The Use of Elastically-Based Mechanical Energy Storage in Motor Vehicles

Honors Thesis
Nicholas J. Direnzi
Department: Mechanical Engineering
Advisor: Dr. Andrew Murray
Dr. David Myszka
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Abstract

The overall goal of this research project is to assess the feasibility in designing a strain-based mechanical hybrid device to be incorporated in a motor vehicle to improve fuel efficiency. An in depth search was conducted to discover any past works pertaining to spring-based energy storage in vehicles. Material testing was done to determine the suitability of using a spring made from a hyperelastic material over a conventional steel spring and to confirm the theoretical higher energy density of elastomers. Lastly, a novel design is conceptualized which harvest wasted energy from shock absorbers and stores it in a spring-based device.
Acknowledgements

I would like to thank all those who collaborated on this research project: Dr. Drew Murray for being my primary advisor and helping me through the entire thesis process. Dr. David Myszka, for advising me on materials research and testing as well as data analysis and calculations. Also, the members of the research team at the University of Dayton, Chris Gillum, Andrew Hazlett, and Travis Schubert. I would also like to thank General Motors for providing the funding that made this research possible.
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1. Introduction

Within the past decade, the quest for creating a more fuel efficient motor vehicle has led to many developments in hybrid and onboard energy storage technology. The realization that the world’s oil supply is dwindling has caused gasoline prices to surge, generating a significant level of consumer demand in both hybrid vehicles and vehicles that use alternative energy sources, such as ethanol. Additionally, the current “green movement” has made everyone more conscious of wasteful energy practices and has placed even more pressure on automotive manufacturers to develop energy-efficient vehicles.

The mindset caused by the recent spike in oil prices is similar to that of the first oil crisis of the United States several decades ago. In October of 1973, OPEC nations agreed to place an oil embargo on the United States as punishment for supporting Israel during the Yom Kippur war. For the next sixteen months, gasoline became a scarce commodity. Congress passed legislation in order to limit the oil usage in the U.S., such as a national 55 mph speed limit. Even after the embargo was lifted, high prices continued for the next decade. The major U.S. automotive manufacturers stopped building large, inefficient vehicles in favor of more efficient models to remain competitive with foreign automotive manufacturers. The Ford Pinto and Chevrolet Chevette were two popular vehicles introduced to compete with models such as the Volkswagen Beetle. Figure 1 shows oil prices over the past several decades, adjusted for inflation (Recession.org, 2011). Note the dramatic spike from 1970 to 1985 followed by a significant drop in price until approximately 2005. Oil prices then climbed once again, remaining high to present day (Williams, 2011). During the 1970s and into the ‘80s, a considerable amount of research was performed to make vehicles more fuel efficient, such as Lionel Hoppie’s work to create a mechanical hybrid. However, once gasoline prices dropped back to “normal” rates, funding for this work ceased until recent concerns about fuel economy.
Currently, most automotive manufacturers offer hybrid vehicle options which consist of batteries and an electric motor in addition to a conventional internal combustion (IC) engine. Toyota’s Prius, for example, uses both an IC engine and an electric motor in parallel to propel the car. An onboard computer is used to continually adjust the power received from each source in order to optimize fuel efficiency.

While electric-hybrid technology has increased fuel efficiency, the additional upfront cost to the consumer nearly makes up for the amount of money that would be saved in fuel expenses. Also, when considering the amount of energy needed to manufacture and dispose of an electric motor and a bank of batteries, the current hybrid technology is not as environmentally friendly as most people might think. One study shows that, when including manufacturing and disposal, some hybrid models can require almost double the energy of their non-hybrid counterparts (DiMauro, 2008), although this
extreme is atypical. Additionally, in order to store energy with batteries, shaft work from regenerative braking must be converted to electrical energy, then to chemical energy. When releasing energy stored in the batteries, it must be transferred from chemical to electrical and then ultimately back to mechanical energy. Losses associated with each conversion limit the efficiency electric hybrids. A mechanical hybrid has the potential to solve these problems and significantly reduce the cost of hybrid vehicles. There are three main types of mechanical hybrids; compressed air, flywheel, and strain energy (springs). Of these, flywheels and strain energy show very high efficiencies in energy storage and release.

