The Importance of Tire Pressure Regulation and the Self-Inflating Tire

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Abstract

Modern vehicle tires are not safe enough because of their susceptibility to becoming over or under-inflated. The inherent safety risks are analyzed along with a variety of solutions that have been developed for different applications. The self-inflating tire is investigated in depth through the use of research, theoretical, and analytical approaches. An experiment is conducted which replicates the function of such a tire. The efficacy of the concept is proven with suggestions for future experimentation, and recommendations are proposed for the optimization of future designs. While modern technology will continue to add to the safety and ease of operating a motor vehicle, the need to inspect tires before use will always be a legitimate concern.

Introduction

The history of the pneumatic tire dates back to almost 130 years ago. In 1888, John Boyd Dunlop invented the first air-filled, rubberized tire to be used on a bicycle. In the decades that followed, the mounting methods and materials used were slowly developed into what we think of today as a modern car tire [14]. Without this crucial bit of ingenuity, the car would have never surpassed the role of a mere self-driven wagon. Tires reduce vibration and increase traction, allowing vehicles to travel very quickly on paved road surfaces and handle tough, off-road terrain.

The secret of the tire's success is the oft-overlooked pressure chamber, which commonly uses air to seal the tire bead to the vehicle's rim. Without it, tires would be hard, unyielding, and unable to cope with the varied stresses that they are subjected to on a daily basis. This is why it is so important that tire pressure is adequately maintained at all times. Too much tire pressure can easily cause the outer layers to rupture, and too little pressure will render the design useless by allowing the bead to roll off the rim. Both of these cases can be disastrous and are easy to avoid through constant visual and manual inspection of the tire pressure.

But recently, tire pressure sensors have become the standard on most vehicles, taking the guesswork out of when it's time to adjust for changing temperatures and regular pressure loss. These indicators are very handy, but even more recently, a need has been addressed for tires that regulate their own tire pressure or otherwise guard against complete failure.

Background Research

Proper tire inflation is extremely important to the safety of vehicles that are on the road today and will continue to become integral to the performance of vehicles as they start reaching faster speeds on highways. According to the US National Highway Traffic Safety Administration, proper tire pressure can improve vehicle handling, improve fuel economy, increase tire life, and help protect against breakdowns and crashes [1]. In fact, about five percent of vehicles involved in crashes experienced problems with their tires leading up to the collision, and almost 92 percent of tire-related crash vehicles had tires that were improperly inflated. Furthermore, it has been shown that tires that have been overinflated by more than 25 percent of the recommended tire pressure will increase the likelihood of being involved in an accident [2]. This preventable problem is also somewhat ubiquitous; a European study estimates that 71% of drivers are driving on under-inflated tires. That translates to billions of dollars lost and millions of tons of carbon emissions that could be prevented each year [8].

But your average daily commuter is not the only person that could benefit from solutions to this problem. The performance demands on tires are at an extreme while racing on a track. Race car tires must be inflated precisely in order to reach the correct pressure when heated to track temperatures. Even a half psi of difference from the target pressure can cause a noticeable change in performance characteristics during a race [3]. Conversely, vehicles that are designed for off-road use must lower their tire pressures significantly when driving through rough terrain such as mud and rocks. This decrease in pressure gives a longer tire footprint, thereby reducing contact pressure and increasing traction for the vehicle [4]. Typically, off-roading enthusiasts must weigh down their vehicles with a means of re-inflating their tires before driving home, which takes time away from recreational outings.

As this is being written, companies are developing solutions to meet the ever-growing needs of the automotive market when it comes to tire maintenance. There are two main types of systems that accomplish this goal. The first inflates the tires from a centralized tank or compressor, which feeds all the tires simultaneously or individually as needed. A company called AirGo has developed a solution called the T3 Automatic Tire Inflation System (ATIS) which mounts to the outside of a tractor-trailer's wheel hub and uses air from the brake supply tank to regulate tire pressure [7]. The Meritor Tire Inflation System is similar in function but uses a dedicated compressed air tank from the trailer to accomplish the same goal.

