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Development of a Dynamic Sensor for Monitoring Tyre Pressure

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Abstract: *Improperly inflated tyres contribute immensely to road accidents in Nigeria. 36% of passenger vehicles on the road are under-inflated tyre while about 20% are under-inflated. The aim of this project is to develop a dynamic sensor for regulating tyre pressure in automobiles. This design utilizes the development an embedded dynamic sensor system comprising of a sensor and display unit connected wirelessly for regulating tyre pressure. A sensor is attached to the tyre to send the tyre pressure in real time to a monitoring station located in the car's dash board to display the tyre air pressure measurements via a communication system implementation. The dynamic sensor consists of Arduino Development Board/ Microcontroller Unit hardware, the pressure sensor, NRFL201 and a 1602 Liquid crystal Display and the firmware for code running on the hardware. The firmware is an Arduino integrated development environment (IDE) that is a cross-platform application written in the programming language Java was used on to run the hardware for the system to work hand in hand effortlessly. This project will help ensure that the tyre pressure is always within the required standard.*

Keywords: Arduino IDE, Embedded dynamic sensor, TPMS, CIP, Wireless data transmission

1. INTRODUCTION

Often pressure loss in tyres is a result of natural permeation of the gas through the elastic rubber, road conditions (such as potholes), and seasonal changes in temperature that result to drastic accidents. For every drop of 10 ºF, tyre pressure drops by 1 psi. Improperly inflated tyres cause serious problems on passenger vehicles. 80% of passenger vehicles on the road have at least one under-inflated tyre [7, 11] and 36% of passenger cars have at least one tyre that is 20% or more under-inflated [8]. Most vehicle owners are unaware of the fact that their tyres are not at the correct pressures because it is difficult to determine the tyre pressure visually; a tyre that is properly inflated to the correct pressure looks very similar to one that is either over-inflated or under-inflated. According to the Rubber Manufacturing Association (RMA) survey, 80% of people are unsure of how to check their tyre pressures.

Tyre designers attributes the root cause of improperly-inflated tyres is due to vehicle owners not knowing proper tyre pressures for certain conditions, difficulty finding an air pump, lack of pressure measuring device while the vehicle owner's lose money due to increased tyre wear arising from improper inflated tyres [3,9]. It is this problem that this work seeks to address.

A Tyre Pressure Monitoring System (TPMS) is a safety device that measures, identifies and warns the driver when one or more tyres is significantly under-inflated. Flat tyre occurs for every 46,000 miles (74,029 kilometres) driven with more than half due to under-inflation. 75% of all tyre problems are due to under inflation as a slow leak or loss of pressure. A loss of 3 PSI relates to an increase of tyre wear by 1.5% and the life of the tyre is reduced by 10 % [1, 11]. Intelligent tyres, also known as smart tyres, are equipped with sensors for monitoring quantities such as air pressure, applied strain, temperature, acceleration, wheel loading, friction, and tread wear, and are expected to improve the reliability of tyres and tyre control systems such as anti-lock braking systems (ABS) [10].

A simple TPMS method is based on indirect measurements and fuses information from several different physical sensors to compute tyre pressure. [5] Proposed an indirect TPMS using wheel-speed sensors and an electronic control unit (ECU) of ABSs based on vibration and wheel radius analysis. [9] Developed an indirect TPMS using the signal from wheel speed sensors focusing on the relation between tyre pressure and tyre torsional stiffness [8]. Although indirect systems use existing sensors and are easy to install, the degree of accuracy and reliability is minimal as changes in road conditions inversely affect measured pressure. The combined pressure loss of more than two tyres is also problematic, thus calibration is often required when one or more tyres are changed, or when the pressure is adjusted [1, 5]