Mechanical energy storage in motor vehicles is often overlooked due to the lower energy density, that is, the stored energy per unit mass. Table 1 shows gravimetric energy density of gasoline and batteries as well as rubber and steel springs which could be used in a mechanical hybrid. Gasoline has an extremely high energy density which makes it an ideal fuel source. However, kinetic energy produced by gasoline is wasted during actions such as braking. Because of the recent high gas prices, manufacturers have been exploring ways to minimize these losses and decrease fuel consumption, thus making their vehicles more desirable to the consumer. Batteries have been traditionally used as a way to regain some of this wasted energy, as with current hybrid vehicles. Yet their high cost and weight, along with the inherent inefficiencies of the energy conversions, leave room for improvement. A spring-based mechanical hybrid would be able to regain the same energy without the disadvantages of using large batteries. The device to be developed would ideally be lightweight, cost effective, environmentally benign, and capable of delivering a controlled burst of energy.
Table 1: Gravimetric Energy Densities. 1.(Caldirola, 1968), 2.(Panasonic.com, 2010)

<table>
<thead>
<tr>
<th>Medium</th>
<th>Energy Density (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline$^1$</td>
<td>47500</td>
</tr>
<tr>
<td>Battery$^2$ (Li-ion)</td>
<td>600</td>
</tr>
<tr>
<td>Rubber (using a linear approximation method)</td>
<td>11</td>
</tr>
<tr>
<td>Spring Steel</td>
<td>0.4</td>
</tr>
</tbody>
</table>

To develop spring-based mechanical hybrid technology, General Motors has sponsored a research team at the University of Dayton. This paper focuses on key developments of the ongoing project. Section 2 is an in-depth look at prior developments that pertain to strain based mechanical energy storage. Section 3 describes the material testing that was done while searching for materials to be used as a spring. Section 4 presents a design for a mechanism capable of harvesting wasted mechanical energy from shock absorbers. Section 5 presents conclusions, contributions, and recommendations for future work.
2. Investigation of Previous Works Pertaining to Mechanical Energy Storage in Vehicles

The earliest patent regarding strain-based energy storage to be uncovered was issued to John Rogers in 1890. Shown in Figure 2 (Rogers, 1890), Rogers designed several concepts for a Spring-Propelled Vehicle. His design used a wagon-like vehicle (not described in detail) which had a series of shafts and mechanisms that allowed energy to be sent to and taken from one of the main axles. The device utilized a large spring, of which the material is not specified, to store the energy that would be used to propel the vehicle. The operator would control multiple hand levers which would determine whether the spring would be set to charge or release energy. Rogers says that his vehicle is “adapted for use of invalids and cripples who are deprived of the use of their legs, but who have the use of their arms,” implying that his vision was never to produce such a device as a suitable alternative to horse-drawn or internal combustion engine driven transportation. Additionally, Rogers mentions that this device would be suitable for children’s toys as well as road-worthy vehicles but makes no further mention as to the scale or the range of the “improved” vehicle. One can see that, in the way Rogers has designed his device as the sole source of energy, the range of the vehicle would be greatly limited.

In 1917 a patent was issued to Anna Gephart for a “Spring-Motor-Driven Vehicle,” shown in Figure 3 (Gephart, 1917). This design is similar to Rogers’ in that it used springs to store and release energy to an axle and had a series of mechanisms
controlled by the operator which could either engage or disengage the spring. Gephart, however, used a series of springs in rotating drums that were coaxially mounted to a central shaft. To charge the springs, she included a “rectangular” extremity whereby one can engage by “suitable wrench” the shaft used for winding the springs. The material of the springs was not specifically called out, but based on the drawings, one could infer that Gephart envisioned a type of metal spring, possibly spring steel. Also included was a mechanism to steer the vehicle, which turned the entire front axle. As with Rogers’ patent, range of the vehicle could be an issue. Also, the input required to wind the springs would be considerable and that manual work would be a limiting factor in the design.

![Figure 3: Gephart's 1917 patent design](image)

Both previously discussed patents were some of the first attempts in the U.S. patent database to use energy stored using strain energy to propel a vehicle. These designs were very conceptual in nature and if actually put into practice, significant modifications would have to be made in order to make the mechanisms suitable for any practical application. As the sole means to power a vehicle, a metal coil spring has very limited potential due to its energy density. However, in 1938, a patent was issued to Emanuel

![Figure 4: Kromer’s energy storage device](image)
Kromer which used a device to improve the efficiency of an automobile by capturing wasted energy (Kromer, 1938). Kromer noticed that when braking, a vehicle’s kinetic energy is wasted as heat. His device “transferred the potential power of the momentum of a vehicle in motion into the tensioning of coil springs or into the compressing of air in tanks, or both, and utilized this kinetic energy to rotate the propeller shaft of the vehicle in starting forward or backward.” Rather than having the spring as the only source of power for the vehicle, Kromer saw that a much more practical application of strain energy was to use it to ease the burden of an internal combustion engine at the time when the most energy is needed – when starting a vehicle from rest. Again, the spring used was a traditional metal coil spring. He envisioned this device working with not only automobiles, but airplanes and boats as well. Unfortunately, nothing was discovered in which this mechanism was put to use on any significant scale.