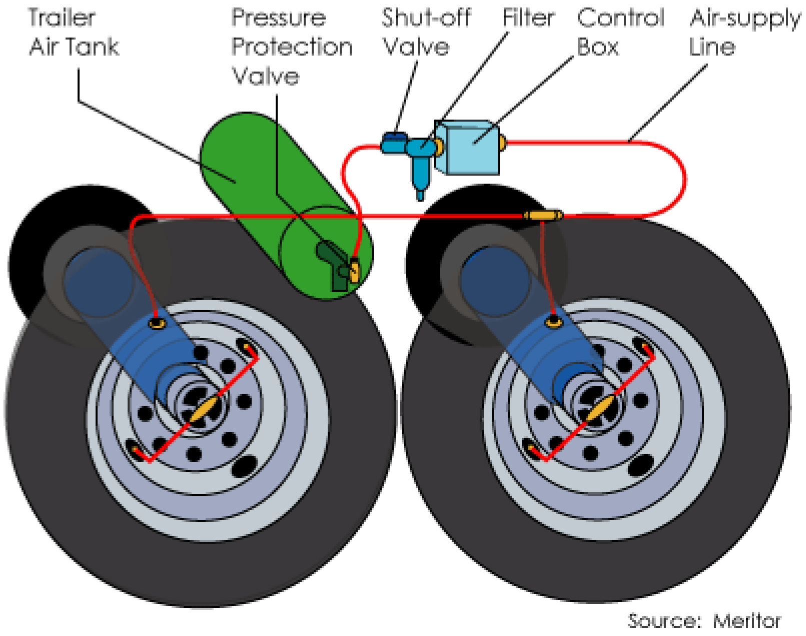

Fig. 1. An example of a common main-source automatic tire inflation system [15].

Dana Corporation and Syegon manufacture a Central Tire Inflation System (CTIS), which inflates the tires to an automatically controlled or user-set ideal level. The CTIS has been adapted to off-road vehicles such as the Hummer [15]. While these designs are well built to cut down on costs and make maintenance a breeze, they are too large, heavy, or complicated to meet the need of most commuters.

The second type of self-inflating tire actually harnesses the energy from its rotating motion to compress air into itself. Both Goodyear and Coda Development have alternative designs that are in the last stages of development. Coda Development's Self Inflating Tire (SIT) system utilizes the concept of a peristaltic pump to inflate the tire as the car is being driven [6]. Air from the atmosphere is sucked through a filter mounted in the tire sidewall and into a tube which internally wraps around the circumference of the rim. The weight of the vehicle pushing on the tire causes a deformation where the tire contacts the pavement. This deformation is used to squeeze the tube together and push air through the system as the tire rotates.

Fig. 2. Coda Development's Self-Inflating Tire [16].

This allows the pump to provide a slow, high pressure flow of air into the tire without the need for electricity or a motor of any kind. An automatic pressure regulator is also implemented so that excess air may be let out of the tire as needed. This design can "compensate for typical monthly leakage of 2-3%" in little over half a mile of driving and is already being sold as a license to tire manufacturers [10].

Goodyear's Air Maintenance Technology (AMT) is extremely similar in design to the SIT system. The only plain difference seems to be that the pressure regulator is mounted at the entrance to the peristaltic tube, thereby preventing airflow when it is unnecessary. Unfortunately, speculation would lead the consumer to believe that this design is incapable of releasing excess pressure, unlike the SIT system [13].

Fig. 3. Image courtesy of The Goodyear Tire & Rubber Company [13].

However, AMT is getting a lot of attention with a grant from the government of Luxembourg and a 1.5 million dollar grant from the United States Department of Energy [5]. AMT was also named in the top 25 “Best Inventions of the Year 2012” by Time magazine, among other awards and commendations [9]. As of last October, Goodyear is beginning testing of the technology on commercial fleet vehicles [13]. But Goodyear’s ingenuity does not stop there. They have released concept tires that can charge electric vehicles using thermoelectric fibers and piezoelectric material and use three tubes instead of one to adjust to road conditions. These are called the BH-03 and Triple Tube, respectively [17].

The importance of this problem for automotive manufacturers is clearly illustrated by what has turned out to be no less than a debacle between Ford and Firestone. In the year 2000, Firestone announced a recall of about 14.4 million tires that were equipped on the Ford Explorer SUV. These tires were related to an unlikely number of tire-related crashes that caused 101 fatalities [11]. For about a decade, Ford insisted that the tires be inflated to 26 psi instead of the Firestone-recommended 30 psi. They defended this pressure rating with research showing that the SUV was much more likely to roll over with the tires inflated past 26 psi [12]. However, Firestone was aware that these tires would fail at 19 psi, dangerously close to that 25% underinflated line. In the end, Ford increased the recommended pressure, and Firestone had to recall the tires, causing both companies to lose a great deal of reputation [11]. However, if tire pressure maintenance technology had existed at the time, Ford could have regulated the tire pressure to prevent both tire failure and rollovers.

The entire concept of a pneumatic tire has been abolished by the research and development team at Michelin, who prefer to attack the problem at its source. They have created a fusion between tire and wheel that they call the Tweel, which uses flexible polyurethane spokes to match the characteristics of a traditional air-filled tire.

Fig. 4. The Michelin Tweel Airless Tire [18].

