

# ENERGY HARVESTING FOR TIRE PRESSURE MONITORING SYSTEMS: DESIGN CONSIDERATIONS

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**Abstract:** As of September 2007, all cars sold in the United States must be equipped with a Tire Pressure Monitoring System (TPMS). Pending legislation in the European Union and some Asian countries makes universal adoption likely in many parts of the world. Given this large mandated market along with the fact that current TPMS modules require a battery for operation, interest in energy harvesters for TPMS is high. All TPMS modules currently on the market attach to the rim or valve stem rather than the tire. The focus of this paper is to explore the application requirements, feasibility, and design considerations for rim and valve stem based energy harvesters to replace the battery in TPMS modules. The energy input along with the application requirements make a MEMS based design highly impractical. However, a technical solution to the problem that meets the current requirements from the energy available is feasible if difficult considering some of the extreme requirements.

**Key words:** Tire Pressure Monitoring, TPMS, Inertial Energy Harvesting

## 1. INTRODUCTION

A Tire Pressure Monitoring System (TPMS) consists of a wireless Tire Pressure Sensor (TPS) module inside each tire and a single receiver in the car. As of September 1<sup>st</sup>, 2007 all light vehicles sold in the United States must be equipped with a TPMS as a result of the TREAD Act [1]. The European Union and a number of Asian countries are currently considering TPMS related legislation. TPMS modules currently on the market are attached to the inside of the valve stem with a very few exceptions. An example TPMS module is shown in Figure 1. The top image shows a module, and the bottom image indicates how the module is mounted to the rim. Most modules consist of 5 basic physical elements: a pressure sensor, a motion sensor or accelerometer, circuitry (sense circuitry, microcontroller, RF transmitter, etc.), a coin cell battery, and packaging. Some of these elements can be integrated into a single part. For example, Figure 2 shows the LV Sensors' *iTPS*<sup>TM</sup> product which integrates a pressure sensor, two-axis accelerometer, and all the electronics except an antenna and a few passive components.

Virtually all TPMS modules currently on the market are powered by coin cell batteries. These batteries must support 10 years operation as the module does not get replaced when the tires are replaced. The CR2450 is a commonly used coin cell battery which has a capacity of roughly 600 mAh. Module integrators are moving to smaller batteries with the CR2050 (330 mAh) being a common option. Although energy budgets differ depending on the state machine prescribed by different car makers, generally

the RF transmission and sleep state consume most of the charge.

Recently, there has been significant interest in replacing the battery in TPMS modules with an energy harvester [2-4]. There are at least three motivations to remove the battery: 1) 10 years is not sufficient in some cases, 2) car makers are concerned with warranty costs if batteries do not last as long as expected, 3) in some usage scenarios, such as in the trucking industry, batteries last much less than 10 years.



Fig. 1: A TPMS module. Top – image of a module. Bottom – indication of how a module sits on the rim. Courtesy of Beru AG.

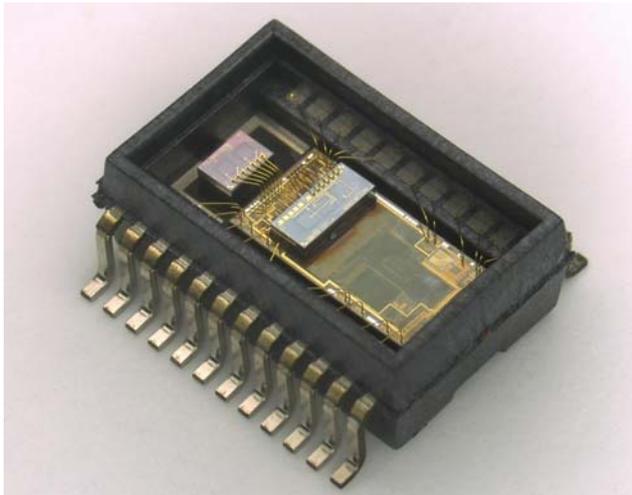


Fig. 2: LV Sensors' iTPS™ product.

Although all TPMS modules currently on the market attach to either the valve stem or rim, some companies are working on systems that mount to the inside surface of the tire [4]. Clearly, the environment on the inside surface of a tire is much different than on the rim, and so these two systems need to be treated separately.