Arthur Hayek developed a device which used wind-up energy and stored it until needed at a later time (Hayek, 1964). This device, shown in Figure 5, was portable and capable of plugging into anything which needed shaft-work, although not necessarily for an automotive application. Hayek noted that the device should employ “rubber or a rubber-like material, a mechanical arrangement for stressing the material in torsion to store mechanical energy therein, and a mechanical arrangement for the orderly discharge and use of the stored energy.” This is the earliest patent discovered in which an elastomer is said to be the ideal medium to store energy because “energy storage per unit of material is much greater in some forms of rubber than in steel.” Hayek’s design stressed the elastomeric elements in torsion rather than tension because of the compactness of this design and the energy density lost compared to axial strain was
relatively minor.

Jeremiah Black’s patent titled “Spring Power Cell for Vehicular Spring Motor” outlines a vehicle which uses banks of springs as a power source (Black, 1976). Shown in Figure 6, multiple metal coil springs are connected in parallel and used to drive his golf cart-sized vehicle. These springs would be mounted in removable “cartridges” that would need to be charged most likely by an off-board (either AC or DC) motor. By allowing the cartridges to be removable, they can be replaced with already charged cartridges to allow for near continuous operation. Similar to the very first mechanical vehicle patents, Black’s work lacked any sizing calculations which lead one to believe that while a novel design, the range and expense of his vehicle may be far from practical.

![Figure 6: Energy Cartridge Connected to the Drive Shaft](image)

Stephen Jayner was issued a patent (Jayner, 1979) on an “Automotive Energy Absorption, Storage, and Retrieval System.” As explained in the patent, this device was
similar to Kromer’s 1938 device in that it used regenerative braking to harvest kinetic energy from the moving vehicle and store it as strain energy. However, the “spring” in this case is made of an elastomeric material such as rubber. Jayner claims that the elastomeric material “can absorb approximately forty times more the amount of energy a [steel] spring can absorb, for the same size. Also, rubber weighs much less than steel.”

This design uses a grounded elastic member under uniaxial strain, a brake to hold the charged member, and two clutches to determine whether the system is charging or releasing energy. This patent is notable in that Jayner recognizes the advantages of using an elastomeric spring and develops a mechanism which can be used on an automotive scale. However, as described in the patent, his intention is to use the charge for assisting in the launch of the vehicle. Once the charge is exhausted, the device will wait until braking to recharge. It would then not release energy again until the vehicle has come to a stop. While this could dramatically reduce the energy required to get the vehicle moving, it is not a constant give-take of energy. Jayner’s device is shown in Figure 7. This patent was of great interest to the research team because it accomplishes one of the team’s original goals.

Figure 7: Jayner’s Launch Assist Device
The works of Lionel Hoppie, an engineer with the Eaton Corporation, is of particular interest to the University of Dayton Research Team. He holds seven patents, ranging from 1981 through 1985, which pertain to regenerative breaking and energy storage using elastomeric members in torsion to store energy and then release it back into the drivetrain of a vehicle, propelling it forward (Hoppie, 1981a, 1981b, 1981c, 1982a, 1982b, 1984, 1985). Shown below in Figure 8 is the device from his patent issued in June of 1982. This design, which had gone through many iterations and small changes, is the one in which Hoppie decides is the most promising for an automotive application. The device includes a “power isolating assembly, an infinitely variable transmission interconnecting an input shaft with an output shaft, and an energy storage assembly. The storage assembly includes a plurality of elastomeric rods mounted for rotation and connected in series between the input and output shafts.” The rubber rollers (elements 44 and 46 in Figure 8) were pre-tensioned in the axial direction which helped prevent them from “knotting” or buckling under the torsional strain. Because of the many changes to the mechanics of the design and updates to previous patents, it is clear that Hoppie fully intended to both design and engineer a road-worthy and practical device rather than merely patent a new idea for regenerative braking energy storage.

Figure 8: Hoppie’s variable ratio regenerative braking device
By engaging one clutch and disengaging the other, as well as setting the continuously variable transmission so one shaft rotated more slowly than the other, the device was able to place an additional load on the driveshaft and the wheels which would in turn slow the vehicle down. As this happened, the kinetic energy from the moving car would be stored in the rubber rollers, as they wound around their respective shafts. To release the energy, the clutches are reversed and the CVT set so the opposite shaft rotates more slowly. This has the opposite effect as when charging, and allows the stored torsional energy to assist the driveshaft, launching the vehicle forward. If the CVT was set exactly to the ratio 1:1, both shafts would rotate at equal speed, allowing the system to idle while carrying stored energy. Past mechanisms were only able to accomplish this with the use of an additional clutch and a brake to completely disengage the elastomeric member from the rest of the system.