Conventional capacitive pressure sensors measure capacitance between two electrodes, which changes owing to applied pressure [2] has been used for direct TPMS measurements. [6] found that Nb_2O_5 has good sensitivity to applied pressure. Since the sensitivity is related to particle size, small or Nano sized particles are excellent materials for high-sensitivity pressure sensors. This sensor is cost effective and can be produced as a film which is rugged in nature and can operate in many harsh environments. However, the output capacitance is usually nonlinear with respect to input pressure changes and the sensitivity in the near-linear region is not high enough to ignore many stray capacitance effects [9]. In order to solve this problem, the touch-mode pressure sensors have been developed and are shown in figure 1. This sensor operates at the instants of two electrodes coming into contact. When two electrodes touch, the contact area increases as the external pressure increases. The advantages of the touch mode operation are good linearity in contact range, mechanical robustness, and large overload protection [11]

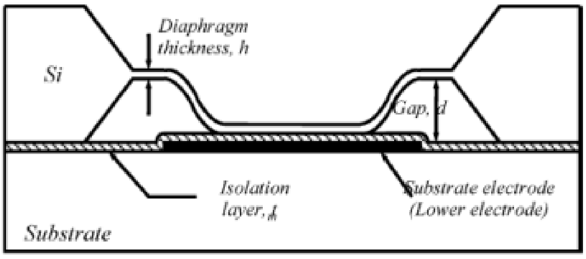

Figure 1: Touch mode [10]

Simple wireless data transmission uses the resonance of a capacitor and an inductor. Data can be converted to the resonance frequency or Q value. To enhance the function of data transmission, most wireless transmission uses an integrated circuit wireless transmitter. Most cases take advantage of the unlicensed ISM (industrial, scientific, and medical) bands, and use communication protocols such as Bluetooth, ZigBee, and IEEE 802.11. Basically, these wireless communications require a power supply to send a radio signal. Yi (2008) developed piezo-sensor-based intelligent tyre system, and used ZigBee wireless communication protocols between a sensor data processing module and a receiving unit. A small battery to power the circuits is located inside the wheel. The receiving unit with an antenna is connected to the on-board laptop.

[5] developed a wireless data transmission of the in-tyre acceleration signal made via a Datatec™ (Langenhagen, Germany) telemetry system. The transmitter and its battery are mounted on the wheel rim. The receiver antenna is placed on the car roof; the acquisition of the sensor signals is made by a DSpace Autobox™ (Michigan, USA) acquisition system. In most cases, wheel-sensor activities are autonomous of any central intelligence and typically require an accelerometer to control wake-up and sleep-mode switching to conserve battery life. [7] developed a low-power sensor for tyre pressure monitoring using low-power oscillators. It consists of four tyre modules transmitting their data via an HF-link to a central receiver, the hardware of which is shared with the remote keyless entry receiver system. However, a battery limits the operation time of the sensor and wireless communication. To guarantee an effective lifetime of 5–10 years, the battery needs to have a capacity of several hundred mAh, which increases the weight and size of the sensing system [6].

[2] developed a tyre pressure and temperature monitoring system, which continuously updates latest tyre pressure, and temperature and alert driver from time to time to avoid accidents. The system takes the readings of the tyre pressure and sends it via Bluetooth to the driver's mobile phone which serves as the display unit. The accuracy of tyre pressure and temperature is considered very important to forestall road accidents. Harvesting energy from a rotating tyre involves powering wireless devices implanted in the surface of the vehicle. Placing charge on the capacitor plates and then moving the plate's apart converts mechanical energy can into electrical energy for storage. The energy increases as more charge is induced on the capacitor. However, the capacitive generators need an initial voltage to produce power [3]. [4] Proposed an electromagnetic generator that consists of a magnet on a polyimide spring. When the generator is vibrated, there is a net movement between the magnet and housing. This relative displacement generates electrical energy by the interaction of the magnet with a planar pick-up coil. [6] Developed bender-type piezoelectric devices for micro power generator as shown in the figure 2 and figure 3.