The objective of this paper is to discuss design considerations for energy harvesters targeting rim mounted TPMS modules. In order to adequately consider the design space, we must first consider the application requirements, the feasibility of the design problem, and design constraints specific to the TPMS application.

## 2. APPLICATION REQUIREMENTS

### 2.1 Energy Requirements

The primary function of a TPMS module is to periodically measure the tire pressure and report the value via an RF link to the car. However, each car maker specifies their own state machine describing how this will be done, and how often. The auto maker's state machine definition partially determines the energy requirements. The energy consumption characteristics of the hardware in the module affect the energy required to implement a specified state machine. TPS products that are more highly integrated, and more efficiently designed will be able to implement a given state machine for less total energy. Most state machines go into a sleep mode while the car is stationary for a predefined period of time. When a motion sensor detects motion, the state changes to a moving state in which the pressure is measured and transmitted much more frequently, typically about once per minute. This, of course, is an

oversimplification and there are other intermediate and special states. However, most TPMS modules will spend most of their life in either a sleep state or a standard moving state.

To implement such a state machine with an energy harvester would require an energy reservoir for continued operation in sleep mode while the car is stationary. This reservoir would need to be able to support the car in stationary mode for months at a time. Given the very tight cost requirements (see section 2.5 below), it seems unlikely that a backup energy reservoir could be included. We assume a simple ceramic capacitor large enough to supply only one or two transmissions. In this case, the state machine needs to be altered as there can be no operation while the car is stationary for extended periods. The assumed operating scenario is that as the car moves, energy is built up in the capacitor until there is enough to support a transmission. At that time a pressure measurement is made and the data is transmitted. The energy stored in the capacitor then begins to build back up. In this case, the overall energy used during a sleep mode is either insignificant or non-existent.

The primary requirement is the amount of energy needed for a single measurement and transmission. In fact, the measurement energy is generally very small compared to the energy needed for a RF transmission. Again, each car maker differs in how much data is transmitted, the data rate, and how often a transmission must occur. Nevertheless, the requirements fall within a finite range. The data rate will usually be either 4200 or 9600 baud. The number of bytes per transmission generally varies from 12 to 90. This gives a range of 10 to 75 mSec per transmission. An assumption of 30 mSec per transmission will provide for a rough estimate of energy requirements. Generally, a transmission must occur once per minute, however, some specifications call for periods of 30 seconds or 2 minutes. The transmitter current will also vary, but is generally between 10 and 15 mA. So, as a standard base case let us assume a 30 mSec transmission every minute requiring 12.5 mA of current. This base case then requires 375  $\mu$ C per transmission. At a supply voltage of 3 volts, that is 1.125 mJ per minute. Of course, this does not account for the energy required for measurements, but as this is small, it does give a rough estimate of the energy required for TPMS system operation.

### 2.2 Operating Speed

Given the fact that the energy harvester based TPMS system will not be operating when the car is stationary, the operating speed requirements are usually listed as two separate specifications: time or distance to first transmission, and top operating speed.

A standard requirement for distance to first transmission is about 200 meters, or 100 tire revolutions. The top operating speed will be something close to 300 km/hr. Given these requirements, the energy harvester needs to generate at least 1.2 mJ within the first 100 tire revolutions, which occur at very slow speeds.

### 2.3 Operating Life

Current systems are generally required to last 10 years. An energy harvester based solution must significantly improve on this, lasting 15 years or more. Assuming 20,000 km/year and 2 meters per tire revolution, the expected lifetime would be approximately 150 million tire revolutions.

### 2.4 Size / Weight Constraints

Modules vary in size. However, a module similar to the one shown in Figure 1 measures approximately 40 - 60 mm in length (tangential direction), 25 - 30 mm in width (axial direction), and 8 - 10 mm in height (radial direction). The dimension with the least flexibility from an application point of view is the smallest one, the height. Because of the large centripetal loads, the total weight of the module is critically important. A standard maximum weight is approximately 25 grams, however, the trend is to move to lighter modules. Perhaps the more important weight consideration for an energy harvester is the battery that it would replace. A CR 2450 battery weighs about 6.3 grams while a CR 2050 weighs about 4 grams.

### 2.5 Cost Requirements

It is difficult to accurately specify cost requirements as this information tends to be highly confidential between supplier and buyer. However, an energy harvester would be competing with the installed cost of a battery. While there are advantages to the energy harvesting solution, those will not outweigh a large cost increase. Coin cell batteries are very inexpensive in large volumes. To be competitive, an energy harvester should probably not cost more than one US dollar.

