Saimaa University of Applied Sciences
Technology, Lappeenranta
Mechanical Engineering and Production Technology

Arjun Paudel

Bicycle driven by pneumatic cylinder

Thesis 2019

Abstract

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Instructor: Lecturer Simo Sinkko, Saimaa University of Applied Sciences

The objective of this thesis was to test the use of compressed air as an energy source for a short distance bicycle ride assistance. The concept idea was to inspire people to ride a bicycle for shorter commute by offering the feeling of automated ride. Furthermore, to have the cleanest possible energy, the idea for producing compressed air was by using a bicycle pump. A pneumatic cylinder was used as a tool to use energy stored in compressed air to run the bicycle. The thesis also suggests a possible pneumatic system and mounting of the pneumatic drive on the bicycle to assist in riding.

The thesis is mainly a theoretical work. Data for making conclusions and performing necessary calculations are collected mainly from books, the internet articles etc. The main calculations performed are based on well-established principles in physics.

The results of the thesis concluded that the energy stored in compressed air is very low in terms of energy density. It was found that a very large amount of stored pressurised air would be necessary to ride the bike for even short distances which makes the idea impractical.

Keywords: Clean energy, Compressed air, Pneumatic cylinder, Bicycle

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1 Introduction

Mankind has come a long way from being a caveman. Starting with harnessing fire, inventing stone tools, to developing agriculture and domestication of animals and writing, building cities, and to mastering metals, we humans have made a huge leap in our living style and standard. During the last few centuries, we are advancing even more rapidly. The lifestyle of each generation is becoming very different. With all this advancement in technologies, people are living a very luxurious life. Everything is available at their door by a mere press of a button of a cell phone. While this all sounds like we are already living in the future, technology also has significant dark sides.

Social isolation, lack of social skills, obesity, degrading mental health, etc are a few to list out. While all of them are dangerous and have severe effect, the most alarming one is the obesity. Technology made everything digital, autonomous. While use of cars, televisions, computers, and cell phones has increased sedentary time, the time involving physical activities has substantially decreased. We are becoming so lazy and dependent on technology that even to commute a kilometre distance, we use a car and other means of transport that do not require to put physical effort.

The goal of the thesis is to design a prototype vehicle appropriate for commuting short distance, encouraging people in more physical activities. While bicycle is already a popular means for short distance travel, it is losing popularity recently because of the degree of physical effort it requires to ride especially in slopes and a little longer distance travel. This thesis introduces a concept to make bicycle semi-automatic and make it easier to ride. With this concept not only, it will be easier to ride a bicycle, it will also encourage people to commute a further mile.

1.1 Project motivation

The world's energy demand is constantly increasing. Fossil fuel which is a non-renewable energy source and limited on stock is currently supplying most of the energy need. Although fossil fuels are the major and reliable source of energy, they have major negative effects on the environment. Combustion of fossil fuels is causing environmental problems on global level. Because of these problems, people are desperately searching for an alternative source of energy. Among some clean energy sources like wind, solar, hydropower, compressed air is also a viable option. Compressed air is mostly used in applications such as clamping tools, lifting and lowering, pneumatic presses, door controls, screw drivers, grinders, extinguishers etc.

Transportation shares a huge part in energy consumption. Introducing a practicable and clean energy option in the transportation field will definitely play a significant role in saving the environment. This thesis work presents a possible application area of compressed air and anticipates raising awareness in using clean energy powered vehicles.

Although compressed air energy is as clean as it can be, an important thing to consider is the method of compression used or the energy used to pressurize air. If we are using fossil fuel generated energy to compress the air in the first place then the compressed air would not be a clean energy at all. This project checks the practicability of a human powered compressor to generate the compressed air and use that as energy to power the bicycle.

1.2 Project objectives

The main goal of this thesis is to design a compressed air powered bicycle by using pneumatic cylinders to generate the necessary force. The thesis would make necessary calculations and summarize the pros and cons of this method of powering the bicycle and conclude if it is feasible. The major goals of this project can be summarised as follow:

- Designing of main frame of the bicycle considering force distribution through the frame.
- Calculation of approximate force required to ride the bicycle.
- Designing appropriate pneumatic system.
- Selection of suitable pneumatic parts like cylinder, valves etc.
- Design a secondary transmission system to deliver power from pneumatic cylinder to bicycle.
- Designing a 3d model of transmission system for computer simulation and analysis.

2 Constraints of the project

Like most projects this one also has its own constraints. The major constraints with significant affect when planning of this project are cost and safety issues. Other constraints like time are not a major issue in this project as it is an independent research and documentation work.

2.1 Cost

Cost of a project is a crucial factor. As this bicycle is targeted for ordinary people, the customers are willing to spend a certain amount of money. On the other hand, market for a two-wheeler is competitive. So, when designing and selecting the necessary parts, the cost factor is taken in mind. The costs of the chosen parts are listed at the end of the thesis. Various sources were compared, and the best available, cost-effective parts are selected. The cost of the parts helps in estimating the overall cost of the bike.

2.2 Safe usage

For the major part the bike looks and functions as a conventional bicycle. However, the major modification in the bike is the pneumatic system mounted to assist it. Pneumatic cylinders generate the force required to move the bicycle. The so generated force can harm the rider if appropriate safety precautions are not taken. Also, the cylinders are mounted on such a place where the rider can avoid frequent contact, making safe ride possible.

2.3 Technical specifications

The specifications of the project and the parts designed or recommended in the project are listed as follow:

- The overall bicycle weight: 15-20 kg
- One-piece frame, alloy Al 6061 T6
- Primary transmission : chain drive
- Secondary transmission: chain drive with integrated crank mechanism
- Pneumatic cylinder: 50 mm diameter, 100 mm stroke
- Operating pressure: 5 bars

- Reservoir capacity : 135 litres
- Speed: 20 km/hr pneumatic assisted
- Range : 1 km with full tank.

3 Background

3.1 History and development of bicycles

Several unverified claims have been made for the invention of the bicycle. Among them, one claim was made for a bicycle designed over 2500 years ago. The claim was made by a Chinese historian Xu Quan Long who recreated the bicycle from the design of the Chinese inventor Lu_Ban (Phillips, 2010). Another claim is for the sketch from early the 15th century and is credited for Gian Giacomo Caprotti, a student of Leonardo da Vinci, whose bicycle sketch was discovered during the restore and rebound of Leonardo da Vinci’s Codex Atlanticus. However, there is an authenticity dispute about the paper (The Leonardo Da Vinci Bicycle Hoax, n.d.).

The first verified and practically useable bicycle was made by German Baron Karl von Drais. Drais made the invention in 1817 and it was named Laufmaschine (German for “running machine”) (The bicycle in the spotlight, 2017). The bicycle was almost entirely made of wood and was propelled with legs.

Figure 1 The first bicycle

https://www.200jahre-fahrrad.de/en/the-bicycle-in-the-spotlight/The-famine-year-of-1816

The first pedal driven bicycle was invented by Scottish blacksmith Kirkpatrick in 1839 (Kirkpatrick Macmillan (1812 - 1878), n.d.). His idea of a pedal driven bicycle was later copied by others and gradual developments and improvements were made.

3.2 History of pneumatics

The use of compressed air to generate force started as early as 2500 BC, in the form of bellows. Progressive development in the technology expanded the use of pressurised air in fields like pipe organ construction, metallurgy, mining etc.

However, regular use of compressed air in engineering fields started from the mid19th century. Some examples are pneumatic post systems, locomotives, compressed air driven tools, pneumatic drills, etc. In the middle of the 20th century, with the development of pneumatic cylinders, the application of compressed air made automation and mechanization of various tasks possible. (Hasebrink, 1991, p. 12)

3.3 Advances and Development in Bicycles and Pneumatics

I. Bicycles

From the last fifty years there has been a rapid development in many forms of technology and the world of bicycles is no exception. Bicycles have become more comfortable, durable and light weight. The major advances made in bicycles are gearing, suspension, disc brakes, light weight frame, etc.

II. Pneumatic

Nowadays the use of pneumatic cylinders is in almost all fields of engineering from manufacturing to control engineering. Pneumatics have become safer and more accurate. With the development of pneumatic valves, more accurate and reliable control of pneumatic cylinder is made possible thus opening wider application fields. Furthermore, the development of pneumatic valves has made reliable, accurate and safer control of pneumatic cylinders possible thus opening for wider applications.

4 Mechanical design

The main goal of the project is to test the viability of the use of compressed air as an energy source for short a distance two-wheeler. Most of the parts used in designing of the frame and the pneumatic system are standard parts. The only part that is customised will be the frame of the bicycle. The concept is to use the frame itself as a storage tank for pressurised air. The traditional bike frames are not designed for this purpose, so a customised frame will be designed according to need of the project. Pneumatic cylinders are also mounted on the main frame of the bicycle.

The power generated by a pneumatic cylinder is used as an assistive source. Therefore, an additional transmission system is also designed along with the traditional pedal mechanism. The additional transmission system will convey power to the main transmission system whenever the rider wants to. The control system is also designed to control the pneumatics system on the bike.

4.1 Bicycle

The main part that is going to be custom designed for this project will be the main frame of the bicycle and the assistive transmission system. Bicycles have been around for a very long time, the frame design in most of the bicycles is already optimised. Therefore, almost all the bikes have similar frame design. Consequently, the design idea and references in the design of the frame are inspired by the traditional bike.

I. Frame design

The frame is the key node of a bicycle. All other parts of the bicycle are attached to the frame. The upper part of the frame supports the rider's seat and steering handle while the rear wheel, the pedal, the transmission and the front wheel fork are attached on the bottom part. The designed bicycle is of medium size. Riders of height in range of 165 to 175 cm should be able to ride the bicycle with comfort. Several bike manufacturers' web sites were checked to determine the appropriate frame dimensions for a rider of medium height (Covill & Drouet, 13 Feb 2018).

The standard terminology used in referring to different parts of a bicycle frame are shown in Figure 2.

