UNIVERSITY OF WATERLOO

Faculty of Engineering

COMPRESSED AIR CAR

Project 1
MTE 309 - Introduction to Thermodynamics and Heat Transfer

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1 Introduction

Tata Motors developed an environmentally friendly compressed air powered AirPod (Figure 1). The vehicle is powered by the expansion of compressed air that moves from the storage tank and drives the air turbines located at the four wheels (Figure 2).

Figure 1: Tata Motors AirPod

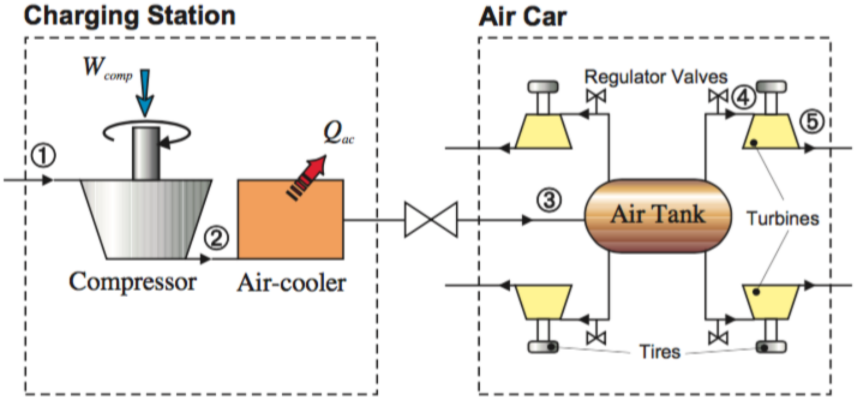

Figure 2: AirPod charging and operation schematic

The AirPod's advantage is the low cost, light weight and being environmentally friendly. The total weight of the vehicle is 200 kg of which 24 kg is the engine. The operation of the car is simple, compressed air powers the turbines until the air in the tank reaches equilibrium with the surroundings.

The main disadvantages of the AirPod is its speed, range, carry load and pressurized container. The maximum speed of the vehicle is 70 km/hr, and range varies from 120 - 150 km. To recharge the vehicle a specialized high pressure station is required. Lastly, vehicle's range depends on the load of the car thus making the transportation of anything besides the driver inefficient.

2 Analysis

2.1 Assumptions and Simplifications

- Negligible mechanical losses
- Air is an idea gas
- Negligible pressure losses in pipes, joints and the air-cooler
- Specific heat is a function of temperature.
- Assume correlations in Table A-2 are valid over full range of temperature
- Time to reach maximum velocity is independent of total mass
- When the air tank reaches atmospheric pressure the vehicle stops immediately, thus no deceleration.
- During the acceleration phase the mass of the vehicle remains constant

The assumptions made in this report are to simplify calculations as well as be able to evaluate the ideal case of the car design and determine the vehicles maximum performance.

2.2 Control Volumes and Calculations

2.2.1 Thermodynamic Analysis

The calculation for thermodynamics of the AirCar are done based on the initial conditions shown in Table 1.

Table 1: Initial Conditions

Properties		
Ambient Temperature	(T_1)	20°
Ambient Pressure	(P_1)	100 kPa
Pressure Ratio	(r_p)	300
Polytropic Coefficient	(n)	1.3
Volume of the air tank	(V)	500 L
Air gas constant	(R_{AIR})	0.2870 $\frac{kJ}{kg \cdot K}$
Effectiveness of the cooler	(ϵ_{ac})	0.5

The amount of specific work required to fill the 500L air tank is calculated below (Equation 1).

$$\begin{aligned} w_{comp} &= \frac{nRT_1}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \\ &= \frac{nRT_1}{n-1}\left[(r_p)^{\frac{n-1}{n}} - 1\right] \\ &= 995.1008383\ \frac{kJ}{kg} \end{aligned} \tag{1}$$

The air temperature after compression T_2 is required to find the temperature in the air tank T_3.

$$\begin{aligned} T_2 &= T_1\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} \\ &= 1093.284686\ \text{K} \end{aligned} \tag{2}$$

Solving for temperature in the air tank that is used to solve for total mass of the tank when its full (m_{FULL}) in Equation 4.

$$\begin{aligned} T_3 &= \left[1 - \epsilon_{ac}\right](T_2 - T_1) + T_1 \\ &= 693.2173432\ \text{K} \end{aligned} \tag{3}$$

