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DEVELOPMENT OF AN AUTOMATED PORTABLE TYRE INFLATOR REGULATOR

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ABSTRACT

Tyre pressure is a critical factor influencing vehicle safety and performance. Overinflated tyres are prone to blowouts, whereas underinflated tyres can overheat quickly, causing structural damage and shortening their lifespan. To mitigate these risks, there is need to develop an inflation monitoring device that automatically cuts off the air supply once the recommended tyre pressure is achieved. The device integrates an ATmega8A microcontroller, a strain gauge pressure sensor, an LCD, a matrix keypad, a solenoid valve, a pressure relief valve, a polyurethane hose, and quick-connect fittings within a PVC junction box casing. Thirty tests were conducted on each tyre type to evaluate the device's accuracy and precision. Metrics such as absolute error, percentage error and standard deviation were used. The results showed absolute error, percentage error and standard deviation ranged from 0.01 PSI to 0.157 PSI, 0.013 to 0.522% and 0.255 PSI to 0.364 PSI respectively. Paired t-test at a 95% confidence level were conducted with the p-values for trucks, motorcycles and off-road tyres showing the results are statistically significant but that of passenger car and bicycles were not statistically significant. While the metrics for accuracy and precision varied slightly with various tyre types, the values remained within the ± 2% acceptable limit recommended by the International Organisation for Standardisation in ISO 21759:2006. The findings show that this inflation control device can significantly enhance vehicle safety and reduce the risks associated with overinflating and underinflating.

Keywords: Automation, Control, Inflation, Microcontroller, Pneumatic

INTRODUCTION

Pneumatic (air-filled) tyres are crucial in ensuring safety, performance and comfort on the road. They provide the interface between the vehicle and the road. Tyre inflation artisans, also known as “vulcanizers” in Nigeria, are entrusted by road vehicle users to gauge their tyre pressures; inflate them when pressure is low; and also perform tyre repairs. Some of these artisans, however, do not observe best practices in carrying out these operations. Not adhering to procedures, carelessness and the use of unreliable pressure gauges for measurement (Adeyemi, *et al.*, 2020) are some of the factors, which lead to adverse effects resulting in overinflation or underinflation.When a tyre is underinflated, a larger contact surface is formed between the driving surface and the tyre; the larger area results in increased friction which can cause overheating, premature wear, blowouts, high fuel consumption and speedometer registering lower speeds than the vehicle’s actual speed (Mehta, *et al.*, 2017; Dyukov, 2016; Osueke & Uguru-Okorie, 2012; Aldhufairi & Olatunbosun, 2018; Mathew, *et. al.*, 2014; Mahendra & Rao, 2014). Tyre overinflation results in a smaller contact patch than normal, thereby reducing friction and this makes the vehicle more difficult to handle (Bawa, *et al.*, 2015). Overinflation also decreases the life of tyres by causing uneven wear (Mirzaee, *et. al.*, 2021). Both underinflation and overinflation can result in poor handling, cornering and braking (Bawa, *et al.*, 2015). There is a high probability of having uneven tyre pressures across the tyres of a vehicle when inaccurate readings are taken during inflation. Uneven inflation pressure greatly increases lateral acceleration while braking with maximum force (Janulevicius & Pupinis, 2020).

Significant strides have been made in both direct and indirect methods for tyre pressure management, yet each approach faces some peculiar limitations. For direct inflation systems, Dabair and Reddy (2020) used a vehicle's battery to power a compressor, but this design required frequent maintenance due to wear and tear. Similarly, the centralized compressor system developed by Prakash *et al.* (2017) was aimed to keep pressure within a prescribed range but this system didn't entirely prevent under- or over-inflation. This drawback highlighted a key challenge in maintaining consistent pressure. Furthermore, while Cao *et al.* (2019) developed a direct Tire Pressure Monitoring System (TPMS) with an alarm for high pressure, the system lacked the ability to prevent overinflation during the inflation process itself. This points to a need for more comprehensive control mechanisms.

