SCHOOL OF SCIENCE AND ENGINEERING

COMPRESSED AIR GENERATION
FROM VEHICLE SUSPENSION
COMPRESSED AIR GENERATION FROM VEHICLE SUSPENSION
COMPRESSED AIR
GENERATION FROM VEHICLE
SUSPENSION

Capstone report

Student Statement:

“I, Younes Skandre, declare that I have applied ethics to the design process and in the selection of the final proposed design. And that, I have held the safety of the public to be paramount and have addressed this in the presented design wherever may be applicable.”

Younes Skandre

Approved by the Supervisor

Dr. Anas Bentamy
ACKNOWLEDGEMENTS

First, I would like to thank Dr. Anas Bentamy for accepting to be my supervisor in my capstone project, which is the encapsulation of all the knowledge and abilities acquired during my entire academic curriculum. I would like to thank him for always making time to meet me and discuss any issue concerning my project.

I would also like to thank all the instructors that I encountered during my year in the university of Florida Institute of Technology and especially my professors at AUI, who made me the scholar I am today.

Finally, I would like to thank my mother, who has always supported me in any endeavor I undertook either mentally or financially. In addition, I would like to dedicate a special mention to my friends here at AUI, who always supported me, motivated me and even helped me complete work, namely Ayman Sallak and Taha Yassine Samir.
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Abstract

Tires are the most important parts of a vehicle that insure its safety and stability. In a questionnaire administered to drivers in the region of Sekondi-Takoradi, more than 33% of drivers think that their tire failure problems are mainly caused by under-inflation [2]. These numbers indicate that a major solution needs to be issued to, at least, reduce this percentage. Therefore, the proposed design configuration of a typical passive suspension comes in handy; it relieves car users from the burden of checking tires in a gas station regularly. The process goes through multiple actions that consist of generating compressed air with the mechanical actions of a piston inside a cylinder, then store the compressed air in a tank that later fills the tires with the needed amount of compressed air when the vehicle is not moving. The main test of the project is to come up with design of a compact and integrated compressor within the vehicle’s suspension without altering the normal functioning of the suspension. This system is designated to be part of the assembly of the vehicle to ensure the functionality of the system and its reliability.
Résumé

Les pneus d’un véhicule sont cruciaux à la sécurité et la stabilité de la voiture. Dans un questionnaire administré aux conducteurs de la région de Sekonli-Takoradi, plus de 33% des conducteurs pensent que les dégâts que subissent leurs pneus sont dus à une sous pression de ces derniers. Ces nombres indiquent qu’une solution majeure se doit d’être produite ou au moins de réduire ce nombre. Conséquemment, le design de suspension proposé répond à cette demande offrant un produit qui maintient la pression des pneus dans la normale. Le TPRS est un système intégré qui mesure régulièrement la pression des pneus et dépendant des résultats de ces derniers informe le conducteur afin d’utiliser l’air comprime se trouvant dans le réservoir.

Ce projet consiste en partie majeur à concevoir des amortisseurs compacts intégrant un compresseur sans altérer le fonctionnement normal de la suspension. Le système est conçu d’une manière à ce qu’il soit intégré dans les véhicules produits dans les années à venir.
1. Introduction

1.1. Problem statement
Tire disablement is considered a major cause of accidents worldwide. Tire failure induces a loss of control over the vehicle, which mainly leads to accidents in the highways. A tire under-inflation is one of the biggest factors that lead to tire failure [3]; since the air pressure inside a tire is what carries the weight of the vehicle, any form of pressure loss can cause the tire to deform, hence, weaken and fail. Therefore, starting in 2007 it was mandatory for all road vehicles to adopt the Tire Pressure Monitoring System (TPMS). [1] However, this system only warns the driver when the tire is in a crisis. In addition, since these under-inflations can occur in a highway or somewhere it is hard for the driver to consult any air station, the optimal solution would suggest having an instant recovery system for any pressure loss in the vehicle’s tires. [2]

1.2. Project description
The proposed solution is to produce a new design for cars’ shock absorbers that would help car users get access to tires pumping machine without having the need to stop by a car station. The new design would have the function of conserving the compressed air produced by the product in a tank equipped to the car. The product’s efficiency relies in the minimized time it takes on the road for it to fill completely. The tank then respectively provides the tires with the air needed when the vehicle is in a static position. The idea comes from the translation movement that the shock absorbers perform when the car is driven, so it can make a compressor produce compressed air. The compressed air can then be used to pump car tires that are depressurized. This system will use the information generated from the sensors of the TPMS that indicates the pressure inside the tire, then warn the driver to stop the car and proceed with connecting the tires to the compressed air tank. The information provided by
the TPMS will constantly help the driver regulate the tire pressure before it reaches any dangerous situation.

