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# **Ambulance Universal Chassis and Suspension (AUCAS)**

**A Major Qualifying Project**

Submitted to the Faculty

Of the

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

**Ambulance Universal Chassis and Suspension (AUCAS)**

By

Nick Gardiner

Doug Griesbach

Connor McCann

Nick McDonald

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Approved

Prof. M.S. Fofana, Advisor

Mechanical Engineering Department

## Abstract

The pre-hospital work conducted by EMTs in an ambulance vehicle is very important. Patients of all kinds can receive a wide range of pre-hospital care; from diagnosis, CPR and stabilization to transportation to medical hospitals. Surface road vibrations are known to influence the quality, efficiency and safety of care in an ambulance. This MQP focuses on understanding the mechanics of the chassis of an ambulance in order to design a new chassis that can sustain the weight of a typical ambulance and also be able to suppress the surface road vibrations. We investigate all alternative suspension designs to implement and analyze the most accommodating design. Furthermore, we chose hydropneumatic suspension as the best alternative to current suspension systems in ambulances. We designed a bolt-on kit for aftermarket installation of hydropneumatic suspension into current ambulances using our 2004 Ford F-350 ambulance as a template. Our proposed chassis provides better ambulance ride quality compared to existing ambulance vehicles. Our final prototype kit has the utmost potential to become a marketed and mass produced alternative for ambulance suspensions.

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# Chapter 1: Introduction

## 1.1 Justification

Emergency medical ambulances are relied upon every day to transport patients in need of care from a place of emergency to a medical facility. It is the role of the emergency medical staff to safely provide this transportation. Ambulances must perform this duty quickly and reliably, despite the time, temperature, or terrain. To effectively handle any medical situation handed to them, EMS personnel have been given the responsibility to perform an endless amount of life saving techniques. Each technique requires its own specialized equipment, which coincidentally needs to be stored within the ambulance. To accommodate the increasing amount of equipment, ambulance manufacturers have had to reconstruct the design of an ambulance over the years.

Today, ambulance manufacturers have adopted heavy duty truck chassis in order to carry and encapsulate all of the necessary equipment for patient care. Heavy duty trucks can weigh up to 10 tons. This creates a need for stiff and heavy duty suspension systems that can handle the substantial payload. With this new adaptation, ambulances now utilize the same foundation of a full size dump truck. There are many by-products associated with poor ride quality. These problems include forcing EMS personnel to take alternate routes due to patient condition or irregularities in the road surface, worsening patient condition, or even law suits against the hospital. With a new suspension system we can eliminate these issues by developing a more efficient means of distributing force that is absorbed into the suspension system. This will produce improved ride quality.

Understanding the need for improved ride quality, M. S. Fofana, Ph.D encouraged our team's investigation and understanding of automotive chassis and suspension. His intention is for our group to improve the ride quality for occupants (both patients and staff) of emergency medical ambulances. It is imperative that our design meets, and in some cases surpass, all current ambulance suspension requirements within the 2011-2012 academic year. Such requirements include: ease of installation, ride comfort, cost effectiveness, load bearing capability, and reliability.

To accommodate for the rough ride associated with the heavy duty truck chassis, it is beneficial to look into other transportation industries. Such industries include aerospace, military and agricultural vehicles whose suspension systems have to support enormous payloads. Alternatively, we are also looking into automotive industry for innovative suspension solutions. We will apply our research into the development of a suitable suspension system that ultimately produces a smoother ride for ambulance occupants. With any mechanical system, there are definitive advantages and disadvantages that we will have to address. Through our research analysis, we have discovered an array of suspensions systems that may be a promising solution. Our main focus will be on implementing hydropneumatic suspension into an ambulance chassis. We feel that this type of suspension system will be the most practical solution to meet the project objectives.

## Chapter 2: Research

### 2.1 Hydropneumatic Suspension

The suspension system of a vehicle serves to provide a comfortable and a safe ride for the vehicles occupants. A balance must be found for the suspension system between being firm enough to support the vehicle chassis and being soft enough to provide a comfortable ride. In cars this is not that difficult a process because the weight is relatively low, so not as much emphasis needs to be placed on providing support. This process however, becomes increasingly more difficult as the weight of a vehicle increases. This becomes a very large problem when it comes to vehicles such as ambulances, which can weigh upwards of seventeen tons. This is a tremendous amount of weight for the suspension system to support and at the same time the vehicle needs to provide a very smooth ride for the extremely delicate cargo that it transports. The challenge becomes how to provide more rigid support than that needed in a car while providing a more comfortable ride so as not to be detrimental to the condition of the patients being transported in the ambulance. In the following chapter we analyze hydropneumatic suspension and compare it to traditional suspension systems.

### **2.1.1 What is Hydropneumatic Suspension?**

Selecting a hydropneumatic suspension system as a replacement for traditional spring and shock absorber suspensions was not an arbitrary decision. We were given the task of softening the ride and improving the comfort of the patients and the staff of the ambulance. This would reduce the risk of further harm in the ride to the hospital as well as reduce wear on the ambulance and the staff working in the ambulance.

### **2.1.2 Current Ambulance Assessment**

Our first task was looking at the current ambulances used. The assortment consisted of a wide variety of Ford, Chevrolet, GMC, and International trucks. The trucks ranged from smaller payload gas powered trucks to very large, commercial grade, possibly 6-wheeled diesel trucks as seen in Figure 1. Most importantly, this meant that there was no standard truck chassis used. However, it can be noted that nearly every truck utilized traditional spring and shock absorber suspension. An important thing to consider is how much the various ambulance types differ in weight and size when coming up with a solution.



**Figure 1 - Ambulance sizes can vary between small, gas powered vans (left) to large, diesel powered trucks (right), yet both use uncomfortable, but simple, traditional suspension systems. ([dayerses.com](http://dayerses.com)) ([greenwoodev.com](http://greenwoodev.com))**

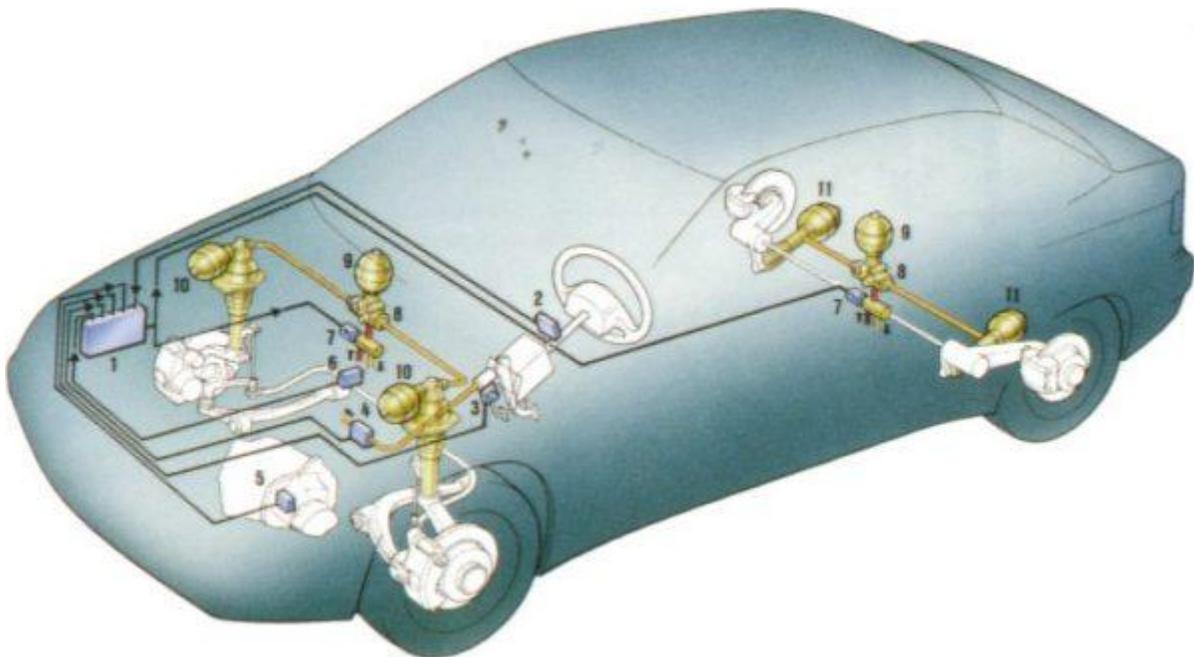
So far, we know there is a large range of commercial grade trucks that have the stock suspension systems they are built with. This is where we have focused our attention because these chassis are made for general use. Some are used for ambulances while others are used for tow trucks, construction trucks, and even dump trucks. Basically, every other application that utilizes these generic chassis needs to be robust and strong. While an ambulance also needs to be robust and strong to accommodate the huge weight of the box, it also needs to carefully handle its occupants who may be in critical condition. This means that almost every ambulance in use utilizes possibly the worst possible suspension system for a smooth ride.

We were informed that some ambulances had been retrofitted with air ride and air bag suspension systems by the ambulance construction companies before they were delivered to the hospitals. Air bag suspension systems do not age well either because slow leaks in the systems can cause gradual failures of the systems. While these ambulances had smoother rides, defects

in the system put wear on the chassis and even fractured some of the chassis with this type of suspension system.

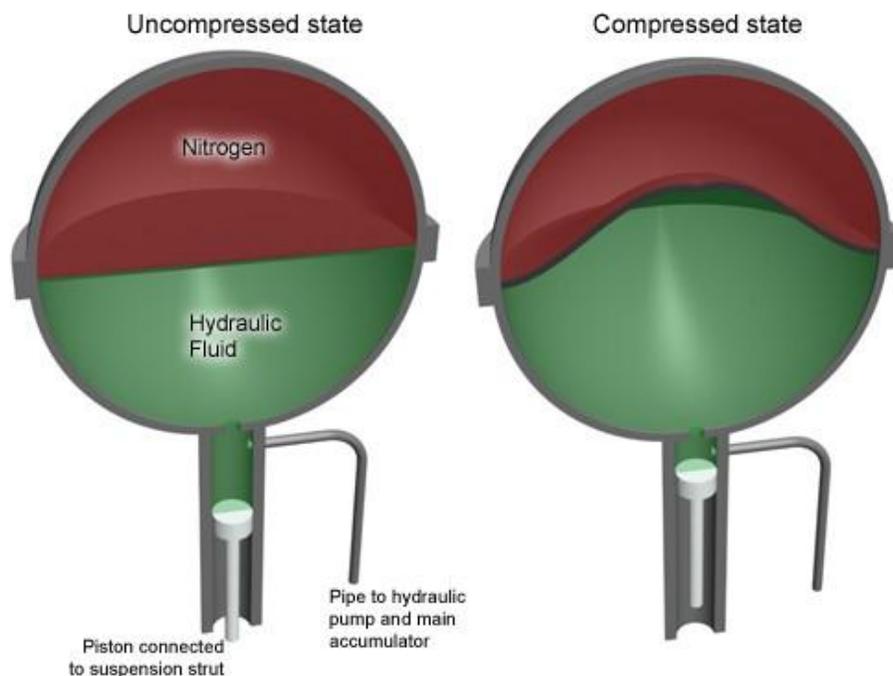
### 2.1.3 Our Proposed Potential Solution

A hydropneumatic suspension system, or CRONE (Commande Robusted'Ordre Non Entier) system uses the idea that you can compress a gas but you cannot compress a fluid to create a smooth ride. A typical hydropneumatic suspension system uses a system of spheres and pipes to create a smooth ride. The spheres can either be mounted right where the spring and shock absorber would be or they can be mounted remotely depending on available space and system complexity as seen in Figure 2.



**Figure 2 - A schematic of a car with hydropneumatic suspension. Note the placement of the spheres. (psi.co.il)**

The spheres of a hydropneumatic suspension system are split into hemispheres with typically a rubber diaphragm separating the two spheres as seen in Figure 3. The top sphere is typically filled with a gas like Nitrogen and is completely sealed off. The other sphere, and subsequently the rest of the system, is filled with some kind of hydraulic fluid. This design creates a sphere that is half gas and half fluid. The crest of the hydraulic fluid hemisphere opens into a tube. The tube houses a piston that is connected to the suspension strut and is what accepts the movement from the tire. A pipe comes off of this tube and leads to the main hydraulic fluid accumulator and pump which controls the pressure and amount of fluid for each wheel. This pipe can add or remove fluid depending on the environment and the vertical displacement of the wheels.



**Figure 3 - A cut-away model of a hydropneumatic sphere. The Nitrogen hemisphere (red) is divided from the hydraulic fluid section (green) by a thin rubber diaphragm. The piston is depicted at the bottom in white. The pipe to the rest of the system is depicted (gtcarz.com)**

The uncompressed state of the sphere is simple and both hemispheres remain equal. The compressed state shows how the Nitrogen gas is compressed when the piston pushes the hydraulic fluid into the hydraulic fluid chamber, over-filling the hydraulic fluid hemisphere and pushing into the Nitrogen gas hemisphere via the rubber diaphragm. The pressure regulated by the main hydraulic pump and accumulator is not arbitrary. Certain vehicles have certain variations to pressure options and capabilities but almost all of them have the ability to adjust to smoothness of the ride based on how much pressure is stored in the accumulator and the spheres. In some cases, this can also affect aspects like ride height which may be better for certain driving environments. However, if the pressure is too low, the handling of the vehicle may become more difficult because of the lack of pressure on the chassis.

#### **2.1.4 Traditional Suspension Versus Hydropneumatic Suspension**

Now that hydropneumatic suspension systems have been fully defined, it is important to note how they are different from traditional spring and shock absorber suspensions. Traditional suspension systems, as mentioned earlier, utilize a basic, heavy duty spring with the assistance of a shock absorber to help “bounce out” the shocks from the tires. In essence, both of these suspension systems do the same thing; however, one performs better than the other. The idea of the suspension is to accept the roughness from the road and buffer the vibrations generated between the tires and the body of the vehicle (which holds the passengers of the vehicle).

The suspension for an ambulance is a special case in that the passengers may be extremely susceptible to vibrations and movement. Even if the patient may not be extremely susceptible to harm from the vibrations, the EMTs helping the patients may be attempting to perform services that require the utmost precision, such as starting an IV as seen in Figure 4.



**Figure 4 - EMTs working in the back of an ambulance. Note the tight working space and adaptive stances for ambulance movement. ([basicemtraining.com](http://basicemtraining.com))**

In addition to making the efficiency of the EMTs and creating a safer environment for the patients, a smoother ride may also help protect the hospital. We found that it is common for the hospitals to have lawsuits filed against them by patients and staff. These lawsuits are filed because patients claim they sustained further injuries from the roughness of the ride in the ambulance. Even if patients do not file a lawsuit against the hospital, there are regular complaints to the EMTs about the discomfort encountered during the ride to the hospital. Sometimes even ambulance staff will complain of discomfort. This is especially a concern because the staff spends so many hours inside the ambulance. Prolonged discomfort for the EMTs can lead to fatigue, pain, and lower work quality.

