

# Design and Mathematical Quantification of a Compressed-Air Vehicle

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## Abstract

*Compressed-air technology is emerging as a promising alternative mode of transportation, offering significant advantages over conventional fuel-operated vehicles. Unlike fossil fuel systems, compressed-air propulsion produces no direct emissions, making it an eco-friendly solution to rising concerns about air pollution and environmental degradation. Owing to its sustainability potential, this technology has attracted considerable attention from researchers, engineers, and energy enthusiasts worldwide, who have conducted extensive studies to improve its efficiency, feasibility, and practical application. The present work contributes to these ongoing efforts by designing and developing a compressed-air vehicle powered by a pneumatic motor. Special emphasis has been placed on addressing the limitations typically associated with compressed-air systems, such as low efficiency and limited operational range. The developed prototype integrates an onboard compressor and an air motor, enabling self-sustained functioning without external refilling. Experimental evaluation demonstrates that the vehicle achieves a maximum speed of approximately 30 km/h with an effective runtime of around 30 minutes under standard operating conditions. These results confirm the viability of compressed-air propulsion as a short-distance, low-speed transportation option, particularly suitable for urban mobility where sustainability is a priority. This study not only validates the concept through a working prototype but also provides a foundation for further research aimed at enhancing performance, extending runtime, and broadening the scope of applications for compressed-air vehicles.*

**Keywords:** Compressed-air vehicle (CAV), energy density, recharging, zero-emission, state of charge (SOC), green transportation

## INTRODUCTION

The introduction clearly states the object of your work, its scope and the main advances you are reporting. It gives reference to relevant results of previously published work. A theoretical and experimental methods section gives sufficient information about the research carried out by the researcher. The results and discussion section states your results and their potential implications. In the discussion you should state the impact of your results compared with recent work.

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Numerous non-communicable diseases are spreading on a large scale throughout the world due to many reasons. One such reason for the cause of this crisis is air pollution. Air pollution is responsible to the mortality of kids under the age of five, and other respiratory diseases, diabetes, heart diseases and stroke. Recent studies have shown that air pollution is also linked to over 8.1 million fatalities worldwide. After the industrial facilities,

transportation is responsible for producing the second-highest amount of CO<sub>2</sub> emissions worldwide, which have grown up to 80% since 1990 [1,2]. Natural resource scarcity positively correlates with fossil fuel energy consumption, agriculture, forestry, increased greenhouse gas (GHG) emissions and fishing [3]. It is very possible that by 20250, the GHG emissions could reach up to 60%. In brief, air pollution has become a serious health hazard and 14% of this is caused due to all the emissions from vehicles globally [4].

Fossil fuel is the primary source of energy covering over 82% of the needs of industries, automobiles, etc. Maximum amount of air pollution exists due to burning of fossil fuels in sectors like transportation, industries, electricity generation, etc. A shift to low-carbon transport has become a necessary solution which could decrease the carbon or other GHG emissions by 20% and it should be implemented as early as possible. The world is taking an effort to reach the net-zero targets by focusing on low-emission or almost zero-emission technologies and integrating it in energy generation industries, transportation, etc.

Recent advancements in compressed air vehicle (CAV) technology have focused on enhancing both design and mathematical modeling to improve efficiency and performance. A notable study by Okonkwo *et al.* (2023 [42]) analyzed a three-wheeled pneumatic vehicle, achieving an efficiency of 78% by utilizing a pneumatic cylinder with specific dimensions and operating at 0.5 MPa pressure. In parallel, mathematical modeling has been pivotal in understanding and optimizing CAV systems. For instance, [43] developed a detailed model of a two-stage piston air compressor, incorporating heat transfer effects to enhance performance. Additionally, Korbut and Szpica [44] presented a computational model of a piston pneumatic engine, analyzing the impact of various parameters on its operation.