### 2.6 Alignment

The alignment of the part is a requirement that may often be overlooked, but is very important from a design perspective. Alignment axes are shown in Figure 3. The part must operate properly being misaligned by  $36^\circ$  about the X axis (tangential direction) and  $9^\circ$  about the Y axis (axial direction). While this is a typical set of alignment requirements for current modules, there is a desire for valve stem based energy harvester designs that are independent of alignment.

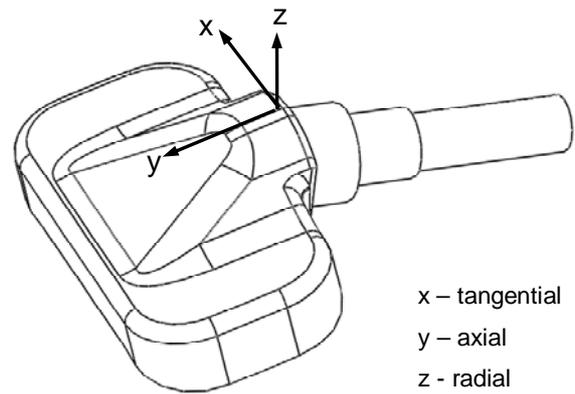


Fig. 3: Alignment axes.

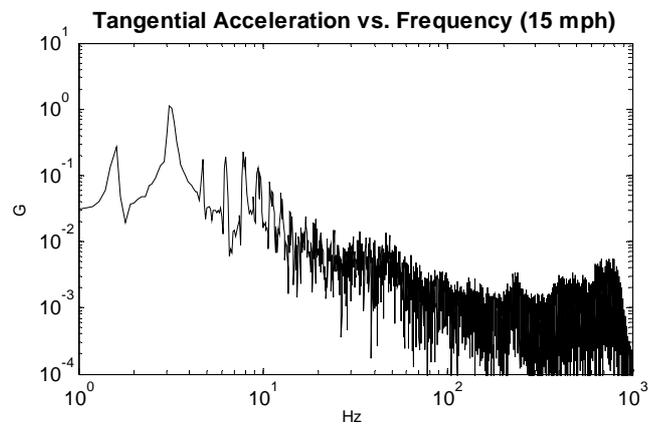


Fig. 4: Tangential acceleration spectrum at 15 mph.

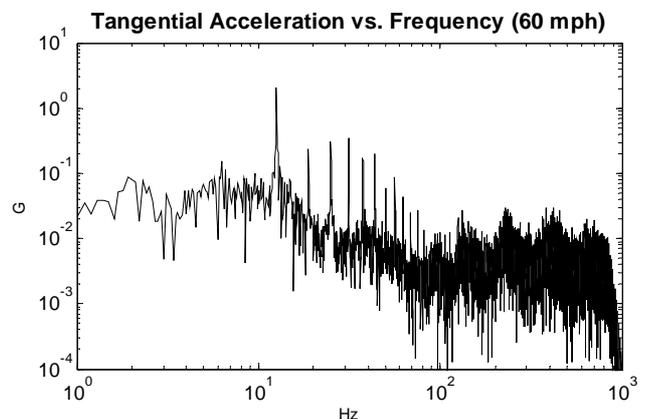


Fig. 5: Tangential acceleration spectrum at 60 mph.

## 3. FEASIBILITY

### 3.1 Inertial Input

Figures 4 and 5 show measured acceleration inputs at different rotation speeds. Two important characteristics are evident. First, as one would expect, the largest excitation in terms of acceleration is at the wheel's rotation frequency, or at the first harmonic of

the rotation frequency. (As the wheel rotates through the earth's gravity, it sees a +/- 1G acceleration signal.) Second, higher frequency vibrations are not stable in terms of frequency, and are of very low amplitude at slow speeds. These two considerations make a design that relies primarily on resonance unlikely to be robust over a wide speed range.