Meanwhile for indirect monitoring, Silva *et al.* (2019) explored methods to detect pressure changes by analyzing tyre radius and vertical oscillation, but these have not been fully tested and struggle with scenarios involving multiple deflated tires. Likewise, Kang (2019) successfully used tyre vibration resonance to monitor pressure, but this method was limited by the need for precise parameter estimation. Beyond monitoring, innovative technologies have also been explored, from a neural network for pressure prediction by Kost (2018) which has not been tested in real-world conditions to a drag wind-powered compressor by Mushiri *et al.* (2016); which is seen to be unsuitable for larger vehicles. Even self-powered TPMS systems by Jian *et al.* (2020), which eliminate battery replacement, did not address pressure regulation.

These studies collectively highlighted significant progress in tyre pressure monitoring and management, yet several challenges remain. There remains a lack of low-cost, portable, and retrofittable devices that when fitted to a traditional compressor can automatically regulate tyre inflation while maintaining ISO-compliant accuracy. This study addresses that gap by developing a microcontroller-based inflator regulator designed for use with conventional roadside compressors.

MATERIALS AND METHODS

The conceptual design is portrayed in Figure 1 while Figure 2 depicts the inflation monitoring system block diagram. The operator is prompted to enter the desired pressure value as soon as the device is turned on,. The device then continually reads the air pressure within the system. The pressure value is shown on the display in real-time. The inflator compressor is turned on and pressure builds up in the system as air is pumped into the tyre. When the set pressure is attained, the solenoid valve within the device closes and stops the tyre from further inflation.

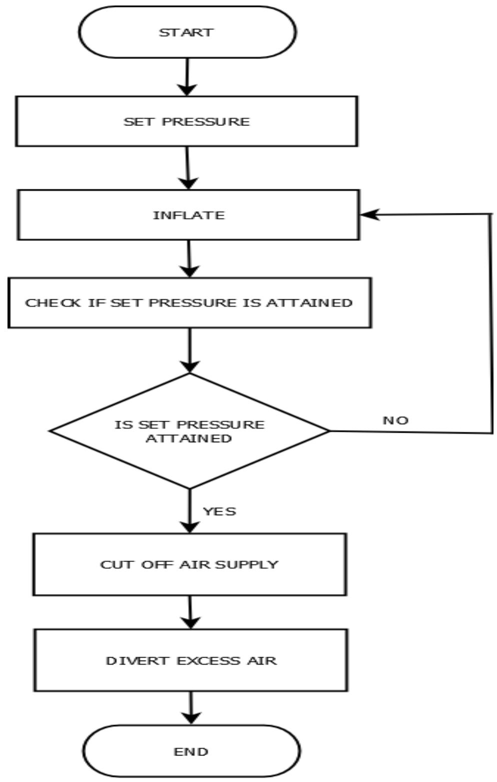

Figure 1: Inflation Monitor Flowchart

Figure 2: Inflation Monitor Block Diagram

Design Requirements

The inflator is designed to meet the following requirements:

i. The device will measure pressures up to at least 140 psi as heavy-duty trucks can have recommended tyre pressures of up to this value (Abdel-Motaleb, 2020).
ii. A simple interface for setting the desired pressure and viewing real-time pressure readings.
iii. The device will operate on a standard 12V DC power supply.
iv. The device is to be retrofitted to a mechanical air compressor used by roadside vulcanizers.

Circuit Design

The circuit diagram is shown in Figure 3. The ATmega8A serves as the central control unit of the circuit. It reads inputs from the keypad and the pressure sensor, processes these inputs, and controls the solenoid valve and the LCD display. Components used are ATmega8A microcontroller, Liquid Crystal Display, Matrix keypad, Normally-closed solenoid valve, Relief valve, Strain gauge pressure sensor, Polyurethane hose and Quick-connect pneumatic fittings.