Solving for m_{FULL} at T_3 and P_3.

$$\begin{aligned} m_{full} &= \frac{P_3 V}{RT_3} \\ &= \frac{r_p P_1 V}{RT_3} \\ &= 75.39454815\ \text{kg} \end{aligned} \tag{4}$$

Finally solving for the work done by the compressor to fill the tank in Equation 5.

$$\begin{aligned} W_{comp} &= w_{comp} m_{FULL} \\ &= 75025.17807\ \text{kJ} \end{aligned} \tag{5}$$

Determining the heat transfer from the air cooler Q_{ac} using Equation 6 below and the charging process control volume shown in Figure 3.

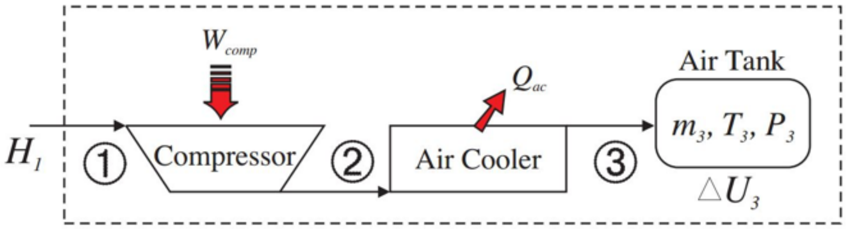

Figure 3: Control volume of the charging processes

$$\begin{aligned}\Delta U &= E_{IN} - E_{OUT} \\ \Delta U &= (W_{comp} + H_1) - (Q_{ac}) \\ Q_{ac} &= W_{comp} + H_1 - \Delta U\end{aligned} \tag{6}$$

Its mandatory to solve for the enthalpy (H_1) entering the air tank, but first the specific heat of ambient air must be determined using polynomial Equation 7 and the Table 2 of specific heat constants for air.

Table 2: Specific Heat Constants of Air from Table A-2

Constant	$\frac{kJ}{kmol \cdot K}$
a	28.11
b	$0.1967 \cdot 10^{-2} K^{-1}$
c	$0.4802 \cdot 10^{-5} K^{-2}$
d	$-1.966 \cdot 10^{-9} K^{-3}$

$$\begin{aligned}Cp_{@T_1} &= \frac{a + bT_1 + cT_1^2 + dT_1^3}{M_{AIR}} \\ &= 1.00275343 \; \frac{kJ}{kmol \cdot K}\end{aligned} \tag{7}$$

Further, need to solve for mass of the empty air tank (m_{EMPTY}).

$$\begin{aligned}m_{EMPTY} &= \frac{P_1 V_1}{R T_1} \\ &= 0.594289708 \text{ kg}\end{aligned} \tag{8}$$

$$\begin{aligned}H_1 &= Cp_{@T_1} T_1 \Delta m_{IN} \\ &= Cp_{@T_1} T_1 (m_{FULL} - m_{EMPTY}) \\ &= 21988.07215 \text{ kJ}\end{aligned} \tag{9}$$

Solve for initial internal energy of the empty tank, U_1, using $Cv_{@T_1}$ (Equation 10 and 11).

$$\begin{aligned} Cv_{@T_1} &= Cp_{@T_1} - R \\ &= 0.71575343 \ \frac{kJ}{kmol \cdot K} \end{aligned} \tag{10}$$

$$\begin{aligned} U_1 &= Cv_{@T_1} T_1 m_{EMPTY} \\ &= 124.6957196 \text{ kJ} \end{aligned} \tag{11}$$

Solving for $Cv_{@T_3}$ to calculate final internal energy of the full tank, U_3.

$$\begin{aligned} Cp_{@T_3} &= \frac{a + bT_3 + cT_3^2 + dT_3^3}{M_{AIR}} \\ &= 1.074429951 \ \frac{kJ}{kmol \cdot K} \end{aligned} \tag{12}$$

$$\begin{aligned} Cv_{@T_3} &= Cp_{@T_3} - R \\ &= 0.787429951 \ \frac{kJ}{kmol \cdot K} \end{aligned} \tag{13}$$

$$\begin{aligned} U_3 &= Cv_{@T_3} T_3 m_{FULL} \\ &= 41154.87548 \text{ kJ} \end{aligned} \tag{14}$$

Finally solving Equation 6.

$$\begin{aligned} Q_{ac} &= W_{comp} + H_1 - \Delta U \\ &= W_{comp} + H_1 - (U_3 - U_1) \\ &= 55983.07046 \text{ kJ} \end{aligned} \tag{15}$$

To determine the work produced by the turbine (W_{turb}), the driving control volume in Figure 4.