### 3.2 Estimates of Energy Output

It is convenient to specify power generation in units of energy per wheel revolution ( $E_{rev}$ ). Assuming inertial excitation of the energy harvester, and a non-resonant energy harvester, the very simple equation (1) below for energy available applies. This equation assumes that all of the energy being converted originates from the fundamental rotation frequency. Note that because this is a non-resonant system, the standard concept of efficiency applies [5].

$$E_{cyc} = 2\eta mAx_{pp} \tag{1}$$

where  $E_{cyc}$  is the energy per cycle,  $\eta$  is the efficiency of conversion,  $m$  is the oscillating mass,  $A$  is the driving acceleration (one G in this case), and  $x_{pp}$  is the peak to peak displacement. If there are no artificial constraints,  $x_{pp} = 2A^2/\omega^2$  where  $\omega$  is the circular frequency of oscillation.

Figure 6 plots the energy per cycle versus frequency for different masses. The plot assumes a constant 5% total efficiency over all frequencies, which is generous, but reasonable, for a non-resonant system. It furthermore assumes that the displacement of the proof mass is limited only by the frequency of oscillation, not by artificial constraints such as limit stops. The energy per revolution required to generate a 1.2 mJ transmission every minute is superimposed on the graph. Figure 6 indicates that a proof mass on the order of at least 1 gram is necessary, which is just less than 0.5 cm<sup>3</sup> of silicon. This, of course, is completely unreasonable for a silicon based MEMS implementation. Furthermore, at 10 km/hr, the peak to peak displacement of the proof mass would be 26 mm, again much too large for a MEMS implementation. Figure 7 implements constraints on the peak to peak displacement, and assumes a proof mass of 5 grams. The same 5% efficiency assumption applies. Figure 7 indicates that a proof mass of 5 grams with a 5 mm peak to peak displacement would generate enough energy for successful operation.

These numbers clearly rule out MEMS implementations. In fact, the only way to make a MEMS implementation look attractive is to play with the application requirements to set up a situation where significantly less energy will suffice. This of course opens the door to smaller and cheaper batteries.

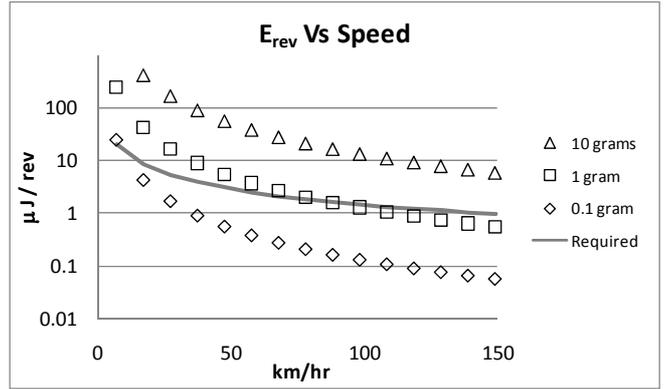


Fig. 6: Energy per tire revolution vs. speed for different proof masses. Assumes 5% constant efficiency and no limit on proof mass displacement.

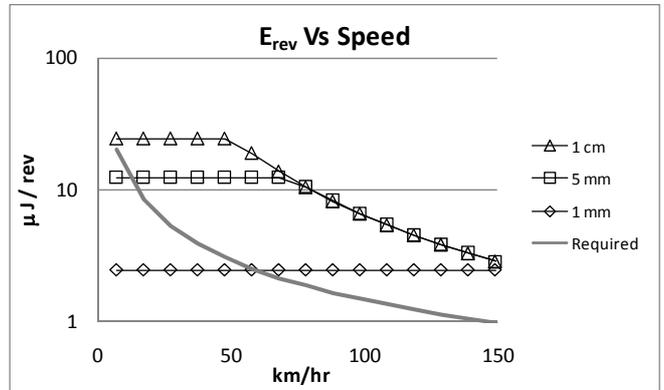


Fig. 7: Energy per tire revolution vs. speed for different displacement limits. Assumes 5% constant efficiency and a 5 gram proof mass.