1.3. **Methodology**

The project will adopt a structured methodology to ensure quality and delivery time of the product. The use of the literature study will include a research of the related works such as the TPMS and the current state-of-the-art, and investigate the physical properties of the product and identify the variables and the relationships between the variables. The first phase would be the analysis of the different quantities that go with the product. The second phase is the design of the optimized shock absorbers that ideally would fit most car models. The third and last part is the implementation of the sensors and digital circuit controlling the system and the testing of resistance of materials used in the design. Additionally, the proposed timetable for the project would split the three main objectives based on their importance and load of work: Analysis (5 weeks), Design (2 to 3 weeks) and Implementation and Testing (3 to 4 weeks). However, since the time period of the project is relatively short (one semester), the minimum outcome would be to realize the full analysis and design of the product, which can be used to manufacture the shock absorbers. The implementation, which is still extremely important to the project, can be illustrated using models to be implemented later on. In addition, the testing and simulation are a major part that are comprised within the minimum subset of the objectives. Regarding the societal and ethical implications of the work performed, the project targets the new wave of eco-friendly technologies since under inflated tires increase fuel consumption. The product is also economically competitive by its technological advancement that appeals to prospective car buyers because of that societal trend towards more sophisticated systems.
2. Literature review

2.1. Related Works

2.1.1. Suspension System

The main function of a suspension system in a vehicle is to absorb or damp out all the vibration transmitted from the road to the vehicle’s body through the wheels’ vertical movement. The suspension system consists of four main components: sprung mass, or quarter the car body, unsprung mass (wheels), springs, and dampers. The road irregularities act on the wheels and create displacement input on the level of the wheels. The vibration motions get transmitted from the wheels to the car body following a certain frequency. The suspension system components such as the springs and dampers filter the vibrations between the wheels and the car body to prevent the motion from acting upon the car body, and to also prevent the wheels from losing contact with the road for an optimal driving situation.[4]

There are three types of suspension systems that are classified as passive, semi-active, and active suspension systems. The passive suspension is widely used for the majority of commercial cars since it has a high market value. The damping force in this case is tuned to a constant value. The semi-active suspension relies on the road input to calculate a better isolation value for the vibration of the wheels by linking the change of the damping force to the road profile. As for the active suspension system, the components apply an opposite force from the actuator to negate the force applied by the road through the oscillation of the wheels.

2.1.1.1. Passive Suspension System

Passive suspension system is commonly used in the majority of today’s car industry. The system is designed to diminish car vibration energy by a mechanical damping through fluid or dry absorption of motion. The system consists of springs and single-tube or twin-tube dampers. The dampers are the suspension system components that control the ride comfort and vehicle...
stability. Soft dampers generate a smoother motion on the level of the suspension which results in a more comfortable ride for the driver, while stiffer dampers maintain an optimal stability of the car by maximizing reduction the oscillations on the level of the suspension. Using the previous knowledge, the damping force in the passive suspension system then gets tuned to a chosen value or condition that is optimal for most of the road’s irregularities. Thus, this system only operates on roads in which the road condition does not shift constantly.

2.1.1.2. **Semi-Active Suspension System**

Different to the condition stated in the passive suspension system, the semi-active suspension system has the advantage of altering the damping force in respect to the external power exerted on the wheels when the vehicle experiences different road irregularities. This system consists of sensors and micro-controllers that receive an input signal from the road and change the damper characteristics to match the road profile. The dampers then eliminate all the vibrations in the shortest period of time for a better driving experience. Thus, the performance of the semi-active suspension system proves superior to that of the passive suspension system especially when responding to a sudden effect of hitting an acute road irregularity. The semi-active suspension system relies on an electronic controller, and it is electrically powered by the car, but even if the controller fails the system still automatically operates as a passive suspension system for that period, which is still optimal as using a passive suspension system vehicle.

2.1.1.3. **Active Suspension System**

The active suspension system is a fully electric system that relies on both the power provided by the car’s battery and the external power exerted by the ground on the wheels. The performance of the system uses feedback control by mounting an actuator that acts as an external force that diminishes and suppresses the vibrations. However, the active suspension system can only be implemented for large vehicles due to its immense size, weight and electricity consumption. Moreover, since the system totally relied on the car electric power to operate, if the power is down, the vehicle will have zero damping force, thus, the system safety
remains questionable.

2.1.4. Dampers in Vehicle Suspension System

The dampers or the shock absorbers in a vehicle’s suspension system are considered major components of the system. They are designed to suppress vibration energy through fluid, air, or dry frictions. There are two types of dampers, the passive dampers that are commonly used in cars and that use mono-tube or twin-tube oil damping, while the semi-active dampers use a wider variety of damping strategies in the vehicle’s suspension system such as Solenoid-valves, ER-fluid, MR-fluid, Eddy current and electromagnetic dampers [4]. The last type is an active damper that works on reaching the best suppression performance in return of power consumption, price and weight.

2.1.4.1. Passive Dampers

The passive damper is commonly referred to as hydraulic damper. This system is conventional for the use in most automobiles due to its market value and simplicity. The hydraulic damper works on the mechanical movements on the level of the piston valve in the oil chamber to absorb the vehicle vibration due to the viscosity of the oil that helps absorb the oscillation inside the damper.

