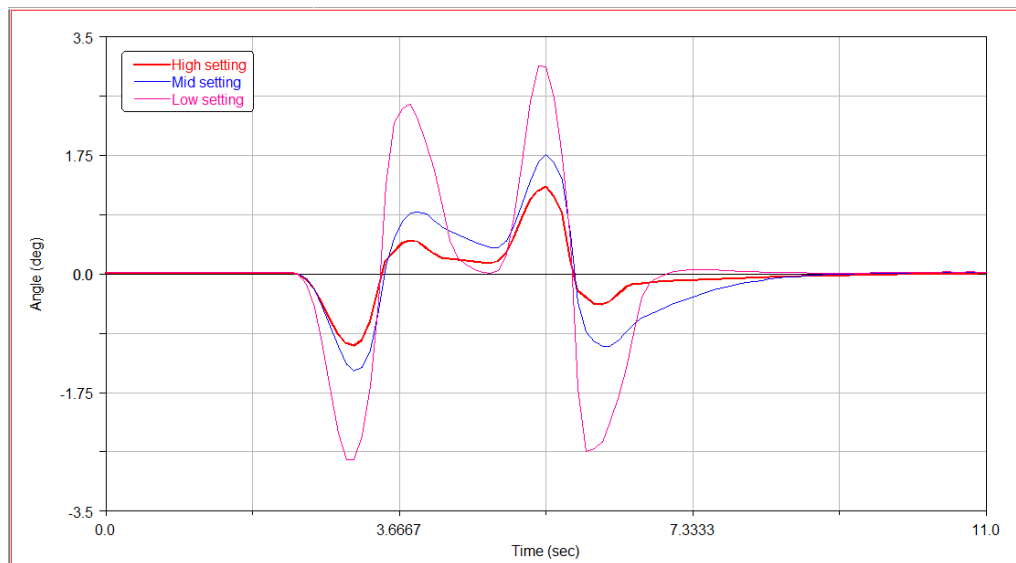


Figure 40: Roll angle for different settings of electrorheological shock absorber

This figure proves the values shown in table 13. To be more precise, the amplitude of the roll angle is lower for the high setting of shock absorber. The difference between the graph for the low setting and the graph for the high setting is significant for this type.

11.3. Ideal magnetorheological shock absorber

In table 14, the simulation results for the ideal magnetorheological shock absorber is given:

Table 14: Simulation results magnetorheological shock absorber on ISO Lane change maneuver

	Magnetorheological shock absorber		Magnetorheological shock absorber		Magnetorheological shock absorber	
	Low setting		Mid setting		High setting	
	Lateral acceleration [$9.81 \frac{m}{s^2}$]	Roll angle [°]	Lateral acceleration [$9.81 \frac{m}{s^2}$]	Roll angle [°]	Lateral acceleration [$9.81 \frac{m}{s^2}$]	Roll angle [°]
Minimum	-0,77	-2,25	-0,78	-1,24	-0,78	-1,09
Maximum	0,84	2,54	0,87	1,52	0,87	1,33
RMS	0,30	0,95	0,30	0,45	0,30	0,38

It is again very clear that the lateral acceleration is very identical for the 3 different settings, where the minimum value and the RMS value barely differ. There is a small difference for the maximum value, however, this difference is negligible.

The roll angle of the highest setting offers the lowest values of roll angle for the minimum and maximum as well as for the RMS value. The low setting will offer far higher values for the roll angle. With a RMS value that's more than double.

11.4. Ideal passive shock absorber

In table 15, the simulation results for the ideal passive shock absorber is shown:

Table 15: Simulation results passive shock absorber on ISO Lane change maneuver

Passive shock absorber		
	Lateral acceleration [$9.81 \frac{m}{s^2}$]	Roll angle [°]
Minimum	-0,79	-2,75
Maximum	0,86	3,07
RMS	0,31	1,11

11.5. Conclusion ISO Lane change

This simulation focusses on the stability of the vehicle. The higher settings of each type of semi-active shock absorber provides a lower roll angle and thus better performances. This is in contradiction with the previous 2 simulations, where the setting had to be as low as possible to offer good performances for the comfort. The contradiction in best setting for this simulation and the previous 2 simulations gives an idea of the shortcoming for a passive shock absorber.

Figure 41 shows the different maximum values for the roll angle:

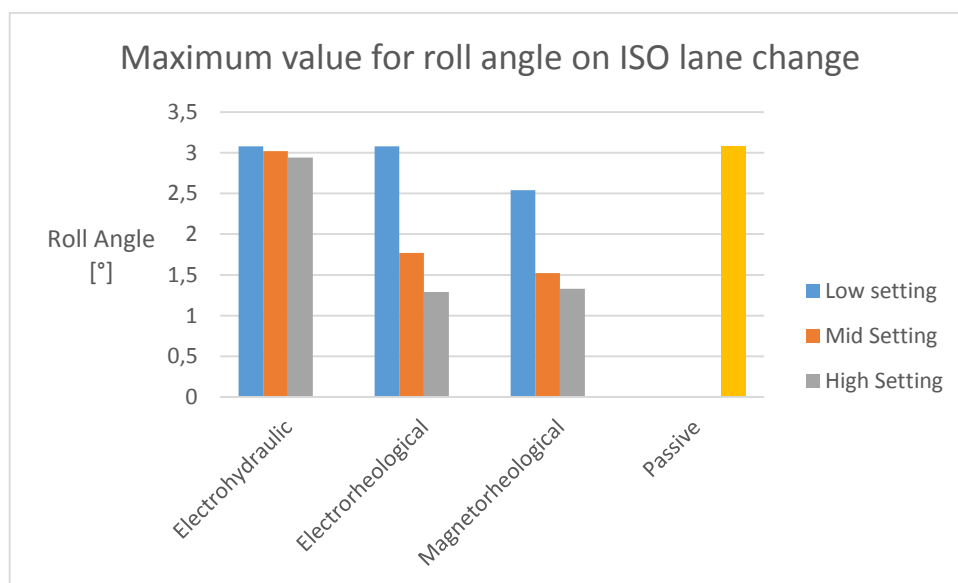


Figure 41: Maximum value for roll angle on ISO Lane change

It is very clear, using the figure above, to determine the performances of the semi-active shock absorbers in relation to the passive shock absorber. As they offer, in the worst case, the same roll angle as a passive shock absorber.