Equation 16 is obtained from the driving control volume.

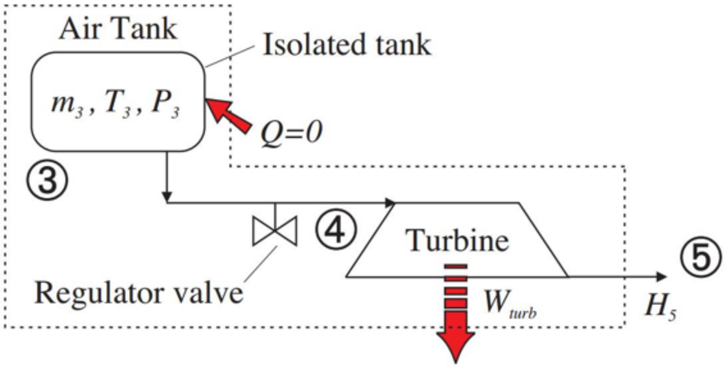

Figure 4: Control volume of the driving processes

$$\begin{aligned}
\Delta U &= E_{IN} - E_{OUT} \\
\Delta U &= (0) - (W_{turb} + H_5) \\
W_{turb} &= -\Delta U - H_5 \\
&= -(U_5 - U_3) - H_5 \\
U_5 &= U_1 \\
U_5 - U_3 &= -(U_3 - U_1) \\
W_{turb} &= (U_3 - U_1) - H_5,\ H_5 = H_1 \\
&= (U_3 - U_1) - H_1 \\
&= 19042.10761 \text{ kJ}
\end{aligned} \tag{16}$$

The mass ratio of the AirCar is determined in Equation 17.

$$\begin{aligned}
m_{ratio} &= \frac{m_{FULL}}{m_{EMPTY}} \\
&= 126.8649737
\end{aligned} \tag{17}$$

The efficiency is then calculated below.

$$\begin{aligned}
\eta &= \frac{benefit}{cost} = \frac{W_{turb}}{W_{comp}} \\
&= 25.38095624\%
\end{aligned} \tag{18}$$

2.2.2 Mechanics Analysis

The calculation for mechanics of the AirCar are done based on the initial conditions shown in Table 3.

Table 3: Initial Conditions

Properties		
Maximum velocity	(V_f)	$70\ \frac{km}{hr}$
Initial velocity	(V_i)	$0\ \frac{km}{hr}$
Time to reach V_{max}	(t)	12 s
Coefficient of friction	(f)	0.3
Mass of the car	(m_{CAR})	180 kg
Mass of the driver	$(m_{DRVIVER})$	75 kg
Mass of the passenger	$(m_{PASSENGER})$	75 kg

Calculating the distance it take for the AirCar to accelerate, ΔX_{acc}.

$$\begin{aligned} \Delta X_{acc} &= \frac{V_i + V_f}{2} t \\ &= 116.6666667 \text{ m} \end{aligned} \tag{19}$$

The acceleration of the vehicle is determined by Equation 20 below.

$$\begin{aligned} a &= \frac{\Delta V}{\Delta t} \\ &= 1.62037037\ \frac{m}{s^2} \end{aligned} \tag{20}$$

To determine the work done to accelerate the vehicle, the force balance in Figure 5 is used to formulate Equation 21.

$$W_{acc} = (F + F_f)\Delta X_{acc} \tag{21}$$

Solving for the total mass of the car, $m_{total-full}$.

$$\begin{aligned} m_{total-full} &= m_{CAR} + m_{DRIVER} + m_{TANK},\ m_{TANK} = m_{FULL} \\ &= 180 \text{ kg} + 75 \text{ kg} + 75.39454815 \text{ kg} \\ &= 330.3945482 \text{ kg} \end{aligned} \tag{22}$$

Calculating F and F_f.