![Hydraulic Damper Diagram](image)

Figure 2.1 Hydraulic Damper Diagram

2.1.2. Ground Vehicle Dynamics

When talking about reality, the road is not totally flat. Vehicles always experience various types of disturbances, which act on the car as a form of vibration. Road roughness differ from a road
to another resulting in a variation in the energy dissipated by shock absorbers. Thus, it is highly recommended to understand the possible flow of energy suppressed by dampers when the vehicle experiences different speeds on a high oscillation road. Thus, studying the road roughness helps know and predict the multiple roads the vehicle can be experiencing.[7]

2.1.2.1. Road Roughness

When the vehicle is traveling on the road, the wheels move in respect to the trajectory of the imperfections of road surface. Thus, as stated before, the road imperfections can be referred to as ground displacement input. This displacement input is a space variable working on a space domain, therefore, it is needed to convert it into time domain for future calculations for the suspension velocity.

2.1.2.2. Suspension Displacement and Velocity

The modeling of road disturbance works as a displacement input from the ground to the wheels. The process of the transition consists of transforming the vehicle’s speed into an increase in the root mean square value of displacement (RMS). When driving with a speed of 96kmh on an average road, the RMS suspension velocity can reach 0.25 m/s. The following figures show respectively both the suspension displacement and suspension velocity of a car traveling at 96kmh on an average road.[5]

![Figure 2.2 Displacement and Velocity Analysis over Vehicle Speeds](image-url)
2.1.3. Direct TPMS

A direct TPMS system identifies tire pressure through pressure sensors. Those pressure sensors are attached to the tire valve; they change color when the pressure starts decreasing below the normal values. Even though the pressure sensors have relatively low accuracy, the most sophisticated version of the direct TPMS comprises radio frequency transmitters and receiver implemented to warn the driver in case of car under-inflation or over-inflation. The warning system can consist of a LED, an audible warning or displaying a warning message.

Figure 2.3 Direct TPMS System. Each tire comprise a sensor and a transmitter

Generally, the sensors used in a direct TPMS system are small and light in order to avoid centrifugal forces effects. They can operate in a temperature range from -40°C to 120 °C.

The package consists of a transmitter, a control unit and a long-life battery. Thanks to their manufacturing using CMOS technology, the system consumes very small amount of energy, which holds the battery’s lifespan even longer.[6]
2.1.4. Indirect TPMS

An indirect TPMS system tackles under inflation identification using wheel speed computations. The vehicle’s weight causes the tires’ diameter to decrease when their pressure is lower than standard. A tire with diminished diameter rotates at an angular velocity different from the one when it is a normal pressure. The angular velocity of a tire is defined by:

$$\omega = \frac{v}{r - \delta r}, \quad \delta r = r - r_c,$$

where $v$ is the vehicle’s speed, $r$ is the tire’s nominal radius, $r_c$ is the tire’s effective radius, and $\delta r$ is the tire deflection.

The calculation is processed using a software based on an algorithm that works with cars that possess antilock system. The antilock system usually provides angular velocities of each tire. The monitoring of tire inflation outputs a variable $\beta$:

![Image](image.png)
\[ \beta = \frac{(\omega_{LF} + \omega_{RR}) - (\omega_{RF} + \omega_{LR})}{\omega_a} \]
\[ \omega_a = \frac{\omega_{LF} + \omega_{RR} + \omega_{RF} + \omega_{LR}}{4} \]

where \( \omega_{lf}, \omega_{lf}, \omega_{lr}, \omega_{rr} \) denote left front, right front, left rear, and right rear wheel angular velocities, and \( \omega_a \) is the average angular speed. The variable \( \beta \) is negligible when the tire pressure is within the allowed range of pressure.

However, there are many disadvantages to the system; it does not actually measure the pressure of each tire. The system only operates when the vehicle is in motion, and it does warn the conductor only when the pressure drop is below 25% of the normal pressure.

The above systems are both used to calculate the tire’s pressure while the car is moving and send feedback to the driver about the state of the tire. Thus, our product system is relying on the TPMS output to monitor both the tire’s pressure and the compressed air inside the air tank of the product itself.

### 2.2. Overview on compressors functioning

An air compressor is a device used to condense air into a storage device that later will contain compressed air. The process varies from an air compressor to another. There are three distinctive types of air compressors working up to date. The first type is the rotary-screw compressor, it is mainly used to generate high pressure compressed air, and relies on a mechanical function of rotation to produce condensed air. The latter is often used to replace reciprocating compressors when high pressured air is needed.
The second type of compressors is the centrifugal or radial compressor. This type works by increasing the entering velocity of the air that gets converted into static pressure through a rotating motion on the level of the diffuser that reduces the air flow, thus, resulting in a more compressed air when exiting the diffuser.

The third type of air compressors, which is the tool we’re using in our model, is the reciprocating air compressor. The latter uses the mechanical movements of a piston inside a cylinder to compress air. There are two sub-types of reciprocating air compressor: the first type is the single-stage compressor, which compresses air only once for each complete movement of the piston. The second type is the two-stage compressor that compresses air twice for one movement of the piston. The two-stage compressors are used to create medium pressure air up
to 200 psi, while the single-stage compressors are considered a low pressure air compressors as it produces a compressed air for less than 150 psi.

