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TIRE PRESSURE MONITORING SYSTEMS (TPMS): RECENT ADVANCEMENT AND POTENTIAL ENERGY HARVESTING SOLUTIONS

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ABSTRACT

This paper presents recent advancements and new features integrated into tire pressure monitoring systems (TPMS). The increase in consumption and the application of new environmental standards raise the question of energy recovery to power these TPMS. A state-of-the-art review of potential energy sources inside and outside a tire has been conducted, and the main results are presented. Based on this study, the energy harvesting technique based on a thermoelectric generator (TEG) appears to be a promising technique. A real-world test was conducted, revealing a temperature gradient of more than 10 degrees between the inside and outside of a tire. This demonstrates the potential of a solution using TEG to electrically power TPMS.

KEYWORDS

Tire Pressure Monitoring, Energy harvesting, Thermo-generator, metal valve, sensor

INTRODUCTION

Car manufacturers are integrating wireless sensors into their vehicles to improve efficiency and safety in automotive transportation. One of these sensors, installed in every new vehicle, is the TPMS (Tire Pressure Monitoring System). Adopted following the controversy surrounding the failures of Ford-Firestone tires [1], the TREAD Act mandates the installation of TPMS in all new vehicles in the USA. In addition to preventing tire failures and informing drivers of under-inflated tires, this system aims to enhance road safety and energy efficiency, as proper tire pressure optimizes traction, reduces braking distances, and decreases tire rolling resistance. As a result of these benefits, similar legislation has been adopted in the European Union, which makes the use of TPMS mandatory for all new vehicles as of 2012, the information regarding the pressure of all four vehicle tires must be transmitted to the dashboard every 10 minutes [2].

A TPMS is mounted on the rim of a car, as shown in Figure 1 (the right figure shows the TPMS mounted inside the tire, while the left figure illustrates the TPMS mounted on the rim). In most cases, these sensors consist of several modules, including the housing, the pressure sensor, the accelerometer, a microcontroller, an RF (radio frequency) transmitter at 433/315MHz, an LF (low frequency) receiver at 125KHz, and a non-rechargeable battery. It is now possible to integrate all these functionalities into one integrated circuit (such as Infineon's SP4X).

TPMS are currently powered by non-rechargeable batteries with a lifespan of 10 years [3]. The power consumption of TPMS has continually decreased, allowing for a reduction in battery size. For instance, before 2016, Continental's TG1x sensors were powered by a larger

CR2050 Lithium battery (mass: 4.2g, diameter: 20 mm, thickness: 5.0 mm). In recent versions, such as the TGE 2.0(Continental's TPMS acronym), the smaller CR2032 battery (mass: 3g, diameter: 20 mm, thickness: 3.2 mm) is used.

Advancements in electronics have enabled miniaturization and the integration of new features, with research focusing on areas such as Tread Depth Monitoring (TDM) and bidirectional communication using Bluetooth Low Energy (BLE). The potential increase in consumption due to these new features and the application of new environmental standards raise the question of energy harvesting to power TPMS as a replacement for primary batteries.

Significant work has been done on energy harvesting to power TPMS [4]. An analysis of 177 patents on this subject, published between 1998 and 2021, shows a predominance of piezoelectricity-based technique (Figure 2). However, the lack of commercial products suggests that the intense mechanical constraints do not allow for the required reliability. To a lesser extent, there are methods based on electromagnetic coupling. It is noteworthy that thermoelectric generation (TEG) has not garnered much interest. In addition to avoiding mechanical constraints, this method may be a viable solution for powering TPMS [5].

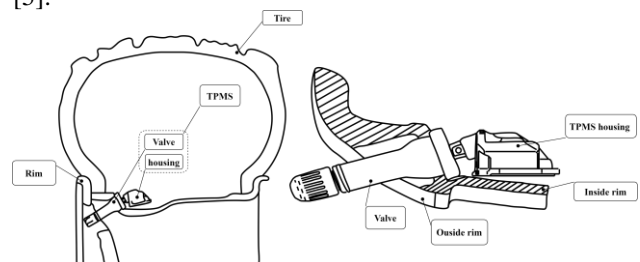


Figure 1: The position of a TPMS mounted inside the tires (left) and a view of the TPMS installed on the rim (right).