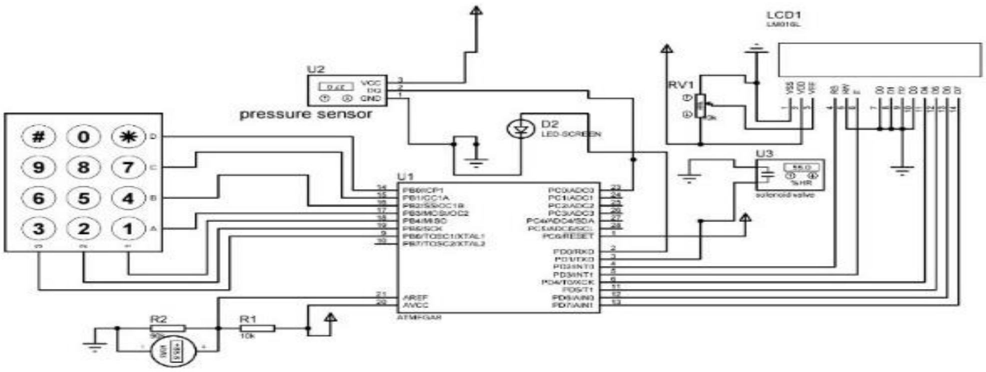

Figure 3: Circuit Diagram

Fabrication

The device is encased in a box made of PVC. A perf-board is utilized for soldering electrical components together. All internal pneumatic components are joined by hoses and quick-connect fittings.

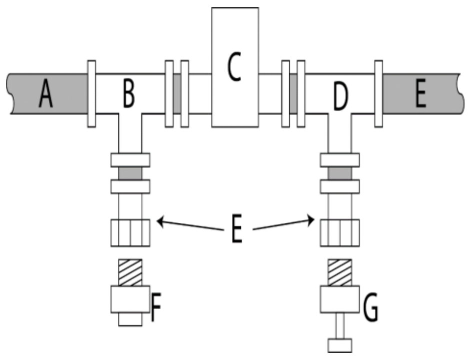

Figure 4: Arrangement of Internal Components

The configuration of the system's internal parts is presented in Figure 4.The hoses are shown in grey. A T-shaped quick-connect fitting (B) connects the hose (A) from the inflator to the safety relief valve (F) and the inlet of the solenoid valve (C). Another T-shaped quick-connect fitting (D) connects the outlet of the solenoid valve to the pressure sensor (G) and to the tyre valve through a hose (E). The safety relief valve and pressure sensor are threaded; hence, they are connected to the quick-connect fittings using threaded adaptors (E) with quick-connect mechanism on one end. Short hose segments are used to join fittings and components together. Figure 5 shows the internal components placed in the PVC box and Figure 6 shows the device with the cover on.