These studies underscore the critical role of both innovative design and robust mathematical modeling in advancing compressed air vehicle technology is a potential alternative energy source which can be implemented in vehicles. This might seem like a new concept but its development dates back centuries ago. The following Table 1 represents various parameters comparing energy sources: gasoline, electric, hydrogen fuel cell, and compressed air. It can be attributed from the following table that compressed air as a fuel source does not emit any exhaust gases and is cheaper in comparison to the rest of the sources. But when compared to the energy sources in terms of the remaining parameters such as range, refuelling time and load carrying capacity, its performance is suppressed.

## TECHNOLOGICAL ADVANCEMENTS

Numerous researchers have tried to utilise compressed air as an energy source to power automobiles since the 17<sup>th</sup> century. Denis Papin was the first person to develop a pressure cooker in 1679 and was the first person to ever propose the idea of a steam engine. The idea was further developed; several engineers enhanced the designs which influenced the Industrial Revolution [14].

**Table 1.** Comparison of energy sources used in automobiles.

Energy source	Carbon emissions	Energy Density	Charging time	Initial production cost	Range	Loads
Gasoline	250g/km [5]	44 MJ/kg [6]	2-5 mins	10-15 lakhs	400-600 km	Heavy loads
Electric	+24-31% Higher than ICE vehicles [7]	2.52 MJ/kg [8]	30-60 mins	15-22 lakhs	200-400 km	Medium loads
Hydrogen Fuel cell	135-465g/km (for grey H <sub>2</sub> ) [9]	142 MJ/kg [10]	3-5 mins	50 lakhs & above	500-1000 km	Heavy loads
Biofuels	116-128g/km [11]	40 MJ/kg [12]	Same as gasoline			
Compressed Air	0g/km	0.1 – 0.2 MJ/kg [13]	A few minutes to 1 hour	5-8 lakhs	100-150 km	Lightweight loads

Thomas Savery improvised his design and developed a steam-driven suction pump and applied it in the coal mining industry. The first air engine was developed by Thomas Newcomen, which helped to deliver power to a machine. His studies laid a strong foundation for utilizing steam as an energy source [15]. James Watt improved the functionality of the Newcomen engine in 1776 by adding a separate condenser to the design [16].

In the 19th century, Robert Stirling developed the Stirling engine, which was used as a functional pump to force water into a quarry in 1818. His design consisted of an external combustion thermal engine for non-automotive usage.[17]. Bompas created the first-ever compressed-air locomotive in the year 1828 [18]. Andraud and Tessie of Motay from France were the first known to construct a compressed-air vehicle in 1838.[19]. Later, Charles B. Hodges made significant advancements, and it became successful in the mining industry [20].

The Mekarski air engine, engineered by Louis Mekarski, made a noteworthy name for itself [21]. Robert Hardie implemented a re-heating system for the motor that converts energy generated by braking. In the Hoadley-Knight system, a multi-stage air-powered engine was created to increase the locomotive's working range before requiring system recharge [22, 23].

All these advancements were before the 20<sup>th</sup> century, which focused on the fundamental development of compressed-air technology, giving a solid ground to future advancements and compressed-air solutions in the automotive sector.

## **COMPRESSED AIR TECHNOLOGY**

The compressed-air energy source phenomenon utilises the energy stored in high-pressure air, and it is used in various applications such as industries for power tools, light-duty vehicles, etc. This compressed air can be generated with the help of a compressor and is generally stored in air-tight places or containers [24]. It is possible to meet the requirements if compressed air is used on a large-scale basis. As far as its application in the transportation sector is concerned, there are several types of technologies developed mainly using:

- (a) Compressed Air Engine
- (b) Compressed-Air Motor
- (c) Hybrid Powertrain Systems

### **Compressed Air Engine Technology**

The compressed-air technology could include modifying a conventional gasoline engine and using the principle as it is, without any combustion of fuel. M. Vishnuvardhan and et. al replaced the spark plug with a solenoid valve to carry out functions like intake and exhaust of air. On further detailed analysis of the modified compressed air engine, they stated that the engine output had greater improvements in the output torques, speed and some of the other parameters [25].

### **Compressed Air Motor Technology**

The pneumatic motor or rotary-vane motor uses the principle of expansion similar to the air engine. The only difference in an air motor is that the air expands to rotate the vanes creating the necessary torque and rotary motion. Yonghong Xu et. al. studied a pneumatic motor and its uncertainties, torque, speed, and power outputs, and concluded that a 62% maximum efficiency of the pneumatic motor was obtained [26].