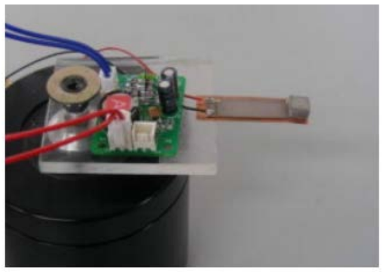

Figure 2: Two-layered piezoelectric bender device for micro power generation

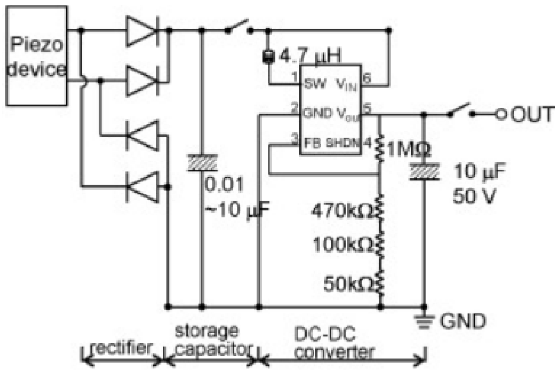

Figure 3: Systematic diagram of Two-layered piezoelectric bender device for micro-power generation

To match the external vibration frequency with the device resonant frequency, the device consists of two different thick layers, with each layer having different resonant frequency. [4] Also proposed a battery-less TPMS where piezoelectric reeds are included in the tyre sensor units and generate electricity. [1,5] demonstrated nanowire generators that are driven by an ultrasonic wave to produce continuous direct-current output for harvesting local mechanical energy produced by high-frequency vibration.

2. Materials and Methods

The dynamic sensor consists of Arduino Development Board/ Microcontroller Unit hardware, the pressure sensor, NRFL201 and a 1602 Liquid crystal Display and the firmware for code running on the hardware. The firmware is an Arduino integrated development environment (IDE) that is a cross-platform application written in the programming language Java used on to run the hardware for the system to work hand in hand effortlessly. The Arduino microcontroller board controls the tyre unit and the monitoring system integrated with fire alarm monitoring device, radio frequency transmitter and receiver demodulator; and Bluetooth modules for sending and receiving data via a 2.4GHz wireless link.

2.1 Pressure Measurement and Regulation

The tyre sensor uses a pressure sensor, a microcontroller, the power source and a NRFL201 to measures the tyre pressure. The microcontroller process and send tyre pressure to the monitor system via the NRF communication module as shown in figure 4.

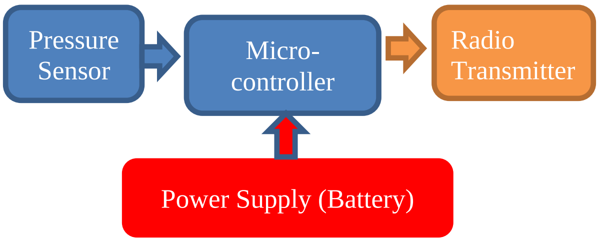

Figure 4: Tyre Sensor Hardware Flow chart

The Arduino Uno is a microcontroller board based on the ATmega328 as shown in figure 5. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analogue inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started.

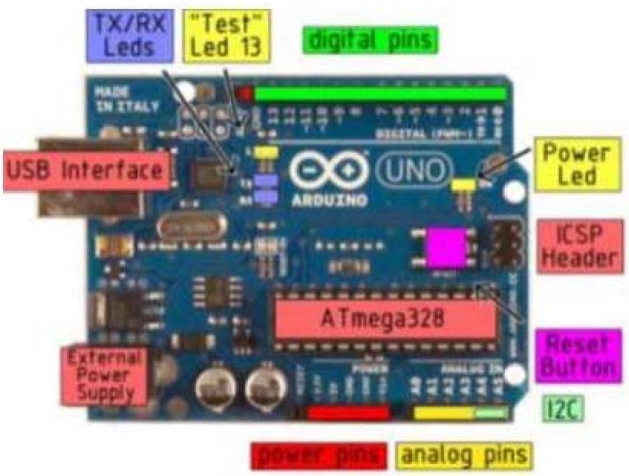

Figure 5: Arduino Development Board.

The Uno differs from all preceding boards as it uses Atmega16U2 (Atmega8U2 up to version R2) programmed as a USB-to-serial converter instead of FTDI USB-to-serial driver chip. This work uses eight of the digital pins for appliance controls, one for motion sensing to detect intruders and the second one to activate the alarm system when an intruder is detected. Table 1 shows the detailed specification of the Uno board.