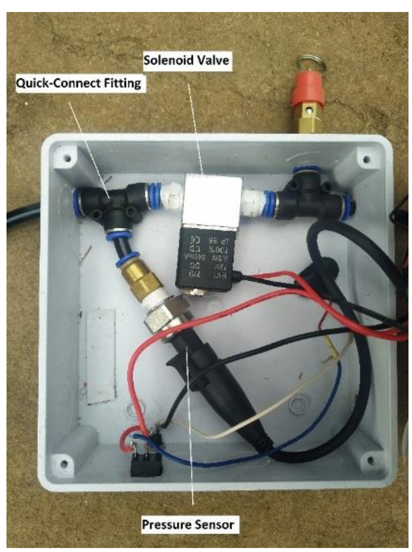

Figure 5: Internal Components Inside the Pvc Housing

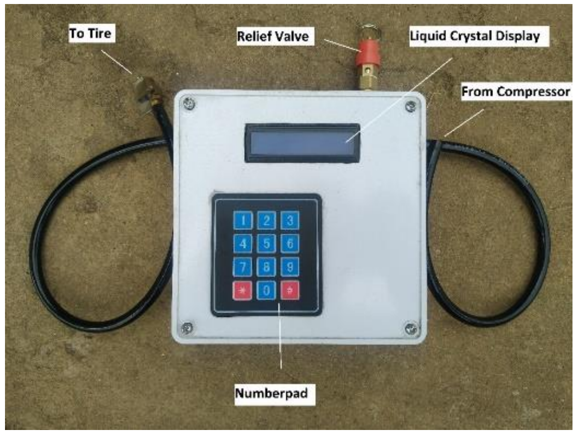

Figure 6: LCD and Number-Pad Mounted on the Cover

Testing and Evaluation

The Atmega8A microcontroller is equipped with a 10-bit analogue-to-digital converter (ADC). The pressure sensor gives a voltage output of 0.5 to 4.5 Volts, corresponding to a pressure range of 0 to 174 psi. The ADC converts the output voltage of the sensor to a 10-bit binary number. The decimal representation of this binary number is used in the conversion of the pressure sensor voltage as follows:

The ADC value, ADC_{min} , that corresponds to the 0 psi sensor voltage of 0.5 V is obtained using equation (1).

$$ADC_{min} = \frac{V_{IN} \times ADC_{max}}{V_{REF}} \quad (1)$$

where,

$V_{IN} = 0.5\ V$

$V_{REF} = \ 4.5\ V$

$ADC_{max} = 2^{10} - 1 = 1023$

The pressure sensor's reading, P in psi is determined from the ADC value is obtained with the expression in equation (2).

$$P(PSI) \ = \frac{174(ADC - ADC_{min})}{ADC_{max} - ADC_{min}} \quad (2)$$

The pressure value displayed on the LCD is given by equation (2).

In order to ensure that the pressure sensor gives accurate readings, the five-point calibration procedure was carried out. Calibration points at 0%, 25%, 50%, 75% and 100% of the full-scale range were selected. For the 174 psi sensor, the calibration points were 0 psi, 43.5 psi, 87 psi, 130.5 psi and 174 psi respectively. A digital pressure gauge was employed as the calibration standard. The digital gauge was connected along the outlet hose of the inflation monitor using a T-quick-connect fitting. Pressure readings on the inflation monitor were within $\pm$ 0.5 psi of the digital gauge readings for all five calibration points. As the inflation monitor displays pressure to the nearest psi, no further calibration was necessary.

Thirty (30) tests each were carried out on various tyre types at the corresponding selected typical pressure. The performance metrics utilized were the absolute error as depicted in equation (3), percentage (relative) error expressed in equation (4) and standard deviation presented in equation (5). The absolute and percentage errors are indicators of the accuracy of the device. For each tyre type, the average value (mean) of the actual pressures was determined, and the difference between the inflation monitor's set pressure and this mean was used to determine the absolute error. The relative error is also determined as a percentage of the actual pressures. To evaluate the precision of the device, the standard deviation was determined for each tyre type and the paired t-test (Ayodele, *et al.*, 2025**)** was used to determine if the results obtained were statistically significant. The null hypothesis being there is no difference between the means of the two groups while the alternative hypothesis is there is a difference between the means of the two groups.

$$absolute\ error = mean - true\ value \quad (3)$$

$$percentage\ error = \frac{absolute\ error}{true\ value} \times 100\% \quad (4)$$

$$standard\ deviation = \sqrt{\frac{\sum_{i=1}^{n}(value_i - mean)^2}{n-1}} \quad (5)$$

RESULTS AND DISCUSSION

By analysing the absolute error, percentage error, standard deviation and t-test of the actual pressures achieved in comparison to the desired pressures, this section aims to assess the device's reliability and effectiveness.