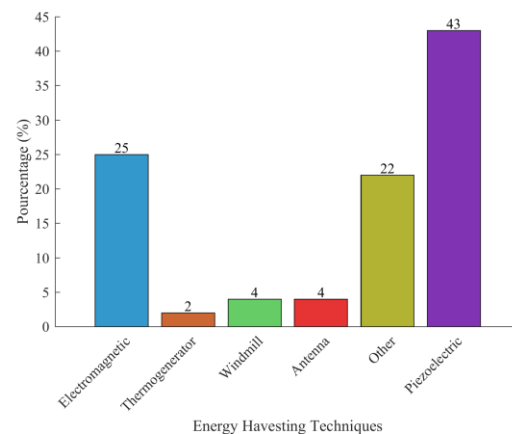


Figure 2: The position of a TPMS mounted inside the tires (left) and a view of the TPMS installed on the rim (right).

The paper makes the following contributions:

- The analysis of operating modes and energy estimation of current TPMS systems
- The collection of internal and external tire temperature data
- A simplified model of a valve associated with a TEG.

The rest of this paper is organized as follows: we will analyze the state machine and energy consumption of a TPMS, then we will apply the TEG in the context of energy harvesting to power TPMS systems, and finally, we will conclude with a discussion and conclusion.

OVERVIEW AND ENERGY ESTIMATION OF A STEM-BASED TPMS

The primary function of a TPMS is to periodically collect tire pressure data and transmit it via an RF link at 315/433MHz or through a BLE link at 2.45GHz. However, to conserve energy, automakers implement this primary function using state machine. This state machine typically governs the energy consumption of a TPMS. The state machine illustrated in Figure 3 represents a simplified example of what can be implemented in a TPMS.

Generally, the state machine remains in sleep mode (which can be triggered by an LF signal) when the vehicle is stationary for a predefined period. When movement is detected by the accelerometer, the state machine switches to a localization state, where the different TPMS units are identified by an algorithm. During this localization phase, several frames are sent periodically for around 10 minutes. If the TPMS units are successfully localized, the state machine enters driving mode, where frames are transmitted every 60 seconds, for example. The state machine enters intermediate mode if no movement is detected after the localization or driving phases.

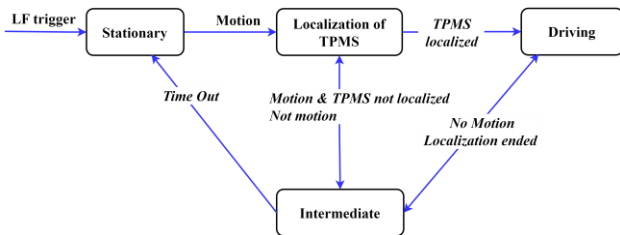


Figure 3: Example of a state machine for TPMS.

In general, most TPMS modules operate in either stationary mode or driving mode.

To implement this state machine with a TPMS powered by energy harvesting, super-capacitors, or Solid-State Batteries (SSB) would need to be integrated to temporarily store energy, allowing the TPMS to operate when the vehicle is stationary.

For our estimation, we will not take this temporary storage into account. We will assume that while the vehicle is in motion, an energy harvesting system would charge a super-capacitor or SSB, and once enough energy for RF data transmission is accumulated, pressure measurement, data processing, and data transmission will be performed.