Many studies have been conducted testing the effectiveness of hydropneumatic versus traditional suspension systems. Results show that the ride quality of the hydropneumatic suspension systems is always better than that of traditional suspension systems. The traditional suspension systems in these tests were sometimes those of cars, not trucks, yet the

hydropneumatic suspension systems would still out-perform for comfort. However, while the ride may have been smoother, the handling of the vehicle may have been affected or merely felt different because of the new suspension. This was only the case when the pressure was extremely low and would not be a normal level for operation. Figure 5 shows a comparison between a traditional suspension system and a hydropneumatic suspension system. The first pair of graphs show the responses of sprung mass for both suspension types. The second pair of graphs show the responses of the wheels of the vehicle for both suspension types.

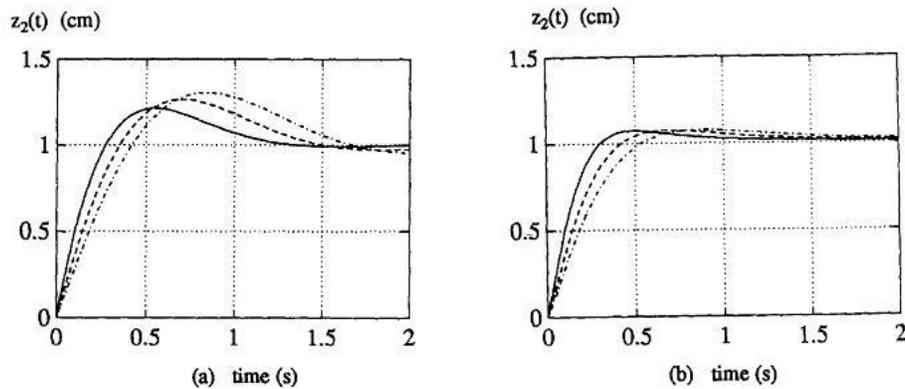


Fig. 7. Step responses of sprung mass for traditional (a) and CRONE (b) suspensions:  
 (————)  $m_2 = 150$  kg; (-----)  $m_2 = 225$  kg; (- · - · -)  $m_2 = 300$  kg

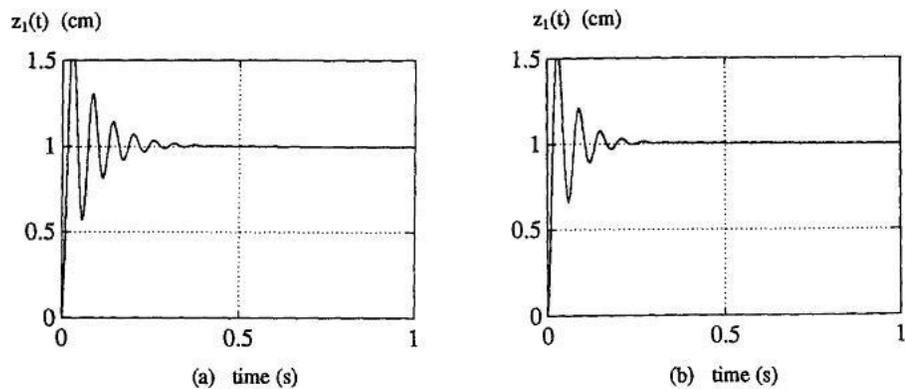


Fig. 8. Step responses of wheel for traditional (a) and CRONE (b) suspensions:  $m_2 = 150$  kg

**Figure 5 - Graphs comparing data of traditional suspension versus hydropneumatic suspension (CRONE) under loading (top) and graphs comparing data of tradition suspension versus hydropneumatic suspension (CRONE) body travel (bottom). [7]**

Hydropneumatic suspension has been applied in automobiles since the 1950's but there are very few heavy duty applications of the systems. This is due to the high center of gravity most of these vehicles have. The fear is that the high center of gravity would create greater roll-over possibilities with a heavy vehicle fitted with hydropneumatic suspension. The key is to find a common ground between ride comfort and vehicle handling. Studies have suggested that an interconnected hydropneumatic suspension system could both decrease the possibility of a roll over and the damping endured from roll-mode motion without affecting the ride comfort.

## **2.2 How It Works**

### **2.2.1 Traditional Vehicle Suspension**

Automobile suspension is as old as the modern automobile, just over 100 years. Over the past century, automotive suspensions have gone through several different variations and designs, and there is still room for improvement. There are several variations of automobiles, and each variation has its own unique purpose. For each purpose, there is generally a need for an individualized suspension. A race car for instance, is intended to be driven at high speeds on a flat and smooth paved surface. These parameters call for a low suspension travel, high spring rate suspension that provides desirable handling qualities. On the other hand, a vehicle that is subjected to extreme variations in terrain, will require a low spring rate and a large amount of suspension travel. For the reader's discretion, please refer to Table 1 for suspension terminology.

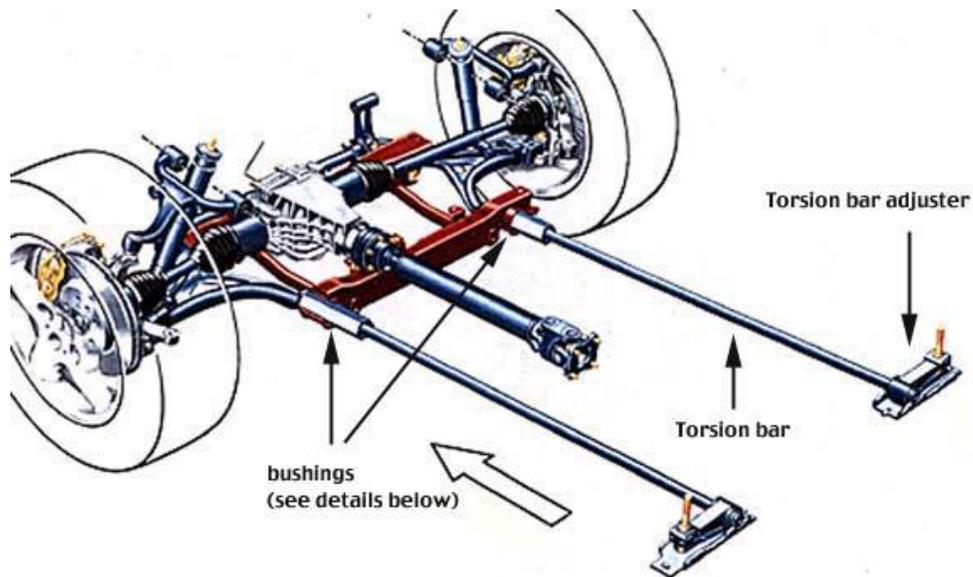
Automobile suspension is a series of linkages, springs, and shock absorbers that makes connection from the vehicle's chassis/ uni-body to its wheels. The purpose of automotive suspension is not limited to this connection. The real purpose of a suspension system is to keep a point of contact between the road surface and the tire tread, while providing the most

comfortable ride. In order to achieve this, the average street automotive suspension has to have a high enough spring rate to quickly react to road surface irregularities, yet have a low enough spring rate to have some compliance so that the wheel can travel with the irregularities. A robust damping system that limits the spring rate when necessary is often, if not always used. In addition to driving conditions, there are design considerations for varying payloads. Suspension design for a road car needs to only consider its own weight (on average 1.75 tons) plus a couple passengers and some groceries. A full size dump truck is a different story, not only does the suspension have to carry its own weight (upwards of 25 tons), it also has to carry a payload variation of 0 to 20 tons. As you can imagine, the differences in the suspension systems between these vehicles vary by a great deal in respect to size, shape, and geometry.

**Table 1 - Terminology**

Spring Rate	Hooke's Law $F=-kx$ A spring's resistance to being compressed or expanded
Wheel Rate	Effective spring rate measured at the wheel, typically equal or considerably less than the spring rate alone
Weight transfer	Effected by amount of acceleration, center of gravity, wheelbase/ track width, and the vehicle's mass
Sprung weight	The weight of components supported by the suspension (Chassis, body, etc)
Unsprung weight	The weight of the components that are not supported by the springs (wheels, axles, some steering components)
Travel	The total distance the suspension travel (top to bottom of the suspension stroke)
Damping	Controls the travel speed and resistance of wheel vertical movement.
Jacking forces	The sum of the vertical force experienced by the suspension linkages. The Jacking force lifts the sprung mass.



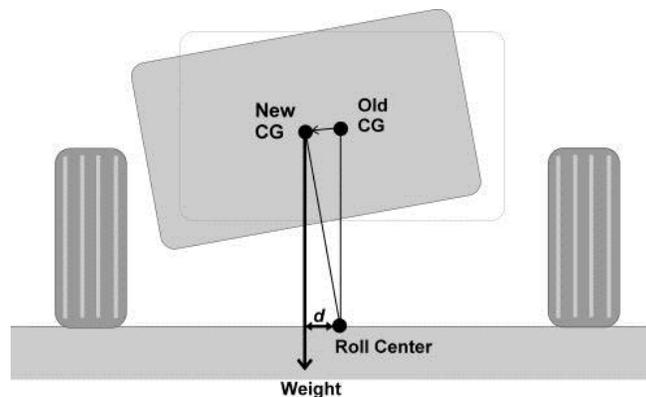


**Figure 8 - Torsion bar suspension (pirate4x4.com)**

### **2.2.3 Disadvantages of Traditional Suspension Systems**

Conventional suspension systems all suffer from one common parameter that cannot be completely overcome. Steel sprung systems all suffer from stiffness, and stiffness causes a large number of other problems and limitations. Although steel springs have a certain degree of compliance, because it is a rigid body, there will always be some level of stiffness. Stiffness of the suspension system is what causes the abrupt and uncomfortable vertical motion in when driving over surface irregularities. In addition to poor ride comfort, excess weight transfer around the vehicle's center of gravity (body roll) is also common. This excess body roll is primary cause of rollovers and loss of control of trucks, vans, and SUV's.

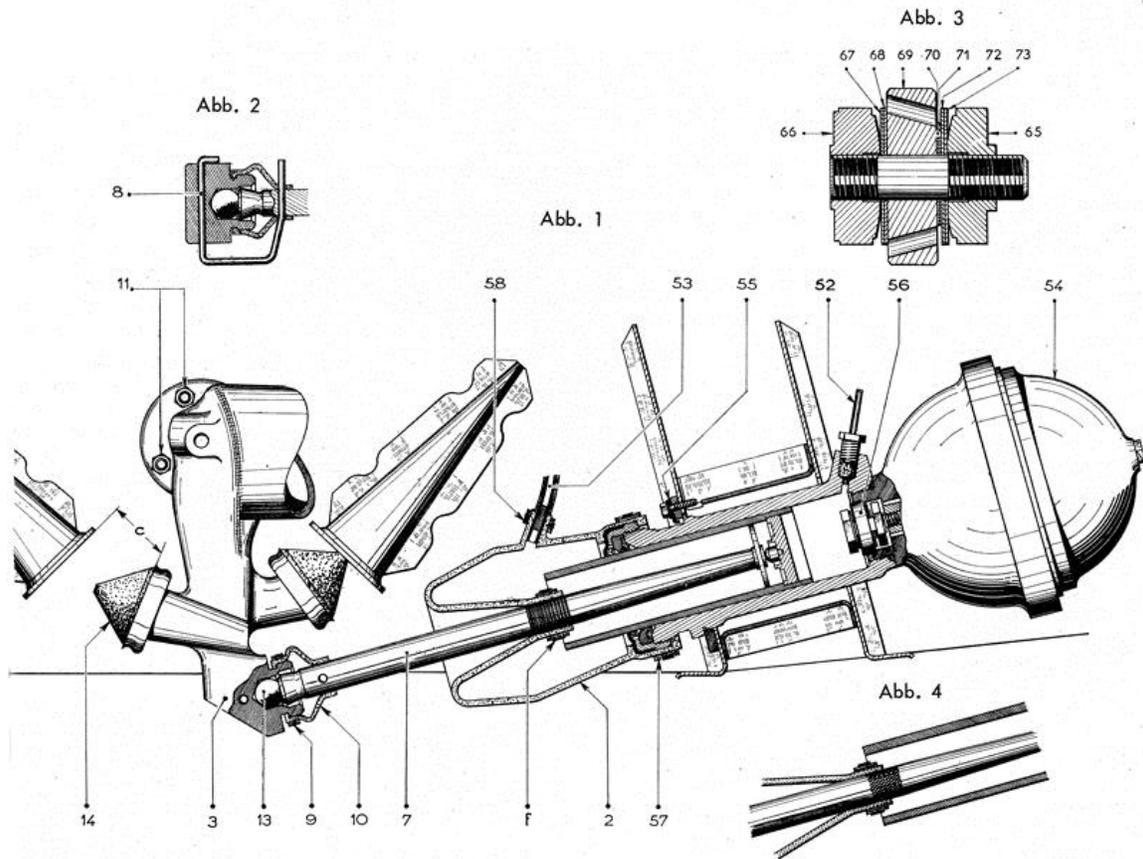
The taller the vehicle, the higher the vehicle's center of gravity. The higher the center of gravity, the larger tangential force that is exerted during both normal and extreme driving conditions, which can lead to roll overs and loss of control. Figure 9 displays this relationship between body roll and the vehicle's center of gravity.



**Figure 9 - Visual demonstration of the relationship between center of gravity (CG) and roll center (pirate4x4.com)**

#### **2.2.4 Hydropneumatic Suspension: How it works Introduction**

Unlike typical suspension systems, hydropneumatic suspension does not have springs. The springs were replaced with only fluid and gas filled interconnected shock absorbers similar to the one seen below. This system was created around the concept that you can compress a gas, but cannot compress a liquid. In this suspension system, the gas (typically nitrogen) acts as a spring, and the hydraulic fluid acts as a damping and leveling mechanism. Figure 10 and Figure 11 describes this concept by displaying how hydropneumatic struts work.



**Figure 10 - A Hydropneumatic Sphere and Strut in one possible configuration**

[Citroen.et.org](http://Citroen.et.org)

The system relies on an engine powered hydraulic pump which pressurizes the hydraulics of the system and enables various capabilities including self-leveling, variable ride height, assisted jacking forces, and near zero body roll through hard cornering and hard braking/acceleration. This system also has the capability to power the steering and braking systems to reduce the number of individual components, if desired.

Overall, the hydropneumatic suspension system provides qualities that can be considered, ideal conditions. These ideal conditions are a constantly level passenger compartment, limited road surface irregularity oscillations, no abrupt vertical motions.

### 2.2.5 The Springs

In hydropneumatic suspension systems, the nitrogen gas acts in place of the steel spring of typical suspension systems. The gas has around six times the flexibility of conventional springs which adds to ride comfort due to decreased spring rate. Although this would initially provide a soft transition between the bump and no bump, the wheel rate would be so high that the travel would max out and cause a harsh bump at the top of the suspension travel. To overcome this, the suspension for all four wheels have been interconnected thus incorporating a self-leveling capabilities that allow the entire vehicle to travel over the bump while keeping the body level, rather than the individual wheel.