We chose to use the reciprocating air compressor because it only relies on the mechanical movements of the wheel. Without any need for electricity or energy, we will reduce the materials used for the product, along with the space taken. Also, we chose the single-stage air compressor over the double-stage one because it only consists of one piston which is optimal for placing it above the tire.

2.3. Introduction to vehicle suspension

A vehicle’s suspension is a system linkage between the tires and the body of the vehicle that allows a movement between the two. The whole system works as an oscillation nullifier while the vehicle goes through any of the vehicle dynamics principles (Road isolation, Road handling and cornering). The job of a suspension system is fundamental to the vehicle’s movement since it keeps the tires at constant friction with the horizontal road. There are three types of suspension that can be used in a vehicle. The first one is the active suspension that uses electronic monitoring of the vehicle and tire’s placement in respect to the ground. That way it automatically resets to the road level to keep the tire in friction with the road.
The semi-active suspension is another type that consists using multiple electronic based devices such as air springs that consist of an electrically powered compressor. This type of suspension is often used in buses, trucks and trains.

The passive suspension is the third type of suspension which relies only on the mechanical movements of its parts to absorb the vertical movements of the tire.

This system appears to be optimal for our product designed since it only relies on a mechanical movement which suits our product’s mechanism.
3. Analysis

3.1. System prerequisites

The system needs to constantly keep the compressed air tank full in order to ensure reliability of the overall design. The car tires need to be at a pressure of about 2.5 bars. Since, the transfer occurs twice: from the pneumatic cylinder to the tank and from the tank to the tires. Therefore, the tank needs to at least provide air at a pressure around 4 bars, so the air can move to the tire. The tank chosen needs to operate at a maximum pressure higher than 4 bars, and the pneumatic cylinder needs to provide air at 4 bars or higher.

3.2. Dynamic flow

3.2.1. Pneumatic cylinder specifications

The most crucial component of this project is without any doubt the pneumatic cylinder incorporated in the suspension. In order to simplify the calculations, an industrial pneumatic cylinder was chosen with compliance to space restrictions. The cylinder chosen is a double acting pneumatic cylinder from ASCO having a bore of 63 mm and a stroke of 100 mm. Additional information can be found in the cylinder’s datasheet in the appendix.

3.2.2. Energy efficiency

Generally, pneumatic cylinders have a efficiency factor from 50% up to 90%. In order to ensure a valid pressure output transmitted to the tank, the minimum efficiency of the system needs to be calculated.

First of all, the force applied by the piston needs to be calculated using the following formula.

\[ F = P_{atm}A_{out} + m_gs\cos\theta \]

Having \( P_{atm}=101.325\text{kPa}, \) outstroke are \( A_{out}=0.0027m^2, \text{m}_s300\text{kg}, \) and an angle of inclination of 45 degrees, we obtain a force \( F=2354.59\text{N}. \)

Now, the input power to the distance is needed:
\[ P_{in} = F \dot{x}_{max} \]

Having F already calculated above, and a max velocity of the piston with respect to the road profile of 0.15 m/s according to [4], the input power is 353.19W.

The desired output power is known through the formula:

\[ P_{out} = PQ \]

Where, P is the output pressure and Q is the air flow entering the system. The tank needs at least to be at a pressure of 4 bars in order to inflate the tires; therefore, \( P_{\text{min}} \) needs to be used if we are to calculate the minimum efficiency for the system to work properly. The entering air flow is proportional the maximum velocity of the piston.

\[ Q = A_{in} \dot{x}_{max} \]

Having the instroke area \( A_{in}=0.0031 \text{m}^2 \) and the maximum velocity of the piston same as used before, the intake air flow equals 0.000467\text{m}^3/\text{s}. Therefore, the minimum output desired would be 186.8W.

Now, the minimum efficiency required for a normal functioning of the system is about 53% using the formula:

\[ \eta = \frac{P_{out}}{P_{in}} \]

Clearly, the system has a wide margin of efficiency drop in the system since cylinders operate above an efficiency of 50% unless there are leaks or parts wear.

### 3.2.3 Air tank specifications

The air tank used for the design project needs to comply with various constraints; it has to be relatively light, have a decent capacity and working pressure. There are industrial tanks that conform to our specifications.
The figure above shows compressed air tanks from Pneumatiek that have characteristics perfectly fitted for our requirements. They have different configurations to choose from; the tank chosen has a maximum working pressure of 7 bars, a capacity of 7 liters. Their dimensions are suited for a car application having a length of 240 mm, a diameter of 210 mm and a weight of 3.2 Kg. Additional information can be found in the appendix.