Hoppie also conducted a significant amount of material research, focusing on the types of commercially available elastomers to be used as springs. In his 1981 paper “The Use of Elastomers in Regenerative Braking Systems” he explains his findings. The energy density of an elastic element stressed in axial tension is higher than the same element being stressed in torsion. However, Hoppie pointed out tension’s disadvantage from a packaging standpoint in an automotive application. A tensile member would need to be strained several hundred percent of its original length, which could make placing it on an existing automotive chassis a challenge. For this reason, Hoppie concluded that straining elastic elements in torsion would be the best compromise of energy density and ease of packaging.

Hoppie conducted several tests to determine the energy density and fatigue life of various elastomers. He tested many synthetics and natural rubber and concluded that natural rubber had both a higher energy density with lower hysteresis losses and a longer fatigue life. With this knowledge, he ran a test with two rods that, unstressed, were 24 inches long and 7.5 inches in diameter. At first stretching them to 3 times their relaxed length, he rotated one end 7.2 revolutions and then returned it back within 15 seconds. This was repeated 100,000 times. The data showed that hysteresis losses could be seen during the axial load but not when loading in torsion. The same samples were then
stretched to 4 times their length and the torsional test continued. This time the samples failed at 159,000 cycles. Based on this data, an elastomeric regenerative braking system is technically feasible but an improved fatigue life would be a necessity.

The research team located and contacted Lionel Hoppie. The team was interested to know what had come of his research. His response was that while he was working through some of the technical difficulties of attaching the rubber members to the device, interest by the sponsor of the project diminished and the funding ended. Reduced interest was due to the end of high gas prices during that era.

John Gill (1984) received a patent for an “Elastomeric Energy Recovery System” which includes an elastomeric energy storage device that is placed coaxially around the main propellor shaft of a vehicle, as shown in Figure 9, item 10. The energy path is defined by two planetary gear systems and two continuously variable transmissions, one at each end of the device. This system used regenerative braking to charge and then the energy is released by propelling the driveshaft. An advantage of this configuration is that the system could continuously be transferring energy to and from the driveshaft as shifting would be made very easy by the CVTs. However, with two CVTs and two planetary gear trains, is significantly more complicated and expensive as previous works. Also, the issue of premature fatigue of the elastomer from contact and friction is not addressed and could cause difficulties in a practical embodiment of this design.

Figure 9: On the left, Gill’s energy storage device around the main drive shaft. On the right, a diagram of how the elastomers would be stressed.
In 1997, Herbert Marshall was issued a patent which used a long, slender elastomeric member that was woven around a set of pulleys to capture braking energy from an automobile (shown below in Figure 10, item 33). This design allows the elastomer to be stressed in the more efficient mode of tension while keeping the packaging somewhat small (Marshall, 1997). However, what is not addressed is the issue of abrasion. At the point where the elastomer contacts the pulleys, premature fatigue could occur, dramatically reducing the lifespan of the elastomer.

The Institute of Transport Studies produced a report (Kirby et. al., 1997) entitled “An Elastomeric Energy Storage System to Improve Vehicle Efficiency.” The goal of the research was to determine whether a system using regenerative braking and elastomers would be technically feasible and cost effective. Many types of elastomers were initially reviewed including synthetic and natural rubbers. The study states, “The present findings confirm that natural rubber is the most suitable material and show that a
total volume of approximately 45 liters will be sufficient to store the equivalent kinetic energy of a car traveling at 30 miles/hour.” They also decided that storing the energy in tension was superior to torsion, despite being aware of Hoppie’s previous works. Figure 11 below shows their suggested “movable rack” configuration.

This study is the most complete of those uncovered in that it provided a feasibility analysis and accounted for certain inefficiencies. Ultimately, they concluded that fuel consumption could be drastically reduced and warranted further research by automotive manufacturers.

![Figure 11: Proposed movable rack design](image)

Based on these limited sources, relatively little work has been done in the field of using mechanical strain as a means of energy storage on a vehicle. The majority of patents were little more than conceptual designs that still had significant engineering obstacles to be overcome before they could be implemented in a useful manner. Lionel Hoppie’s work is the exception and his design was almost realized as a working prototype. However, interest waned and funding ran out before the device could be implemented. What these works do show, however, is that strain-based energy storage on a vehicle is not an entirely novel concept and, with fuel economy being an ever increasing concern, warrants further investigation.
3. Material Research

3.1 Theory of Strain Energy Storage

Mechanical potential energy stored in an elastic material is a function of stress ($\sigma$) and strain ($\varepsilon$). The relationship is shown below where $U$ is the stored energy.

$$U = \int F dx$$  \hspace{1cm} (1)

Where:

$$dx = L \, d\varepsilon$$ \hspace{1cm} (2) \quad \text{and} \quad F = \sigma \, A$$ \hspace{1cm} (3)