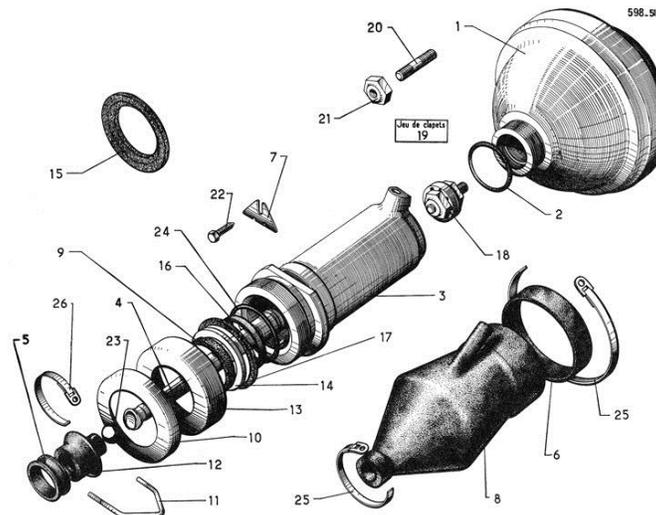
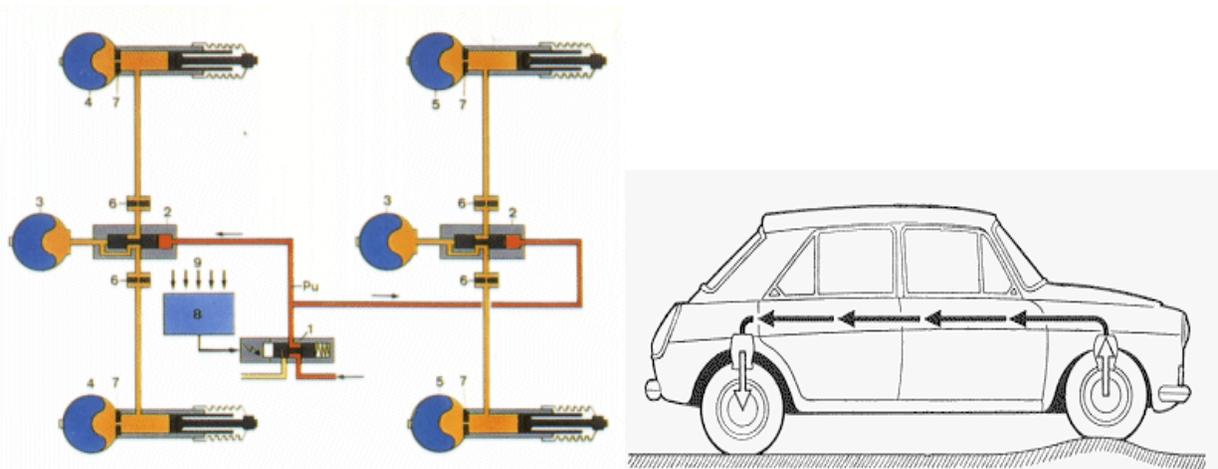


Figure 11 - An exploded view of a Hydropneumatic Sphere and Strut (Citroen.et.org)

Unlike steel springs, the ‘gas spring’ of the hydropneumatic suspension system, as seen above, has a variable spring rate. The more the gas is compressed, the higher the spring rate. One could say that the spring rate is proportional to the loading of the spring. So while driving under normal conditions, the gas spring has a high compliance that provides a smooth ride. Alternatively, under hard cornering, braking conditions, and heavy loads, the hydropneumatic suspension’s varying spring rate keeps the vehicle level and the driver in control.

### 2.2.6 The Damping

With having all four wheels hydraulically interconnected, when a vertical force is applied to one wheel, the net force of the other three wheels provide an equal and opposite reaction. The figures below illustrate the hydraulic connection, and the self-leveling phenomenon. Figure 12 and Figure 13 show the hydropneumatic struts (one located at each corner of the vehicle) and how they are interconnected via hydraulic lines. These hydraulic lines are what distribute the wheel vibrations and motion to the other unaffected struts.



**Figure 12 - Hydraulic layout**      **Figure 13 - The automatic leveling concept (Carbibles.com)**

### 2.2.7 Hydractive

The Hydractive suspension system is a conventional hydropneumatic system with sensors in the steering, suspension, and braking systems that deliver information to the on board computer, deciphering changes in ride height, road conditions, and driving conditions. The on board computer then delivers information to adjust the suspension on the fly. The primary adjustment being made is the on an off switching of a pair of central reserve spheres that add or take away additional spring rate. By closing off the spheres from the system (hard mode), a great deal of stiffness is added, which assists in extreme cornering and braking conditions. Alternatively, if the spheres remain open (soft mode), this allows for a soft and comfortable ride. Figure 14 provides a simple diagram of how hard and soft mode is accomplished in Hydractive and hydropneumatic suspension systems.

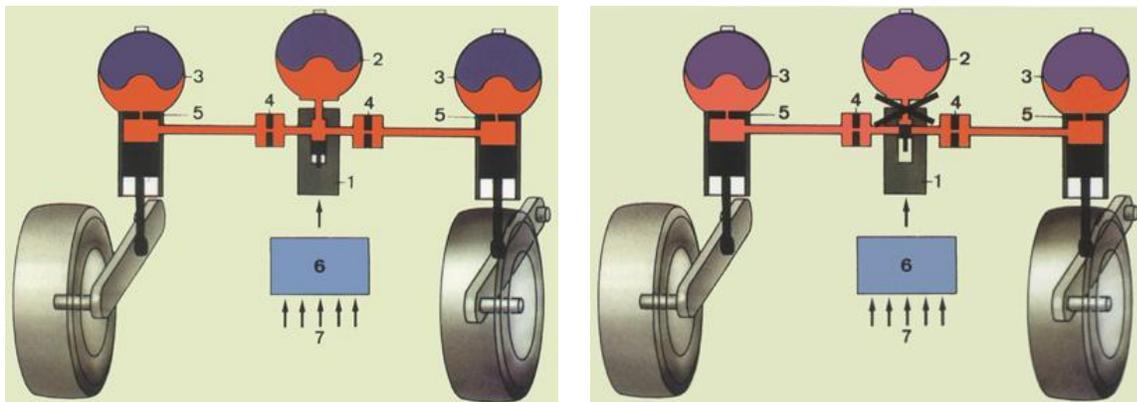


Figure 14 - Soft mode (Left) Hard mode (right) (Carbibles.com)

## 2.3 Problems and Solutions

### 2.3.1 Problems

The suspension system of a vehicle has two primary functions, isolating vibrations and maintaining road contact. The suspension of a vehicle must be able to isolate the vibrations and the forces that are applied to the vehicle. The forces are applied to the vehicle through the wheels when traveling over uneven road surfaces. Subsequently these vibrations and forces are passed through the vehicle if there is not adequate suspension and can possibly injure the occupants of the vehicle. The other purpose of the suspension is to keep all of the tires in contact with the road no matter what type of surface it is traveling across. Figure 15 shows the current suspension in our ambulance. We identified this suspension system as the key issue in causing road vibrations.



**Figure 15 - The suspension setup in our ambulance with the leaf spring (left) and the shock absorber (middle)**

A concerning problem associated with inadequate suspension systems (especially in ambulances) is injuries. This is a recurring problem especially in the context of a vehicle with very poor suspension, in which the occupants spend a large amount of time. Over a short period of time this is not big problem for employees because the vibration is tolerable. However, over extended periods of time the vibrations can prove to be exceedingly harmful. The other main concern is the wellbeing of the patient. While a short bumpy drive may not harm the paramedics it can be life threatening for a critical patient.

### **2.3.2 How Injuries Occur**

Extensive research has shown that drivers (truck drivers, agricultural machinery operators, subway operators, tractor drivers...) are common victims of lower back pain. Figure 16 displays how these injuries are so common. EMT's must operate in such positions while the Ambulance is in motion. This sort of composure could cause injuries after prolonged periods of time without motion, which is further justification of why road vibrations must be reduced. This lower back pain is caused by frequent vibrations passing through their entire body, and more importantly their back. The spine is highly sensitive to vibrations of low frequencies.



**Figure 16 - EMTs attempting delicate work in a potentially harmful environment**

**([emttraining.com](http://emttraining.com))**

The vibrations found in common vehicles driving on paved roads are usually between two and twenty Hertz, ideal for causing spinal injuries. These injuries are cumulative, meaning that they build up over time as a result of the constant vibration. This why people who just drive their car around for a little while every day do not necessarily end up developing lower back injuries. However, for people that drive for a living, truckers, paramedics, etc. are subjected to these vibrations throughout the day, every day.

### 2.3.3 What Does It Mean to Companies

It seems somewhat odd to think that riding in a vehicle for extended periods of time can be harmful to a person but studies have shown that it is true. Not only that but these injuries play major part in company expenses. Studies have shown that twenty percent of work related injuries in workers under the age of forty-five are lower back pain. These injuries are often generated through the uncomfortable repeated use of vehicles without adequate suspension. The total cost for work related injuries in the United States per year is ninety billion dollars. So it is of great interest to all employers to spend the capital now and invest in better suspension for their vehicles to prevent injuries. By acting in a preventative way the companies can avoid needing to spend large sums of money on doctors and medication to alleviate the injuries that workers have sustained, with the possible risk that the employee will not be able to return to work after their injury. Figure 17 displays a typical ambulance repair shop where our suspensions system could potentially be installed.



**Figure 17 - The Boston EMS Ambulance facility where maintenance and modifications to ambulances are completed**

Some countries have already recognized this as a problem and are working to address it. The European Parliament has enacted several standards which limit the number of hours workers are allowed to use machines that are capable of producing these injuries in a day. While this is a step in the right direction, preventing injuries from occurring instead of treating them after the fact, this approach would still benefit from a change in direction. If these machines are improved so that they do not produce these harmful vibrations, there will not be a need to limit the number of hours workers can spend using them. This will also be beneficial to the workers because they will then not need to worry about their wages decreasing because of shortening shifts to prevent injuries.

### **2.3.4 How This Relates to Our Project**

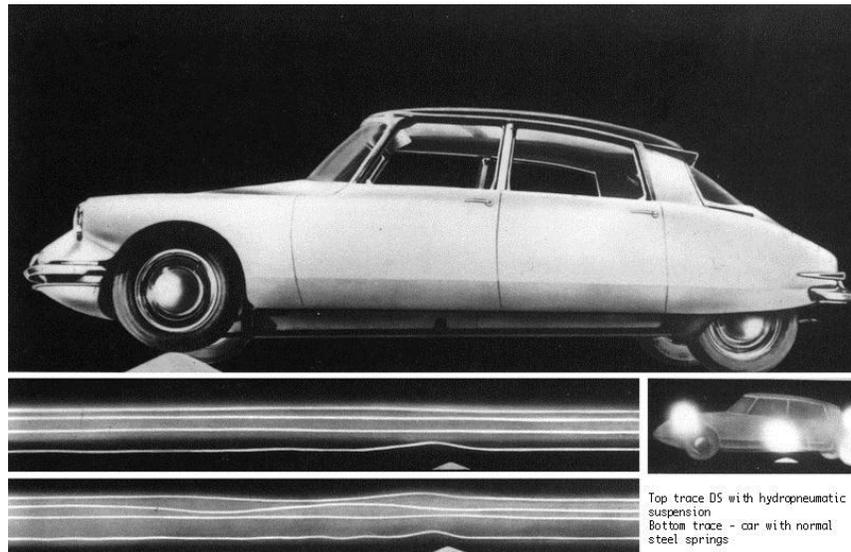
Due to the nature of these vibration induced injuries, they are extremely prevalent in paramedics. Paramedics spend their time at work riding in an ambulance, constantly subjected to these vibrations. To make matters worse the paramedics are not always sitting in the ambulance like other workers who sustain these injuries such as truck drivers. Moving around in the ambulance and being in different positions aiding patients while absorbing these vibrations can place more stress on the back and lead to more rapid and extensive injuries. As mentioned this can be extremely expensive to employers and is detrimental to employees' health, making it more difficult for them to perform their duties.

### **2.3.5 Short Term Patients**

When it comes to injuries the paramedics are not the only ones whose safety must be taken into consideration. The safety of patient is also a major concern. The effects of vibrations on the paramedics is harmful over a period of time, however, when it comes to the patient the vibration possess a much more immediate threat. With a critical patient on board an ambulance even slight vibrations could seriously injury or possibly even prove fatal to the patient.

### 2.3.6 Improvements

There are many different types of suspension that can be used in a vehicle to dampen the effects of an uneven road surface. Some methods provide a more comfortable ride than others but when selecting a suspension system cost must also be taken into consideration, making it difficult to balance rider comfort and cost. One of the best suspension systems currently on the market as far as providing ride quality is the hydropneumatic suspension system. An example of hydropneumatic suspension as compared to typical steel springs is shown below in Figure 18.



**Figure 18 - Car Displacement Test ([citroen.et.org](http://citroen.et.org))**

The above picture and charts show just how effective the hydropneumatic suspension can be when compared to the typical steel springs. While it does not look like there might be that much vibration produce or force transmitted to the driver, tests show that it is significant, and there is a very clear difference between the charts for the steel spring and hydropneumatic suspension.

Hydropneumatic suspension can be further broken down into categories, passive suspension, semi-active suspension, and active suspension, with the options of hard and soft modes for the suspension. Each of these different categories has their own strengths and weaknesses, including cost and ride comfort. Companies are often forced to pick the middle ground so that they are able to provide a comfortable ride for their passengers but at the same time are able to produce an economical product.

### **2.3.7 Passive Hydropneumatic Suspension**

Passive hydropneumatic suspension is the most basic option of hydropneumatic suspension. It features all of the basic parts of hydropneumatic system, but is designed with only one dampening setting. The dampening strength is an exponential curve, meaning that the harder further bump pushes the suspension up the great the force required to push it higher. In this manner, the bump in the road will only be able to push the suspension up so far before the dampening stops it from rising anymore. This is a good system. However, it is only has one dampening strength, meaning it will only work well within a given range of force. If the force is too great or too little the suspension will not be able to adequately respond.

### 2.3.8 Hard and Soft Passive Suspension

Within passive suspension there are two further divisions, hard and soft suspension. These suspensions have different setups which allow for greater strength in some areas while providing weaknesses in other areas. The two different types can be seen below in Figure 19. As shown in the diagram in soft suspension all of the dampening cylinders are interconnected. This allows for some of the fluid from one chamber to pass into that of another if that side of the suspension is suddenly compressed. This is in contrast to hard suspension which does not directly link the different chambers to one other; instead they act separately and therefore provide a much firmer ride.