Another study regarding the optimisation of a rotary-vaned motor was carried out by Dr. B.R Singh and Dr. O. Singh. They studied several parameters such as injection angles, casing diameter ratios, number of vanes, etc. of a rotary-vaned motor to indicate its performance under crucial parameters [27–35].

### Hybrid Air System Technology

A hybrid air system could work as an alternative method to use a hybrid system in the vehicle. This system forms a hybrid powertrain with compressed air and conventional fuels such as gasoline combined in the engine. By having this integrated system, it was possible to eliminate up to 50% of carbon emissions [36].

The air motor was selected as it has a simple design and less friction as compared to air engine. Due to this, the air motor faces fewer energy losses, improving the overall efficiency. It is possible to maintain a higher torque at a lower rotational speed [37].

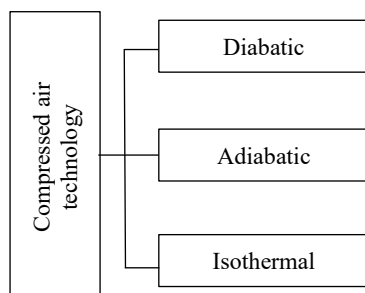
From the studies done by other scholars, researchers, engineers, etc., the major drawback identified was the low energy density compared to conventional gasoline fuels, its limited range, speed, etc. The main aim is to develop a CAV prototype with moderate range and speed, with minimum-to-zero carbon footprints generated. The compressed air technology working on thermal performance processes and shown in Figure 1.

When high-pressure compressed air is released into an air motor, it expands and performs work. The expanding air pushes the vanes or pistons inside the air motor, which in turn rotates the output shaft, generating torque to move the vehicle. The air compressor powered by a 12V battery compresses atmospheric air and stores it in a high-pressure storage tank. From the tank, high-pressured air is passed through the 4/3 direction control valve (DCV). The valve is manually operated using a hand lever and it regulates the flow of air into the air motor. The energy produced by the air motor is transformed into rotational mechanical energy, which is then transferred to the drive train system followed by the wheels. An alternator is coupled to the shaft to generate electricity while the motor is running. This power is used to recharge the battery, creating a small recharging loop.

The prototype was developed and analysed in SolidWorks 2022 with several iterations and a square pipe of 40×40 mm with 4 mm thickness and shown in Figure 2. The objective of the frame is to support all the components of the prototype such as compressor, motor, alternator, battery, etc are shown in Figure 3. The components specifications are mentioned in Table 2.

**Table 2.** Components and parameters.

S. No.	Components	Parameters
1.	Battery	12 V, 130 Ah
2.	Chassis Frame	40 × 40 × 4 mm
3.	Air Compressor	3 hp
4.	Air motor	2.5 hp
5.	Alternator	14.4 V, 80 A
6.	Gear-box (CVT)	6:1
7.	Driving shaft	25 in, $\phi$ 20 mm
8.	Wheels	17 in, 120/90
9.	Flow control valve	4/3 DCV