An example of the current profile of a TPMS is

illustrated in Figure 4. This current profile varies from manufacturer to manufacturer. Generally, three main phases can be distinguished: the sleep phase (PH1), where the sensor consumes virtually no power (approximately 1.6 μ A); the data collection and processing phase (PH2), which consumes around 1.3mA; and finally, the RF transmission phase (PH3), which consumes about 10mA. Typically, data is transmitted at speeds ranging from 4200 to 9600 baud, with the number of bytes varying from 12 to 90, resulting in a transmission interval of 10 to 75ms per RF transmission. To ensure that the RF frames are received by the Central Reception Unit (CRU), the same frames are generally sent 2 to 3 times consecutively.

If a TPMS consumes currents of 1.6 μ A, 1.25mA, and 10mA during PH1, PH2, and PH3, respectively, and that the total time to complete all phases is approximately 300ms, this results in an energy consumption of about 400 μ C. Considering that a minimum voltage threshold below which the TPMS cannot operate is 1.9V, the minimum energy required to perform data collection, processing, and transmission in this specific case is approximately 700 μ J. It is important to note that this energy estimation may vary from one automotive manufacturer to another.

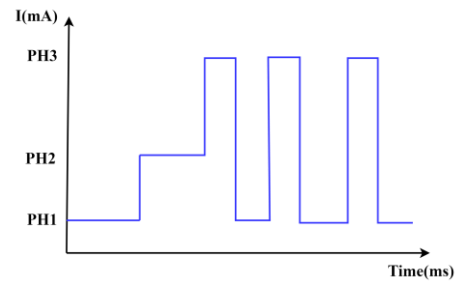


Figure 4: Example of a current profile for a TPMS.

Our investigation indicates that no modeling has been performed on the valve and no real data has been collected from vehicles.

Collection of Internal and External Tire Temperature Data:

To collect temperature data, we first equipped a Scenic vehicle (Figure 5, left) with two TPMS units from the manufacturer Continental to measure the internal and external tire temperatures as well as the speed.

The data collection took place throughout the round-trip journey between Toulouse and Albi, France, from 08AM to 5PM. The collection process was organized into three distinct phases:

- First phase (08 am – 12 am): Data was collected during the morning.
- Second phase (12 am – 2 pm): Measurements were taken during the midday break
- Third phase (3 pm – 5 pm): Data collection resumes in the afternoon.

The weather was sunny, with ambient temperatures ranging from 16°C to 33°C.

The data was transmitted via an RF link at 433 MHz to a receiver placed inside the vehicle. This setup allowed us to obtain a thermal gradient (Figure 6) throughout the

journey between Toulouse and Albi (Figure 5, right).

Figure 6 shows the thermal gradient and vehicle speed divided into several time intervals (in minutes):

- Intervals [0, 50] and [150, 178]: Correspond to the time when the vehicle traveled at speeds below 100 km/h, typical of urban driving.
- Intervals [50, 100] and [130, 150]: Represent the periods when the vehicle was on the highway, traveling at a speed of 130 km/h.
- Intervals [100, 120] and [180, 230]: Corresponding to periods when the vehicle was stationary.

Throughout the journey, a temperature gradient ranging from 0°C to 12°C was observed.

To utilize this data, a very simplified model of a valve and a TEG has been implemented.

Simplified Modeling of a metal Valve Associated with the TEG:

For simplicity, we have chosen to use an aluminum valve instead of a rubber valve. Figure 7 (left) illustrates the two types of valves along with the component housing the core of the sensor. The valve is represented by two stacked cylinders, as shown in the top view in Figure 7 (right). The thermal resistance of this valve is the sum of the thermal resistances of the two cylinders [6]:



Figure 5: Position of the external and internal sensors on the Scenic (left) and the round-trip journey from Toulouse to Albi, France.