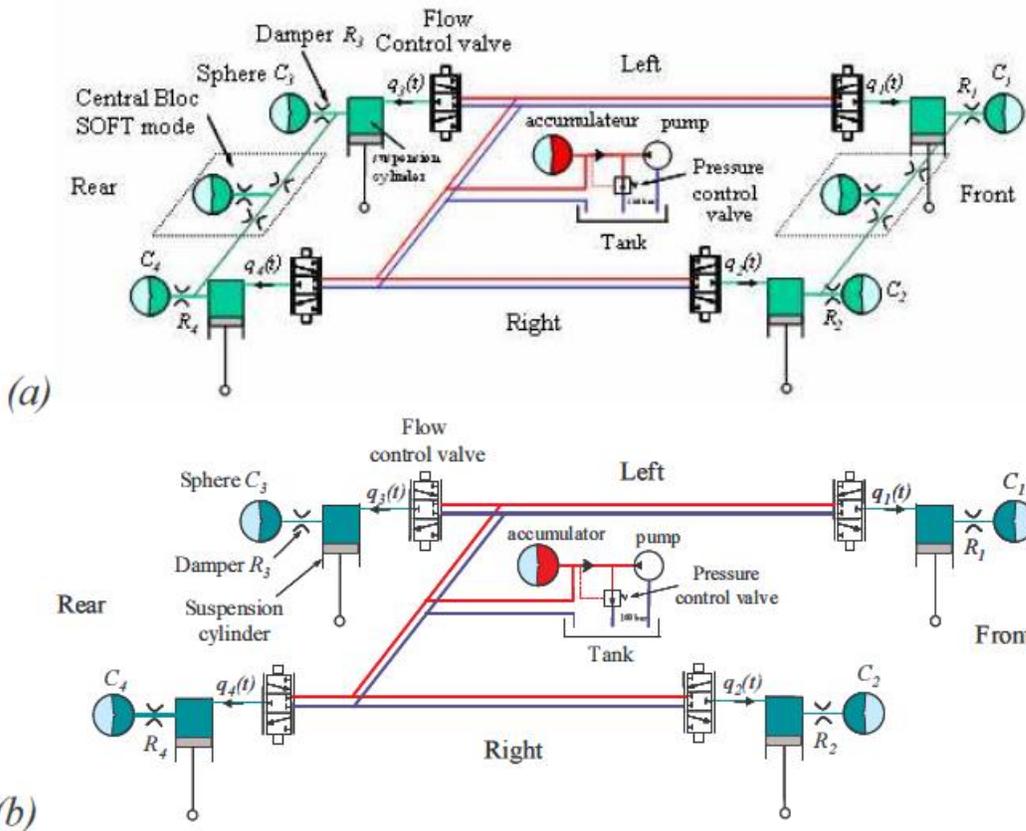


Figure 19 - a. Hydropneumatic Soft Suspension. b. Hydropneumatic Hard Suspension

(citroen.et.org)

Each of these systems is not without their problems however. These problems are illustrated below in Figure 20. Soft suspension is susceptible to problems when driving on rough roads. If a sharp or large bump is suddenly hit, it will compact the suspension in that area rapidly forcing the fluid to the other corners of the suspension causing instability. The chassis of the vehicle could also potentially drag on the ground if the suspension compresses too much in one corner. On the other hand hard suspension can be too rigid. It does not allow the fluid to be transferred between the different cylinders; it is contained within each individual one. This can become a problem while driving around sharp corners or when suddenly stopping. Unlike the soft suspension, in hard suspension the fluid has nowhere to go. This makes it very difficult for cars to lean into tight turns or tilt forward to absorb some of the shock of a sudden stop.

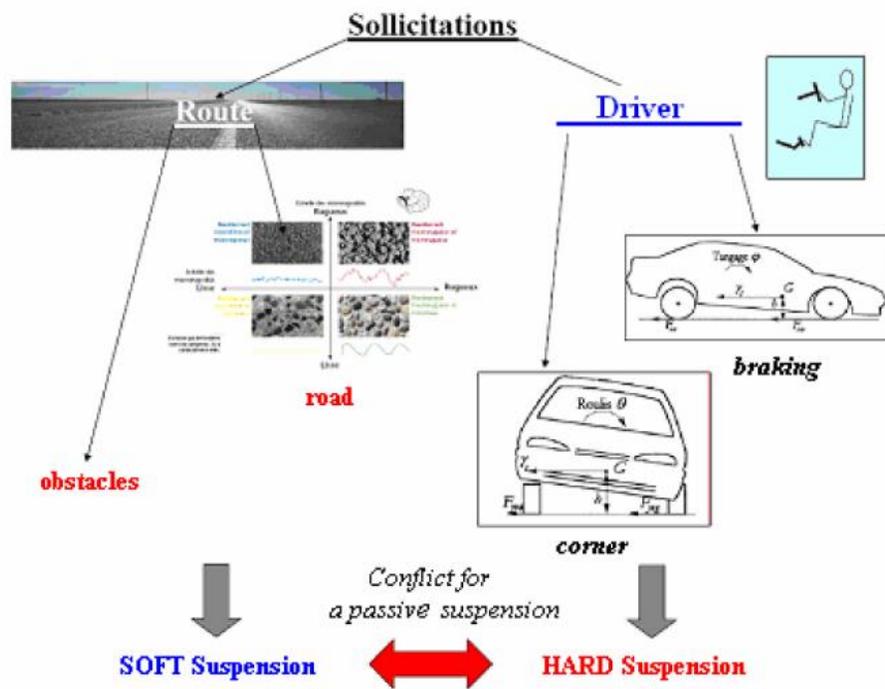
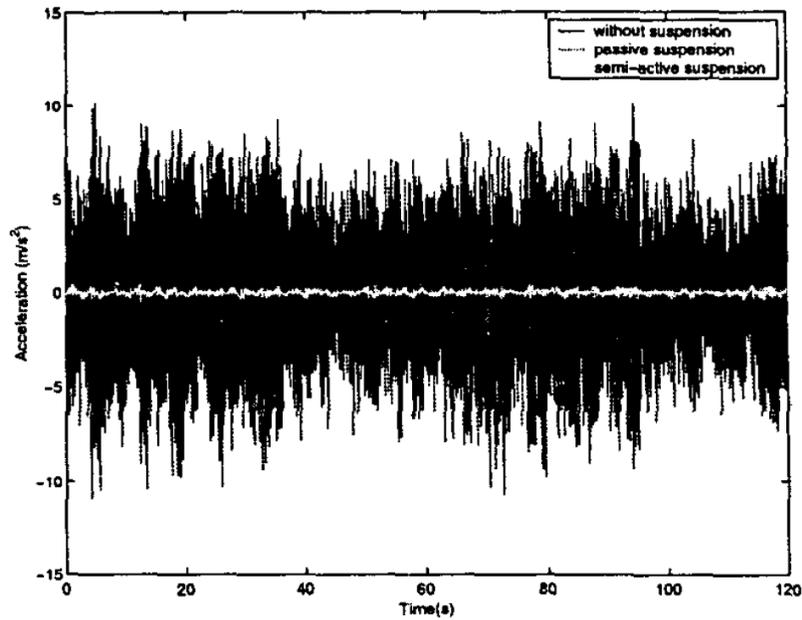


Figure 20 - Problems with Hard and Soft Suspensions [9]

### 2.3.9 Semi-Active Suspension

Semi-Active suspension is the next step up from passive suspension. It has been designed slightly differently so that it is able to encompass a wider range of input forces allowing the suspension to properly perform under more circumstances. The suspension is typically set up with two tolerance levels, unlike the one level in passive suspension. These tolerance levels work by having different dampening strengths applied to them to handle different levels of force. This way the first tolerance level will provide the dampening strength up until a certain amount of force is applied and then it will switch to the other dampening strength. Having two different dampening strengths is very useful. This allows for one of the dampening strengths to be set low to cover small forces and one high to cover large forces, instead of having to pick a dampening strength in the middle to cover everything. This suspension system is very commonly used for this reason, it allows for a much smoother ride than passive suspension or with no suspension, as can be seen below in Figure 21 and Table 2.



**Figure 21 - Graphical Comparison of Suspension Methods [4]**

The above graph shows the extreme difference different suspension types can make. The graph shows that there is some difference between no suspension and passive suspension. However, the striking difference is the change from no suspension or passive suspension to semi-active suspension. Here there is a very clear difference between the two, semi-active suspension being a drastic improvement.

**Table 2 - Displacement Values of Different Types of Suspension [4]**

input profile	suspension	VDV [ $m/s^{1.75}$ ]	effRMS [ $m/s^2$ ]
field(4km/h)	non	4.135	1.009
	passive	0.237	0.058
	semi-active	0.121	0.025
unpaved road (11km/h)	non	3.051	0.686
	passive	0.387	0.094
	semi-active	0.279	0.054
paved road (28km/h)	non	6.353	1.502
	passive	2.067	0.352
	semi-active	0.340	0.063

Table 2 shows the effects of the different suspension systems on different types of surfaces. They are also measured using two different methods, Vibration Dose Value and effRMS. The Vibration Does Value is calculated using the time exposed the number of vibrations and the acceleration of these vibrations. This equation for VDV can be seen below in Equations 1 and 2. The effRMS value is calculated independently of time and is used to give a general idea of the average acceleration per vibration. The equation for the effRMS can also be seen below in Equations 1 and 2.

$$VDV = \left[ \frac{T_s}{N} \sum_{n=1}^{n=N} a^4 \right]^{\frac{1}{4}}$$

**Equation 1 [4]**

$$effRMS = \left[ \frac{1}{N} \sum_{n=1}^{n=N} a^2 \right]^{\frac{1}{2}}$$

Equation 2 [4]

### 2.3.10 Active Suspension

The last hydropneumatic suspension option is active suspension. Active suspension provides the highest quality ride; however, it is also the most costly and therefore is rarely implemented especially in commercial vehicles. This is because while active suspension provides the greatest comfort, it is also very expensive. In most cases the semi-active suspension is able to provide the necessary suspension at a fraction of the cost. In active suspension, the dampening strength has many different tolerance levels allowing it to adapt much more easily to different forces than the other two types of suspension. Having all these different dampening strength levels though cause this technology to be rather expensive and it is not used very frequently since semi-active suspension is much less expensive and usually able to provide adequate ride comfort.

## **2.4 Heat Transfer Effects on Hydropneumatic Suspension Systems**

### **2.4.1 Introduction**

A hydropneumatic suspension system is a type of automotive suspension system. The purpose of his system is to provide superior ride quality. The way it works is a nitrogen reservoir with variable volume yields a spring with non-linear force-deflection characteristics. The actuation of the nitrogen spring reservoir is performed through an incompressible hydraulic fluid inside a suspension cylinder. By adjusting the filled fluid volume within the cylinder, a leveling functionality is implemented. The hydraulic fluid is used to convert the pressure into a force. The nitrogen gas as a spring medium is about six times more flexible than conventional steel, thus allowing the vehicle to cope with the extraordinary road irregularities. The system uses a pump from the engine to pressurize a fluid which then powers the brakes, suspension, and power steering.

### **2.4.2 Types of Modes**

One of the problems experienced on these types of systems is the effect of temperature change on the spring, thus resulting in variations in the spring rate and ride height. There are two types of heat transfer modes. The first is between the gas and its surroundings. The second is the transfer between the damper oil and the gas. Heat is built up and strongly impacted by the roughness of terrain, vehicle velocity, and damping levels. Heat generation in the damper causes a rise in gas temperature which has a harmful effect on the spring force characteristic. The nitrogen gas used as spring medium cannot be treated as an ideal gas under the pressures and temperatures found in hydropneumatic suspension systems. Most hydropneumatic suspension

systems incorporate the spring and damper into one unit for reasons of cost and packaging. This results in undesirable temperature effects causing variations in ride height and spring rate. Typically in hydropneumatic suspensions units, the average gas temperature varies between -20 and 200 degrees Celsius as gas pressure varies between 2 and 110 MPa. When pressures are higher than 30 MPa, large errors can result. The main cause of temperature effects in hydropneumatic suspension systems is the heat generated by the damper. The hydropneumatic suspension system is a better alternative than conventional coil, lead, and torsion bar suspension systems. This is because the use of a semi-active damping system may reduce the amount of heat build-up in the damper.

### **2.4.3 Heat Transfer of Gas and the Environment**

When gas is stored in a closed container and is being compressed, the volume decreases while pressure and temperature increase. Gas is allowed to expand, thus causing storage of energy. However energy is lost during this process because of the transfer of heat between gas and its surroundings. Low compression speeds allow for enough time for the heat transfer to occur and therefore the gas temperature stays constant, known as the isothermal characteristic. High speeds yield very little time for heat transfer causing a variation in gas temperature, known as the adiabatic characteristic. In between these speeds, the spring characteristic forms a loop which represents the energy loss in the cycle, usually due to friction and fluid losses. To describe the heat transfer between the gas and the environment a differential equation can be used in the form which is on the next page.

$$T^* = (T_1 - T_2)/x - (T_2/C_v)(dP/dT_g)^* v,$$

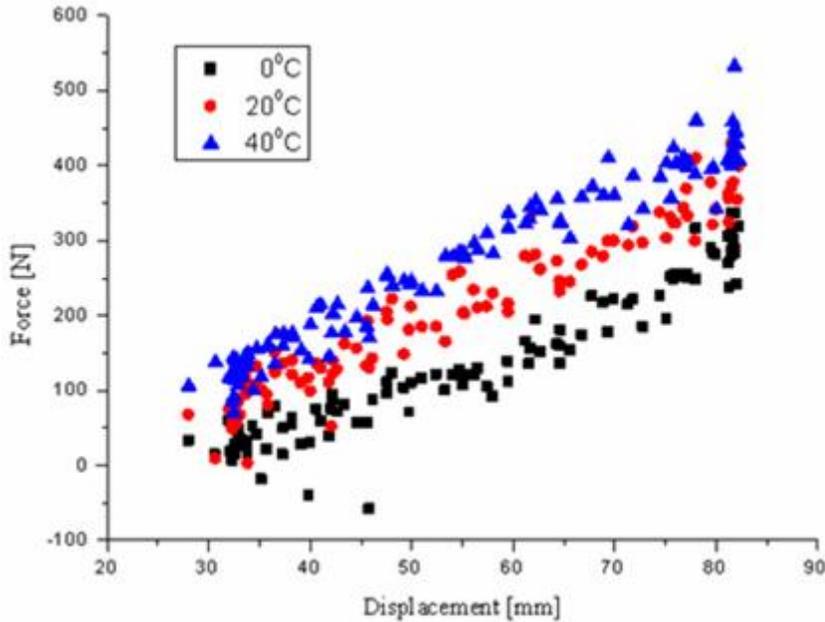
Where  $x = m_g C_v / h A_w = p C_v V / h A_w$  = thermal time constant,  $T^*$  = change in gas temp,  $T_1$  = ambient temperature,  $T_2$  = gas temperature,  $C_v$  = constant volume specific heat capacity of gas,  $P$  = gas pressure,  $V$  = change in specific volume of gas,  $M_g$  = gas mass,  $H$  = convection coefficient,  $A_w$  = wall area,  $p$  = gas density,  $T$  = gas temperature,  $V$  = gas volume

The thermal time constant varies during the cycle as the wall area varies due to piston motion. The time constant is defined as the time needed for the pressure, temperature, or force to decrease by 63% of the difference between the peak and final values. The convection coefficient also varies due to a change in speed of the gas over the inside surface of the cylinder. This equation can be used to predict spring the dynamic spring force.