**Figure 1.** Thermal processes of compressed-air technology.

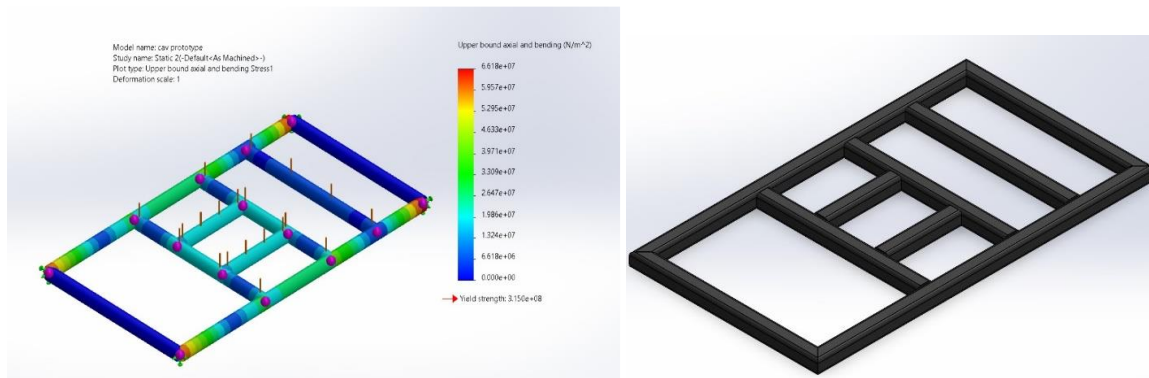


Figure 2. 3D Frame of model.

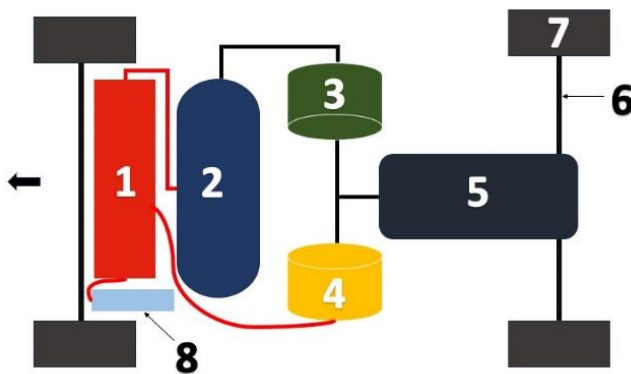


Figure 3. Flow of components.

Table 3. Air Compressor power required.

Tractive Effort	Speed (kmph)	Speed (m/s)	Conversion Factor	kW Power	HP
248.687	10	2.778	1000	0.691	0.926
248.687	20	5.556	1000	1.382	1.853
248.687	30	8.333	1000	2.072	2.779
248.687	40	11.111	1000	2.763	3.705

The estimated weight of the model is assumed to be 145 kg. The tractive effort required for propulsion is:  
 $F_p = F_d + F_r + F_g + F_a$

Where,  $F_d$  = Aerodynamic drag

$F_r$  = Rolling resistance

$F_g$  = Gradient resistance

$F_a$  = Inertial force

Therefore, assuming the aerodynamic drag coefficient is 0.35, the rolling resistance coefficient is 0.15, with a gradient of 5° and desired acceleration as 0.7 m/s<sup>2</sup>, we obtained:

$$F_{\text{total}} = 248.687 \text{ N}$$

The Table 3 shows the hp required for propulsion of the prototype.

The maximum speed that can be theoretically calculated is around 32.36 kmph. The air compressor chosen for the prototype is 3 hp as it meets the project's requirement and is cost-effective [38].

Motor power for 30 kmph calculated:

$$\begin{aligned} \text{Tractive effort} &= 248.687 \text{ N} \\ \text{Maximum desired speed} &= 30 \text{ kmph} \\ \text{Motor Power} &= F_{\text{total}} \times v = \text{Motor Power} = F_{\text{total}} \times v = 2072.29 \text{ W} \\ \text{HP required} &= 2.779 \text{ hp} \approx 3 \text{ hp} \end{aligned}$$

The average running time of the battery can be evaluated based on the speed of the vehicle and drive cycle of the vehicle; the battery capacity and power utilised can be determined.

The state of charge (SOC) works as a fuel gauge to determine the amount of charge present on the battery.

$$\text{SOC drop} = 71.73 \%$$

Remaining SOC = 28.27%, which may not be considered a safer solution for long-term running, but the vehicle would not operate continuously at maximum speed. Hence, a 12V, 130Ah battery will be safe to use [39]. The current requirement for the air compressor is 186.4A for approximately 30 minutes. After calculating the battery rating, the battery capacity determined is 1.56 kWh.