Substituting equations 2 and 3 into equation 1 yields equation 4.

$$U = AL \int_0^\varepsilon \sigma \, d\varepsilon$$ \hspace{1cm} (4)

Dividing by area (A) and length (L) yields the volumetric stored energy, $u$ (Roylance, 2001).

$$u = \int_0^{\varepsilon_{max}} \sigma \, d\varepsilon$$ \hspace{1cm} (5)

This can be seen on a stress-strain graph as the area under the curve, shown in Figure 12a. A material’s ability to store elastic energy can be characterized by its energy density, which is a ratio of the maximum energy storage potential to either the material’s weight or volume. It follows that a material with a high mechanical energy density can handle high stresses and allows high strains.
Another material property of interest is hysteresis losses. As shown in Figure 12b, a material may follow two different stress-strain curves for loading and unloading. As a material is unloaded, friction between molecules generates heat, wasting some of the stored mechanical energy. A perfectly efficient material would have no internal friction and generate no heat during the unloading process. Hysteresis losses can be determined graphically by calculating the area between the loading and unloading curves. Materials with many molecular bonds tend to have lower hysteresis losses (such as spring steel) when compared to those with looser molecular bonds (such as elastomers). Additionally, hysteresis losses are a function of time. The quicker the specimen is unloaded, the more energy is lost as heat.
A unique property of some materials, including elastomers, is stress-softening. As a viscoelastic material is strained for the first time, the stress is relatively high. However, when the material has been unloaded and then strained to the same point as in the first cycle, the stress will be significantly lower. One particular type of stress-softening is called the Mullins effect (Roland, 1988). “Physically, Mullins softening arises from adjustment of local imbalances in segment density and from contraction of the primitive path of network chain ends. The resulting more random chain configuration contributes to the relaxation of the stress.” When a specimen is loaded to less than the prior maximum, consistent elastic behavior is achieved.

The ideal material for storing mechanical energy in strain would have a high energy density, very low hysteresis losses, and predictable stress-softening that can be neutralized quickly. Additionally, a high fatigue life is needed as well as stability in temperature extremes that it may face in an automotive application.
3.2 Relative Energy Densities

The gravimetric energy densities of some common materials used to store energy are shown in Table 1 in the introduction. Gasoline has an energy density that is unlikely to be matched by any alternative means in the foreseen future. However, counteracting this high energy storage, internal combustion engines are only about 20-30% efficient due to conversion losses. While hybrid vehicles do not reduce these conversion losses, they are able to harvest energy that is dissipated by the vehicle during operation. By recapturing the wasted kinetic energy, usually by regenerative braking, and using it to assist the internal combustion engine, the efficiency of the automobile can be greatly increased. This is typically done using batteries and electric motors.

A linear approximation model, adapted from equation 5 is shown in equation 6. This assumes that a material’s stress varies linearly with respect to strain, that is $\sigma = E\varepsilon$. This model is traditionally an acceptable method to estimate energy storage in steel. This linear approximation method was used to determine the values in Table 1 of both steel and rubber from published material properties.

$$u = \frac{\sigma_Y^2}{2E} = \frac{E\varepsilon_Y^2}{2}$$ (6)

While the energy density of a battery is significantly higher than mechanical energy storage, there are some inherent disadvantages that come along with it. The large banks of batteries and electric motor are very expensive, and the number of charging cycles a battery can handle is finite. By using a different approach to the hybrid concept, a mechanical hybrid could be possible, even with springs having a significantly lower energy density than batteries. In a typical electric hybrid, the vehicle is powered completely by the battery until it has no more power or the vehicle reaches a certain cruising speed at which point the internal combustion engine turns on. In a spring-based hybrid, this is not a practical design due to the comparably small amount of total energy capable of being stored. Instead, the mechanical system and the internal combustion would always work together in parallel. When there is an opportunity for the spring to assist the engine, it does so. By using this method, a mechanical hybrid could
significantly increase the fuel economy even though the spring has a much lower energy density than a battery. Still, it is desired to use a spring with the highest energy density possible in order to reduce size and weight of the device.

3.3 Available Material Data

The American Iron and Steel Institute and Society of Automotive Engineers have long standing classification systems for steel which precisely governs the type and amount of alloy elements (Brockenbrough, 2006). The American Society of Testing and Materials has well established testing standards for determining mechanical properties of steel (ASTM, 1996, 2001). This data is readily available and material properties typically made available to the public. Because of these records, a very precise calculation can be done for determining the mechanical energy storage in various types of spring steel.