Table 1: Uno Board Specification

S/N	ITEM	SPECIFICATION
1.	Chip used	ATMega328
2.	Working voltage	5v
3.	Input voltage	7 – 12v
4.	SRAM	2KB
5.	EEPROM	KB
6.	Clock speed	16MHZ
7.	Length	68.6 mm
8.	Width	53.6mm
9.	Weight	25g

The microcontroller unit used in this project is ATmega328P. It is a low-power, High performance CMOS 8-bit microcontroller with 32K bytes In-System Programmable (ISP) flash program memory and 2K bytes of EEPROM data memory. It has 32 programmable input and output lines. A microcontroller already contains all components which allow it to operate standalone, and it has been designed in particular for monitoring and/or control tasks. In consequence, in addition to the processor it includes memory, various interface controllers, one or more timers, an interrupt controller, and last but definitely not least general purpose I/O pins which allow it to directly interface to its environment. Microcontrollers also include bit operations which allow you to change one bit within a byte without touching the other bits. The MCU function to control all the peripheral attached to it, it act as the brain of the system. A Microcontroller is a single chip micro-computer that contains all the components such as the CPU, RAM, some form of ROM, I/O ports and timers. Unlike a general-purpose computer, which also includes all of these components a microcontroller is designed for a very specific task--to control a particular system. Micro controllers are sometimes called "embedded microcontrollers", which just means that they are part of an embedded system, that is, one part of a large devices or system. A Microprocessor is a general purpose digital computer with central processing unit (CPU), which contains arithmetic and logical unit (ALU) a program counter (PC), a stack pointer (SP), some working registers, a clock timing circuit, and interrupt circuit. The main disadvantage of microprocessor is that it has no on-chip memory hence a micro controller with on-board programmable ROM and I/O was adopted with MPX411 pressure sensor mounted on a break out board operational voltage of 3.3 V as shown in figure 6.

Figure 6: Pressure Sensor on a Break out Board

2.2 Wireless Communication Warning System

The nRFL201 communication module was adopted for the system under-inflation warning. The nRF24L01 is a single

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chip 2.4GHz transceiver with an embedded baseband protocol engine (Enhanced ShockBurst™), designed for ultra-low power wireless applications. The nRF24L01 is designed for operation in the world-wide ISM frequency band at 2.400 - 2.4835GHz. The nRF24L01 is configured and operated through a Serial Peripheral Interface (SPI.) Through this interface the register map is available. The register map contains all configuration registers in the nRF24L01 and is accessible in all operation modes of the chip. The embedded baseband protocol engine (Enhanced ShockBurst™) is based on packet communication and supports various modes from manual operation to advanced autonomous protocol operation. Internal FIFOs ensure a smooth data flow between the radio front end and the system's MCU. Enhanced Shock-Burst™ reduces system cost by handling all the high-speed link layer operations. The radio front end uses GFSK modulation. It has user configurable parameters like frequency channel, output power and air data rate. The air data rate supported by the nRF24L01 is configurable to 2Mbps. The high air data rates combined with two power saving modes makes the nRF24L01 very suitable for ultra-low power designs. Internal voltage regulators ensure a high Power Supply Rejection Ratio (PSRR) and a wide power supply range. The circuit diagram of the developed tyre sensor is shown in figure 7 with the following technical specifications:

i. Power supply: 1.9V~3.6V
ii. Working current:13.5mA at 2Mbps / 11.3mA at 0dBm output power
iii. IO counts :8
iv. Sensitivity: 85dBm at 1Mbps
v. Emission distance :70~100 meter at 256kbps
vi. Data rate :256kbps / 1Mbps / 2Mbps
vii. Communication mode: Enhanced Shock Burst TM / Shock Burst TM
viii. Working mode: Power Down Mode / Standby Mode / RX Mode / TX Mode
ix. Temperatures: Operating: 40°C ~ 85°C / Storage:-40°C ~ 125°C