#### 2.4.4 The Magneto-Rheological Accumulator:

A MR (magneto-rheological) accumulator can adjust the pressure of the gas chamber through the use of an MR device. It can effectively compensate for the pressure variations by an increase in the gas temperature. An accumulator is a device that is used in dampers and hydraulic pressure systems. Its purpose is to provide a volume for the hydraulic fluid, and to provide a pressure offset that prevents the low-pressure side of the piston assembly from forming “bubbles” in the hydraulic fluid. Accumulators maintain the initial pressure, keeping it relatively constant, with very small variations, even in the case of long strokes. The problem is that the gas pressure inside varies with temperature which alters the damping force thereby altering the damper performance. The new MR devices aim at compensating for temperature change by

supplying an additional force. Dampers used in vehicles today are affected by temperature changes that alter from -30 to 70 degrees Celsius. When temperature increases, pressure in the chamber increases which then increases the damping force. Figure 22 is a plot of force vs. displacement at different temperatures. In some cases the variation in temperature affects the performance of the damper, which affects the maximum damping force.



**Figure 22 - Plot of force vs displacement at varying temperatures**

The MR accumulator compensates for the variation in temperature. The Figure 23 is a schematic and free body diagram of the MR accumulator. The shaft is fixed to the piston. It is located at the side of the gas accumulator and consists of a bobbin and a flux return element, which MR fluid flows. An insulated wire around the bobbin creates a magnetic field as an input current is applied. The field increases the stress of the MR fluid that is between the bobbin and the flux return. Varying the stress creates a damping force due to fluid-flow resistance in the gap.

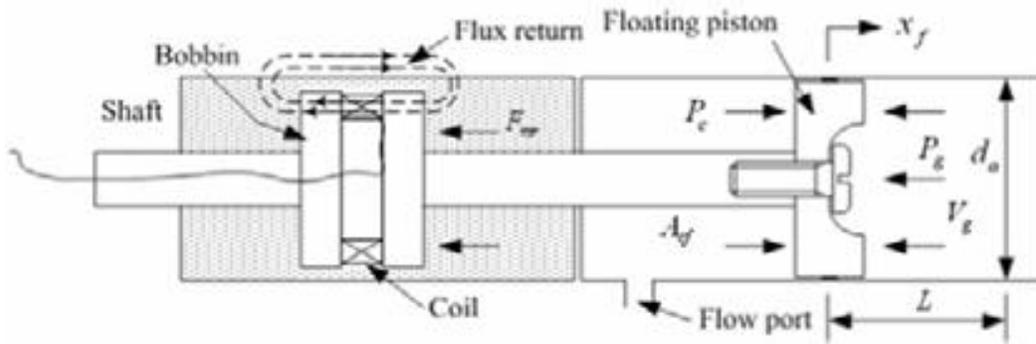


Figure 23 - The MR Accumulator [7]

Figure 24, 25, and 26 show the force vs. displacement plot of the MR device. From this figure, we can see that the force produced varies with the intensity of the magnetic field.

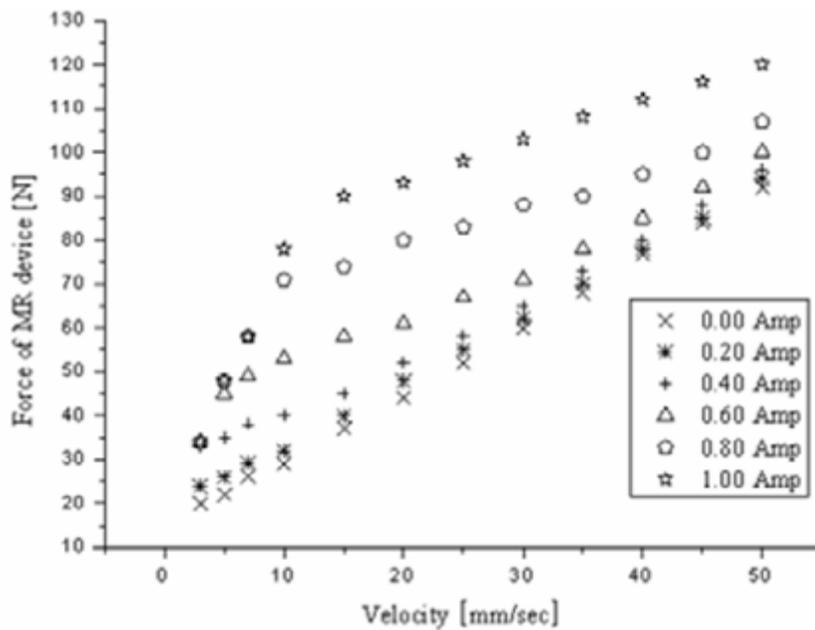


Figure 24 - Force vs. Displacement after the MR Accumulator is installed [7]

#### 2.4.5 Pressure and Force in Chamber:

A conventional damper consists of three pressure chambers. The gas chamber, known as the accumulator, consists of a compressible gas used as the springing medium. The gas chamber is separated from the compression chamber by the floating piston. In the compression and rebound chamber a hydraulic fluid is used to convert pressure to force. The accumulator accounts for the variation in volume caused by the rod insertion. There is a relationship between the accumulator force and displacement of the floating piston. The pressure in the gas chamber can be found by the following equations.

$$P_g(x_f) = P_{go} * (A_{float}L / A_{float}L - A_{rod}x_f)$$

$P_g$  is the gas pressure,  $P_{go}$  is the initial pressure,  $A_{float}$  is the area of the floating piston and  $L$  is the length of the chamber. If we multiply the pressure by the area of the piston we get the force produced in the gas chamber:

$$F_{gas}(x_f) = F_{go} (1 / (1 - (A_{rod}/A_{float}))) (x_f/L)$$

From a comparison in slopes of the graphs below, its evident that an MR device damper is more efficient than the conventional oil damper. Other advantages are that the pressure in the gas chamber can be adjusted, it compensates for the effect of temperature changes, and the damping force can be controlled which is extremely important because this affects the damping force.

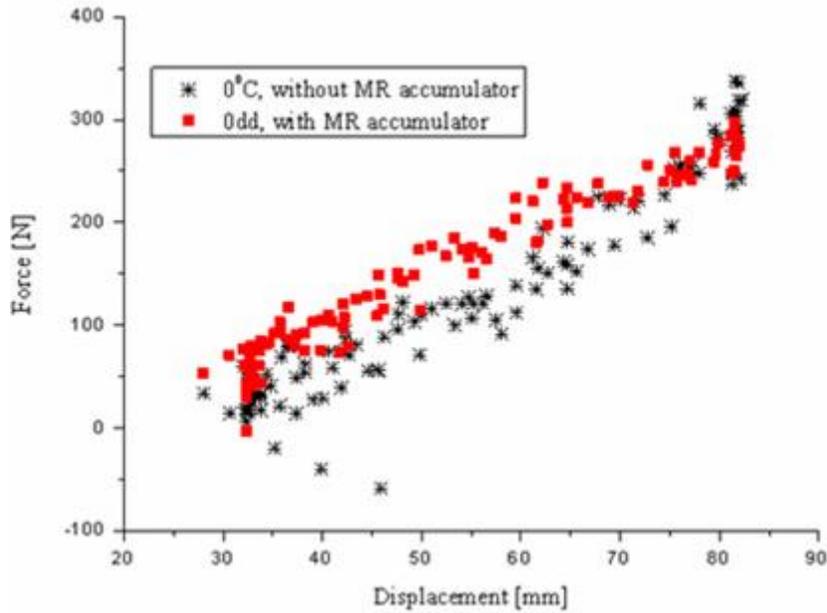


Figure 25 - Joined plots of with an without the MR accumulator [7]

The force vs. displacement curves for the MR vs no MR. The curves for damper that uses the MR accumulator are more intact because an additional force is supplied by the device.

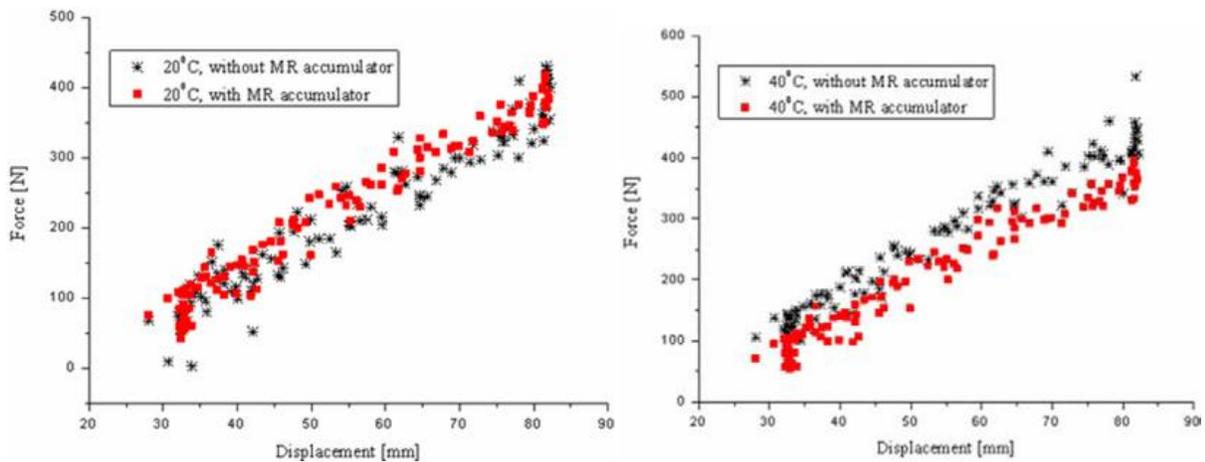


Figure 26 - Combined plots of with and without the MR Accumulator at two different temperatures 20 C (Top) 40 C (Bottom) [7]

The curve obtained from the conventional oil damper is compared with the curve obtained by the MR accumulator used with damper. As temperature increases from 20 to 40 degrees Celsius, its evident that the MR accumulator damping force is lower than that of the conventional oil damper. Therefore MR devices account for temperature changes.

#### 2.4.6 Effectiveness of Hydropneumatic Suspension:

The hydropneumatic suspension system is a very complex system with a few complicated ideas. The interaction between the chassis and the wheels and the solicitations which are heavily random pose two problems with this type of system. The purpose of this system is to isolate the vehicle body from the forces applied between the wheels and the roads and to keep the wheels in close contact with the road to enhance driving standards. Constraints involve workspace, maneuvering, and power consumption. Figure 27 shows how our suspension system will help reduce road vibrations under various conditions.

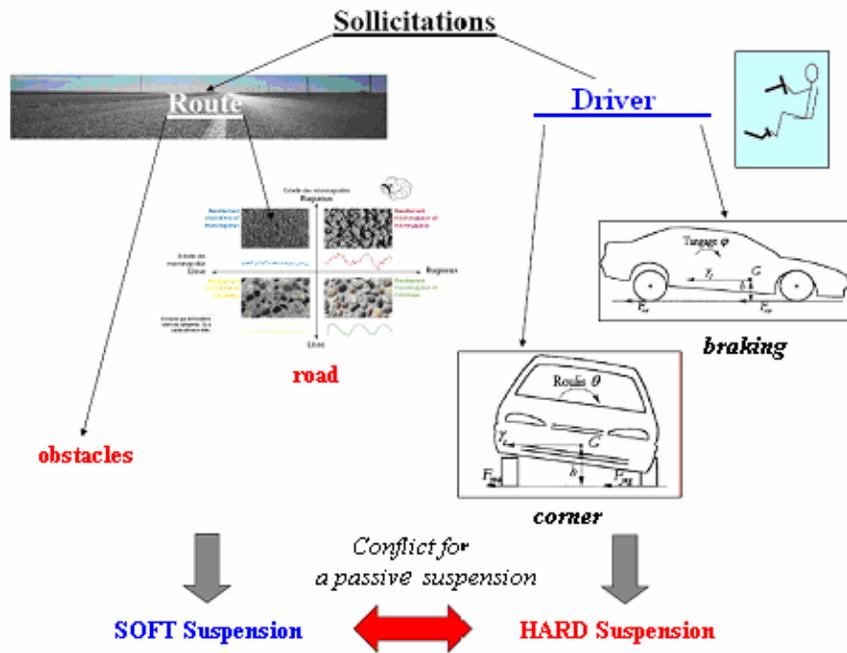
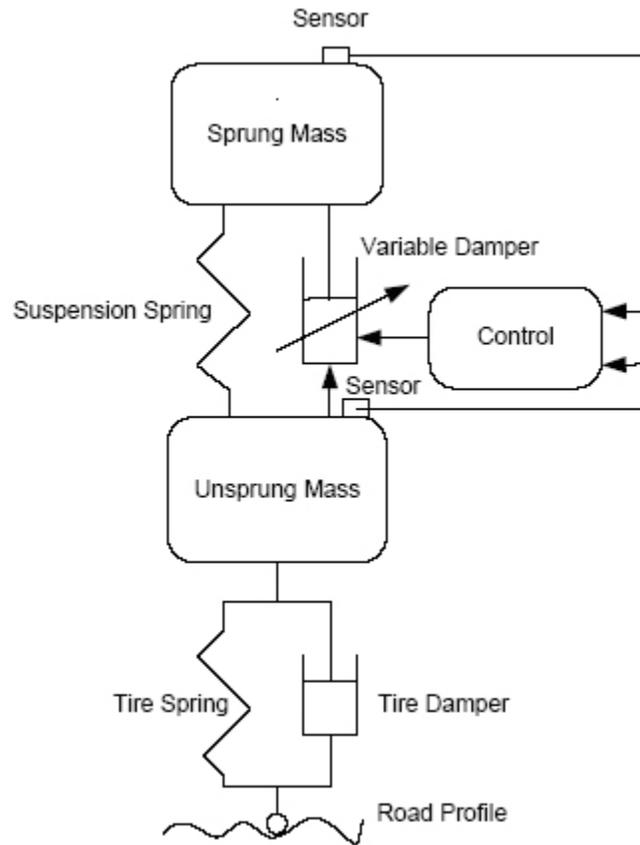


Figure 27 - Plot of varying driving conditions [9]

#### **2.4.7 Passive Suspension:**

Passive suspension consists of a damper, an energy dissipating element and an energy-storing element, which is the spring. Since these two elements can't add energy to the system this is called passive. The problem with passive systems is that it can't control all aspects of comfort and safety. Semi active systems allow for a controlled damper. Figure28 shows the composition of a semi active suspension strut. Multi-mode systems allow or control of the damper and the stiffness of the suspension. It focuses on both modes hard and soft. Ride comfort defines soft mode and sportsmanship defines hard mode. Hydropneumatic suspension allows for the implementation of this strategy. It is composed of one hydractive part (soft mode) which improves the isolation for the vehicle body and one low frequency active part, (hard mode) when action is taken on the steering wheel.