3.2.4. Flow Control of the System

Once the air tank reaches its maximum capacity, the pneumatic actuator should no longer provide it with compressed air. In order to achieve this task, a solenoid control valve is used to control the system. The control valve used is a 3/2 valve, which translates to 3 ports and 2 positions. Switching from a position to another in a solenoid valve is performed using a solenoid as the name states. One port is always connected to the outlet of the pneumatic actuator; the two remaining ports interchange based on the position of the valve. The left position connects the outlet of the pneumatic cylinder to the tank; while the second one acts as an exhaust for the unused compressed air. Additional processing elements should be implemented in the pneumatic circuit like air regulators; however, they are omitted in this
circuit for the sake of simplicity since we are mainly focusing on the performance of the design. The figure # shows the simplified pneumatic circuit used for the design drawn using PneuDraw tool.

![Pneumatic Circuit](image)

**Figure 3.2 Pneumatic Circuit**

The control valve changes positions to connect with the tank whenever a pressure sensor inside the tank indicates that the pressure is below the minimum pressure required.

### 3.2.5. Thermodynamics modeling of the system

Assuming air to be an ideal gas, the volume of the air in the tank has to contain a certain number of moles of air. \( n = \frac{PV}{RTo} \), where \( V \) is the volume of air in the tank, \( P \) is the pressure the air needs to be at, \( T_o \) is the ambient temperature and \( R \) is the ideal gas constant.

Assuming that the air in the tank starts at a pressure \( P_o \), it then contains an initial number of moles \( no = n \left( \frac{P_o}{P} \right) = P_o \cdot \frac{V}{RT_o} \). So, the number of moles that needs to be added to the tank is \( na = n - no \), replacing each term we end up with \( na = n(P - P_o)/P \).

Now, we focus on the cylinder that has a working volume \( V_c \) smaller than the volume of the tank \( V \).
\[ n_c = \frac{P_{\text{atm}} V_c}{RT_c} \]

Therefore, multiple strokes are needed in order to fill the tank. We can calculate the number of strokes using the formula:

\[ \text{Strokes} = n_o/n_c = \frac{P - P_o}{P_{\text{atm}} V_c} \]

Obviously, a single stroke would only make a tiny difference to the tank’s pressure. In order to retrieve the volume of air in the cylinder at a pressure \( P_i \) at the end of the \( i \)th stroke, we assume an adiabatic compression process.

\[ V_{c_i} = V_c \left(\frac{P_{\text{atm}}}{P_i}\right)^{5/7} \]

From the law of adiabatic compression of an ideal gas (air our design’s context), we retrieve the following formula used in the previous equation.

\[ PV^\gamma = PV^{7/5} = \text{cte} \]

Consequently, a rise in the temperature of the air in the compression chamber of the cylinder is noticed.

\[ T_i = T_o \frac{P_i V_{c_i}}{P_{\text{atm}} V_c} \]

\[ T_i = T_o \left(\frac{P_i}{P_{\text{atm}}}\right)^{2/7} \]

We can then calculate the temperature rise that occurs in the compression chamber.

\[ \Delta T = T_i - T_c = T_o \left[\left(\frac{P_i}{P_{\text{atm}}}\right)^{2/7} - 1\right] \]

This means that there is work done on the system in order to increase the internal energy (temperature).

\[ W = n_p c_v \Delta T = \frac{P_{\text{atm}} V_c}{RT_c} \frac{5}{2} RT_o \left[\left(\frac{P_i}{P_{\text{atm}}}\right)^{2/7} - 1\right] \leftrightarrow W = \frac{5}{2} P_{\text{atm}} V_c \left[\left(\frac{P_i}{P_{\text{atm}}}\right)^{2/7} - 1\right] \]
In order to transfer the air to the tank, additional work is required.

\[ W' = P_i V_c' = P_i V_c \left( \frac{P_{atm}}{P_i} \right)^{5/7} = P_{atm} V_c \left( \frac{P_i}{P_{atm}} \right)^{2/7} \]

So, the total work needed to realize a single stroke is the sum of the work done to increase internal energy and the work needed to fill the tank.

\[ \sum W_i = W + W' = P_{atm} V_c \left[ \frac{7}{2} \left( \frac{P_i}{P_{atm}} \right)^{2/7} - \frac{5}{2} \right] \]

The initial energy of the air in the compression chamber is added to the total work calculated above.

\[ \Delta U_i = \sum W_i + \frac{5}{2} P_{atm} V_c = \frac{7}{2} P_{atm} V_c \left( \frac{P_i}{P_{atm}} \right)^{2/7} = \frac{7}{2} P_{atm}^{5/7} P_i^{2/7} V_c \]

The general equation for internal energy is related by:

\[ U = c_v n RT = c_v PV = \frac{5}{2} PV \]

Therefore, the change in pressure after the \( i \)th stroke is:

\[ \Delta P_i = \frac{2 \Delta U_i}{V} = \frac{7}{5} P_{atm}^{5/7} P_i^{2/7} \frac{V_c}{V} \]

For an infinitesimal change in pressure, we obtain the following differential equation

\[ \frac{d(P_i)}{P_i^{5/7} V_c} = \frac{7}{5} P_{atm}^{5/7} \frac{V_c}{V} di \]