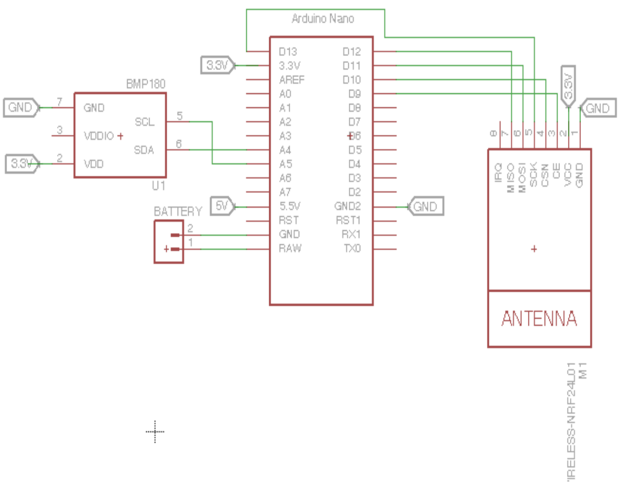

Figure 7: Tyre Sensor Circuit Diagram

2.3 *Software Implementation*

The software implementation represents the firmware methodology for the micro controller unit. The microcontroller's firmware is a set of computer instruction or codes running on the microcontroller, this helps the micro controller makes decisions and determines the action to take per time based on the inputs to the system. The firmware was developed using the Arduino IDE which uses a variation of C programming language called Arduino C.

The Arduino integrated development environment (IDE), which is a cross-platform application written in the programming language Java. It originated from the IDE for the languages, Processing and Wiring. It is designed to introduce programming to artists and other newcomers unfamiliar with software development. It includes a code editor with features such as syntax highlighting, brace matching, and automatic indentation, and provides simple one click mechanism to compile and load programs to an Arduino board. A program written with the IDE for Arduino is called a "sketch" shown in figure 8. The Arduino IDE supports the languages C and C++ using special rules to organize code [11].