A few comments on the behavior of real implementations might be in order here. First, there really is more energy input to the system than just the +/- 1G signal from the fundamental rolling frequency at medium and high speeds. In practice this may increase the energy output of the harvester by as much as a factor of 2. However, at low speeds, where the energy requirements are most challenging, almost no extra energy is available. So, the analysis presented, does accurately apply to the design problem. Second, equation (1) assumes a  $1/\omega^2$  decline in energy per revolution. However, two competing factors are at play as the speed increases. As already mentioned, the energy contribution from harmonics and road noise increases, which tends to improve the energy output. However, at some speed the large static centripetal acceleration typically begins to impede harvester performance, which causes a very fast drop in energy output. This can happen because some of the static centripetal acceleration couples into the axis of motion due to imperfect alignment. It can also occur due to increasing out of plane loads on flexures or rolling or sliding surfaces. One way to view this phenomenon in

a test system is to measure the time between successive RF transmissions. Figure 8 shows experimental data indicating the time between transmissions. The energy required for each transmission in this graph is roughly 1 mJ. As the car speeds up, the time between transmissions goes down until some high speed threshold is reached at which point the time between transmissions begins to rise. Above 200 km/hr the time between transmissions rises very rapidly.

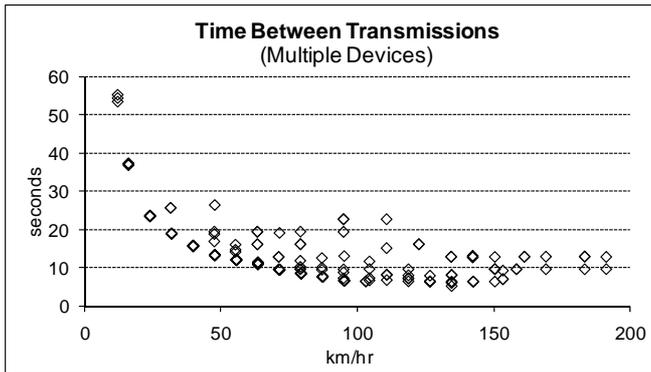


Fig. 8: Experimental data showing the time between transmissions for a rim mounted energy harvester.

#### 4. DESIGN CONSIDERATIONS

The standard energy harvesting design challenges also apply to an inertial generator for TPMS. For example, especially with low frequency excitation, source to load impedance and voltage mismatches can be extreme. Power conditioning circuitry must be designed to deal with these mismatches, optimize power transfer to the load, and consume extremely little power. However, perhaps the most challenging design considerations for TPMS are not these common ones.

##### 4.1 Off Axis Accelerations

The TPMS module sees very high static accelerations on top of a +/- 1G signal in the radial direction, and a +/- 1G signal centered (or close to centered) about zero in the tangential direction (see Figure 3). At 120 km/hr, the radial acceleration is usually over 200 G. An inertial energy harvester must be able to generate energy from a 1G alternating acceleration either with a static acceleration greater than 200 G superimposed, or with a 200 G static acceleration in the orthogonal axis. The latter case means that the system must be extremely stiff in one dimension and very soft in the orthogonal dimension.

##### 4.2 Shock

The TPMS energy harvester must be able to withstand a 5000 G shock pulse. Typically, parts

designed to withstand shocks this size have a much higher stiffness to mass ratio (natural frequency). Immunity to this shock level is difficult to achieve in a system that must be very compliant to generate sufficient energy.

##### 4.3 Alignment

The misalignment constraints may not seem particularly difficult. However, considering the large imbalance in acceleration in orthogonal axes, they are quite severe. Assume that a seismic mass is translating back and forth in the tangential direction due to the +/- 1 G excitation. At 120 km/hr, the radial acceleration is greater than 200 G. If the module is misaligned by 1 degree about the X axis, 3.5 G of static acceleration will couple into the axis of motion. This, of course, would swamp the +/- 1 G signal. So, the energy harvester must be capable of either extracting energy from a small AC excitation on top a large DC excitation, or must be self-aligning to within less than 1 degree.

##### 4.4 Size and Weight Constraints

Of course size and weight constraints are very common to energy harvester design in general. Unfortunately for TPMS, the dimension with the tightest constraint is the one that would allow the most design freedom. Perhaps embarrassingly for those now working on this problem, it has been solved many years ago [6]. A picture of an energy harvester for TPMS by Epic Technologies is shown in Figure 9. However, this design does not suffice for current TPMS modules. First, the mass of the energy harvester is 30 grams, much too large. More importantly, the piezoelectric beam is oriented in the radial direction. This solves the problem of the large static bias acceleration, and misalignment, but cannot be implemented for current modules because there are only about 5 mm to work with in the radial dimension. Any solution to the large static acceleration problem and the alignment problem must work within this size constraint.