After integration, we obtain the equation for pressure at the \( i \)th stroke

\[ P_i^{5/7} = P_{atm}^{5/7} \frac{V_c}{V} + P_o^{5/7} \]

\[ P_i = (P_{atm}^{5/7} \frac{V_c}{V} + P_o^{5/7})^{7/5} \]

The maximum pressure in the tire is

\[ P_{max} = (P_o^{5/7} + P_{atm}^{5/7} \frac{P - P_o}{P_{atm}})^{7/5} = P_o, \left[ 1 + \left( \frac{P_{atm}}{P_o} \right)^{5/7} \frac{P - P_o}{P_{atm}} \right]^{7/5} \]

The maximum temperature is the tire is found using the following formula
Finally, the total work done while compressing and transferring the air into the tank is:

\[ W = U_f - U_o = \frac{5}{2} (P_{max}V - P_{atm}V - NP_oV_c) \]

\[ \leftrightarrow W = \frac{5}{2} P_o V \left(1 + \left(\frac{P_{atm}}{P_o}\right)^{5/7} \left(\frac{P - P_o}{P_{atm}}\right)^{7/5} - \frac{P_{atm}}{P_o} - \frac{P - P_o}{P_{atm}}\right) \]

Using the appropriate values concerning our study, Po initial pressure in the tank: 1 atm, V tank volume: 7 liters, P pressure to reach in the tank: 4 bars to 7. We obtain a total needed work of \( W = 142.89 \text{ kJ} \) spread over a 15 minutes of cumulative oscillation, it requires 158.77 W of power, which complies with the output power generated.

### 3.3. Suspension analysis

In this subsection, an analysis of the normal passive suspension system of a car is to be performed to later be compared to the system proposed by this project. This analysis is targeting the dampening effect of the solution and how it is in no way affecting the normal functioning of the suspension. The approach used in this analysis is the quarter car model employed in many studies targeting vehicle suspension. The quarter vehicle model is a simplification used to study vehicle suspension. There are many variations of the model. The model used in this paper is based on the assumptions that the tire is modelled as a linear spring with damping as opposed to other similar models; also, no rotational behavior neither in the wheel nor the body is considered, the motion of the damper and spring are linear and the tire never loses contact with the surface of the road. [5]

#### 3.3.1. Normal Passive Suspension

##### 3.3.1.1. Force Analysis

A basic free body diagram of the suspension is drawn and used for the analysis.
The figure above shows the forces applied on both the sprung and unsprung mass. The sprung mass defines the fraction of the vehicle’s total mass supported by the car’s suspension; the unsprung mass is simply what remains of the mass, which is the mass of the suspension and wheel.

Separate free body diagrams of both the sprung and unsprung mass are made to analyze the forces applied on them.

\[ \sum F = F_{B2} + F_{K2} = -m_s \ddot{x}_s \]

The forces applied on the sprung mass are the spring force \( F_{K2} \) and the dampening force \( F_{B2} \).

Replacing the above equation with its respective definitions, we obtain:

\[ m_s \ddot{x}_s + B_2 (\dot{x}_s - \dot{x}_u) + K_2 (x_s - x_u) = 0 \]
Where, $K_2$ is the suspension stiffness

$B_2$ is the dampening coefficient of the suspension

Applying the same analysis on the unsprung mass while considering the reaction forces of the forces applied on the sprung mass, we obtain:

$$
\sum F = F_{B2} + F_{K2} - F_{B1} - F_{K1} = m_u \ddot{x}_u
$$

$$
\leftrightarrow m_u \ddot{x}_u - B_2 (\dot{x}_s - \dot{x}_u) - K_2 (x_s - x_u) + B_1 (\dot{x}_u - \dot{x}_r) + K_1 (x_u - x_r) = 0
$$

Where, $K_2$ is the suspension stiffness

$B_2$ is the dampening coefficient of the suspension

$K_1$ is the tire stiffness

$B_1$ is the dampening coefficient of the tire

Those two equations obtained constitute a system of second order differential equations describing the positional behavior of the sprung and unsprung mass with respect to the road profile.

3.3.1.2. Simulink modeling and simulation of the normal passive suspension

In order to solve the above system of second order differential equations, a computer aided simulation software is needed. Simulink was used to obtain the graph of whichever output is needed (position, position difference, velocity, acceleration).

The initial data required in order to model the system was extracted from previous studies.

The most important parameter to analyze in order to make relevant conclusions about the
damping functioning of the suspension is the difference of positions of the sprung and unsprung mass.

![Simulink Model to Solve Passive Suspension Analysis](image)

**Figure 3.6 Simulink Model to Solve Passive Suspension Analysis**

The figure above shows the model of the system of second order differential equations made for the normal passive suspension studied earlier. Simulink models the gravity forces and masses (unsprung and sprung) of inertia. It determines the damping behavior of the system induced by the excitation of the suspension at various frequencies and damping factors. The values used in the modelling of the quarter car model are retrieved from datasheets concerning a common passenger vehicle.