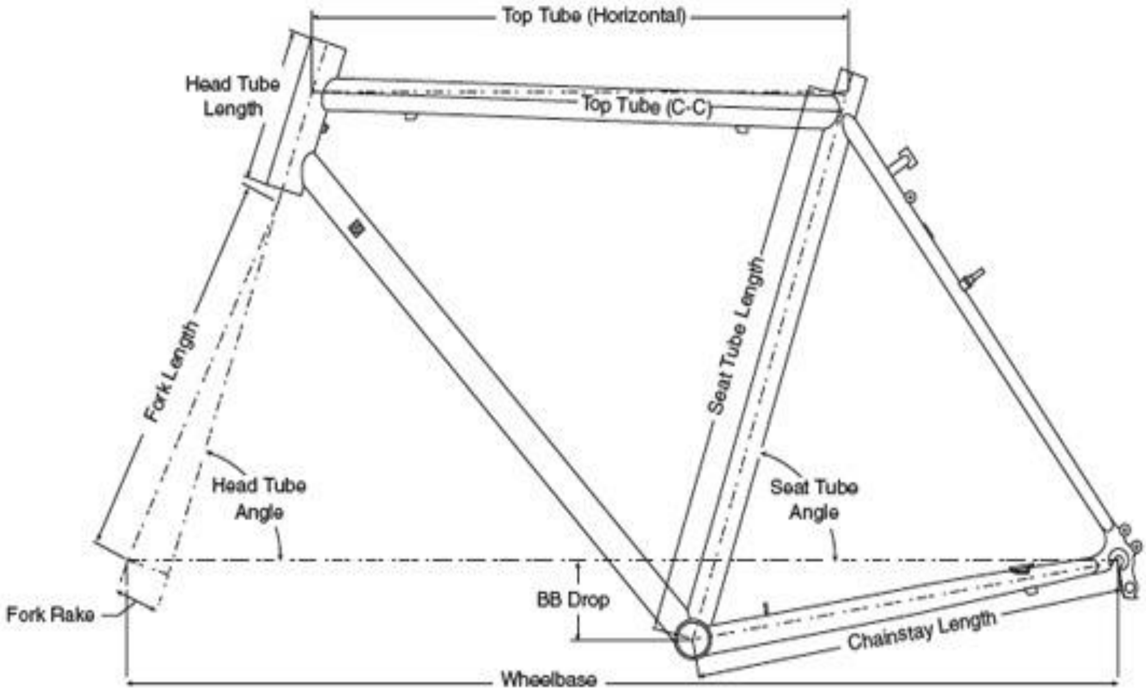


Figure 2 Names of different parts of a bicycle frame

https://www.cyclingabout.com/understanding-bicycle-frame-geometry/

The frame geometry of a bicycle greatly affects its performance. Precision of the frame affects the general accuracy and built quality of the whole bike. Dimensions that have the major effect on the comfortability are the head tube angle and the fork rake. A steeper head angle allows fast steering. The fork rake as shown in Figure 2 is the distance between the steering axis and the front wheel axle. More fork rake makes steering fast and easy. Similarly, a longer wheelbase also makes the ride more stable and comfortable. The frame designed for this project is of a city bicycle. City bicycles are generally made for moderate speed, easy and fast steering and comfort. The dimensions that are used in designing of the frame are listed in Table 1.

Parts/Lengths	Dimensions
Seat tube	550 mm * 30 mm * 0.8 mm
Top tube	580 mm * 30 mm * 0.8 mm
Head tube	145 mm *40 mm * 0.8 mm

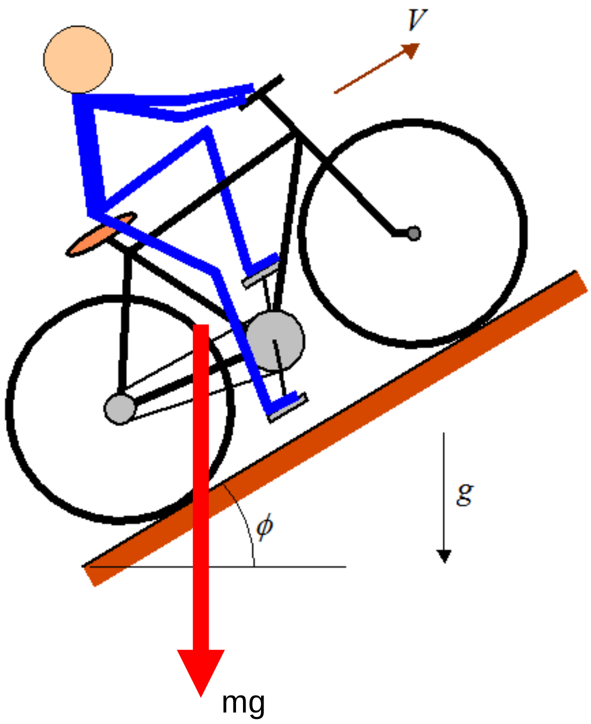
Seat tube angle	73°
Head tube angle	69°
Fork	450 mm *15 mm * 0.5 mm
Chain stay	455 mm *15 mm * 0.5 mm
Wheel base	1100 mm
Bottom bracket (BB) drop	55 mm
Rake	38.45 mm

Table 1 Frame dimensions

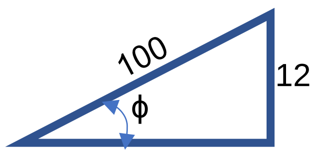
II. Bicycle physics

Force and power calculation

To make a conservative approach, the maximum force required in riding a bicycle is calculated. The maximum force is required when pedalling a bicycle uphill. A road with 12% slope is considered. Figure 4 shows a bicycle going uphill on a road of slope 12% with constant velocity v.



Slope 12%



$$\Phi = \sin^{-1}(\frac{12}{100}) = 6.8°$$

Figure 4 Bicycle driven along an inclined road Figure 3 Slope calculations

Figure 5 shows the free body diagram with forces acting on the system.

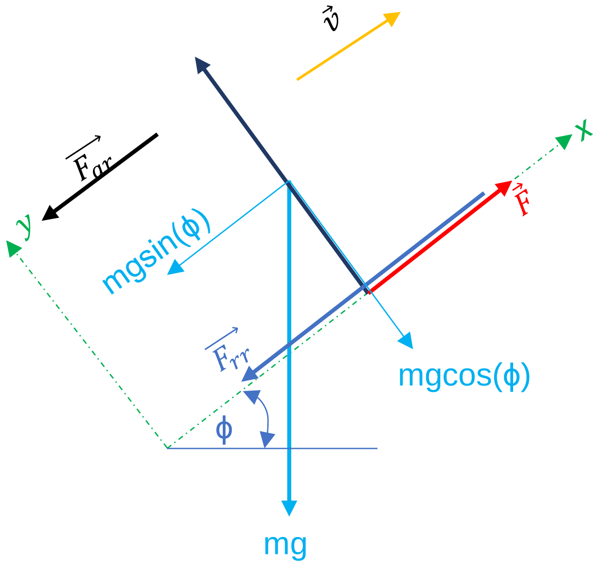


Figure 5 Free body diagram of force acting on a bicycle driven uphill

In figure 5,

The weight of the bicycle and rider (W) = mg = (80+15)·9.8 = 931 N

Forward velocity of bicycle = v = 20 km/h = 5.556 m/s

From Newton's second law of motion in figure 5,

$$F_{ar} + F_{rr} + m \cdot g \cdot sin(\phi) - F = m \cdot a \qquad (1)$$

In equation 1, a is acceleration of the bike , a = 0 at constant velocity.

Equation (1) further simplifies to

$$F = F_{ar} + F_{rr} + m \cdot g \cdot sin(\phi) \qquad (2)$$

F_{ar} is air resistance force and calculated by formula

$$F_{ar} = \frac{1}{2} \cdot C \cdot d \cdot \rho \cdot A \cdot v^2$$

Where, C_d is drag coefficient and C_d = 1.15 for bicycles (Wilson, 2004, p. 188).

P = density of air through which bicycle is moving = 1.225 kg/m^3

A = project area of the cyclist and the bike = 0.55 m^2 (Wilson, 2004) page 188

V = velocity of the bike = 20 km/hr = 5.556 m/s

F_{rr} = Rolling friction force = C_r·m·g·cos(ϕ)

C_r = coefficient of rolling resistance and is dependent on serval factors such as tire inflation pressure, road surface etc.

C_r = 0.0039 (Wilson, 2004, p. 229)

Substituting all the values in equation (2)

$$F = \left(\frac{1}{2}1.15 \cdot 1.225 \cdot 0.55 \cdot 5.556^2\right) + (95 \cdot 9.8 \cdot cos(6.8) \cdot 0.0039) + \left(95 \cdot 9.8 \cdot sin(6.8)\right)$$

$$F = 11.95 + 3.61 + 110.23 = 125.79\ N$$

F is the force propelling the bicycle forward. This force is calculated assuming the head wind is 0 m/s. The power required to propel the bicycle forward can be calculated by multiplying this force with the velocity of bicycle relative to ground.

Power (P) $= \mathrm{F} \cdot \mathrm{v} = 125.79 \cdot 5.556 = 698.88 \approx 700\ \mathrm{W}$

700 watts of power is required to ride the bicycle uphill of slope 12% with velocity of 20 km/hr.

Figure 6 shows the free body diagram of internal forces in force transmission mechanism. Where,

F_1 is the force applied by rider to the pedal

R_1 is pedal radius.

F_2 is the force acting on the main crank of the bicycle.