**Figure 28 - Diagram of a semiactive suspension system [9]**

## **Chapter 3. Product Design and Manufacturing**

### **3.1 Design process and Material Choice**

For our project we chose to use the knowledge that we gathered about suspension systems and applied it to designing a new system for ambulances. Through our research we decided upon using hydropneumatic suspension to replace the current leaf spring and /or coil system used in ambulances. We made this decision because our research showed that hydropneumatic suspension is likely to provide the most comfortable and safe ride for both patients and medical staff. To accomplish our goal we decided to design and manufacture a simple aftermarket bolt on

kit for ambulances. We decided to proceed in this way because a change to the suspension that will only be implemented during the manufacturing of ambulances would take some time to start benefitting people. Due to the fact that many ambulance companies will generally only replace their ambulances ever five years or so it would take a long time for the new design to penetrate the market. This is why we have decided on a bolt on aftermarket kit. This kit will be able to be added on to any current ambulance using the same mounting locations that are used by the traditional suspension. Since the switch to our aftermarket suspension kit does not require any major modifications or changes to the vehicle or its chassis the work can be done by the regular ambulance maintenance workers. Also because it is a bolt on kit it can be added to ambulances as they are being produced.

### **3.1.1 Linkages**

The first step in designing the kit was to decide what type of linkage would be used in the suspension and how to design the links. This is a complicated step, which involves careful calculations and analysis of movement. The first thing that must be considered when deciding what type of linkage to use and how to design the links is the forces that will be applied to it. The links must be designed in such a way that they are able to support the loads that will be applied to them so that they do not fail while in use. The strength of the links can be changed in several ways including; material type, size and shape of materials and the configuration of the links. The type of material can make an enormous difference in the strength of the links. Different types of metal and even variations within a type of metal or alloy can make an immense difference in strength and flexibility of the metal. This can be seen in Figure 29.

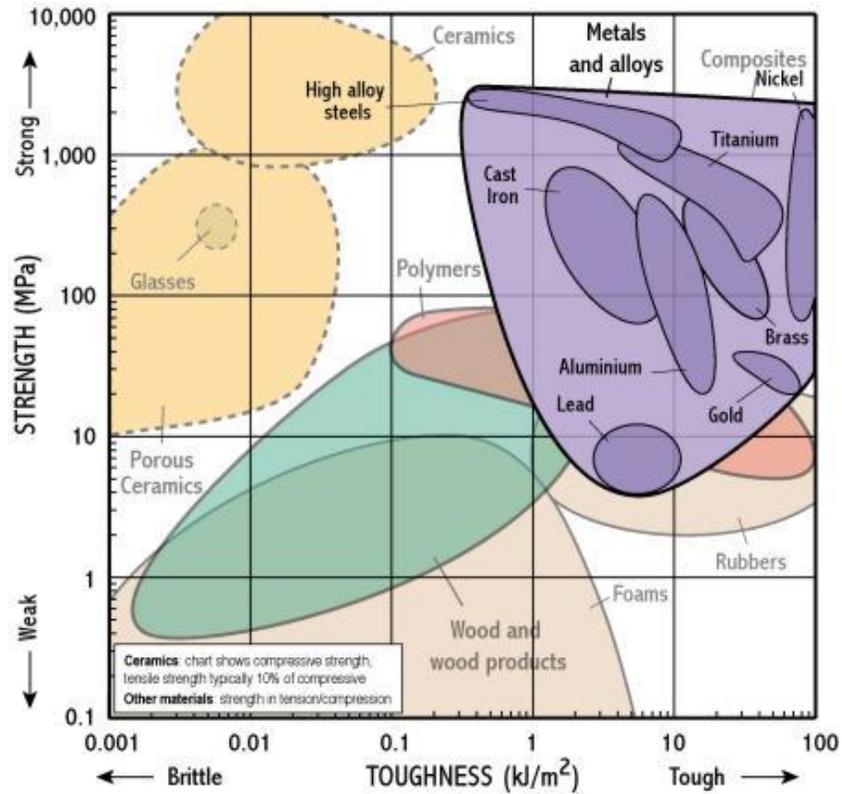


Figure 29 - Material Properties Chart ([materials.eng.cam.ac.uk](http://materials.eng.cam.ac.uk))

Due to the high forces that will be applied to the linkage during everyday use in an ambulance we chose to use 1025 Carbon Steel. This steel will provide a great deal of strength and is also rigid to prevent unwanted movement in our suspension components. The next aspect that must be taken into account is the size and shape of the metal that will be used. For this portion of the design process it was necessary for us to perform calculations for different type of tubing, square and round, for possibly use as the linkage bars. Based on our calculations we decided that it would be more beneficial for us to use round tubing. Once we had decided to use round tubing for the links we next needed to decide on the inner and outer diameter that should be used. To determine this we tested different nominal sizes for the pipes. We tested them using

the full amount of weight that the rear end of the ambulance could possibly apply to the bars if the hydropneumatic shock absorbers were to collapse.

$$\mathbf{Stress = \frac{Force}{Area}}$$

$$\mathbf{Force = 2500\ lbf}$$

$$\mathbf{Area = 1^2 * \pi - 0.75^2 * \pi = 1.37\ in^2}$$

$$\mathbf{Stress = \frac{2500\ lbf}{1.37\ in^2} = 1825\ psi}$$

We then compared the stress values that we calculated above to the known strength values of the steel type that we had selected for our design. For our design we chose to use 1025 Carbon Steel because it was one of the cost effective options with our limited budget, that was still able to provide the strength and rigidity required.

$$\mathbf{Tensile\ Strength\ of\ Steel\ Used = 60,000 - 103,000\ psi}$$

$$\mathbf{Shear\ Strength\ of\ Steel\ Used = 45,000 - 77,250\ psi}$$

As can be seen above the forces that could potentially be applied to the linkage arms are not high enough for failure to be a concern. The final step is to decide on the shape and type of the linkages. In this particular case the two options considered were a three or four bar linkage system as seen below in Figures 30 and 31.



Figure 30 - 3 Bar Suspension (Thirdgen.org)



Figure 31 - 4 Bar Suspension (Thirdgen.org)

In each case there are several things to consider. The main concerns are the strength and the path that the linkage travels through. For either case the linkage could be made strong enough so it came down to which would provide a straighter path of travel. Stuff about how it needs to go up and down and cannot move forward or back much because of the type of drive shaft. For this reason we chose to use a four bar linkage for the kit because of the straight movement that it can provide, seen in Figure 32.

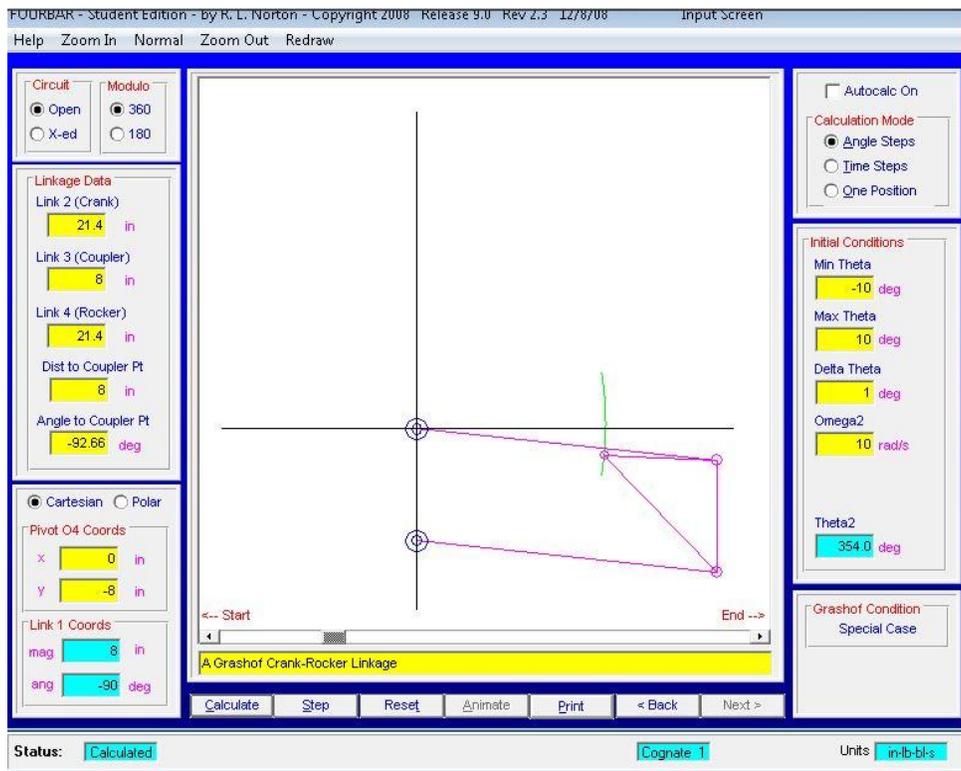


Figure 32 - FOURBAR Simulation

Once we established that we would use a four bar linkage for our suspension kit. We then needed to begin examining different possible configurations of four bar linkages. We have included several different iteration ideas that we examined before arriving at our final design.

### 3.1.2 Mounting Bracket Design

For the mounting bracket we chose to make use of the mounting location where the leaf springs were previously attached. We chose to do this because it requires less modification than alternatives. Instead of needing to put new holes in the chassis rail and potentially weaken the chassis, the stock leaf spring mount is removed and the same bolting holes are used by our bracket. If we utilize the stock leaf spring mount holes, this means less work for the installation of the kit and an easier job for the mechanic that would install the kit. Figure 33 shows the location and size of the stock leaf spring mount that would have to be removed in order to mount our kit.

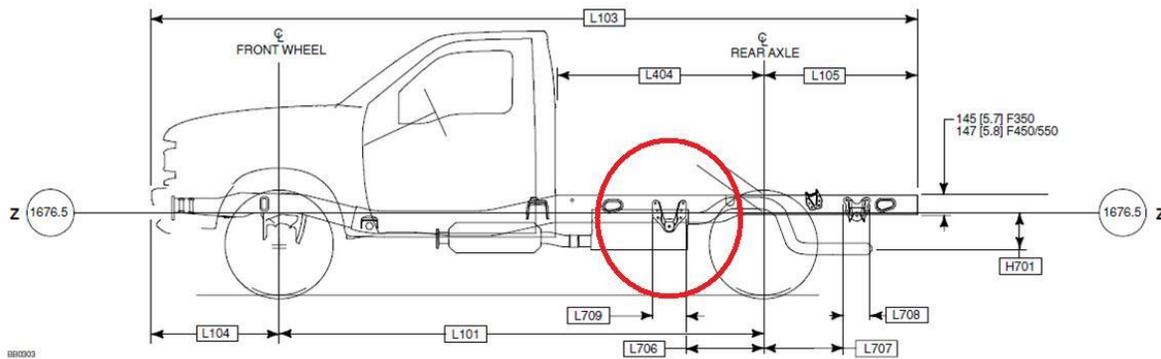


Figure 33 - Leaf Spring Mount Location (Fleet.ford.com)

The design of the bracket itself is very similar to the current bracket but it is much more robust to safely accommodate any additional weight the ambulance might possess versus a stock truck. We designed this bracket such that in the event that the hydropneumatic struts failed and the entire weight of the ambulance was placed on the brackets, they would still be able to hold the ambulance thus preventing a catastrophic failure. While the new leaf spring mounts are

larger and heavier than the previous leaf spring mounts, they are certainly more robust and as a final assembly, the kit is lighter than the components that would be removed. Figure 34 shows our final, constructed design for the front mounting brackets.



Figure 34 - Mounting Bracket

### 3.1.3 Axle Bracket Design

The bracket that mounts the linkage to the rear axle proved to be a difficult part to design. It needed to be strong enough to support the strong forces applied to it but also be designed in a way that remained as lightweight as possible. It also needed to be designed with places that extra securing brackets could be attached for heavier duty ambulances. In addition to this, when designing the bracket a great deal of thought needed to be put into the bolt hole locations that the linkage rods would attach to. If these holes had been made too far above or below the axle it would be possible the moment forces created by the axle movement might cause these joints to fail. This is why we chose to space the mounting holes out, one above and one below the axle in an attempt to cancel out as much of the moment forces as possible. Figure 35 displays a preliminary design for our axle bracket.

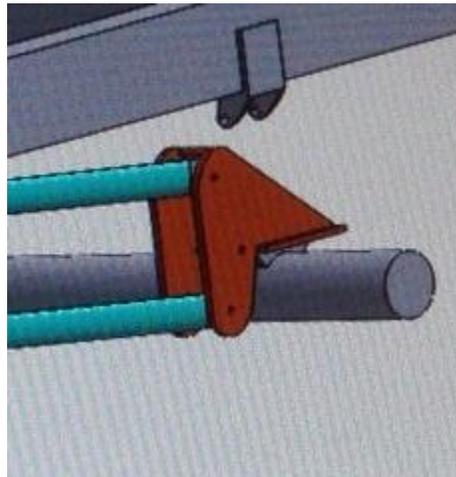


Figure 35 - Axle Bracket

### 3.1.4 Final Design

Our final design was one that incorporated both available space underneath the ambulance as well as minimal alteration or interference with other ambulance parts on or around the rear axle. To follow our design specifications, we created a kit that was completely bolt on and required absolutely no welding that would have to be done by the customer. Our final parts list for our rear suspension linkage can be seen Table 3:

**Table 3 - Final Design Components**

Part	Quantity
Replacement Mounting Brackets	2
"Horsehead" Axle Mounts	2
Schedule 80 Trailing Arms	4
Heim Joints	4
Bushings for Trailing Arms	8
1.5" OD Shank for Bushing	8

The mounting brackets, horsehead axle mounts, and trailing arms were constructed from  $\frac{3}{8}$ " hot rolled steel. The rest of the pieces were bought to complete the final design. To analyze our final product, we used SolidWorks Simulation Xpress to test whether or not the manufactured kit would deform under ambulance size loads. Figure 36 shows our front mount being analyzed in SolidWorks Simulation Xpress. For each component of our manufactured kit, we had a minimal safety factor of approximately 2.5 meaning we were well within the boundaries of creating a robust and durable after market kit for modifying an ambulance for hydropneumatic suspension.