<table>
<thead>
<tr>
<th><strong>Sprung Mass</strong> $M_s$</th>
<th>300 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unsprung Mass</strong> $M_u$</td>
<td>40 kg</td>
</tr>
<tr>
<td><strong>Spring Constant</strong> $K_2$</td>
<td>15,000 N/m</td>
</tr>
<tr>
<td><strong>Spring Constant</strong> $K_1$</td>
<td>150,000 N/m</td>
</tr>
<tr>
<td><strong>Damping Coefficient</strong> $B_2$</td>
<td>1000 N.s/m</td>
</tr>
<tr>
<td><strong>Damping Coefficient</strong> $B_1$</td>
<td>150 N.s/m</td>
</tr>
</tbody>
</table>
Consequently, a scope is linked with the position difference and therefore plotted. The plot below represents the behavior of the position difference of sprung and unsprung masses.

Figure 3.7 Position Difference of Sprung and Unsprung Masses

As we can see in the figure 3.7, the position difference starts oscillating when hitting a bump. This oscillation is damped critically until it reaches the initial distance between the two masses. This graph represents the normal behavior of vehicle suspension, where the sprung and unsprung masses start at specific distance from each other depending on the suspension system used. After being disturbed (bumps for example), the dampers absorb the shock and consequently the oscillating movement of the two masses until reaching equilibrium back.

3.3.2. Suspension with incorporated pneumatic cylinder

3.3.2.1. Forces analysis

Similarly, the same force analysis is performed on the suspension including now the pneumatic cylinder.
Figure 3.8 Quarter Car Model for Suspension including Pneumatic Cylinder

Again, splitting the sprung and unsprung mass into two separate free body diagrams:

Figure 3.9 Sprung Mass FBD

\[ \sum F = F_{B2} + F_p + F_{K2} = m_s \ddot{x}_s \]

The forces applied on the sprung mass are the spring force \( F_{K2} \), the dampening force \( F_{B2} \) and the dampening force of the pneumatic cylinder \( F_p \). Replacing the above equation with its respective definitions, we obtain:

\[ \leftrightarrow m_s \ddot{x}_s + B_2(\dot{x}_s - \dot{x}_u) + c(\ddot{x}_s - \ddot{x}_u) + K_2(x_s - x_u) = 0 \]

Where, \( K_2 \) is the suspension stiffness

\( B_2 \) is the dampening coefficient of the suspension

Applying the same analysis on the unsprung mass while considering the reaction forces of the forces applied on the sprung mass, we obtain:
Figure 3.10 Unsprung Mass FBD

\[ \sum F = F_{B2} + F_p + F_{K2} - F_{B1} - F_{K1} = m_u \ddot{x}_u \]

\[ \leftrightarrow m_u \ddot{x}_u - B_2(\dot{x}_u - \dot{x}_u) - c(\dot{x}_u - \dot{x}_u) - K_2(x_s - x_u) + K_1(x_u - x_r) + B_1(x_u - x_r) = 0 \]

Where, \( K_2 \) is the suspension stiffness

\( B_2 \) is the dampening coefficient of the suspension

\( K_1 \) is the tire stiffness

\( B_1 \) is the dampening coefficient of the tire

\( C \) is the dampening coefficient of the cylinder

Identically to the analysis done previously, these two equations resulted describe the positional behavior of the sprung and unsprung mass with respect to the road profile.

3.3.2.2. Simulink modeling and simulation of the new design

The same model for the normal passive suspension is again used with the addition of the pneumatic cylinder and its dampening effect on both masses. Again, we are interested in seeing how the difference of position of the two masses behaves as we incorporate a pneumatic cylinder between the two.
The figure above is very similar to the one realized for the normal passive suspension. However, it features the damping coefficient of the pneumatic cylinder as an extra term to one of the differential equations as developed above. The same data retrieved for the typical passenger car summarized in table# is used in this study in order to ensure consistency of the results and a reliable comparison between the two configurations. Similarly, the scope is used here to plot the position difference of the two masses in order to retrieve the behavior of the two masses when the car hits a bump.
Table 2 Values Datasheet for Typical Passenger Car

<table>
<thead>
<tr>
<th>Sprung Mass $M_s$</th>
<th>300 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsprung Mass $M_u$</td>
<td>40 kg</td>
</tr>
<tr>
<td>Spring Constant $K_2$</td>
<td>15,000 N/m</td>
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<tr>
<td>Spring Constant $K_1$</td>
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<tr>
<td>Damping Coeff. Cylinder $c$</td>
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</table>

Consequently, a scope is linked with the position difference and therefore plotted. The plot below represents the behavior of the position difference of sprung and unsprung masses.

![Figure 3.12 Position Difference of Sprung and Unsprung Masses](image)

Identical to the results from figure 3.7, this figure shows the difference in position between the two masses when the car goes over a road bump. Clearly, we can observe the damping behavior of the added pneumatic cylinder as the two masses reach equilibrium faster in this suspension configuration as opposed to the normal one studied earlier.
4. STEEPLY Analysis

The STEEPLE analysis is a model that identifies-in the same order- the major social, technological, economic, environmental, political, legal and ethical factors in a certain process that would affect, either positively or negatively, the targeted audience.