This tire was first announced in 2005 and represents an alternative future for the way our cars contact paved surfaces, and is one of many new technologies that are starting to appear in the tire market [18].

Onboard tire pressure monitoring and adjustment could help prevent traffic accidents while improving fuel economy and tire life on our roadways. It could also add to the competitiveness of racing and ease the transition between driving on and off the road. The ever-increasing need for a robust solution to this problem is evident, and companies are actively developing designs to cater to the average consumer. However, one design cannot meet the needs of every person, and there are always ways to improve and expand upon the technology of today to prepare for the future.

Analysis

Theoretical Approach

To better understand how a self-inflating tire functions, a mathematical model was derived, which calculates the mass of air flowing into the tire per mile based on peristaltic tube geometry and the resulting change in tire pressure from the geometry of the tire and the ideal gas law. For the purpose of simplicity, all variables for length will be in ft.

The following are the assumptions used during analysis:

1. Ideal Gas Law, $\Delta P = \frac{mRT}{V}$

2. Constant temperature of air, T = 530°R

3. Constant density of air, ρ = 0.0023769 ${}^{slug}\!/_{ft^3}$

4. Tire volume can be approximated by sidewall height (h), section width (w), and rim diameter (D).

5. Change in tire volume under pressure is negligible.

6. The geometry of the peristaltic tube can be approximated as a cylinder with a radius (r).

First, the flowrate must be found using the peristaltic tube volume, rotations per mile, and density of air.

$$Q\left(\frac{slug}{mi}\right) = \pi r^2 \times \pi D \times \frac{5280\frac{ft}{mi}}{\pi(D+2h)} \times 0.0023769\frac{slug}{ft^3}$$

This is then inserted as the mass into the Ideal Gas Law formula, using R = 1716 $\frac{ft\cdot lb}{slug\cdot °R}$, to give:

$$\Delta P\left(\frac{psi}{mi}\right) = \pi r^2 \times \pi D \times \frac{5280\frac{ft}{mi}}{\pi(D+2h)} \times 0.0023769\frac{slug}{ft^3} \times \frac{1716\frac{ft\cdot lb}{slug\cdot °R} \times 530°R}{w\left[\pi\left(\frac{D}{2}+h\right)^2 - \pi\frac{D^2}{4}\right]} \times \frac{1\,ft^2}{144\,in^2}$$

Simplifying, this gives:

$$\Delta P\left(\frac{psi}{mi}\right) = 79264\frac{ft\cdot psi}{mi} \times \frac{Dr^2}{w(D^2h+3Dh^2+2h^3)} \qquad (1)$$

Equation (1) is the general formula for the inflation rate of a self-inflating tire.

Coda Development's SIT Design

Now equation (1) can be used to better understand the Coda Development's SIT technology. According to their website, Coda Development claims their tires can account for 2-3% deflation by being driven a single kilometer. This seems like a very high inflation rate for a product so simple in design, but the peristaltic tube radius can be calculated to check for feasibility.

Using 225/45R18 tires with a recommended pressure of 32 psi as an example:

The rim diameter (D) would be about 1.5 ft., the sidewall height (h) about 0.333 ft., and the section width (w) about 0.7383 ft.

$$\frac{0.8\,psi}{0.621\,mi} = 79264\,\frac{ft \cdot psi}{mi} \times \frac{1.5ft \times r^2}{0.7383ft[(1.5^2ft^2 \times 0.333ft) + (3 \times 1.5ft \times 0.333^2ft^2) + (2 \times 0.333^3ft^3)]}$$

Solving for r, the peristaltic tube used in the SIT has a radius of about 0.039 in or 1 mm. While this statistic assumes 100% efficiency, it is extremely feasible. This size for a peristaltic tube seems likely because it would occupy a small percentage of the inside of the tire as well as being easily compressed to achieve its purpose of pumping air.

Experimental Approach

To test this theory, an experiment was designed to externally replicate the conditions demonstrated in figures 2 and 3. To act as the peristaltic chamber, polyethylene tubing with an internal diameter of 0.17 inches was used. This tubing was wrapped around the outside of the tire to cause compression where the tire's contact patch meets the pavement. This is important because the rim diameter (D), from the theoretical analysis, is replaced by the overall tire diameter in the experimental analysis. The peristaltic tube was fitted with a female Schrader adapter using a barbed coupling. To act as the experimental pressure chamber, a bicycle tube with a Schrader valve was inserted into an aluminum bottle with the cap drilled out. The effective volume of this chamber was found to be 0.0232 ft^3 by measuring the internal volume of the bottle and the displacement caused by the tube in a graduated cylinder.

Fig. 5. The materials used to conduct the experiment.