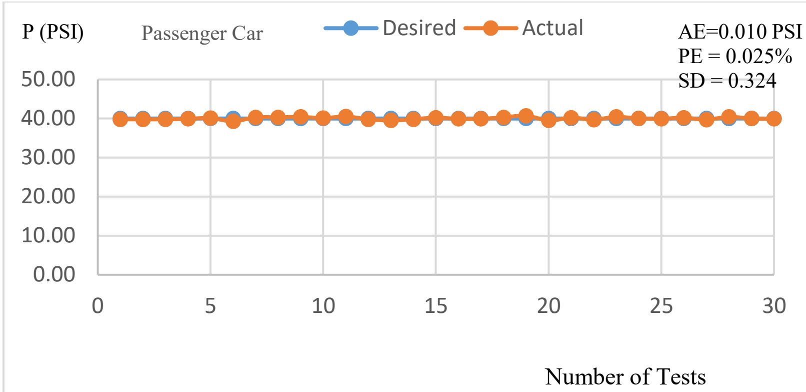

Figure 7: Passenger Tyre

The passenger car tyre results shown in Figure 7, show high accuracy with a very low absolute error of 0.01 PSI and a percentage error of 0.025%. The standard deviation of 0.324 PSI was obtained while a p-value of 0.87 of was obtained for the paired t-test carried out at a 95% confidence level. The p-value obtained suggests that the observed results are not statistically significant.

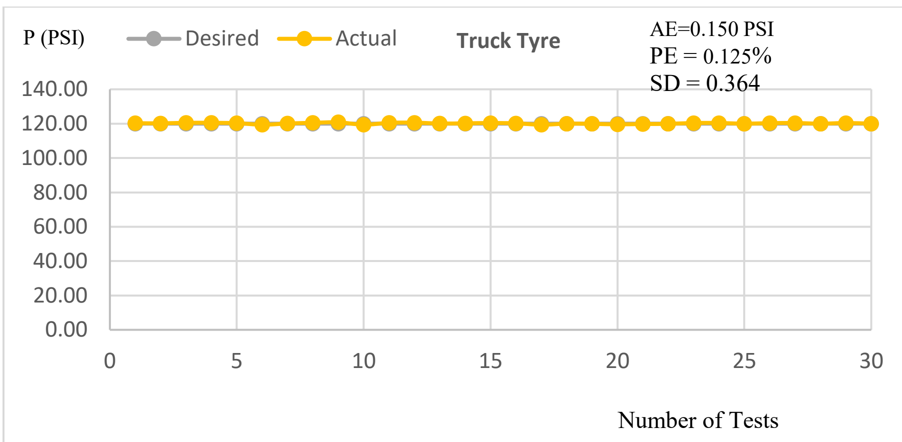

Figure 8: Truck Tyre

The truck tyre results shown in Figure 8 also show high accuracy, with an absolute error of 0.15 PSI and a percentage error of 0.125%. The standard deviation of 0.364 PSI shows slightly lower precision compared to passenger car tyres but is still within an acceptable range. P-value of 0.03 of was obtained for the paired t-test carried out at a 95% confidence level. The p-value obtained suggests that the observed results are statistically significant.