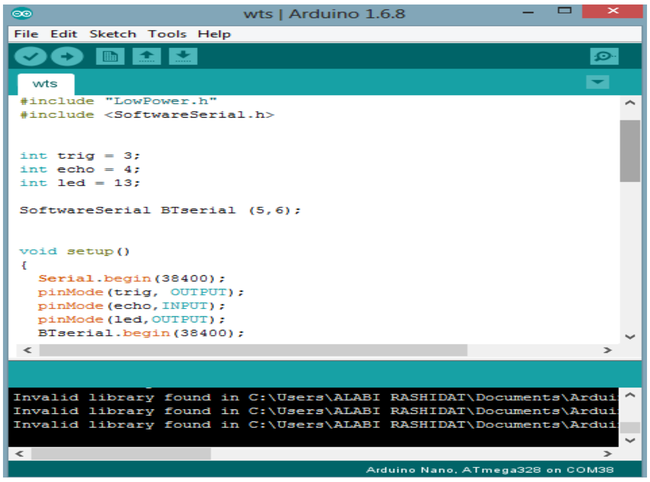

Figure 8: Arduino IDE Sketch

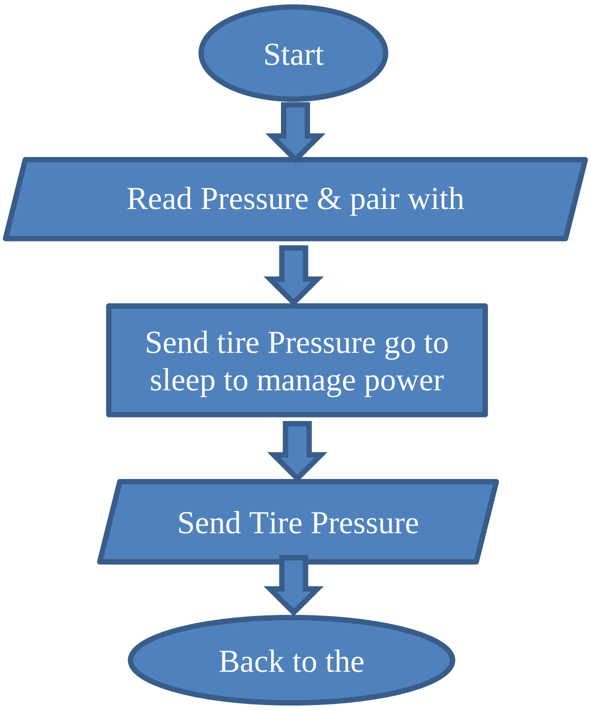

Figure 9: Tyre sensor Software Flow chart

The pressure sensor's data is read and sent through the NRF communication module. After sending the data, to preserve the battery the system using the low power library to put the module into sleep until the module is ready to transmit the signal again as depicted in figure 9. This helps prolong the battery life of the tyre sensor. The firmware was developed using the same platform used in developing that of the tyre sensor's firmware.

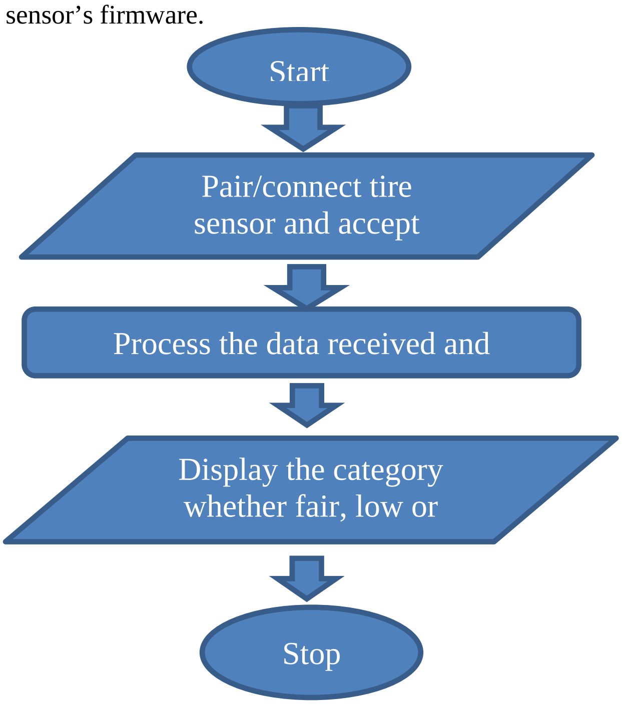

Figure 10: Monitor System Hardware flowchart

Figure 10 shows the flow chart of the monitoring system. The NRF on the monitor unit connects/pairs with the NRF on the tyre sensor and receives the data value sent by the tyre sensor. The monitor unit then categorizes the pressure data received into either good, low or high to help the user easily makes sense of the data. After categorization, the category is then displayed on the LCD screen for the user to see.

2.4 Hardware Methodology

Figure 11 depicts the hardware design of the system based on the Arduino Development platform similar to tyre sensor with the same NRF module adopted for communication. Some of the additional components used are:

i. Arduino Nano
ii. 1602 Liquid crystal Display
iii. nRF24l01

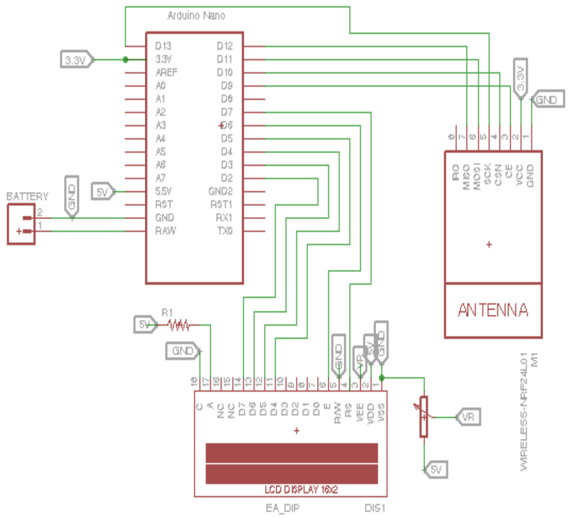

Figure 11: Monitor System Circuit Diagram.