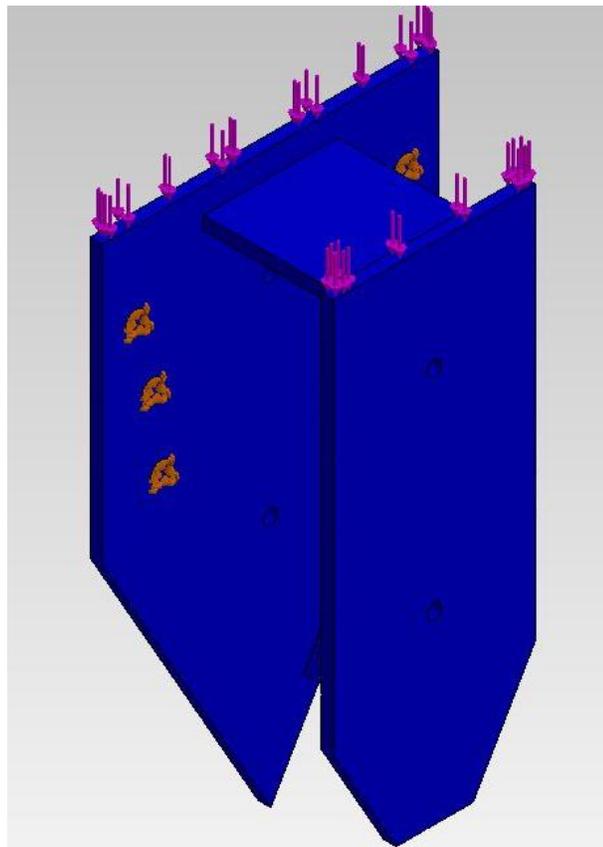


Figure 36 - Finite Element Analysis in SolidWorksSimulationXpress

### 3.1.5 Design Flaws

As with any design, there are areas that can be improved. Though we were able to investigate several different possibilities for the configuration of our linkage design, there are many more options that we were unable to explore. This is due to both time constraints as well as the limiting space in our F-350 chassis. For this reason we chose a parallelogram four bar linkage for use in our kit. This was not an ideal solution however, because while it does keep the rear axle from rotating while it travels up and down, it does create some back and forth movement in the axle. This is also not desirable because the drive shaft allows only very small front to back movements, but it was determined that our design fell within its driveshaft compliance. It is possible that in other vehicles there might be more space for the linkage and therefore a better design that allows for non-rotational vertical movement may be possible.

## 3.2 Manufacturing

We chose sheet metal welding and fabrication as our primary manufacturing process. As we calculated in previous pages, we had to choose proper material grades, thicknesses, and material composition which would have a large enough safety factor for our application. We found that using 3/8 inch steel plate and schedule 80 tubing; we had a minimum safety factor of 2.5 which translates to the fact that our product will be more than strong enough for our application. When ordering our materials, we made sure to order all pieces cut down to relative size from the sheet metal retailer, which would ensure straight edges, and speed up our manufacturing process by eliminating cutting and measuring time. The material ordered is as follows:

- 4 pcs of 12x11
- 2 pcs of 7x6
- 2 pcs of 6 x 15
- 2 pcs of 10x17
- 8 pcs of 4 x 4
- One 10 ft section 1.5 ID Schedule 80 steel pipe (approx. 0.25 inch wall thickness and 2 in OD)

### 3.2.1 Transposing Dimensions

To manufacture our kit entirely using the welding and fabrication process without forgings or steel stampings; each side wall, cover, etc. was cut out by hand via plasma cutter. The dimensions found within our SolidWorks model would have to be transposed to the steel plates. We used speed squares, vernier calipers, tape measurers and chalk to sketch out the proper dimensions, which can be seen in Figures 37 and 38. To ensure that our measuring tools were banking off straight surfaces, we always made sure to measure from factory cut edges.



Figure 37 - Transposing Dimensions



Figure 38 - Axle mount bracket pre-cutout

### 3.2.2 Cut Out

Once all of the parts were sketched onto their corresponding steel plate, they were then cut out via a Hypertherm plasma cutter which can be seen in Figure 39.



Figure 39 -Hypertherm 220V 85 Amp Plasma Cutter ([Hypertherm.com](http://Hypertherm.com))

Figure 40 demonstrates the cut quality of most plasma cutters. As you can see, although using a plasma cutter free hand is quick and relatively easy, it often leaves an abrasive edge, and slag from the cutting process.



Figure 40 -Plasma cutter cut quality

Because our plasma cutter left similar abrasive edges and slag, all of our pieces were hand ground using Milwaukee 4 ½ inch hand grinders which can be seen in the following figure. In addition to the slag and abrasive edges, it is also common to get uneven geometries because the plasma torch is guided free hand. This was because we did not have access to a robotic plasma cutter. So during the manufacturing process, we made sure to cut the pieces larger than the chalk drawn dimensions. This allowed for us to grind our pieces down to the correct size which was displayed by the chalk lines. The grinding process and representation of our before and after cut out can be seen in Figure 41, 42 and 43.



Figure 41 - Hand grinding steel plates to spec



Figure 42 - plates cut and within tolerance



Figure 43 - More plates within tolerance and holes drilled

### 3.2.3 Welding

Once all of the individual pieces were cut, ground, and toleranced, we were able to initiate the welding process, which was completed with a Miller 220V MIG welder with Argon gas as seen in Figures 44 and 45.



Figure 44 - Welding front mounting brackets



Figure 45 - Miller 220V MIG welder

### 3.2.4 Trailing Arm Manufacturing

The trailing arms were made using a slightly different process and required more attention. The trailing arms require a process called fish mouthing. It cuts a perpendicular radius in the end of one pipe which allows for two tubes to be welded perpendicularly to one another, which was necessary for our application. Figure 46 displays the fish mouthing process.

On the opposite end we had to adapt a 2 inch OD tube to a 3/4 -16 thread heim joint. This was done using a part called a weld bung. The fish mouthing process, as well as a Heim joint and weld bung can be seen in the Figures 46 and 47. Figure 48 shows our Trailing arm production 50% complete. Figure 49 shows all manufactured components assembled for prototype representation.



Figure 46 - Fish Mouthing



Figure 47 - Heim Joints and Weld in Threaded Bungs (Speedwaymotors.com)

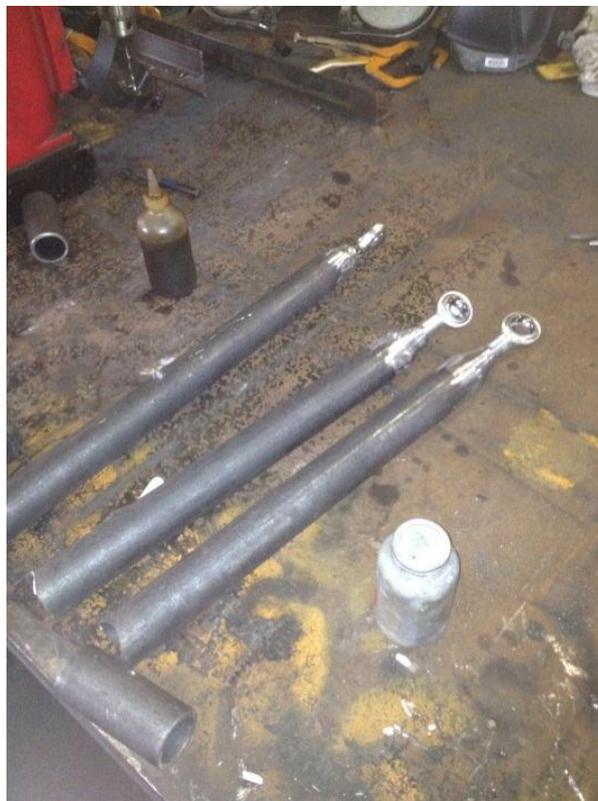


Figure 48 - Trailing arm construction



Figure 49 - Completed prototype (Passenger side)

### 3.2.5 Finishing Process

We chose powder coat as our final surface finishing process. Powder coating is a process which the desired part is grounded to the powder coat machine, and the colored powder has a positive charge applied to it. When sprayed, the powder attaches itself to the grounded part. When the part(s) are covered in powder, the part is then baked to a given temperature for a specified period of time, and the powder melts into a smooth and extremely durable finish.

We chose a gloss black finish so that our suspension kit would be inconspicuous underneath the ambulance, and look like a factory product. Within the same alloy family, there are two kinds of steel stock that can be purchased with the difference being in how it is made; cold rolled steel and hot rolled steel. Because our steel pieces were hot rolled steel as opposed to cold rolled, mill scale had to be removed via sandblaster. Cold rolled steel is notably cleaner than hot rolled, the difference can be seen below. The steel surface needs to be clean in order for the powder to properly adhere to the surface. The sand blasted parts can be seen in the Figure 50, as well as a cold rolled/ hot rolled steel comparison in Figure 51.



Figure 50 - Parts After Sandblasting



Figure 51 - Hot Rolled Steel on Left, Cold Rolled Steel on Right

When the steel was cleaned, we suspended the parts with steel hooks, which is a non-invasive way of being able to spray the entire part while simultaneously being grounded. After the parts were sprayed, they were put in the oven to be baked at 392 degrees F for 10 minutes. It is imperative that the parts themselves (not just the ambient air around them) reach 392 degrees for the entire 10 min or the powder coat will not adhere correctly and will most likely flake off. The completed finishing process can be seen below. Figure 52 and 53 shows our finished parts cooling after the powder coat process.



Figure 52 - Axle Mount and Trailing Arms After Powdercoat



Figure 53 - Front Mounting Brackets After Powdercoat



Figure 54 - MQP presentation day

## Chapter 4. Conclusion

### 4.1 Project Summary

We were given the task of reducing road vibrations in ambulances. Using a Ford F350 donated by Autotronics, we analyzed all of the possible areas for improvement to accomplish this task. After eliminating vehicle weight and chassis redesign, we landed on the reconstruction of the ambulances suspension system. The current suspension system in almost all ambulances is comprised of two parallel leaf spring packs and corresponding shock absorbers. In some cases the shock absorbers are replaced with air bags. This current system takes vibrations from the road, and transmits them into the ambulance chassis, and therefore the passenger compartment. These transferred road vibrations have been proven to cause or worsen patient and EMT injuries.

After analyzing several suspension systems, we decided to expand our research on hydropneumatic suspension. This suspension system, as explained on previous pages, literally simulates the situation of riding on air, because pockets of gas take the place of mechanical springs. Since hydropneumatic suspension has gone through several proofs of concept including real world production applications, we decided to create a kit to modify our F350 to incorporate this type of suspension system. Most important of the proof of concepts, is in its application of high speed military tanks and agricultural tractors which both compare and exceed the weight of our ambulance. Our kit needed to be designed in a manner which could be installed completely by bolt on techniques, (i.e. No welding or fabrication required). This was necessary because the kit would be installed by standard automotive technicians employed by the ambulance companies who are not required to be certified welders.

Using engineering design tools such as SolidWorks and FOURBAR software, we came up with preliminary and final designs which we performed finite element analysis on to see if our designs could withstand a certain range of forces. We found that the weakest area of our design could withstand more than 2.5 times the weight of our ambulance which is a safety factor much higher than required. When we solidified this design, we manufactured our suspension system using welding and fabrication techniques, and finished it in gloss black powder coat for durability.

## 4.2 Considerations and Difficulties

The efficiency of EMTs and paramedics to perform their tasks is a key element in patient care. If EMT's are hindered or distracted by any means, it could be potentially life threatening to the patient and EMT alike. Since the purpose of an ambulance is to transport patients from the scene of a trauma to a hospital, the patient more often than not requires care during transportation. Because of the current ambulances suspension systems, the ambulance's passenger compartment has a lot of transmitted road vibrations. This forces EMT's to provide care in almost earthquake like conditions. As you could imagine, this is quite a distraction, and can prove to be very dangerous for everyone from all parties. To address this situation, Ambulance drivers often have to reduce speed and thus sacrifice time in a very time dependent situation. Ambulance drivers need to be able to take the fastest route to the hospital, at the fastest possible speeds regardless of road conditions. Hydropneumatic suspension will allow this need and eliminate any sacrifices in speed or time avoiding poor road conditions.

Other attempts have been made by companies to reduce road vibrations but have all fallen short of substantially reducing road vibrations. Such attempts include air bag suspension and rubber leaf spring shackles. Although these attempts theoretically stab at reducing vibrations, they do not eliminate the cause which is the heavy duty leaf spring packs. These steel springs are the source of the high and fluctuating spring rate which fails to dampen or efficiently redirect the road vibrations. Coupled with this, air ride suspension has been known for premature failure as well as cracking the ambulance frames.

Although our suspension system and concepts for installation are not necessarily innovative, the idea of adapting hydropneumatic suspension into a heavy duty ambulance is a new concept. In addition, our entirely bolt on kit is also innovative for 4 link suspensions of this type. Some things to consider when changing our ambulance suspension are the conditions and regulations set by state and federal governments. Regulations included the categories of ride height, vehicle weight, and performance specifications. The final product being installed in ambulances would have to abide by all of these regulations, in order to be sold as a kit for ambulances. Another upside to hydropneumatic suspension is that due to its pressurized hydraulics, it allows for the adjustment of various ride heights, so with careful planning, it should be very easy to accommodate at least this regulation set forth by the KKK ambulance standards.

Our solution has addressed the given problem and our primary and secondary objectives by developing a suspension system capable of improving the quality of care in regards to EMT staff by reducing road vibrations. In addition to addressing these issues, our kit will successfully be able to be installed by any mechanic without specialized training which saves time and money.

### 4.3 Future Work

Although our team worked diligently over the course of an entire academic year, we have enough future work to develop this into a future MQP. Most of this work will include the design and development of hydropneumatic struts. Eventually implementation and official testing will also need to be implemented in regards to our donated ambulance. Our team worked very hard on getting hydropneumatic struts donated in order to cut down design and manufacture time and costs, but lost contact with company representatives.

We had found it more important to design and manufacture a suitable suspension linkage system to give the next group at least a solid foundation to build off for further execution of this project.

In addition, some more items will need to be manufactured, even though the basic designs have been taken care of, they will need to be confirmed upon development of the hydropneumatic struts. Such parts will include mounting brackets and locations for the struts, as well as a suitable panhard bar. The panhard bar is needed to eliminate side to side movement of the axle.

## 5. Works Cited

- [1] Axelsson, Jakob and Leif Lundahl. Hydropneumatic Suspension Unit. Cleveland, OH: Patent 475,930. 17 December 2009.
- [2] Barris, Richard A. Vehicle Suspension Systems. Peoria, IL: Patent 3,168,302. 2 February 1965.
- [3] Cao, Dongpu, Subhash Rakheja and Chun-Yi Su. "Optimal Damping Design of Heavy Vehicle with Interconnected Hydro-Pneumatic Suspension." SAE Technical Paper Series (2007): 1-7.
- [4] Capgras, Rene. Hydropneumatic Suspension. Paris, France: Patent 3,516,683. 23 June 1970.
- [5] Deprez, K, K. Maetens and H. Ramon. "Comfort Improvement by Passive and Semi-Active Hydropneumatic Suspension Using Global Optimization Technique." American Control Conference. Anchorage, AK: Laboratory for Agro-Machinery and Processing, 2002. 1497-1501.
- [6] El-Demerdash, S. M. "Improvement of Trucks Ride Dynamics Using A Hydraulic Semi-Active Suspension System." Truck Vehicle Dynamics & Suspensions (2002): 1728-1739.
- [7] Els, P. S. and B. Grobbelaar. "Heat Transfer Effects on Hydropneumatic Suspension Systems." Journal of Terramechanics (1999): 197-205.
- [8] Elser, Dieter, et al. Hydropneumatic Suspension System. Essingen, Germany: Patent 6,669,216. 30 December 2003.