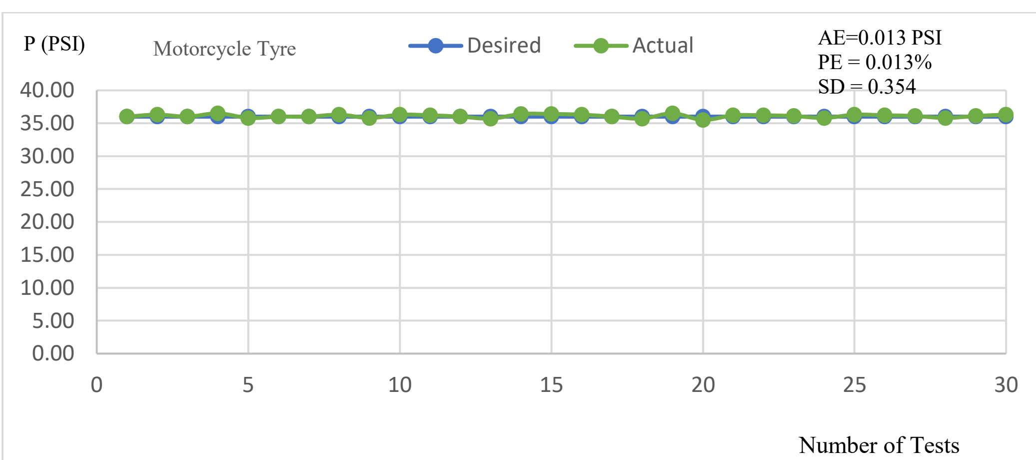

Figure 9: Motorcycle Tyre

The motorcycle tyre results Figure 9 indicate extremely high accuracy with an absolute error of only 0.093 PSI and a low percentage error of 0.259%. The standard deviation of 0.255 PSI indicates high precision. P-value of 0.05 was obtained for the paired t-test carried out at a 95% confidence level. The p-value obtained suggests that the observed results are statistically significant.

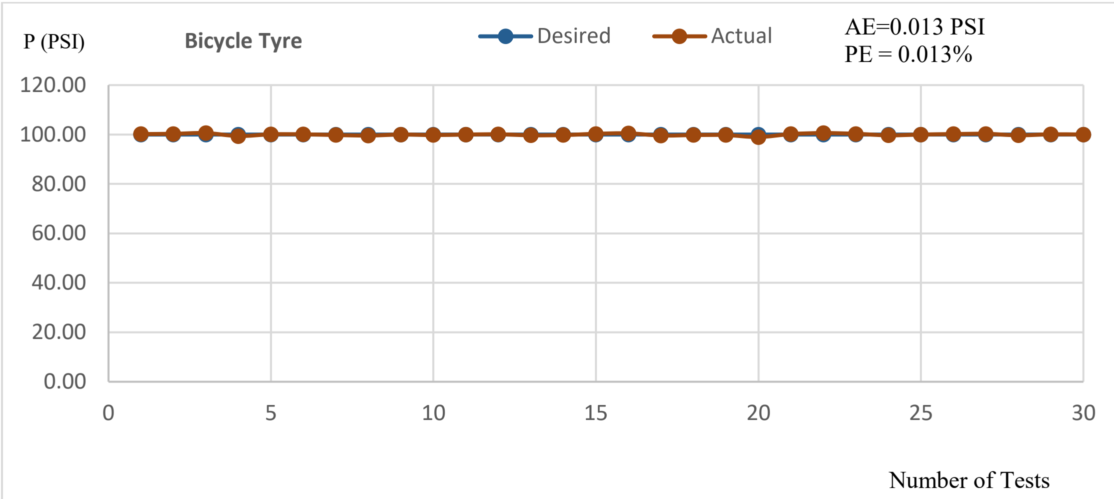

Figure 10: Bicycle Tyre

The bicycle tyre results as shown in Figure 10 show high accuracy with an absolute error of 0.013 PSI and a percentage error of 0.013%. The standard deviation of 0.354 PSI is slightly higher compared to most of the other tyre types but still indicates good precision. The results validate the device's effectiveness for high-pressure bicycle tyre inflation. P-value of 0.84 obtained for the paired t-test carried out at a 95% confidence level. The p-value obtained suggests that the observed results are not statistically significant.