Furthermore, the results of the electrohydraulic shock absorber are peculiar. When comparing the high setting with the low setting, the reduction of the roll angle for the electrohydraulic shock absorber is far below the reduction that the electrorheological and magnetorheological offer. One of the reasons for this difference, is the different types of damping characteristics, used by the semi-active shock absorbers.

The figure below shows the RMS values for the roll angle:

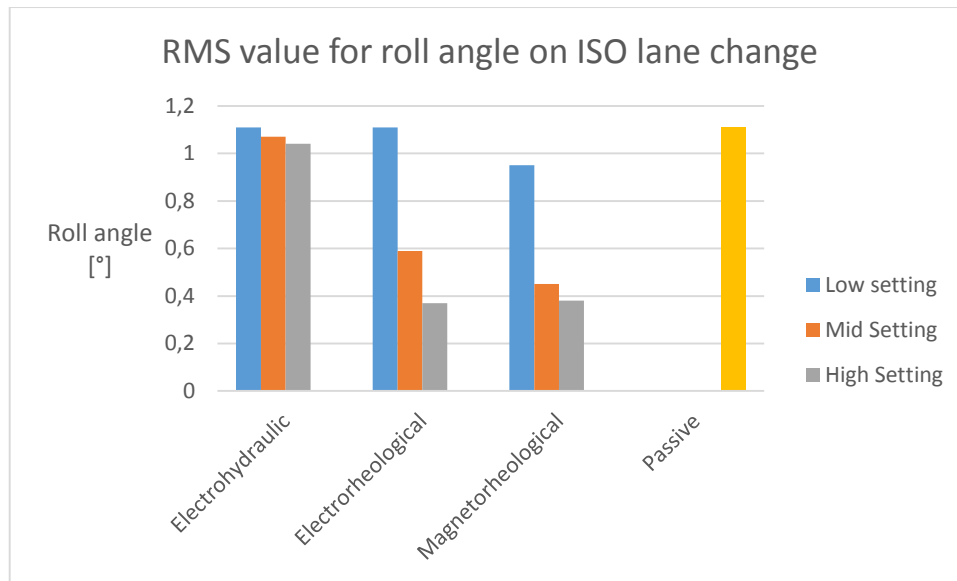


Figure 42: RMS values for roll angle on ISO lane change

This graph, showing the RMS values, shows the difference between the passive shock absorber and semi-active shock absorbers also quite clearly. With the low settings offering the worst results for the semi-active shock absorbers, and the high settings offering the best performances for each of the semi-active shock absorbers. It is quite obvious that the performance of the passive are inferior to the performances of the semi-active shock absorbers.

Even when the semi-active shock absorber is badly tuned and will not function in the best way possible, the performances will still be similar, if not better, to the performances of a passive shock absorber. Furthermore, for the previous 2 simulations, the passive shock absorber offered similar results as the semi-active shock absorber; whereas for this lane change the passive shock absorber is totally outperformed by the semi-active shock absorbers. This indicates the more comfort orientated setting of the passive shock absorber.

12. Conclusion

Chapter one deals with the model of the vehicle. As the suspension is an essential part of the vehicle, it is needless to say that the vehicle is a crucial part of the simulation. The car, and all the parts that are used, are given.

The second chapter gives the list of roads which will be used to do the simulations, as well as the reason for choosing these roads. Next, we take a closer look on every type of road and explained what the characteristics are of the roads. For the city road, every obstacle is explained in great detail.

In the third chapter, the focus is on the settings that will be used on all of the different simulations.

In the fourth chapter we emphasize the importance of the criteria for the simulations. All the different criteria are given, as well as the reason why to use said criteria. Next, the criteria are linked to the different road types.

The following 3 chapters show the results of the simulations. As the results of the simulations clearly show, when the semi-active shock absorber is well set for a type of road, the performances will be similar or better than the passive shock absorber. However, when the wrong setting is set for the shock absorber, the performances may become worse than a passive shock absorber. It is therefore of the utmost importance that a semi-active shock absorber is well tuned, in order to achieve the best possible performances. Lastly, as the results showed, there is also a difference between the different semi-active shock absorbers. These differences are because of the different shape of the force-velocity diagrams of the shock absorbers.

This work can be considered as a start for multiple researches. One possibility is to program an algorithm that automatically can vary the viscosity of the fluid, for an electrorheological and magnetorheological shock absorber, or that can automatically alter the orifice when using an electrohydraulic shock absorber, based on the input of the road surface, to attain the best possible performances. Another possibility is to perform all these simulations with real vehicles, and therefore using real characteristics to compare the shock absorbers.

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Auteursrechtelijke overeenkomst

Ik/wij verlenen het wereldwijde auteursrecht voor de ingediende eindverhandeling:

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Richting: **master in de industriële wetenschappen: elektromechanica**

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in alle mogelijke mediaformaten, - bestaande en in de toekomst te ontwikkelen - , aan de Universiteit Hasselt.

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Voor akkoord,

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Datum: **10/06/2014**