Elastomers have no such governing bodies to regulate their designation and material formulation. Often the exact makeup is specific to each manufacturer and proprietary. This makes any baseline calculations based off of published data rough at best. Additionally, it was discovered through discussion with rubber manufacturers and individual research, there are no known commercial applications in which an elastomer is used to store mechanical energy while being strained near its failure limit. Many of the modern synthetic elastomers have been developed to serve as sealing gaskets in extremely corrosive environments. Little work has been done to develop synthetic rubbers for use in energy storage applications.

The team was able to make contact with a representative from Bridgestone Tires. What was learned was that in the tire industry, manufacturers are in fact interested in a rubber that deforms under load and then returns as much energy as possible. This would serve to reduce losses at the tire’s sidewall when it is loaded and unloaded as it rotates. At first this seemed to be a promising lead. However, the level of strain involved in a tire rarely exceeds 50%. In order to achieve the maximum energy density, the team was considering the rubber to be strained near 1000%. Any data available from an existing tire application would be merely anecdotal.
After extensive searching, no existing material data was discovered on elastomers, and in particular, natural rubber. Testing would need to be done in order to confirm original energy density estimates and to get a better understanding of the other important material properties to determine whether rubber would in fact make the ideal spring for a strain-based mechanical hybrid.

3.4 Testing of Material Samples

Not only is there very little published data on the energy density of various elastomers, there is no testing procedure by which to acquire it. The ASTM has a very well defined standard for testing steel and obtaining a stress-strain curve. A similar procedure was not found for testing elastomers as was needed for the team’s intended use. In order to determine the energy density, a procedure for creating an accurate stress-strain curve would need to be created.

The first attempt to achieve a baseline energy density was to adapt an existing ASTM testing standard. The ASTM C1147 test is used to determine the strength of thermoplastics. This test was modified and black natural rubber was tested using an Instron 4486 tensile testing machine. Crosshead speed (the speed in which the top grip moves relative to the fixed bottom grip) was set to 10 inches/minute to incorporate the dynamic nature of how the rubber would be loading and unloading in the final application. Also, the shape of the specimens was changed to die-cut dog bones with section dimensions of 0.125 x 0.125 inches and a gage length of 1 inch. The stress-strain curve produced for black natural rubber is shown below in Figure 14. This black natural rubber had a published hardness of 35 Shore A, a relatively soft rubber that would allow significant strain.
Using equation 1 to calculate the area under the curve, shaded in blue, the energy density is 8.3 kJ/kg. It should be noted that these specimens broke well before its rated maximum tensile stress, suggesting that the rubber could store significantly more energy if a different procedure was used. Also the shape of the curve is non-linear, unlike steel in its elastic region. A linear approximation cannot be used for making accurate predictions as it can be when working with spring steels.

In order to reach a stress level closer to what was expected, a cyclic test was performed. Using Instron’s Bluehill software, a custom test profile was developed. This profile would increase crosshead displacement (the distance the upper grip moved relative to the stationary lower grip) by one inch each cycle before returning to zero displacement. The purpose of this was to eliminate as much stress-softening (Mullins) effects. Before Mullins effects are eliminated, a specimen would have a much higher stress at the same strain compared to a specimen that has been through stress-softening. By gradually cycling the specimens up to maximum strain, it allowed the rubber to be stretched to significantly greater strains than if it was simply pulled to maximum stress and released. Since energy storage is a
function of both stress and strain, a specimen that is stretched more can store more energy than a specimen at a lower strain but equivalent stress. Red natural rubber specimens were tested in place of the previously tested black natural rubber due to a higher published strength (McMaster-Carr part number 86085K102).

Specimens again were die-cut dog bones with a 0.125 x 0.125 inch cross section and a 1 inch gage length. Specimens were measured with a durometer to have a hardness of 34 Shore A. The stress-strain curve from this first cyclic test is shown below in Figure 16. The last cycle is marked by a red line and the area between the loading and unloading curves is shaded in red. This shaded area represents hysteresis losses.

![Stress-strain curve from the first cyclic test](image)

To find the energy that is available to be recovered, the area is calculated under the unloading curve of the last cycle. Using the trapezoidal rule of integration shown in equation 7, it was determined that the energy density of this particular type of red natural rubber is 20.7 kJ/kg, almost double that of the original energy density estimates using a linear approximation. Initially, these numbers looked promising.

$$U = \frac{1}{2} \sum (\sigma_{k+1} + \sigma_k)(\varepsilon_{k+1} - \varepsilon_k)$$  (7)
3.5 Sources of Error