R_2 is main crank radius

F_3 is force transmitted to rear gear via chain

R_3 is rear crank radius

F_4 is the force acting on the rear wheel

R_4 is the rear wheel radius

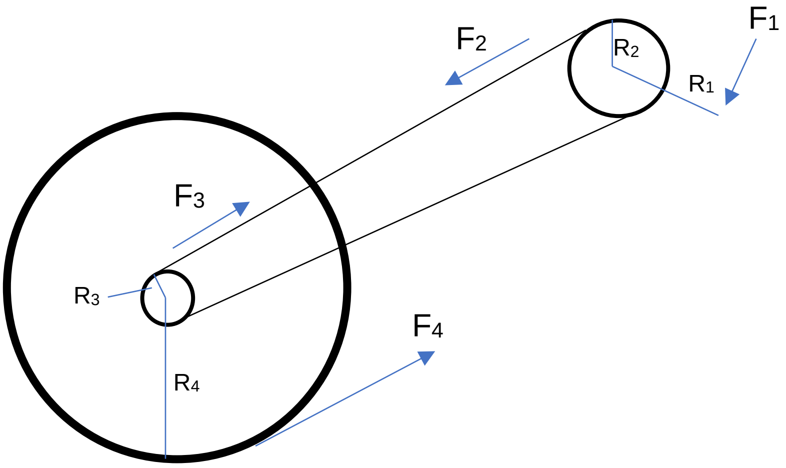


Figure 6 Free body diagram of bicycle pedalled uphill

Again, with assumption that the bicycle is speeding with constant velocity and angular and linear acceleration are negligible. Following torque equations can be written.

$$F_1 \cdot R_1 = F_2 \cdot R_2 \qquad (3)$$

$$F_3 \cdot R_3 = F_4 \cdot R_4 \qquad (4)$$

Since $F_2 = F_3$, equations (3) and (4) can be combined as

$$F_4 = F_1 \cdot \frac{R_3 \cdot R_1}{R_2 \cdot R_4} \qquad (5)$$

The force F_4 is the force that drives the bike forward. Again, with the assumption that the bicycle is moving forward with constant velocity (no acceleration) then this force should be equal to the value of force, F derived in equation (2).

From equation (2) and (5), we can write:

$$F = F_1 \cdot \frac{R_3 \cdot R_1}{R_2 \cdot R_4}$$

or, $F_{ar} + F_{rr} + m \cdot g \cdot sin(\phi) = F_1 \cdot \frac{R_3 \cdot R_1}{R_2 \cdot R_4}$

or, $$F_1 = \frac{R_2 \cdot R_4}{R_1 \cdot R_3}(F_{ar} + F_{rr} + m \cdot g \cdot \sin(\phi)) \qquad (6)$$

The following values for the radius of front crank and rear crank, wheel and the pedal radius are considered. Most of the bicycles are manufactured with these dimensions. So, these values are taken as reference for approximate calculation of force required to pedal.

R_1 = 110 mm = 0.11 m
R_2 = 85 mm = 0.085 m
R_3 = 45 mm = 0.045 m
R_4 = 335 mm = 0.335 m

Now substituting all the values in the equation (6),

$$F_1 = \frac{0.085 \cdot 0.335}{0.11 \cdot 0.045} \cdot (125.79) = \ 723.6\ N$$

F_1 is the force a rider must apply to ride the bike with the speed of 20 km/h in a 12% slope road. With the assumption that the power transmission from pneumatic cylinder to the rear wheel of the bicycle would be like the system shown in Figure 6, pneumatic system should be designed to generate at least of 725 N force.

4.2 Pneumatic system

A pneumatic system is a system that generates energy from pressurised air. It is solely dependent on constant supply of pressurised air to operate and generate energy. The air is pressurised by an air compressor. The energy generated by the compressor is not used immediately but is stored in a storage tank as potential energy. This compressed air is then supplied to the system comprising of pneumatic control valves, pressure gauge, actuators etc. via hoses.

A simple pneumatic system is designed to drive the bicycle. Mainly, the pneumatic system consists of a pneumatic cylinder, control elements: flow control valve, and directional valve. The description of these components is presented as follow:

I. Selection of pneumatic cylinder

Several pneumatic drives are available in the market. Widely used linear motion drives are a single acting cylinder, a double acting cylinder, a diaphragm cylinder, a multi position cylinder etc. Single acting cylinders generate force in one direction and usually spring return mechanism is installed to push the piston rod back to start position. A double acting cylinder exerts force in both directions. Diaphragm cylinders are used to generate large forces (25 KN range). These cylinders have a very short stroke length. The multi position cylinder is a combination of two or more cylinders to attain a number of stop/stable positions. (Hasebrink, 1991, pp. 42-45).

The suitable pneumatic cylinder to drive a bicycle would be a double acting cylinder as it offers push and pull force. The reciprocating motion of the cylinder is converted to rotary motion to drive the bicycle wheel by using a crankshaft mechanism. Pneumatic cylinders are manufactured as a standard part. Their characteristics data are given by the piston diameter, the piston rod diameter and the stroke length. Another criterion for the selection of a pneumatic cylinder is how much force a cylinder generates. The magnitude of force depends upon the operating pressure and the piston area. The approximate force required to drive a bicycle as calculated in chapter 4.1.2 was about 725 N. The next variable in calculation of an appropriate piston area is the operating pressure. Usually the tyre pressure of a bicycle is in range of 5-6 bars. So, 5 bars as the operating pressure is selected for the pneumatic system. Theoretical force generated by a pneumatic cylinder can be calculated as:

$$F = A \cdot p \qquad (7)$$

In equation (7),

F is the theoretical force exerted by the cylinder
A is the piston area
p is the supply pressure into the cylinder

Or, $725 = A \cdot 5 \cdot (0.1)$

$A = 1450\ mm^2 = 14.4\ cm^2$

Now the piston diameter can be calculated as:

$$D = \sqrt{\frac{4 \cdot A}{\pi}} = \sqrt{\frac{4 \cdot 1450}{\pi}} = 42.96\ mm \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8)}$$

The standard pneumatic cylinder available is the cylinder with piston diameter 50 mm. Thus, it can be concluded that an appropriate pneumatic cylinder would be of 50 mm diameter at the operating pressure of 5 bars.

The table (2) shows the effective piston force F_D (push) and F_Z (pull) in daN (deka newton) at the end of stroke, air consumption per cm stroke in direction of outstroke and instroke q_D and q_Z respectively in NL/cm (normal litres per centimetre of cylinder stroke) of a 50 mm piston diameter cylinder at different working pressure. (Hasebrink, 1991, p. 52)

Piston dia. in mm	Effective piston area for	Area (A) cm^2		Working pressure in bar									
				1	2	3	4	5	6	7	8	9	10
50	push	19.63	F_D	12	32	52	71	91	110	130	150	169	189
			q_D	0.039	0.059	0.079	0.089	0.118	0.137	0.157	0.177	0.196	0.216
	pull	17.08	F_Z	10	27	44	61	78	95	112	136	146	163
			q_Z	0.034	0.051	0.068	0.085	0.102	0.12	0.137	0.154	0.170	0.188

Table 2 Piston force and air consumption

At the working pressure of 5 bars a pneumatic cylinder with 50 mm piston diameter can generate effective push force and pull force of 910 N and 780 N. This verifies that an appropriate pneumatic cylinder for the project would be a 50 mm piston diameter cylinder at a working pressure of 5 bars. ISO 155522:2018 Standard pneumatic cylinders with various stroke lengths are available for 50 mm piston diameter. The appropriate stroke length for this project would be 100 mm. Therefore, a 50 mm piston diameter with 100 mm stroke length pneumatic cylinder was selected for the project. Air consumption by the cylinder per double stroke (in- and out- stroke) can be estimated from equation (9) (Hasebrink, 1991, p. 52).

$$Q = H \cdot (\mathrm{q_D} + \mathrm{q_Z}) \cdot \mathrm{n} \qquad (9)$$

Where,

Q= air consumption in NL, normal litres

H = stroke in cm

q_D = Air consumption per cm stroke in the direction of outstroke in NL

q_Z = Air consumption per cm stroke in the direction of instroke in NL

n = number of double strokes

II. Directional control valve

Directional control valves are the most essential parts in a pneumatic or hydraulic system. Directional control valves are used for stopping/allowing flow or changing the flow from one port to another. It usually consists of a spool inside that can be controlled mechanically, electrically or pneumatically to switch position to block/allow flow. A typical directional valve consists of cylinder port(s), supply port(s) and exhaust port(s). The designation of a directional control valve is based on the number of switching positions and the number of ports it has and is designated in general form as n_p/n_s, where n_p is the number of ports and n_s is the number of switching positions. (Hasebrink, 1991, pp. 61-65).

Double acting actuator like the cylinder selected for this project requires a minimum of 4 ports valve. 4 ports, each for the main supply, main exhaust, cylinder supply and cylinder exhaust. And 2 position valves are enough to obtain strokes from one extreme to other. 3 position valves are used to stop a cylinder mid-way of the stroke. Therefore, the appropriate valve for the project is a 4/2 directional control valve.

The switching of the spool in the valve to change the flow path is called actuation of the valve. Methods of actuations are manual, mechanical, pressure and solenoid actuated. Manual actuation is not practical for the application of the project as it requires manual switching of spool at the end of every stroke. Pressure actuation is the best option for the project as the whole system operates on pressurised air. The mechanical and the solenoid require additional parts and power supply for actuation. Figure 7 shows the graphical representation of a 4/2-way directional control valve, actuated by a pneumatic air pilot port from both sides. The diagram is shown according to graphical symbols according to DIN/ISO 1219 (Hasebrink, 1991, p. 61).

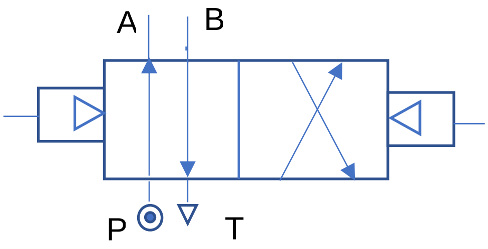


Figure 7 Graphical representation of 4/2 way DCV

The port designations in Figure 7: A and B are working ports and P and T are supply port and exhaust port. The working ports A and B are connected to the pneumatic cylinder's intake and exhaust port, supply port P is connected to air reservoir and port T can be left open or connected to an exhaust silencer to reduce exhaustion noise.