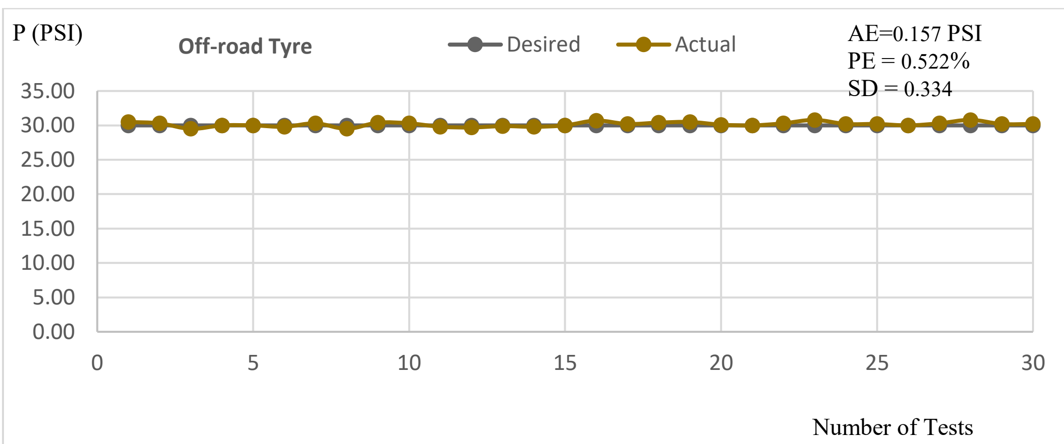

Figure 11: Off-Road Tyre

The off-road tyre results as shown in Figure 11, show good accuracy with an absolute error of 0.157 PSI and a percentage error of 0.522%. The standard deviation of 0.334 PSI indicates slightly lower precision relative to some of the other tyre types. P-value of 0.02 of was obtained for the paired t-test carried out at a 95% confidence level. The p-value obtained suggests that the observed results are statistically significant. These results suggest that the device is reliable for off-road tyres, where precise pressure control is crucial for varying terrain conditions.

Table 1: Absolute Error, Percentage Error and Standard Deviation for the Tyre Types

SN	Types of Tyre	Absolute Error (PSI) (AE)	Percentage Error (%) (PE)	Standard Deviation (SD)
1	Passenger Car Tyre	0.010	0.025	0.324
2	Truck Tyre	0.150	0.125	0.364
3	Motorcycle tyre	0.093	0.259	0.255
4	bicycle tyre	0.013	0.013	0.354
5	off-road	0.157	0.522	0.334

The results in Table 1, showed that the device achieved an absolute error ranging from 0.01 PSI for passenger car tyres to 0.157 PSI for off-road tyres. The percentage errors were similarly low, indicating high accuracy across all tyre types. For instance, the bicycle tyre exhibited the lowest percentage error at 0.013%. The standard deviation was slightly higher for truck (0.364 PSI) and off-road (0.333 PSI) tyres compared to passenger car (0.324 PSI) and motorcycle (0.255 PSI) tyres. This may be attributed to the larger volume and higher-pressure requirements of truck and off-road tyres, which could introduce more variability in the inflation process.

The inflation control device demonstrates high accuracy and precision across different tyre types, with minor variations that fall within acceptable ranges giving a better accuracy when compared to a percentage error of 0.75% obtained in a similar study by Rahayu and Rajagukguk (2021). A paired t-test at a 95% confidence level was conducted with the p-values for trucks, motocycles and off-road tyres giving 0.03, 0.05 and 0.02 respectively. This showed that the results are statistically significant. For passenger car and bicycles tyres, p-values of 0.87 and 0.84 were obtained. This indicated that the results from the passenger car and bicycles tyres were not statistically significant. The device was found to be effective and reliable for all tyre types tested.

CONCLUSION

The development of the inflation control device was motivated by the need for a reliable and accurate solution for tyre inflation. Extensive testing was conducted to evaluate the device's performance across various tyre types, including passenger car, truck, motorcycle, bicycle, and off-road tyres. The absolute error and relative error across all tyre types were minimal, indicating the device's high accuracy. Specifically, the passenger car tyre demonstrated the lowest absolute error of 0.01 PSI and a relative error of 0.025%. The precision of the device, as indicated by the standard deviation, varied slightly depending on the tyre type but were all with the acceptable limits of less than two percent (2%). Paired t-test at a 95% confidence level were conducted with the p-values for trucks, motorcycle and off-road tyres showing the results are statistically significant but that of passenger car and bicycles were not statistically significant.

Findings showed that tyre type and size impact the accuracy and precision of the inflation control device. Tyres with higher pressure requirements and larger volumes, such as truck and off-road tyres, exhibited slightly higher variability in the achieved pressures. This variability is likely due to the increased complexity in maintaining consistent pressure across a larger volume. In contrast, tyres with lower pressure requirements and smaller volumes, such as passenger car and bicycle tyres, demonstrated lower variability and precision. The device was found to be effective and reliable for all tyre types tested.

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