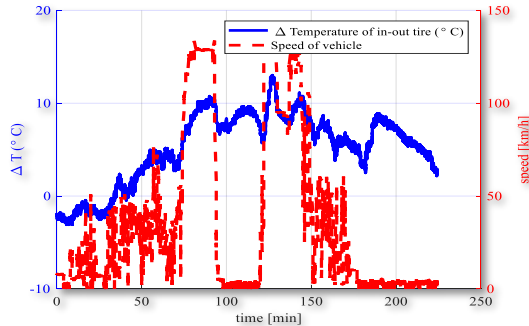


Figure 6: Representation of thermal gradient and speed as a function of time.

$$R_{th1} = \frac{1}{2\pi r_1 L_1 h_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi L_1 k} + \frac{1}{2\pi r_2 L_1 h_2} \quad (1)$$

$$R_{th2} = \frac{1}{2\pi r_1 L_2 h_1} + \frac{\ln\left(\frac{r_3}{r_1}\right)}{2\pi L_2 k} + \frac{1}{2\pi r_3 L_2 h_2} \quad (2)$$

$$R_{thT} = R_{th1} + R_{th2} \quad (3)$$

The radius r_1 (2mm), r_2 (3mm), and r_3 (4mm) represent respectively: the inner radius of cylinder 1, the

inner radius of cylinder 2, and the outer radius of cylinder 2.

The lengths of cylinder 1 and cylinder 2 are represented by L_1 (1cm) and L_2 (1.8cm) respectively. The internal and external forced convection coefficients are designated by h_1 (10) and h_2 (50) respectively. R_{th1} and R_{th2} represent the thermal resistances of cylinders 1 and 2. k (237W/m·K) is the thermal conductivity. Finally, R_{thT} represents the valve's total thermal resistance.

Figure 8 shows a very simplified thermal model consisting of a valve and a TEG. For this model, we consider a TEG with a thermal resistance of $R_{thTEG} = 33K/W$, a Seebeck coefficient of $S = 0.027V/K$, and $R = 9\Omega$ representing the internal resistance of the TEG.

We chose the TEG from the manufacturer EURECA Messtechnik GmbH, with dimensions of 9.1 x 9.1 x 2.3 mm³ since this TEG can easily be adapted to a metal valve. It is also assumed that the air in the tire can be considered as a constant temperature source applied to the TEG's surface. The maximum output power of the TEG can be calculated using equation (4).

$$P_{max} = \frac{\left(\frac{S \cdot \Delta T \cdot R_{thTEG}}{R_{thT} + R_{thTEG}}\right)^2}{4R} \quad (4)$$

Figure 9 illustrates the variation in the output voltage of the TEG and its maximum power as a function of the thermal resistance of the metal valve for a temperature gradient of 10°C. It is evident that the thermal resistance of the valve is a crucial parameter affecting the amount of power that this system can generate.

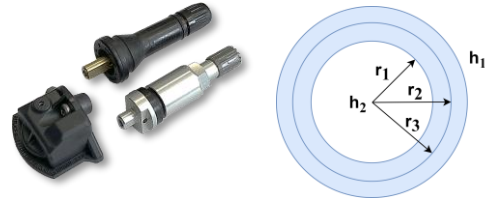


Figure 7: TPMS and the two different types of valves (left) and the top view of the metal valve (right).

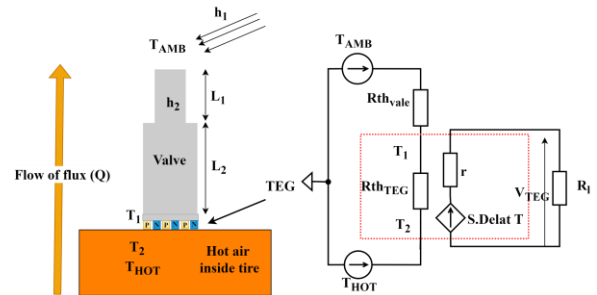


Figure 8: Highly simplified model of the TEG associated with the valve.

In our calculations, we obtained a thermal resistance of 48 W/K for a valve made solely of cylinder 2 (L_2) and 1000 W/K for a valve composed of two cylinders ($L_1 + L_2$). For a temperature gradient of 10°C, a power output of 325 μW could be produced, as shown in Figure 10. This power indicates that it would take at least 2.15 seconds to

store enough energy to perform PH1, PH2, and PH3.