III. Flow control valve

The rate of volume flow of a fluid or gas influences speed of the actuators. Flow control valves are used to restrict/release flow through the hose. Smaller restriction enables higher speed while increase in restriction reduces the speed. Flow control valve can also be turned completely off to stop the motion of the actuator. The figure 8 shows the graphical representation of an adjustable flow control valve according to DIN/ISO 1219. (Hasebrink, 1991, pp. 82-83).

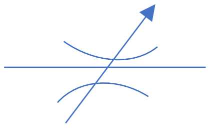


Figure 8 Adjustable throttle valve

IV. Pneumatic circuit design

By using the described pneumatic components, a pneumatic circuit was designed to get a continuous reciprocating motion from the cylinder. Figure 9 shows the pneumatic circuit designed.

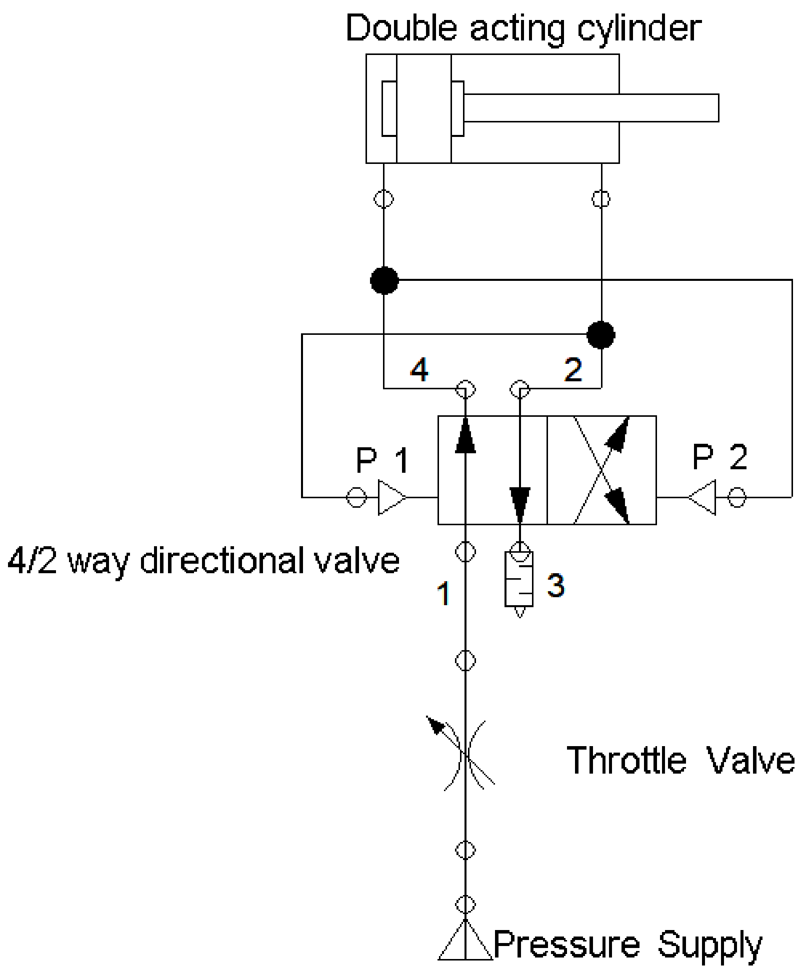


Figure 9 Pneumatic circuit diagram

Figure 9 shows a double acting pneumatic cylinder, a pneumatically actuated 4/2-way valve, a throttle valve and pressure supply. The throttle valve controls the air flow rate into the valve. This throttle valve can be used as an accelerator in the bicycle. The directional control valve is air pilot actuated from both ends (P1 and P2). It contains adjustable permanent magnets in both pilot slots which detent and hold the spool in one of the two positions of 4/2-way valve unit the pilot pressure exceeds the holding force.

The reciprocating motion is started when the pressurised air flows through the throttle valve to 4/2-way valve, allowing the cylinder to extend by pressure from port 4. Exhaust back pressure coming into 4/2-way valve through port 2 and the magnetic detent action prevents the spool from switching position. When the cylinder reaches the end stroke, the pressure in port 2 drops to 0 and the pressure builds up in pilot line P1. This pressure overcomes the force of magnetic detent of the spool thus moving the spool the opposite slot. This will reverse the flow to the cylinder and the retraction movement begins. This cyclic motion will continue until the pressure is cut off from the throttle valve. (Lex air inc., n.d.)

4.3 Power transmission system

I. Mechanism

The bicycle is designed to be powered from two sources of energy. One is traditional manual pedalling mechanism and the other is from the pneumatic system. To make the force generated from the pneumatic system assistive to manual pedalling, it should be integrated into the existing driving mechanism. The force generated by a pneumatic cylinder is a reciprocating force and the force driving a bicycle is a rotary force. So, the reciprocating force generated from a pneumatic cylinder should be converted to rotary mechanism.

The most widely used mechanism that converts reciprocating linear motion into rotary is the one used in an internal combustion engine. Almost all reciprocating engines use cranks with connecting rods to transform the back and forth motion into rotary motion.

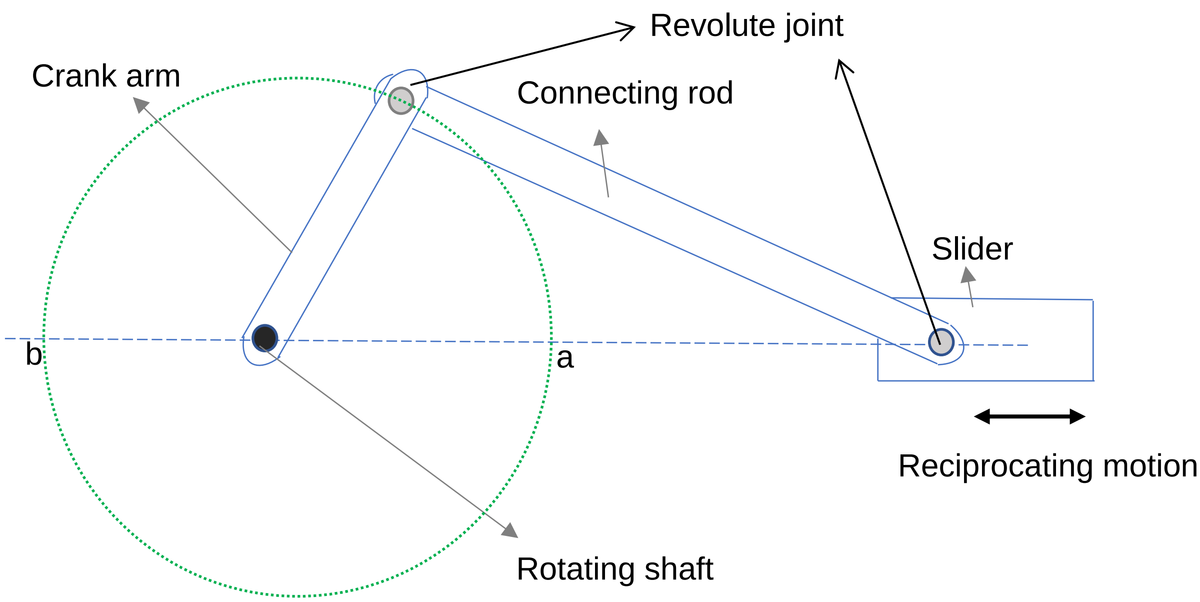


Figure 10 Slider crank mechanism

Figure 10 shows a simple slider crank mechanism that converts reciprocating linear motion to rotary motion. Reciprocating motion of the pneumatic cylinder is applied on the slider. The connecting rod, which is connected to slider and crank with revolute joint, transfers the motion to crank. The force acting on the crank will act as the turning force or torque force for the rotating shaft. At position a and b, the slider, connecting rod and the crank are collinear. At these positions the direction of reciprocating motion changes and these are called dead positions as there is no rotating force acting on the shaft. As the pneumatic system is used as an assistive mechanism in the bicycle, these dead positions are overcome by the momentum of the bicycle and by manual pedalling. (Middle East Technical University, n.d.)

II. Design and mounting

The most critical dimensions in designing of a slider crank mechanism are the length of the crank arm, the length of the connecting rod and the maximum displacement of the slider. A slider crank mechanism whose eccentricity (the vertical/horizontal distance between the rotating axle and slider) is zero is called an in-line slider crank. In an in-line slider crank, the length of the crank arm is always half of the stroke length of the reciprocating motion. The length of the connecting rod should not be less than the length of the crank arm. The stroke length of the selected pneumatic cylinder was 100 mm. Therefore, the crank arm length should be 50 mm.

To make the mechanism compact and efficient, the pneumatic cylinder itself was mounted to act as the connecting rod. An idler sprocket was used as the crank and rotating shaft unit so that power can be directly transferred by using a chain drive. A swivel head with female thread was used to connect the piston rod of the pneumatic cylinder to the idler sprocket. A hole size matching the bore diameter of the swivel head should be drilled in the sprocket at 50 mm radius from the centre. This will make the length of the crank arm 50 mm.