Figure 5 lays out the materials that are used in the experiment. The peristaltic tube, pictured on the left, is used to pump air into the pressure chamber, which is on the right. The pressure is then measured using an automotive tire pressure gauge with a precision of 1 psi.

Fig. 6. Experimental device installed on a standard automotive wheel.

Figure 6 shows the experiment just before beginning testing. The device is secured to a 225/45R18 tire using regular duct tape and zip ties. The device is tested by driving in 0.1 mile increments using the vehicle's built-in odometer and then testing the pressure that has built up within the system. These runs are repeated as necessary until failure, which is inevitable due to the high-stress conditions that are associated with driving on paved surfaces.

Results

After completing five runs, the average pressure produced was found to be approximately 345 psi/mi. This result varied between a minimum of 310 psi/mi. and a maximum of 390 psi/mi. To quantify these results in a way that is easy to understand, equation (1) has been solved using the dimensions of the tire that was used in the experiment to yield equation (2).

$$Q\ \left(\frac{slug}{mi}\right) = 39.427\,\frac{slug}{mi\cdot ft^2}r^2 \tag{2}$$

Using the internal radius of 0.085 in. for the peristaltic tube in equation (2) indicates that an ideal flowrate for this scenario would be approximately 0.001978 slug/mi. To compare this result to those found experimentally, the ideal gas law is used. The gas constant is assumed to be 1716 $\frac{ft\cdot lb}{slug\cdot°R}$. Remember to keep in mind that all calculations are performed in terms of ft.

$$Q\ \left(\frac{slug}{mi}\right) = \frac{\Delta P\times V}{R\times T} \tag{3}$$

Equation (3) yields a maximum experimental flowrate of 0.001433 slug/mi.

Discussion

This result equates to an error of 27.6%, which can be attributed to a variety of factors. The first of these is the tire orientation when the pressure is measured. Due to the air being able to backtrack through the system up until the tire's contact patch, there is compressed air that is released when a measurement is taken. The maximum approximate volume of this part of the system is 0.000788 ft^3, which accounts for 2.46% of the error. Another source of error comes from the amount of air released every time the pressure is measured with a gauge. It was found experimentally that about 3 psi is released from the system from measurement alone. This accounts for 5.76% of the error. An additional 1.92% can be attributed to inaccuracy due to the precision of the pressure gauge itself.

Additionally, inconsistencies in the peristaltic tube diameter contribute to inaccuracies in the predicted outcome, but these are difficult to measure given the material the tubing is made from. There are also inaccuracies that come with measuring the diameter of the tire, distance travelled, and volume of the pressure chamber. A more accurate result could possibly be obtained by using a peristaltic chamber with a smaller cross-sectional area or a pressure chamber with a much higher volume. This would allow the pressure to build more slowly, thereby giving a better estimation of the flowrate in terms of miles. It is also important to remember that the theoretical model is not perfect; assumptions are made about the temperature of the air and tire geometry to calculate the expected flowrate.

Conclusion

While the concept of the self-inflating tire is very simple, there are a variety of complications that would increase the difficulty of designing one for commercial use. The first of these is choosing a material which seals the peristaltic chamber so that it operates efficiently within a reasonable range of pressures. For Goodyear, the risk of producing a leaky seal is mitigated by the check valve that only allows air in under a set tire pressure. Since Coda Development has not implemented a pre-inlet valve yet there is a risk for tire deflation under undesirable conditions. The positive aspect of this shortcoming is the fact that Coda Development's design can automatically deflate the tires when they are over-pressurized due to heating. However, the optimal design would implement check valves at both the inlet and outlet, so that air flows in when pressure is lacking and only escapes when it is plentiful. Another important design factor is the cross-sectional shape and area of the peristaltic chamber. This ties in with the first because it should be small enough to seal easily while also being large enough to inflate the tires quickly.

The ingenuity in this design may be simple, but it is very effective. This experiment has proven the feasibility of implementing a low-cost design that is compatible with almost any commercial vehicle. With materials that can be sourced at a local hardware store, a peristaltic pump was built that can inflate a typical car tire by more than 4 psi per mile. This could inflate a severely underinflated tire in a matter of minutes during even the shortest of commutes.

The self-inflating tire is revolutionary and perhaps the future of the tire market, but it is one of many technologies that are all designed for the purpose of automatically regulating the pressure of automotive tires. Each of these has its own unique application, while the SIT and AMT are directed at the general commercial vehicle audience. They are also among a plethora of tire technologies aimed at making the world's roadways safer for travel. Despite the help of modern technology, it is still important to visually and manually check for adequate tire inflation to maintain the safety and performance of your personal vehicle.

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