3. RESULTS AND DISCUSSION

After initial installation and preparation, the TPMS was calibrated and a series of performance test evaluated on individual tyres with reduced tyre pressures. Calibration test allows the system to make necessary adjustment prior to low tyre pressure detection test. The pressure was set to cold inflation pressure (CIP) at ambient temperature with the TPMS powered up. Initial tyre pressure and temperature readings of both the Computerized Data Acquisition System (CDAS) and TPMS were recorded. If a sensor did not immediately transmit a pressure signal, its reading was taken after the vehicle was put into motion for the calibration procedure.

The vehicle was driven for 12 to 15 minutes to awaken all sensors to actively transmitting pressure signals. The TPMS designed to detect low tyre pressure and alert the driver test was conducted to determine the suitability of performance requirements. TPMS was installed one at a time on 5 vehicles. On detection of low tyre pressure, the ignition switch power to the TPMS was activated to record the alarm signal. The re-inflated signal is also noted as shown in tables 2, 3, 4 and 5.

The developed TPMS have multiple pressure warnings for low tyre pressure, extremely low pressure (or flat tyre), and overpressure. The TPMS have set point or pressure value for low tyre pressure and provide for indication of a slow leak.

Tables 2 and 3 list additional specifications for the 5 TPMS tested under this program.

Table 2 compares the basic functions and features of the five TPMS. Major categories are divided by function group: Sensor/Transmitter, Receiver/Gateway, and Driver display. Sensor details include airflow design, internal or external mounting, transmitting antenna, external visibility, and battery life.

Table 2: System Features

	System				
Features	A	B	C	D	E
Manufacturer	SmartWave Dana	Tire-SafeGuard HCI Corp	Tire-SafeGuard HCI Corp	WABCO-IVTM Michelin	PressurePro Advantage
Sensor Model	S14486	TPM-W206	TPM-P310B1	IVTM	CU41807684
Mounted Position	rim	rim	valve stem	wheel lug bolts	valve stem cap
Inside Tire	Y	Y	N	N	N
Transmitting Antenna	integral	attached	integral	integral	integral
Tire Temperature	Y	Y	Y	N	N
Sensor Visible	N	N	Y	Y	Y
Removal Necessary to Fill Tire	N	N	N	N	Y
Number of Receiving Antennas	1	3	1	1	1
Temperature Compensation	Y	N	N	N	N
Number of Low Pressure Setpoints	2	1	1	2	2
Setpoint 1 Factory Setting	CIP -10%	CIP -12%	CIP -12%	CIP -20%	CIP -12.5%
Setpoint 2 Factory Setting	CIP -20%	n/a	n/a	CIP -35%	CIP -25%
Number of High Pressure Setpoints	1	1	1	1	1
Integral Receiver Display	N	N	N	N	Y
Slow Leak Identification	N	Y	Y	Y	N
Programmable Setpoints	Y	Y	Y	N	N
Specific Pressure vs. Percentage	%	P	P	%	%

Receiver details include temperature compensation, receiving antennas, receiver mounting, and number of system low-pressure set-points. The driver display section lists mounting location, user programming options, and specifications on set-points.

Table 3: System Set-point – Slow Leak and Upper Limits

System	Slow Leak		Setpoints	
TPMS	Rate (psi/min)	Status	Over Pressure (psi)	Over Temperature (°F)
SmartWave Dana S14486 A	function not available	function not available	CIP +10%	195°F
Tire-SafeGuard HCI Corp TPM-W210 B	used -1; rate -3 psi or more within 2 to 10 minutes	detect slow leak in <3 minutes	used 143 max; orig default was 130	used 194°F; range was 176°F to 230°F
Tire-SafeGuard HCI Corp TPM-P310B1 C	used -1; rate -3 psi or more within 2 to 10 minutes	detect slow leak in <3 minutes	used 143 max; orig default was 130	used 194°F; range was 176°F to 230°F
WABCO-Michelin IVTM D	used -1; rate not specified	detect slow leak in <3 minutes	max not specified	function not available
PressurePro Advantage CU41807684 E	function not available	function not available	used default CIP +24%; ranges = off or +10% to +45%	function not available