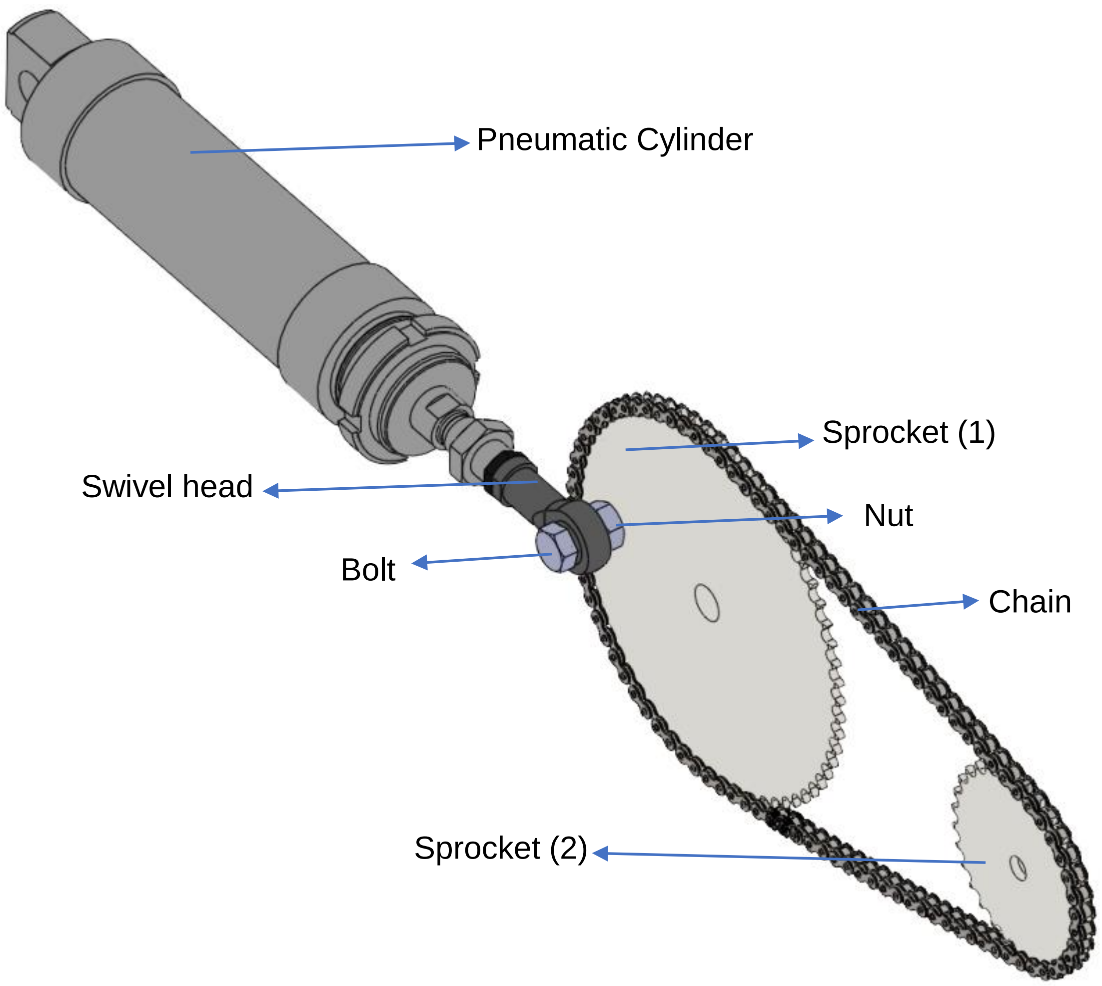


Figure 11 Parts used in secondary transmission

Figure 11 shows the components used in the designing of the secondary transmission system. All the parts used are standard components. The pneumatic cylinder used was selected according to the results of calculation made in chapter 4.2 The standards of the parts are listed in Table 3.

Parts	Standard/Product code	Manufacturer	Retail price (€)
Pneumatic Cylinder	193994 DSNU-50-100-PPS	**Festo**	100

Direction control valve	MCR-531-1001	**Lexair Inc.**	30
Swivel Head	LJAF16	**IKH dealers**	21
Bolt	M16 x 1.5		
Nut	M16 x 1.5		
Sprocket (1)	35BB19H-38	**USA Roller Chain and Sprockets**	40
Sprocket (2)	35A15	**USA Roller Chain and Sprockets**	**30**
Chain	#35	**USA Roller Chain and Sprockets**	**15**

Table 3 Parts used in the design of secondary transmission

Figure 12 shows the assembly of the parts of secondary transmission system in the bicycle frame. A shaft is welded at the intersection point of the head tube and the down tube of the bicycle. The cylinder is mounted in this shaft as shown in figure 12. A female threaded swivel head is tightened on the piston rod. The parts recommended in the table (3) are compatible with each other. Another shaft is welded on the downtube at a distance 50 mm further from the swivel head bore. A M16x.5 hole is drilled on the sprocket (1) at 50 mm radius. The sprocket (1) is mounted on this second shaft while the swivel head is tightened to the drilled hole of the sprocket (1) by using a bolt and nut specified on the list. The nut installed as shown in Figure 11 ensures the clearance of the swivel head from the sprocket surface when rotating with the sprocket. The sprocket (2) is welded in the inner side of the crankarm of the pedal as shown in figure 12. A chain is installed on the sprocket (1) and the sprocket (2) to transfer the power. When the pneumatic cylinder will make reciprocating motion, the sprocket (1) will rotate as described in the chapter of crank mechanism which in turn will rotate the sprocket (2). The sprocket (2) will rotate the pedal thus powering the bicycle.

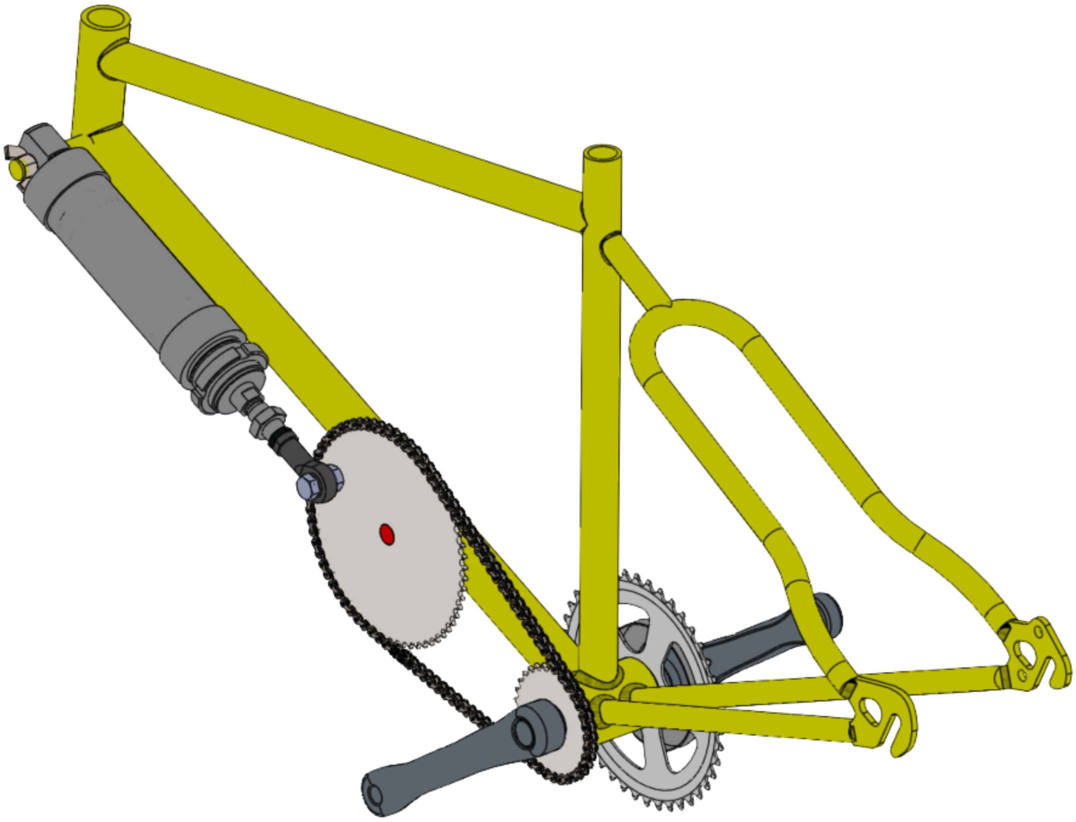


Figure 12 Assembly of secondary transmission in bicycle frame

5 Performance

5.1 Force and torque generated by the pneumatic cylinder

Figure 13 shows the free body diagram of force transmission in the crank mechanism designed for the application. Line AB represents the direction of force exerted by the pneumatic cylinder, Line BC represents the connecting rod and line OC represents the radius of the crank arm. $\vec{X}$ is the force exerted by the cylinder and $\vec{F}$ is the force transmitted along the connecting rod. α, β and θ are the angles of ΔOBC to represent an arbitrary position during the transmission. a, b and c are the lengths of sides of ΔOBC as represented in Figure 13.

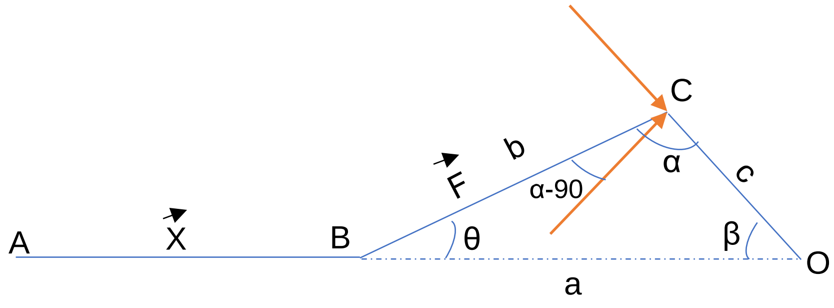


Figure 13 Free body diagram of Crank mechanism

Applying Sine law in ΔOBC;

$$\frac{sin\alpha}{a} = \frac{sin\beta}{b} = \frac{sin\theta}{c} \qquad (10)$$

$$a = b \cdot cos\theta + c \cdot \cos\beta \qquad (11)$$

$$cos\theta = \sqrt{1 - \sin^2\theta}$$

From equation (10)

$$cos\theta = \sqrt{1 - \frac{\mathrm{c}^2 \cdot \sin^2\beta}{b^2}}$$

Equation (11) becomes:

$$a = b \cdot \sqrt{1 - \frac{\mathrm{c}^2 \cdot \sin^2\beta}{b^2}} + c \cdot \cos\beta = \sqrt{b^2 - \mathrm{c}^2 \cdot \sin^2\beta} + c \cdot \cos\beta \qquad (12)$$

$$F = \frac{X}{cos\theta} = \frac{X}{\sqrt{1 - \frac{\mathrm{c}^2 \cdot \sin^2\beta}{b^2}}} \qquad (13)$$