RESULT AND DISCUSSION

In this paper, we studied the case of a metal valve to simplify our analysis. A valve with a plastic cap would allow the generation of 325 μW of power with a temperature gradient of 10°C. The plastic cap acts as a good thermal insulator, effectively reducing the valve to a single cylinder characterized by L_2 , r_1 , and r_3 .

For this specific case, considering an energy storage time of 2.15 seconds, we obtain the minimum energy required to operate a TPMS. This storage time is shorter than the data transmission frequency (16s, 32s, or 64s) of the TPMS to the CRU during specific use cases, such as when localizing the four TPMS units.

For the case of a valve without a cap, the valve consists of two cylinders. In this case, the power generated is 2.5 μW . It would require an energy storage time of 280 seconds to accumulate the minimum energy needed to operate a TPMS.

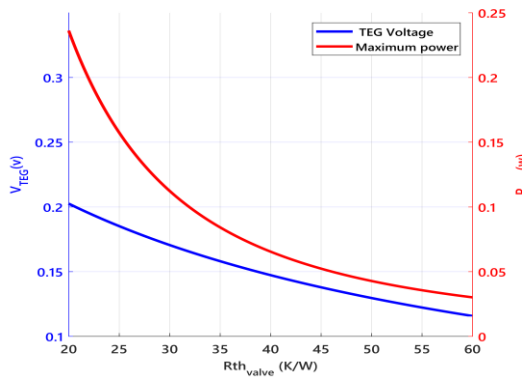


Figure 9: Voltage and power of TEG as a function of thermal resistance of the valve for a $\Delta T = 10^\circ\text{C}$.

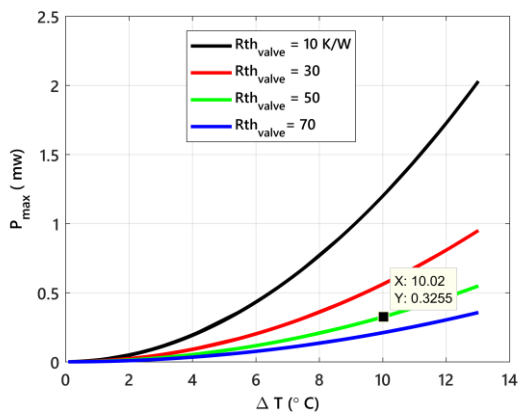


Figure 10: Power as a function of temperature gradient for different thermal resistance of the valve.

Other types of TEGs can be tested, including circular and rectangular types [5], etc. The parameters to consider when choosing a TEG are its dimensions, its Seebeck coefficient, and its thermal resistance. By adjusting these parameters, the output power of the TEG could be increased. In addition to the previous parameters, the temperature gradient helps to boost the output power of the TEG. If the convection inside the tire is efficient, it won't be necessary to add a heatsink to the TEG. The maximum

temperature gradient obtained during vehicle data collection was 12°C. During this data collection, we assumed that the ambient temperature was the one present at the valve. However, considering forced convection due to the fact that a moving wheel is blown by the wind, and the air circulation inside the tire when the wheel makes contact with the ground, we also assume air circulation occurs. Based on this hypothesis, we could expect a relatively significant temperature gradient.

CONCLUSION

We estimated the minimum amount of energy required for a TPMS to collect, process, and transmit data through an RF link at 315/433MHz. It was determined that a minimum voltage of 1.9V and 0.7mJ of energy would be necessary to operate a TPMS. Due to the lack of available data on tire conditions, particularly temperature data during typical vehicle driving conditions, a data collection campaign was conducted to gather internal and external tire temperature. A maximum temperature gradient of 12°C was observed. We applied these temperature data to a simplified model of the valve associated with the TEG. By confirming the hypotheses mentioned throughout this work through experiments, the solution based on the TEG could offer promising prospects.

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