For a 3 hp air compressor, a 2.5 hp air motor will be suitable, keeping a margin of approximately 85%.

$$\begin{aligned} \text{The torque requirement for vehicles,} \\ \text{Motor torque (M}_\tau) &= F_{\text{total}} \times r = 5.1 \text{ Nm} \end{aligned}$$

For a stable delivery of torque and speed from the air motor, the gear ratio assumed is 6:1 with an 85% of efficiency in the transmission system, the overall torque delivery is 26.01 Nm. This wheel torque is adequate for propelling the vehicle [40]. For selection of an alternator, assuming the ratio of the pulley diameter of the alternator and the pulley diameter of the motor is 2:1, the speed obtained is 3000 rpm. Assuming 85% of the alternator efficiency, the power generated by the alternator is 0.669 kW in 2.74 hours to fully recharge.

The current generated by the alternator is:

$$I = \frac{P_{\text{alternator}} \times 1000}{V} = 55.74 \text{ A}$$

Considering, 30% higher ampere for the alternator to avoid overheating and compensate for actual losses [41,42]. For discharge power,

$$\frac{\text{Power generated by alternator}}{\text{Battery capacity}} = 1671.4 \text{ W and similarly for charging } 669 \times 0.85 = 568.65 \text{ W.}$$

$$\begin{aligned} \text{Net Power} &= 568.65 - 1671.4 = -1102.75 \text{ W} \\ &= 1102.75 / 60 = 18.38 \text{ Wh/min} \end{aligned}$$

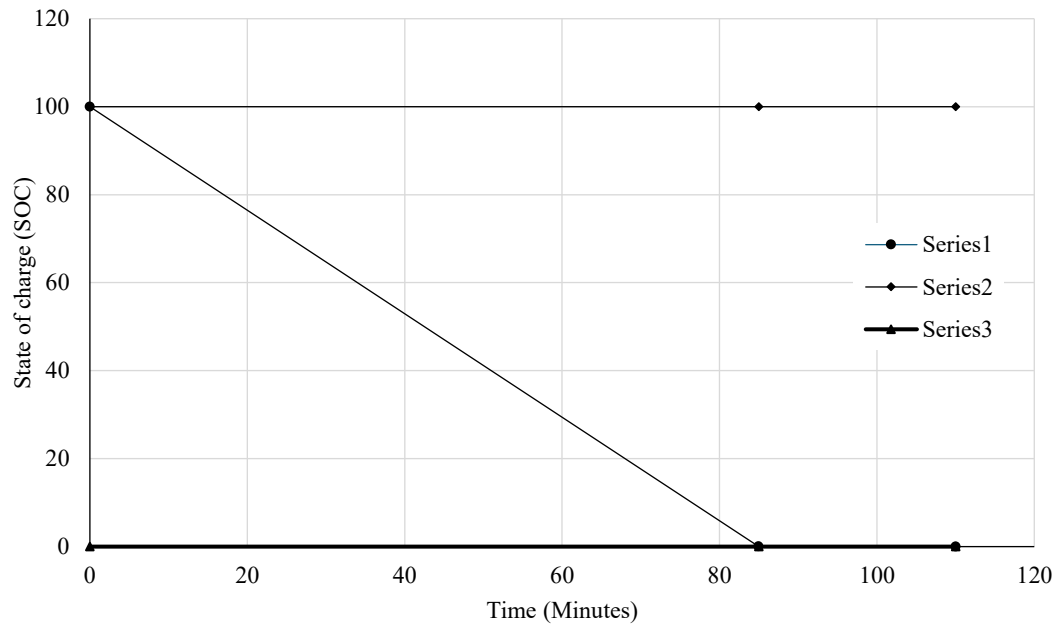
$$\text{Time to reach 0 SOC} = 1102.75 / 1560 \approx 1.415 \text{ hours} \approx 85 \text{ minutes}$$

A graphical representation of battery state of charge and time is shown in Figure 4.