Torque acting at point O is given by:

$$T = F \cdot cos(\alpha - 90) \cdot c = F \cdot c \cdot sin\alpha = F \cdot c \frac{a \cdot sin\beta}{b} \qquad (14)$$

From equations (12), (13) and (14); torque acting at point O can be expressed in terms of force exerted by pneumatic cylinder, length of connecting rod, crank arm and angle at point O i.e. rotation of the crank as follows:

$$T = \frac{X}{\sqrt{1 - \frac{\mathrm{c}^2 \cdot \sin^2\beta}{b^2}}} \cdot \frac{c \cdot (\sqrt{b^2 - \mathrm{c}^2 \cdot \sin^2\beta} + c \cdot \cos\beta) \cdot sin\beta}{b}$$

$$= \frac{X}{\sqrt{b^2 - \mathrm{c}^2 \cdot \sin^2\beta}} \cdot \frac{c \cdot (\sqrt{b^2 - \mathrm{c}^2 \cdot \sin^2\beta} + c \cdot \cos\beta) \cdot sin\beta}{1}$$

Equation further simplifies to

$$T = \frac{X \cdot c \cdot sin\beta \cdot (\sqrt{b^2 - \mathrm{c}^2 \cdot \sin^2\beta} + c \cdot \cos\beta)}{\sqrt{b^2 - \mathrm{c}^2 \cdot \sin^2\beta}} \qquad (15)$$

The torque graph was plotted using MATLAB for one complete rotation at a difference of 10°. The average torque generated by the cylinder was 28.11 Nm and the maximum torque was 51.04 Nm at 70° and 290°. MATLAB script file is attached as appendix 1 at the end of the thesis. Figure 14 shows the torque graph.

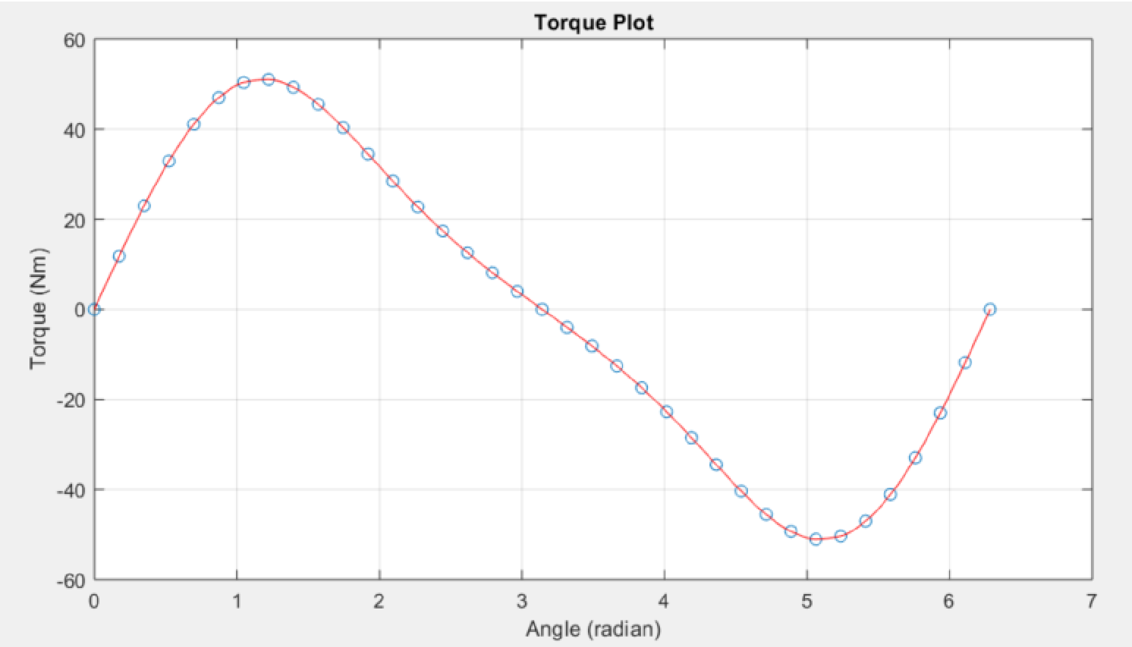


Figure 14 Torque plot

With the assumption of no mechanical losses during the transmission, torque equivalent to average torque generated by the pneumatic cylinder is transmitted to the rear wheel of the bicycle. The force acting on the rear wheel responsible for the forward motion can be calculated as:

$$F = \frac{T}{R} \qquad (16)$$

Where T is the torque acting on the rear wheel and R is the radius of the rear wheel.

$$F = \frac{28.11}{0.335} = 83.91\ N$$

Therefore, the force acting between the rear wheel of the bicycle and road is 83.91N. This force is responsible for the forward movement of the bicycle. The resistive force acting on the bicycle at 12% slope as shown in Figure 3 and calculated in equation (2) is 113.61 N without considering head wind, which is more than the force generated by the pneumatic cylinder. So, the bicycle would not climb the 12% slope. The maximum slope the bicycle can climb with velocity 20 km/hr (5.556 m/s) can be calculated as follows:

The calculation of equation 2 is

$$\boldsymbol{F} = \left(\frac{1}{2} 1.15 \cdot 1.225 \cdot 0.55 \cdot 5.556^2\right) + (95 \cdot 9.8 \cdot cos(\mathbf{6.8}) \cdot 0.0039) + \left(95 \cdot 9.8 \cdot sin(\mathbf{6.8})\right)$$

Where F is the force propelling the bicycle and 6.8 is the slope angle. Substituting force, F with 83.91 N, the slope can be calculated as:

$$\mathbf{83.91} = \left(\frac{1}{2} 1.15 \cdot 1.225 \cdot 0.55 \cdot 5.556^2\right) + (95 \cdot 9.8 \cdot cos(\boldsymbol{\phi}) \cdot 0.0039) + \left(95 \cdot 9.8 \cdot sin(\boldsymbol{\phi})\right)$$

$$\mathbf{83.91} - 11.95 = (95 \cdot 9.8 \cdot cos(\boldsymbol{\phi}) \cdot 0.0039) + \left(95 \cdot 9.8 \cdot sin(\boldsymbol{\phi})\right)$$

$$\frac{\mathbf{83.91} - 11.95}{95 \cdot 9.8} = (cos(\boldsymbol{\phi}) \cdot 0.0039) + \left(sin(\boldsymbol{\phi})\right)$$

$$0.07729 = (cos(\boldsymbol{\phi}) \cdot 0.0039) + \left(sin(\boldsymbol{\phi})\right)$$

This equation holds true at $\phi = 4.209 + 2 \cdot n \cdot \pi$, for every natural numbers n.

For n = 0, $\phi = 4.209$. Therefore, the equivalent slope as can be calculated as $100 \cdot \sin(4.209) = 7.34$.

5.2 Speed of the bicycle

Therefore, the bicycle can ride with velocity 20 km/hr at 7.34% slope. The speed of the bicycle can be calculated again from equation 2. Expressing equation (2) in terms of velocity, equation (17) can be derived:

$$F = \frac{1}{2} \cdot C \cdot d \cdot \rho \cdot A \cdot v^2 + F_{rr} + m \cdot g \cdot sin(\phi)$$

$$[F - F_{rr} - m \cdot g \cdot sin(\phi)] \cdot \frac{2}{C \cdot d \cdot \rho \cdot A} = v^2$$

$$v = \left\{[F - \mathrm{Cr} \cdot \mathrm{m} \cdot \mathrm{g} \cdot \cos(\phi) - m \cdot g \cdot sin(\phi)] \cdot \frac{2}{C \cdot d \cdot \rho \cdot A}\right\}^{\frac{1}{2}} \tag{17}$$

The speed of the bicycle in various slopes is summarised in Table 4.

The speed of the piston of the pneumatic cylinder corresponding to the speeds of the bicycle at various slopes can be calculated using the transmission gear ratio. The figure (15) shows the outline of the transmission system.