4.1. Social Factors

The product between hands is mainly targeting the big social issue of deaths caused by car accidents. This project will directly help reduce the numbers of deceases in the highways by preventing any failure of vehicle tires.

4.2. Technological Factors

The whole project is relying on a technological basis; the use of the mechanical movements of the shock absorbers and the electronic materials to define the air pressure of the tire are both major components in the calculations to regulate the air pressure inside the under-inflated tire.

4.3. Economic Factors

The designed product is an included part in the making of the new issued vehicles, thus, the price will be included in the vehicle’s price in the selling process. Also, under-inflated tires directly cause over- consumption of the vehicle’s fuel. This product will prevent the engine from consuming more, therefore, minimizing the cost of fuel per distance traveled. In other hands, when minimizing tire damage risks, the consumer will avoid the extra fees for tires’ replacement each year.

4.4. Environmental Factors

As stated above, the product will minimize fuel consumption and fuel combustion per distance traveled. This will automatically reduce the toxic emissions of the vehicles.

4.5. Political Factors
Since our product is targeting the vehicle’s factory alone, without having any business dealing with the politics of the company, the political factor does not apply to it.

4.6. Legal Factors

Our product provides the car with an internal operating system that helps the user have access to compressed air at any time. Thus, the product is legally approved since it will not push the vehicle exceed the weight limit.

4.7. Ethical Factors

The project remains side to side with the ethical rules of engineering since it provides the public with an easier way of life. It also helps simplify their daily tasks and reduces the public’s concerns regarding the inconveniences of under-inflated tires.
Conclusion

In this project, the aim is to produce an innovative design of car shock absorbers that integrate a compressor that is capable of producing enough compressed air to pump tires. A vehicle equipped with this system has practically self-inflating tires. The product relieves its users from many burdens such as the inconvenience of checking tire pressure regularly, the cost of changing tires because of damage due to under-inflation, etc… The project is still in project, and many tasks are still to be performed. The most important and crucial part of the project is the analysis that would produce the necessary dimensions to design the compressor. The analysis is still unfinished due to many variables that intervene in the functioning of the system. The design and modeling is relatively easy to complete once dimensions are retrieved from the analysis. In addition, industrial drawings are still to be generated once the modeling using computer aided modeling software. Finally, a simulation of the resistance of the material to friction and heat is pending as well.
References


Appendix

Appendix A

VERIN ROND ISOCLAIR
Ø 32 à 63 mm - simple effet
ISO 6431 - CETOP
avec amortissement élastique

GENERALITÉS
Détection Prévus pour détecteurs magnétiques de positions
Fluide Air ou gaz neutre filtré, lubrifié ou non
Pression d'utilisation 10 bar max.
Temps ambiant -10°C à +70°C
Normalisation ISO 6431 - 8139 - 8140
CETOP RP 43 P - RP 102 P - RP 103 P
Pression mini de commande pour comprimer le ressort : 2 bar
La retrait de l'axe du vérin doit s'effectuer sans charge

CONSTRUCTION
Tube Alliage d'aluminium anodisé dur
Tige Acier chromé dur
Fonds avant et arrière Alliage léger
Piston POM (polyamide), acier, aluminium
équipé d'un allant permanent
Joints de piston PUR (polyuréthanne)
Écrou de tige Acier zingué
Démontage indémontable
Amortissement Élastique

SELECTION DU MATERIEL

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<thead>
<tr>
<th>Ø  (mm)</th>
<th>course  (mm)</th>
<th>code</th>
<th>référence</th>
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</table>

* Les détecteurs magnétiques de positions sont à commander séparément :
modèle "T" (voir page P291), type H 0 ou magneto-résistif
Appendix B

TANKS FOR COMPRESSED AIR

Tanks in painted steel for compressed air are supplied with CEE Certificate of Conformity according to European directives 87/404/CEE (Simple Pressure Vessels) or according to the directive about pressure equipment 97/23/CE (PED).

Are available also tanks not tested without brackets and certificate, with 7 liters as max capacity and 7 bar as max working pressure.

Keep the use and maintenance manual supplied together with each tank.

Tanks not tested without brackets (7 liters as max capacity)

Technical features

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<th>Capacity</th>
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<tr>
<td>Thread</td>
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<tr>
<td>Fluid</td>
<td>compressed air</td>
</tr>
<tr>
<td>Max working pressure</td>
<td>7 BAR</td>
</tr>
<tr>
<td>Number of connections</td>
<td>2 or 4</td>
</tr>
<tr>
<td>Test</td>
<td>inner test</td>
</tr>
<tr>
<td>Material</td>
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</tr>
<tr>
<td>External treatments</td>
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</tr>
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</table>

<table>
<thead>
<tr>
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<th>CONNECTIONS</th>
<th>DIAMETER Ø (mm)</th>
<th>LENGTH L (mm)</th>
<th>BOTTOM THREAD</th>
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<th>WEIGH (Kgs)</th>
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<tbody>
<tr>
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</table>

TAKE NOTE: dimensions are indicative.