Two major sources of error were identified in the experimental procedure, both pertaining to the measurement of strain. First, crosshead displacement was used as the means to measure strain rather than an extensometer. Since the gage length was 1 inch, for every inch of crosshead movement there was an additional 100% strain. An extensometer would have provided a much more accurate measurement of strain but due to the non-rigid nature of the specimens, a contact extensometer could not be attached. Still, over the extreme levels of strain, crosshead displacement provided an acceptable approximation. The second source of error, however, introduced significantly more uncertainty. From the onset of testing, there was a problem with gripping the soft rubber dog bones. If they were gripped too firmly, they would crush and fail at the grip. However, if they were gripped too loosely, the sample would slip. Pneumatic grips with an adjustable regulator were chosen because they would provide a constant pressure despite the changing cross-section of the sample during testing due to Poisson’s ratio. Although every attempt was made to find the maximum pressure without failure in the grips, slipping still occurred. Figure 17 shows a sample after the cyclic testing had been completed. The two arrows point to the marks representing the original 1 inch gage length. Unfortunately, this was deemed to be the best technique with the equipment available. While this may have introduced considerable error in the calculations, the team is confident that the calculations are on the correct order of magnitude and affirms that the energy density of rubber is significantly higher than the published values for spring steel.

Figure 17: A specimen that had slipped in the grips
3.6 Additional Observations

Despite the confirmed high energy density of natural rubber, the non-linear nature of the stress-strain curve and the inherent challenges working in both the upper and lower limits were not originally anticipated. As Figure 14 shows, the majority of the energy storage potential comes from the region where the strain rate is very high. Operating in this region, very close to the failure of the specimen, would be risky as even a small inconsistency in the loading and unloading cycle could potentially cause material failure. Also, as shown in Figure 18 and confirmed by additional research, the duty cycle of natural rubber in this extreme range is limited. The arrow points to a fatigue crack in a specimen after only 20 cycles. Clearly, this material is unfit to operate at such an extreme strain rate in an automotive application where, at minimum, tens of thousands of cycles would be necessary. Even a rubber that has a life span of tens of thousands of cycles presents design challenges. Over the life of a vehicle, the rubber spring would be cycled many more times this. One possible solution would be to have the elastomeric spring element changed at roughly the same interval that oil is changed to prevent catastrophic failure.

![Figure 18: Fatigue crack of a specimen after 20 cycles](image)

There are additional challenges while operating in the lower limit of the stress-strain curve. Until approximately 600% strain, the rubber responded fairly linearly and developed very little stress. Because of this, the lower region is capable of storing a relatively small amount of energy while needing to be strained a great deal. Using this very inefficient region of the stress-strain curve would be impractical. This leaves only
the middle region as an acceptable operating range. This region is capable of storing approximately 1/3 the total energy capacity of the entire specimen, meaning the effective energy density is reduced by a factor of three. Natural rubber is still significantly more energy dense than spring steel, but the advantage is not as great as once thought.

Other serious considerations are worth noting. No testing was done at any temperature other than ambient, but it is well documented that mechanical properties of rubber vary drastically from 0° to 50° Celsius, an approximate operating range that the material would be exposed to in typical automotive application. Also, the weight of the entire mechanism needs to be considered. While rubber weighs significantly less per unit energy than steel, the weight of the spring makes up only a small part of the entire system that would be needed to harvest and return the energy. Another factor that was not investigated is how the elastomer would react in a corrosive underbody environment. Lastly, machining rubber is very challenging and attaching a rubber spring element to a system without imparting significant (and possibly fatal) stress concentrations would prove to be a challenge. With all of these disadvantages in mind, choosing a rubber spring over a steel spring for the higher energy density alone may not be the best decision for this particular application.
4. System to Harness Energy

4.1 Background

Traditional electric hybrid vehicles such as the Toyota Prius harness the energy that is typically dissipated by the brake pads as heat. There are large amounts of energy available by using regenerative braking. Because of this, the team’s research focused on regenerative braking as the main source of harvesting wasted energy. An alternate approach is to look at another component of the automobile that dissipates kinetic energy as heat – shock absorbers.

4.2 Shock Absorber Energy Harvesting Concept

Shown below, Figure 19 is a mechanism capable of harvesting mechanical energy from the displacement of the vehicle’s suspension.

![Shock absorber energy harvester diagram](image-url)

The spring shown is representative of an automobile’s suspension spring. The device winds an elastomeric spring each time the vehicle hits a bump, forcing the wheel upward.
A lever mechanism, shown in Figure 20, is used to convert this upward motion into a pull on a cable. This cable is routed to a remote location because packaging the energy storage device next to a wheel could be problematic. Assuming the displacement is great enough, the other end of the cable is attached to a ratchet gear, which is advanced by at least one tooth.

The ratchet gear is attached to a shaft with a wind-up spool. As the shaft turns, a steel cable is wound around the spool. The other end of the cable is attached to an elastomeric spring which is fixed to ground. As the cable wraps up, the spring is stretched, thus storing energy. The spool is tapered because of the increasing amount of force needed to displace the spring as its tension increases. This would keep the vehicle’s ride from stiffening as more energy is stored while allowing for a near constant torque to be released from the system despite the state of the charge. The geometry of the spool would be tapered to the stress-strain curve of the elastomer used as a spring.