Table 3 compares the additional set-points for each tested TPMS, whose functions include slow leak detection, and both upper temperature and upper pressure limits. Not all of these additional functions were provided by each TPMS and are listed as “function not available

Table 4: TPMS readings for Critical low-pressure Set point = 20% below CIP

Tyre	CIP (psi)	Test Pressure Used	Alarm	Detection Status	Re-inflation Status After Cool down
LF	127	106	***Low deviation, Not Low Critical***	***Alarm while driving T=7.5min, Distance = 0.5ft***	Clear before driving
RF	127	105.3	***Low deviation, Not Low Critical***	***Alarm while backing T= 2.1 min, Distance = 14ft***	***clear while backing T= 3.2 min, Distance = 130ft***
LII	103	85.7	Critical Low Pressure	***Alarm while backing T= 1.5min, Distance = 14ft***	Clear before driving
RRO	103	84.5	***Low deviation, Not Low Critical***	Alarm before driving >1.5min	Clear before driving
Multi	127 & 103	LF-93 RF-92 LII-73	Critical Low Pressure	Alarm before driving	Clear before driving

- ***LF = Left Front, RF = Right Front, LII = Left Intermediate Inner, RRO = Right Rear Outer; Multi = more than one tyre in a low pressure condition.***

Table 5: Tyre- Guard (flow-through) low-pressure Set point = 10% below CIP

Tyre	CIP (psi)	Setpoint Pressure Or Delta %	Test Pressure Used (psi)	Detection Status	Re-inflation Status After Cool down
LF	103	90psi (~ - 10%)	***87***	***Alarm before driving***	Clear before driving
RF	103	90psi (~ - 10%)	***87***	***Alarm before driving***	***clear before driving***
LII	100	86 psi (~ - 10%)	84	***Alarm before driving***	Clear before driving
RRO	100	86psi (~ - 10%)	***84***	Alarm before driving	Clear before driving
Multi	103 & 100	90 &87psi (~ - 10%)	87 & 84 psi	Alarm before driving	Clear before driving

The minimum activation pressure of the TPMS determined after driving for a period of up to 15 minutes. The vehicle was stopped with air was released from one tire to bring its inflation pressure to a point below the minimum activation pressure for the system. The vehicle was driven and the time needed for the system to detect the loss of pressure and alert the driver was recorded and shown in Table 4.

Multiple tyre deflations and failure modes were recorded to run the test as presented in Tables 5. Data were obtained from independent on-board instrumentation that measured tyre pressure, vehicle speed and distance, and ambient temperature. A video of the TPMS driver display was recorded. Other properties were also evaluated, including temperature compensation accuracy of system pressure measurement and failure modes. The study's results are limited to the five systems tested. These tests show clearly that the developed TPMS perform optimally.

4. CONCLUSION

The tyre unit and the monitor system were tested individually to ensure accurate performance as desired before coupling the whole system to reduce the stress of debugging. Connecting the tyre sensor via the Arduino serial monitor, the pressure data received from the pressure sensor was accurate ascertaining effective performance wireless data transmitter. The Dynamic sensor has good communication capability and long span battery life when tested via serial communication with Arduino. For the battery life, it was discovered that the device lasted close to four days running on Duracell 9v battery with the low power/h library implementation in the firmware proving quite useful.

The monitor system was also tested individually with its ability to display data in a user-friendly way, its communication system and the power consumption the main focus of the tests. The entire system worked hand in hand effortlessly and user friendly way of displaying the data was achieved. Also the communication with the tyre sensor device worked out optimally always on status except for when the car is not in been used, the device was on for 48 hours straight without being switched off. Implementation, testing and results of the system development of the two major modules yields a dynamic sensor that enables full automated regulating of tyre pressure in automobiles helping the driver inflate the tyre at any point in time it detects a drop in the tyre pressure and thus guarantee the safety of the passengers.

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