For the tank to be empty,

$$t = \frac{P_1 \times V}{V_{\text{air}} \times P_{\text{atm}}} \ln \left( \frac{P_1}{P_2} \right)$$

$$t = 1.89 \text{ minutes}$$



**Figure 4.** Battery SOC vs time.

Compression Ratio (Only considering pressure and not volume):

$$\text{Compression Ratio (CR)} = \frac{P_{\text{storage}}}{P_{\text{atmosphere}}} = 7:1$$

System Efficiency:

$$\begin{aligned} \eta_{\text{total}} &= \eta_{\text{compressor}} \times \eta_{\text{storage}} \times \eta_{\text{transmission}} \times \eta_{\text{motor}} \times \eta_{\text{alternator}} \\ &= 0.85 \times 0.95 \times 0.9 \times 0.75 \times 0.85 \\ &= 46.33\% \end{aligned}$$

## MERITS

Air engine more efficient than a rotary vane motor

1. High efficiency in large-scale applications
2. Designed to handle high pressures
3. Air engines tend to last longer in harsh environments

## RESULTS & CONCLUSIONS

### Performance Analysis

The developed compressed-air vehicle (CAV) system, powered by an onboard 3 hp air compressor driving a pneumatic motor, was analyzed to quantify its performance characteristics and operational feasibility. The system integrates a battery-powered compressor for efficient on-the-go tank refilling, enhancing practical usability for short-distance mobility.

Theoretical performance calculations indicate a maximum achievable speed of 32.36 km/h, which is adequate for intra-campus or urban short-range commuting applications. This velocity lies within the practical operational limits for low-speed, zero-emission personal transport.

The compressed-air storage tank, under full-load operation of the air motor, provides an effective runtime of approximately 1.89 minutes, reflecting the high volumetric air demand characteristic of pneumatic propulsion systems. The battery-powered compressor has a recharge duration of 2.74 hours, with an operational capability of 85 minutes per full charge, allowing for multiple tank refills during a single battery cycle.

The calculated operational range of the vehicle is approximately 35.42 km, assuming optimal use of stored compressed air and compressor efficiency. This range is suitable for local commuting, campus transportation, and other short-route applications. Importantly, the system operates with zero carbon emissions, confirming its environmental sustainability and alignment with green mobility objectives.

### **System Efficiency and Observations**

The performance metrics underscore that the effectiveness of the CAV system is strongly dependent on:

- Compressor efficiency – dictating the speed and energy cost of tank refilling.
- Air motor design – influencing torque output, efficiency, and runtime.
- Battery capacity – determining operational continuity and refill frequency.

A critical observation is the limited discharge duration of the compressed-air tank, which constrains continuous operation. This limitation necessitates either a rapid refill strategy or an increased tank volume to extend operational runtime. Nevertheless, the system demonstrates a favorable balance between simplicity, low operational cost, and clean energy utilization. Unlike conventional internal combustion engines or electric vehicles reliant on fossil-fuel-derived electricity, the proposed CAV system ensures a completely emission-free operation, both at the energy source and during propulsion.

In conclusion, the study validates that compressed-air propulsion, when integrated with an optimized air motor and battery-powered compressor, offers a technically feasible and environmentally sustainable solution for short-range zero-emission mobility, while highlighting areas for future enhancements in storage and efficiency.

- *Feasibility:* The study confirms that compressed air can serve as a viable propulsion medium for low-speed, short-range vehicles, particularly for applications such as campus transport or localized commuting.
- *Environmental Impact:* The system achieves zero carbon emissions, contributing to sustainable transportation solutions and mitigating environmental pollution.
- *Performance Metrics:* The vehicle's maximum speed of 32.36 km/h and an operational range of 35.42 km demonstrate the practicality of compressed-air propulsion for short-distance applications, with battery-assisted compressor operation enabling multiple refills per charge cycle.

### **FUTURE SCOPE**

For future development, enhancing compressor performance and making it lightweight, reducing air leakage, and integrating regenerative braking or energy recovery systems could significantly improve efficiency and range. Moreover, lightweight vehicle body design and improved air storage methods (such as high-pressure carbon fibre tanks) may contribute to better overall performance.

In summary, the compressed air vehicle system designed in this project shows promising results in terms of zero-emission mobility, with measurable performance in speed and increased range. While further refinement is needed for commercial viability, it serves as a strong prototype for future developments in green transportation technologies

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#### **Ethical Approval**

Not applicable. This study does not involve human participants or animals.

#### **Conflict of Interest**

The authors declare no conflict of interest related to this study.

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