A primary concern is that an entirely new suspension would need to be designed around this mechanism. In a traditional suspension, a car’s spring constant does not change and is not directionally dependent. Energy is dissipated as heat by the shock absorber, taken out of the system on both the up and down strokes. This is not the case in the proposed mechanism. The vehicle’s shock absorber would no longer be necessary (or could be reduced in size) as energy would be transferred from the vertical displacement to the tensile spring via the cable. However, the system would now only be dissipating
energy as the wheel moves upward. On this upstroke, the system’s spring constant would be the sum of both the car’s coil spring and the resistance from the tensile spring being stretched to store energy. Once the wheel begins to return to its starting position, the energy harvesting mechanism is no longer engaged and the system’s spring constant would only be that of the car’s coil spring. The spring constant for the new suspension would change based on direction of movement. It is shown in Figure 21 that a system such as this, with a directionally dependent spring constant, has the ability to dissipate energy without the need of a conventional dashpot. Shown in solid red is the displacement of the spring with different spring constants for the up and down strokes. The dotted line represents the undamped displacement of the vehicle with a suspension having a single spring constant. Notice that when the spring has two different constants, it resembles a spring-dashpot system. Nevertheless, developing such a system would have significant design challenge. An additional challenge that has not been addressed is developing the system which delivers the stored energy back to the wheels to propel the vehicle.

Figure 21: In red is a spring with a bilinear constant. In blue is a spring with a typical, linear constant.
4.3 Available Energy

A simple experiment was performed in order to get a rough approximation of the energy dissipated by a typical shock absorber. A camera was attached to the suspension of a vehicle and focused on a ruler fixed to wheel well. As the car hit bumps, the wheel would move relative to the ruler and a displacement could be measured. Figure 22 shows the camera mounted on the vehicle. Figure 23 shows the graphical results of the displacement when the vehicle was driven over a speed bump.

Figure 22: Experimental Setup
In order to estimate the energy dissipated by the shock absorber, several assumptions were made. First, all the energy from the displacement was recoverable. Second, the spring rate for the vehicle used was 1050 N/cm and the system at equilibrium supported one quarter of the weight of the vehicle. Given that the recorded displacement was estimated at 2 cm, the resulting bump energy dissipated is calculated to be 21.7 J. For four shocks, this equates to approximately 80 J of harvestable energy. Additionally, the mechanism to harvest the energy would most likely not be able to come close to 100% efficiency. Also, a vehicle rarely experiences such a large bump as the one observed. Because of this modest quantity of available energy, the shock absorber energy harvester was dismissed in favor of a more traditional regenerative braking concept.
5. Conclusions

While there have been a number of publications and records pertaining to the subject, very little has been done in regard to implementing a working device on a vehicle on any practical level. The works of Lionel Hoppie are the exception. Mr. Hoppie was able to show quantitatively that the idea is technically feasible and, given enough funding, could be implemented. Unfortunately, his vision never came to fruition. It was also concluded that while rubber does in fact have a significantly higher energy density than spring steel, the low fatigue life and non-linear nature of the stress strain curve would provide additional design challenges over using a conventional steel spring for strain-based energy storage.

5.1 Contributions

In order to help determine if a spring-based mechanical hybrid vehicle has been studied in the past or if the idea was entirely novel, an in-depth search was conducted on past works and patents pertaining to the topic. The U.S. patent database was extensively searched as well as scholarly journals and publications. This research provided a detailed account of the history of strain-based mechanical energy storage. In addition to past research, testing was done to determine the energy density of natural rubber. Since no formal testing protocol existed, experiments were developed that were able to provide useful qualitative estimates to be compared with spring steel. Lastly, a novel design was conceptualized for converting wasted mechanical energy at a vehicle’s shock absorbers into stored strain energy.

5.2 Recommendations

In the process of confirming the high energy density of natural rubber relative to steel, several undesirable characteristics were discovered, such as the non-linear nature of the stress strain curve and fatigue cracking at high levels of strain. Because of these shortcomings of hyperelastics, the research team should proceed cautiously toward its
implementation. The weight savings of rubber vs. spring steel is substantial. However, when the rest of the system is considered, the weight savings becomes less significant and additional design challenges may overshadow the potentially higher energy density of rubber. Also, while mechanical energy is wasted at the suspension, the amount of available energy is relatively small when compared to regenerative braking. Shock absorber energy recovery systems may be more suited towards electric hybrids where a system is already in place to easily store and release captured energy.
Bibliography