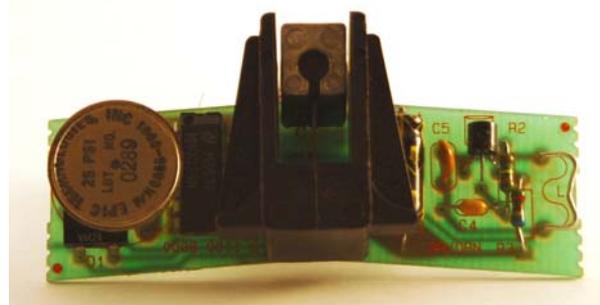


Fig. 9: Tire pressure sensor and energy harvester by Epic Technologies [6].

## 5. DISCUSSION

We can envision at least three different approaches to the existing design challenges detailed above. First, we could pursue creative inertial design solutions that fit within the constraints and produce sufficient power over a large speed range for a very low cost. Second, we could look at non-inertial methods to generate sufficient energy in this environment. This option has been pursued [7-8], but is outside the scope of this paper. And third, we could push back on the requirements to try and open up other inertial design solutions.

While all of the design constraints reduce the set of potential designs, there are two requirements that severely limit the design space and could perhaps be relaxed or overcome. The first is the requirement to operate at very low speeds. The second is the amount of time required for a RF transmission. One way to get around the low speed constraint is to implement a rechargeable battery. But this requires technology that is not readily available on the market. Very low capacity rechargeable batteries that are currently available are no cheaper than the primary batteries used for TPMS. Furthermore, with very few exceptions, they cannot meet the extreme environmental conditions required. This solution, therefore, requires some further technological improvement along with the economies of scale that could drive cost down. A second potential solution to the low speed problem is to use a much smaller primary battery that would only power the TPMS module at low speed. However, reducing the size of a primary battery beyond the common 20 mm and 16 mm coin cell size may not necessarily reduce cost. So, it is not clear whether this solution would be viable from a price perspective.

Regarding the second requirement, the amount of transmission time could be relaxed by reducing the amount of data or by increasing the data rate. Increasing the data rate to 100 kbps is certainly achievable from a technical perspective. However, the car manufacturers will ultimately determine the amount of data and the data rate required, and they are not easily persuaded to change their specifications.

## 4. CONCLUSION

This paper has presented many problems and challenges, and no solutions. As such, the only conclusions that can be drawn refer to the design requirements and challenges rather than to solutions and experimental results. Indeed, the intent is to outline the problem and make explicit design constraints for this specific application that may not be apparent. While the wheel of a car is an energy rich

environment, the requirements for a TPMS energy harvester make the design problem a significant challenge.

As is the case with virtually all energy harvesting problems, each application has its own, usually unique, excitation, and a different set of design constraints. For this reason, a one-size-fits-all energy harvester solution is exceptionally difficult, and perhaps impossible. The real challenge is to adapt existing solutions to each application environment.

## REFERENCES

- [1] <http://www-nrd.nhtsa.dot.gov/pdf/nrd-01/SAE/SAE2001/Weinstein.PDF>, Website accessed on September 30, 2008.
- [2] Kuchler G 2006 Battery-free Tire Information Systems *Intelligent Tire Conference*, October 2006, Dearborn MI USA
- [3] Lohndörf M, Kvisterøy T, Westby E, Halvorsen E 2007 Evaluation of Energy Harvesting Concepts for Tire Pressure Monitoring Systems *Technical Digest PowerMEMS 2007 (Freiburg, Germany, 28-29 November 2007)* 331-334
- [4] Bös T 2008 TPMS: Challenges for Component Supplier *Intelligent Tire Conference*, April 2008, Dearborn MI USA
- [5] Roundy S 2005 On the Effectiveness of Vibration Based Energy Scavenging *Journal of Intelligent Material Systems and Structures*, **16** 809 – 823
- [6] Nowicki D, Munroe C 1996 Data Logging Tire Monitor with Condition Predictive Capabilities and Integrity Checking *US Patent 5,559,484*
- [7] Balasubramaniam M, Fortin J, Smith W, Luo H 2006 Energy Harvesting System, Apparatus and Method *US Patent 7,116,036*
- [8] Roundy S, Bryzek J, Ray C, Malaga M, Brown D 2007 Power Generation Utilizing Tire Pressure Changes *US Patent 7,260,984*