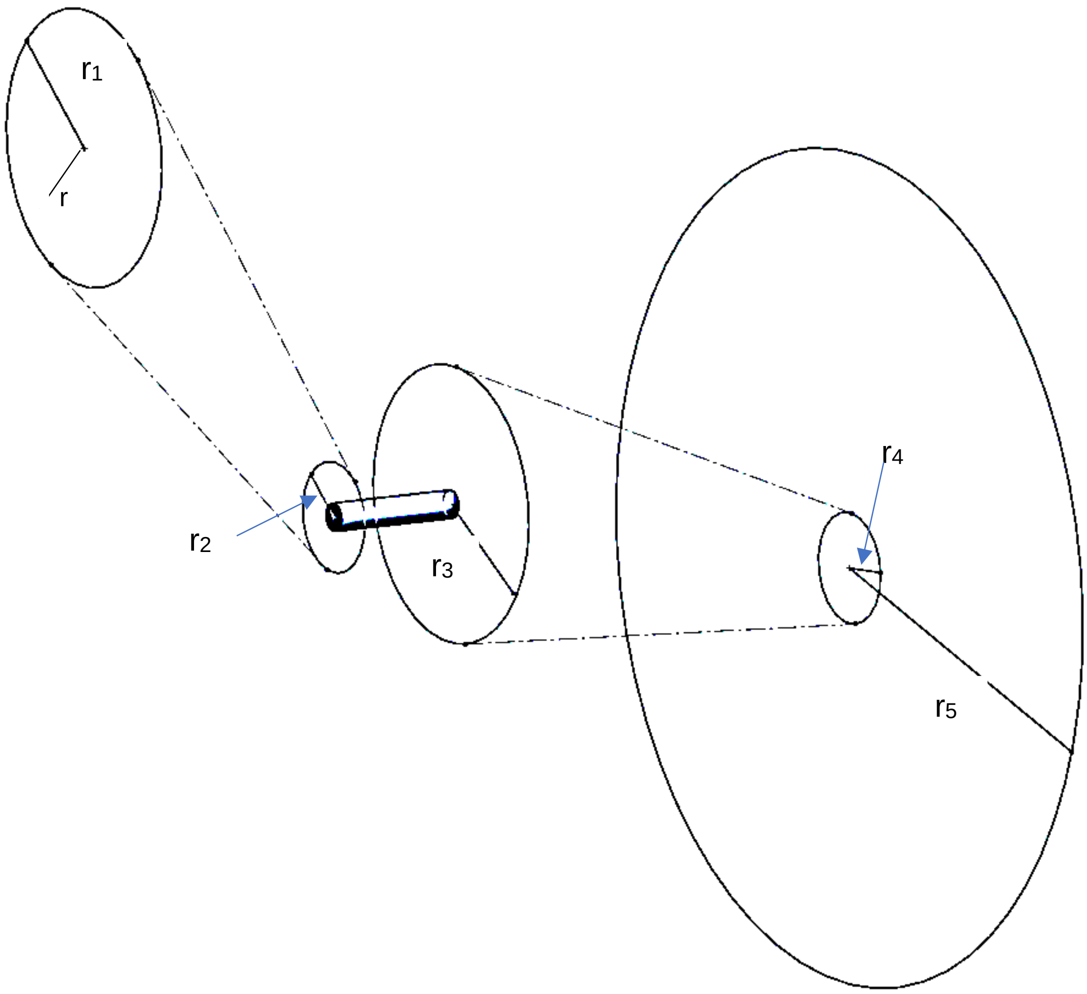


Figure 15 Outline of transmission system

In figure (15), r is the radius at which the pneumatic piston is linked to the transmission gear. r_1, r_2, r_3 and r_4 are the radius of gears involved in the transmission and r_5 is the radius of rear wheel. Let v, v_1, v_2, v_3, v_4 and v_5 be the linear velocity and ω, ω_1, ω_2, ω_3, ω_4 and ω_5 be the angular velocity corresponding to the radii R, r_1, r_2, r_3, r_4 and r_5. In a gear and chain transmission system, gears connected with chain have equal linear velocities and concentric gears have equal angular velocities. Based on these rules following equations can be summarised.

$$\omega = \omega_1; \qquad v_1 = v_2; \qquad \omega_2 = \omega_3; \qquad v_3 = v_4; \qquad \omega_4 = \omega_5$$

In a uniform circular motion, the radius, linear velocity and radial angular velocity are related by the relation v = r·ω. Based on this relation following equations can be derived for each circle in figure (15).

$$\mathrm{v} = \mathrm{r} \cdot \omega; \quad \mathrm{v}_1 = \mathrm{r}_1 \cdot \omega_1; \quad \mathrm{v}_2 = \mathrm{r}_2 \cdot \omega_2 \quad \mathrm{v}_3 = \mathrm{r}_3 \cdot \omega_3; \quad \mathrm{v}_4 = \mathrm{r}_4 \cdot \omega_4; \quad \mathrm{v}_5 = \mathrm{r}_5 \cdot \omega_5$$

Based on the equations listed, the following relation can be derived in between the linear velocity of bicycle (v_5) and linear velocity of the piston (v).

$$\mathrm{v} = v_5 \cdot \frac{r \cdot r_2 \cdot r_4}{r_1 \cdot r_3 \cdot r_5}$$

Substituting the values of radii in the equation; following relation can be obtained:

$$v = v_5 \cdot \frac{0.05 \cdot 0.045 \cdot 0.045}{0.065 \cdot 0.085 \cdot 0.335}$$

$$\text{or, } v = 0.0547 \cdot \mathrm{v}_5 \qquad (18)$$

The equation (18) gives the relation between the linear velocity of bicycle and the velocity of piston of pneumatic cylinder. The velocity of piston of pneumatic cylinder is calculated according to velocities of bicycle calculated for different slopes in equation (17). The values obtained are summarised in table (4).

The velocity of the pneumatic piston depends upon the flow rate of the pressurised air in the pneumatic system. The major component determining the flow rate in a pneumatic circuit is the pneumatic valve used. The valve selected in the design of pneumatic circuit is listed in table (3).

The rated flow coefficient (C_v) of the valve selected was 1.13 for 3/8'' (9.525 mm equivalent) hoses. The maximum flow rate of the valve can be calculated by using the C_v value. (Lansky & Scharder JR., 1986, pp. 129-130).

$$Cv = \mathrm{cfm} \cdot \mathrm{A}$$

Where cfm is flow rate in cubic feet per minute at 7600mm Hg, 20°C, and 36% relative humidity.

A is constant which is a function of inlet pressure and pressure drop.

Constant A for an inlet pressure of 70 psi (5 bars equivalent) and pressure drop of 10 psi is 0.037.

Therefore, $cfm = \frac{C_v}{A} = \frac{1.13}{0.037} = 30.54\, ft^3/\min = 0.01441 \frac{m^3}{s}$

Piston velocity can be estimated from the flow rate value by using formula:

Velocity (v’) $= \frac{cfm\,(\frac{m^3}{s})}{piston\ Area(m^2)} = \frac{0.01441}{\pi \cdot 0.025^2} = 7.4\ m/s$

This is the maximum velocity of the piston of the pneumatic cylinder the selected valve can support. This value is significantly higher than the values of pneumatic piston velocity (v) (calculated in equation (18) and listed in table (4). Therefore, the selected valve supports enough flow rate required by the application.

Slope(%)	0	1	2	3	4	5	6	7
Speed of bicycle (v_5) (m/s)	14.39	13.53	12.62	11.62	10.54	9.33	7.94	6.25
Speed of pneumatic piston (v) (m/s)	0.787	0.740	0.690	0.636	0.577	0.510	0.434	0.342

Table 4 Speed of bicycle at different slopes

5.3 Air consumption

The equation (9) gives the volume of air consumed by a pneumatic cylinder in the given number of double strokes. The equation (9) states:

$$Q = H \cdot (\mathrm{q_D} + \mathrm{q_Z}) \cdot \mathrm{n}$$

H is the stroke length in cm and is 100 mm (10 cm) and q_D, q_Z are air consumption per cm stroke in the direction of outstroke and instroke in normal litres. The values are listed in table 2 and $q_D = 0.118$ and $q_Z = 0.102$. n is the total number of double strokes in the operation time. Substituting the values of variables H, q_d and q_z in equation (9).

$Q = 10 \cdot (0.118 + 0.102) \cdot \mathrm{n}$ (NL, Normal litres)

$Q = 2.2n$ (NL, Normal litres)

The value of n can be calculated based on the run time of the bicycle. Time (T) required by the bicycle to cover a distance (s) with the velocities (v_5) listed in the table 4 can be calculated using following formula.

$$time\ (T) = \frac{distance\ (s)}{velocity\ (v_5)} \qquad (19)$$

This equation gives the run time of the bicycle. The number of double strokes the pneumatic cylinder makes during this time can be calculated using the velocity of the pneumatic piston (v) calculated in equation (18) and the stroke length (100 mm or 0.1m). F

$$n = \frac{v \cdot T}{2 \cdot 0.1}$$

Now the equation for the volume consumption by the pneumatic cylinder can be expressed as:

$$Q = 2.2 \cdot \frac{v \cdot T}{2 \cdot 0.1}\ (NL)$$

$$therefore, Q = 11 \cdot v \cdot T$$

Substituting v and T from equations (18) and (19);

$$Q = 11 \cdot (0.0547 \cdot \mathrm{v}_5) \cdot \left(\frac{s}{v_5}\right)$$

$$Q = 0.6017 \cdot s\ (NL) \qquad (20)$$

The equation 20 gives the volume of air consumed by the bicycle, where s is the distance travelled by the bicycle in meters. The volume is in normal conditions i.e. at atmospheric pressure and 273.15 K temperature.

The volume of vessel required to store pressurised air at 5 bars and environment temperature of 25°C can be calculated using ideal gas law. The ideal gas law states:

$$PV = nRT$$

During compression of a gas, the number of moles remains constant and hence the ideal gas law can be expressed as

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Where P_1, V_1,T_1 and P_2, V_2, T_2 are pressure, volume and temperature at initial and final conditions. The initial condition is the normal litre condition and the final condition is the at temperature 25°C (298.15K) and 5 bars of pressure. The equation can be rearranged to solve for the final volume after compression and temperature change as expressed in equation (19).

$$V_2 = \frac{P_1V_1T_2}{P_2T_1}$$

$$V_2 = \frac{P_1V_1T_2}{P_2T_1} = \frac{1 \cdot Q \cdot 298.15}{5 \cdot 273.15} \tag{21}$$

The rate of consumption of pressurised air by the bicycle per kilometre ride can be calculated by substituting s = 1000 in equation (20) and solving for V_2 in equation (21).

$$Q = 0.6017 \cdot 1000\ (NL) = 601.7\ NL$$

$$V_2 = \frac{1 \cdot 601.7 \cdot 298.15}{5 \cdot 273.15} = 131.35\ litres$$

Therefore, the bicycle would require a tank capacity of minimum 131.35 litres to ride for 1 km. The calculation performed only gives the theoretical value. The consumption in real life can vary depending upon the loading on the bicycle, environment temperature, temperature of pressurised air etc. However, the consumption of air in practical performance should not be significantly different from the calculated value as the values assigned to variables are close approximation of real-life situations. MATLAB script file related to calculation performed in this chapter is attached as appendix 2 at the end of the thesis.

5.4 Pressure decrease rate

The fuel tank i.e. the pressurised air container does not have a constant supply of pressurised air. The tank is filled in advance, therefore with each stroke of pneumatic cylinder the pressure in the storage tank drops resulting in the drop of force generated by the pneumatic cylinder. The pressure drop can be estimated by calculating the mass of the air, the pneumatic cylinder is consuming. Using ideal gas law, pressure of the storage tank can be estimated by calculating the mass of exiting air and subtracting it from the original air mass stored in the tank.