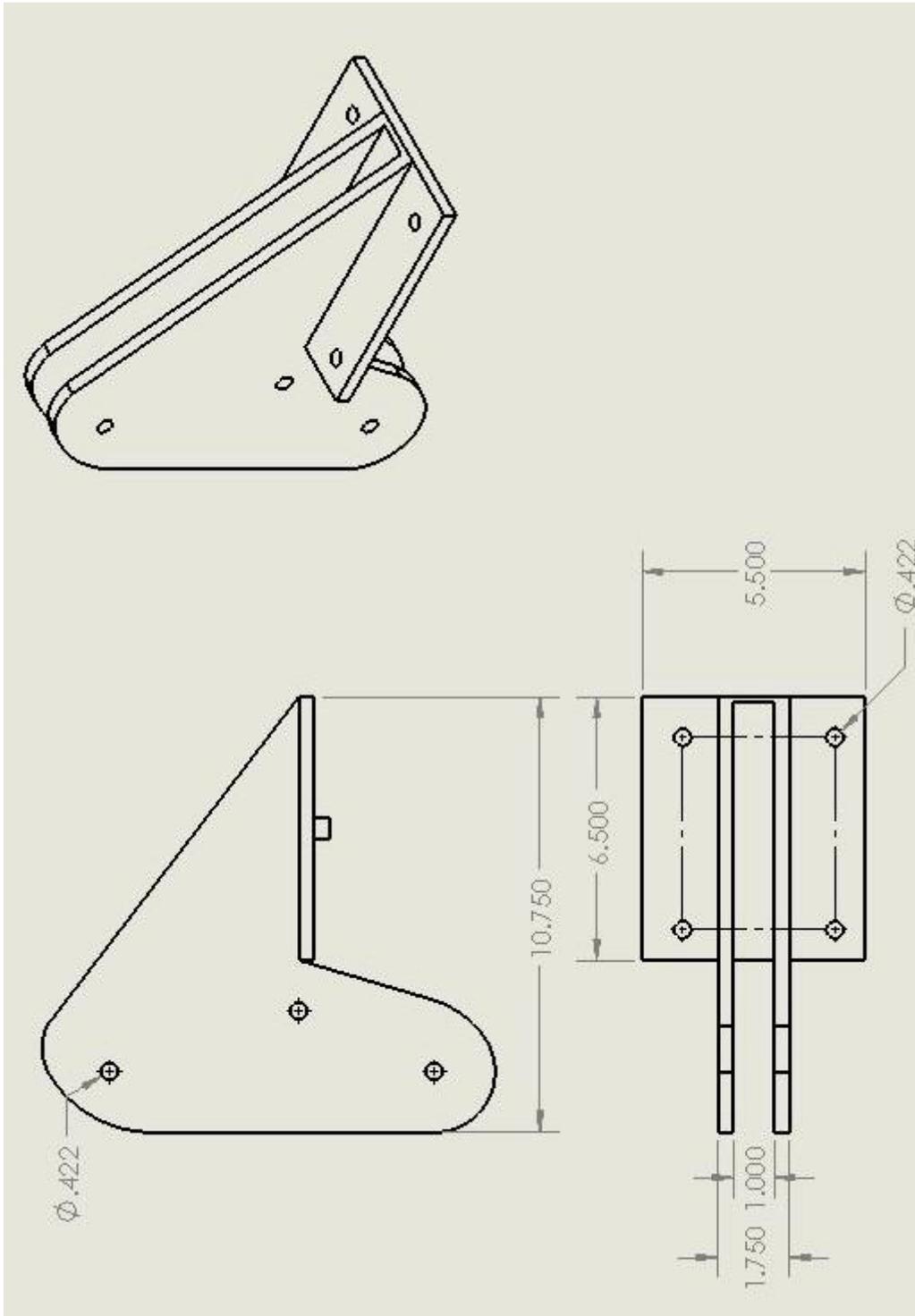
- [9] Ibrahim, I. M., M. O. A. Mokhtar and A. M. El-Butch. "New Suspension Design for Heavy Duty Trucks: Design Considerations." Vehicle Dynamics, Braking, Steering and Suspensions (2003): 1814-1823.
- [10] Marsh, Julian. Citroenet. 18 April 2011. 16 September 2011 <<http://www.citroenet.org.uk>>.
- [11] Moreau, Xavier, et al. "Improvement of Hydractive Suspension Hard Mode Confort Thanks To A Low Frequency Active Crone System." ASME 2009 International Design Engineering [12] Technical Conferences & Computers and Information in Engineering Conference. San Diego, CA: American Society of Mechanical Engineers, 2009. 1-10.
- [13] Nastasic, Zeljko and Gabor Deak Jahn. "The Citroen Technical Guide." 5 June 2003. Citroen BX Do-It-Yourself. 31 January 2012 <<http://citroen.tramontana.co.hu/technical-guide>>.
- [14] Oustaloup, A., X. Moreau and M. Nouillant. "The Crone Suspension." Control Engineering Practice (1996): 1101-1108.
- [15] Rizzo, Audrey, et al. "A New Crone Suspension: More Compact & More Efficient." ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. San Diego, CA: American Society of Mechanical Engineers, 2009. 1-8.
- [16] Ruhl, John H. and Robert H. Wahl. Hydropneumatic Suspension. Dearborn, MI: Patent 3,032,350. 1 May 1962.
- [17] Seo, Jeong-Uk, Young-Won Yun and Myeong-Kwan Park. "Magneto-rheological Accumulator for Temperature Compensation in Hydropneumatic Suspension Systems." Journal of Mechanical Science and Technology (2011): 1621-1625.

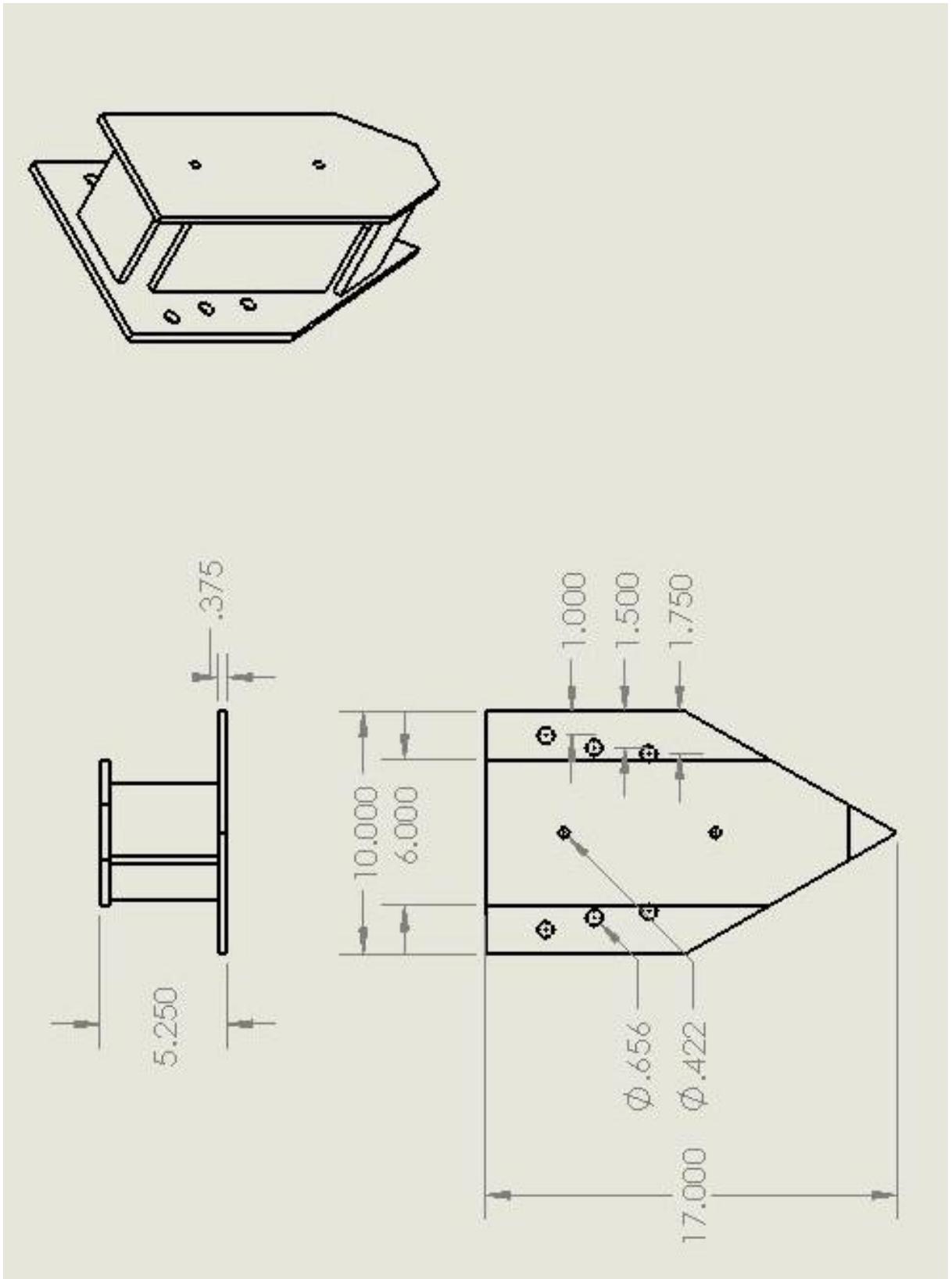
[18] Soliman, A. M. A., Y. A. El-Mashed S. A. Abd Alla and M. S. A. Hamid. "Improvement of Vehicle Ride Performance Using a Hydro-pneumatic Active Suspension System." Human Factors in Driving and Automotive Telematics and Seat Comfort (2006): 1992-2002.

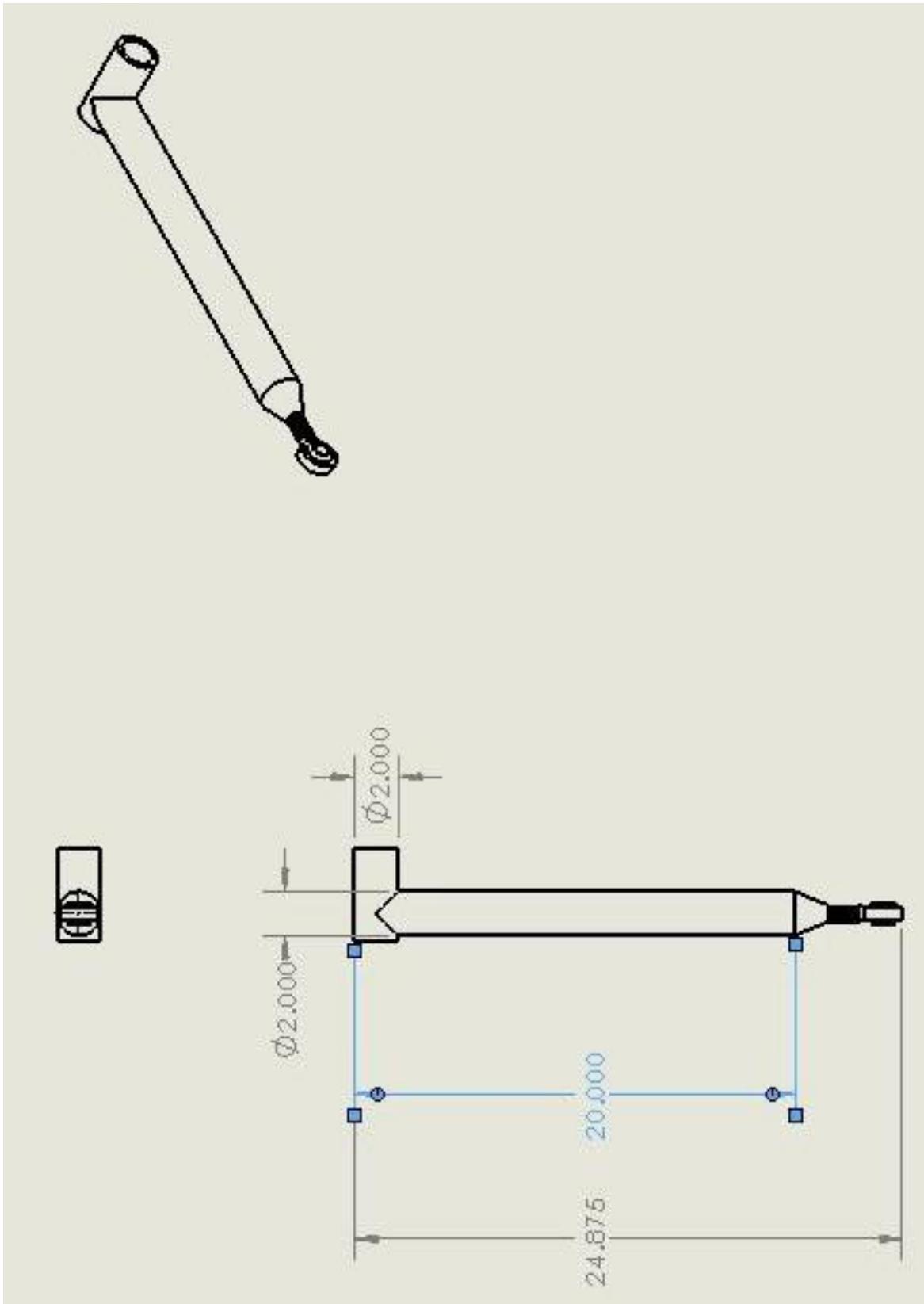
[19] Wan, Mark. Handling-Cornering Speed. 2 February 2000. 29 November 2011 <<http://www.autozine.org>>.

## 6. Appendices

The following three figures are our engineering drawings that we referred to during our manufacturing process.







The following figures were gathered from Professor Paul Cotnoir's Master's Thesis data. These figures helped guide our idea of the vibrations we aimed to suppress via a re-designed suspension system. While we did not explicitly reference them in our report, they were vital in our understanding of what we would be dealing with for ambulance vibrations. The data for these figures was gathered over a period of a few days in 2009 using four different ambulances as well as ambulance crews. The vibration data was gathered from four types of roads. These road types were:

"Unpaved" which obviously had the worst vibrations out of all four road types.

"City" which was far better than the unpaved road, yet it was still the third worst road type out of the four road types.

"Secondary" which are usually in better condition than city roads, thus they scored slightly better than the city roads in vibration measurements.

"Highway" which is understandably the smoothest road surface due to the high speeds at which they are used.

These tests were also conducted at different speeds to test whether or not the vibrations were primarily caused by road conditions and type or by speed. The results from the different speed tests were not surprising. The slower speeds had smaller vibrations than the greater speeds because the ambulance was able to better absorb the road surface at slower speeds.