The volume of the air consumed by the pneumatic cylinder per double stroke as listed in table (2) is $v = q_D + q_Z = 0.118 + 0.115 = 0.22\,\frac{\mathrm{NL}}{\mathrm{cm}} = 2.2\,\frac{\mathrm{NL}}{100\,mm}$.

The ideal gas law in molar form is

$$P \cdot V = \left(\frac{m}{M}\right) \cdot R \cdot T$$

Where,

P is pressure of the gas

V is volume of the gas

R is the ideal gas constant, R = 8.314 Joules per mole-Kelvin

T is temperature of the gas

m is mass of the gas

M is mass of gas per mole, for air mixture M = 28.9697 g/mol

Therefore, mass of air inside the storage tank and the air exiting the tank with each double stroke can be estimated from the ideal gas law.

$$\frac{P \cdot V \cdot M}{R \cdot T} = m$$

If m_1 is the mass of the air inside the storage tank before the double stroke and m_2 is the mass of air consumed by the pneumatic cylinder, then the drop in the pressure in the storage tank can be again estimated by using ideal gas law in molar form.

$$P = \left(\frac{m_1 - m_2}{M \cdot V}\right) \cdot R \cdot T$$

The same calculation repeats with each cycle of stroke of pneumatic cylinder. Numerical calculation was done using MATLAB programme and the trend in pressure drop in the pneumatic cylinder was plotted. The corresponding script is attached as appendix 3 at the end of thesis. Figure 16 shows the decrease in pressure inside the storage tank with respect to the number of double strokes.

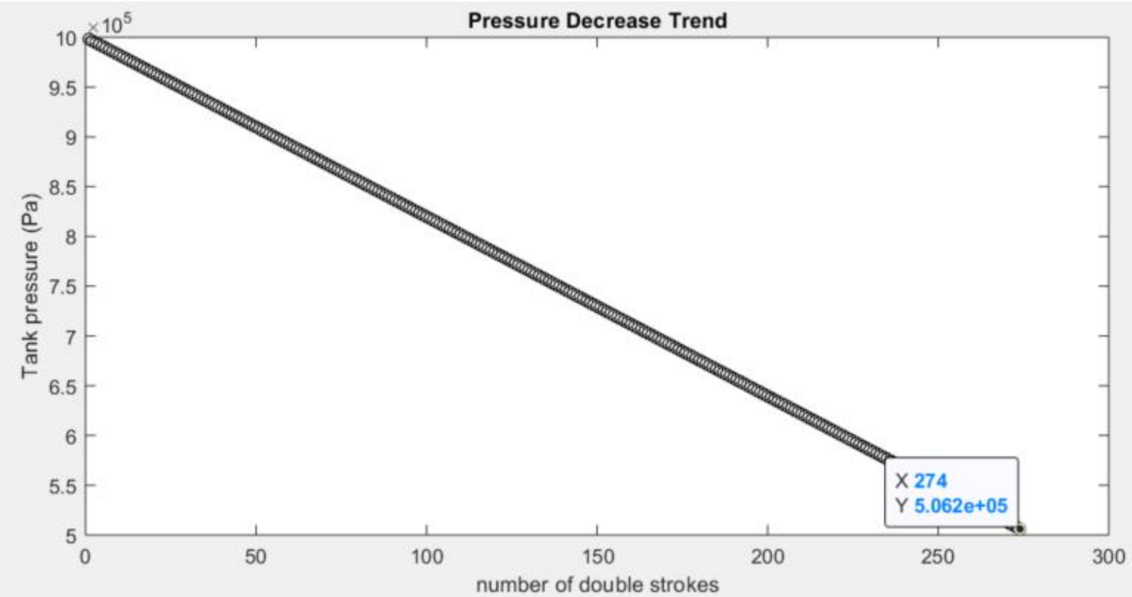


Figure 16 Pressure decrease trend

As the formula suggested, linear decrease in pressure of the storage tank with respect to the number of double strokes can be observed from Figure 16. With the starting pressure of 10 bars, and the tank capacity of 135 litres, the pressure starts to drop below 5 bars after the pneumatic cylinder has made about 274 double strokes. The number of double strokes necessary to run 1000m was about 273 (calculation in appendix 2).

6 Summary

The goal of the thesis was to test the viability of using compressed air as a fuel for short distance bicycle assist. The motivation behind the project was to inspire and contribute in use of “clean energy” powered means of transportation. As long as the methods of production of compressed air do not uses fossils fuel, the compressed air energy is as clean as it can be. A thought-out method of production of compressed air for the pneumatic bicycle was a human powered bicycle pump.

The challenges faced were designing of appropriate pneumatic circuit that supports a continuous reciprocating motion from the pneumatic cylinder, mounting the assistive transmission system in the bicycle, mechanism to convert the reciprocating motion into circular motion etc. The major issue was to design a pneumatic circuit for the required application as almost all pneumatic cylinders are not designed for continuous reciprocating motion. The original idea developed as a solution was to implement a closed loop control system by using solenoid and reed switches, but this idea was dropped after a valve dedicated for the required application was found from a manufacturer’s website. Similarly, extensive amount of time was spent on finding an appropriate and efficient method to convert the reciprocating motion into circular motion and the solution purposed/designed for this problem was by using crank shaft mechanism which is a very popularly adapted mechanism in this kind of application.

This thesis work did widen the authors knowledge in pneumatic systems and components, designing of pneumatic circuits, bicycle physics, and transmission parts like gears etc. This work also further improved the designing and modelling skills of the author. Furthermore, this thesis work for the author was a chance to plan and execute a project from preliminary idea to final stage. In addition, valuable lessons in terms of project planning, research work, decision making etc were also learned from the thesis work.

Although the idea of using cleanest form of energy and motivating people in using bicycles sounds very good, the numbers obtained from the calculations pointed out using this source of energy for transportation is an inefficient utilization of green energy. The calculation showed that just to ride 1km distance, the compressed air of volume above 130 litres at 5 bars is required. And addition to that, the bicycle is limited to a storage tank and does not have constant supply of pressurised air, so to continuously generate the required force for 1 km distance, the tank should be loaded with more pressure than just 5 bars. To cover a kilometre distance, the starting pressure for a tank capacity of 135 litres should be around 10 bars. This is very impractical and ineffective for commercialization or mass adaptation.

Figures

Tables

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Appendix 1. Torque plot calculation (MATLAB script)

```
clc; clear all; close all;
l = 0.1; % length of connecting rod
r= 0.05;  % radius of crank arm
P = 500000; %pressure of the system in pascals
d= 0.05; % diameter of cylinder
A = (pi*d^2)/4; % area of the cylinder
F=910;
B = 0: 10: 360; % angle in degreee
B = B*pi/180; % angle in radians
f=F./((sqrt(1-(r.^2./l.^2).*(sin(B)).^2)));
T = (f.*r./l).*(sin(B)).*(r*cos(B)+l.*sqrt(1-
(r.^2./l.^2).*(sin(B)).^2)); % equation
xx=linspace(B(1),B(end),1000);
yy=interp1(B,T,xx,'pchip');
plot(B,T,'o',xx,yy,'r');
title('Torque Plot')
xlabel("Angle (radian)")
ylabel("Torque (Nm)")
grid on
T = abs(T);
M = mean(T)
ymax=max(T)

xmax=B(find(T==ymax));
xmax = 180*xmax/pi
```

Appendix 2. Air consumption calculation (MATLAB script)

```
clc; clear all; close all;

slope=0:1:7%[0 1 2 3 4 5 6 7] slope of road from 0 to
7 percent
theta = asin(slope/100);
%velocity of bicycle equation (17)
v5 = sqrt((83.91-(0.0039*cos(theta)
+sin(theta))*95*9.8)/(0.5*1.15*1.225*0.55)) % in m/s
%velocity of pneumatic piston corresonding to bicycle
velocity from
%equation (18)
v = 0.0547.*v5;
a = 1000; % distance covered by bicycle in meters

 T = a./(v5); % run time of bicycle in seconds
% number of double strokes
n = 5*T.*v;
%air consumption by bicycle from equation (19)
Q = 11*T.*v % volume of air consumed in  normal liters

% volume of air at 5 bars from equation (20)
V2 = (298.15/(273.15*5)).*Q


clc; clear all; close all;
% pressure decrease rate

p1 = 1000000; % starting pressure in the tank 10 bars
equivalent in pascals
V = 0.0055; % volume of the tank 5 liters in m^3
M = 0.022897; % molar mass of air in kilo grams
R = 8.3144598; %gas constant
T = 298.15; % environment temperature
m1 = 0;
v= 0.112e-3;

for i = 1:1:100
m = (M*V*p1)/(R*T)
m1 = (M*v*p1)/(R*T)
p1 = (R*T*(m-m1))/(V*M)
disp(['p1 = ' ,num2str(p1)])
plot(i, p1, 'ko')
hold on
end
```

Appendix 3. Pressure decrease rate in storage tank (MATLAB script)

```
clc; clear all; close all;
% pressure decrease rate

%% temperature and pressure condition of the storage
tank

P = 10e5; % starting pressure in the tank 10 bars
equivalent in pascals
V = 100e-3; % volume of the tank 100 liters in m^3
M = 0.0289697; % molar mass of air in kilo grams per
mole
R = 8.3144598; %gas constant
T = 298.15; %  temperature of storage tank

%% condition corresponding to air consumed by the
pneumatic cylinder in normal conditions
p1 = 101325; % normal pressure
v1 = 2.2e-3; % volume of the air consumed by pneumatic
cylinder in m3
T1 = 273.15; % normal temperature
m1 = (M*v1*p1)/(R*T1); % mass of the gas consumed by
pneumatic cylinder
%% decrease in pressure with number of double strokes
for i = 1:1:274 % 200 double strokes
m = (M*V*P)/(R*T);

P = (R*T*(m-m1))/(V*M);
disp(['p1 = ' ,num2str(P)])

plot(i, P, 'ko')
title('Pressure Decrease Trend')
xlabel('number of double strokes')
ylabel('Tank pressure (Pa)')

hold on
end
```