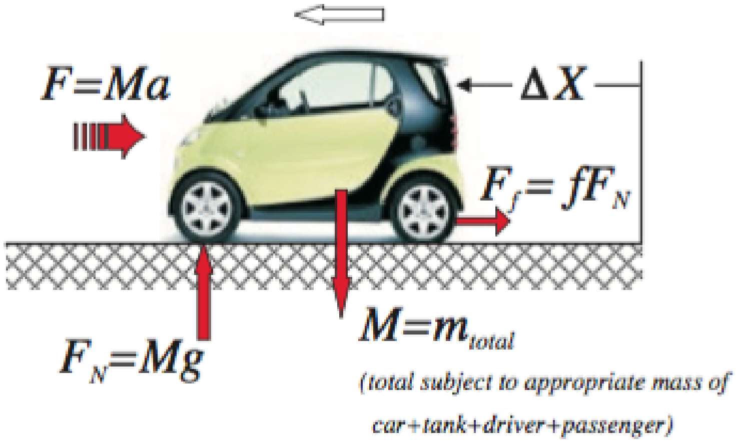

Figure 5: Control volume of the driving processes

$$\begin{aligned} F &= m_{total-full} \cdot a \\ &= 535.3615364 \text{ N} \\ F_f &= f \cdot F_N \\ &= f(m_{total-full} g) \\ &= 972.3511552 \text{ N} \end{aligned} \tag{23}$$

Thus using the calculated forces, solving the work done accelerate the Air-Car.

$$\begin{aligned} W_{acc} &= (F + F_f)\Delta X_{acc} \\ &= 175.899814 \text{ kJ} \end{aligned} \tag{24}$$

Next, determining the mass of the tank after the acceleration stage, $m_{post-accel}$.

$$\begin{aligned} m_{post-accel} &= m_{total-full} - \frac{W_{acc}}{W_{turb}}(m_{FULL} - m_{EMPTY}) \\ &= 329.7035873 \text{ kg} \end{aligned} \tag{25}$$

In addition, determining the mass of the vehicle without any air in the tank, $m_{total-empty}$.

$$\begin{aligned} m_{total-empty} &= m_{CAR} + m_{DRIVER} + m_{EMPTY} \\ &= 180 \text{ kg} + 75 \text{ kg} + 0.594289708 \text{ kg} \\ &= 255.5942897 \text{ kg} \end{aligned} \tag{26}$$

Determine the average mass, m_{avg-cv} after the acceleration stage to be used to calculate the distance travelled at constant velocity, ΔX_{cv}.

$$\begin{aligned} m_{avg-cv} &= \frac{m_{post-accel} + m_{EMPTY}}{2} \\ &= \frac{329.7035873 \text{ kg} + 0.594289708 \text{ kg}}{2} \\ &= 292.6489385 \text{ kg} \end{aligned} \tag{27}$$

Determining ΔX_{cv} by solving Equation 28.

$$\begin{aligned} W_{turb} - W_{acc} &= F_f \Delta X_{cv} \\ \Delta X_{cv} &= \frac{W_{turb} - W_{acc}}{F_f} \\ &= \frac{W_{turb} - W_{acc}}{f m_{ave-cv} g} \\ &= 21.90520886 \text{ km} \end{aligned} \tag{28}$$

Finally calculating the maximum distance of the vehicle, X_{max} neglecting the acceleration. Therefore the $m_{ave-max} = \frac{m_{total-full} + m_{total-empty}}{2}$.

$$\begin{aligned} \Delta X_{max} &= \frac{W_{turb}}{F_f} \\ &= \frac{W_{turb}}{f m_{ave-max} g} \\ &= 22.08337286 \text{ km} \end{aligned} \tag{29}$$

Using the same approach the distances of travel are calculated for the driver with one passenger. The results are summarized in Table 4.

Table 4: AirCar range at initial conditions from Table 1

Distance	**Driver only (km)**	**Driver and one passenger (km)**
X_{acc}	0.11666667	0.11666667
X_{cv}	21.90520886	17.39966537
X_{max}	22.08337286	17.5826172

2.3 Variable Ambient Temperature

Figure 6 on page 12 illustrates the effects of varying ambient temperature has on the AirCar's performance. The efficiency of the vehicle decreases as ambient temperature increases because there is less heat transfer from the air cooler (less energy is removed from the air) thereby decreasing the energy output to the turbines. Therefore the decreasing the range of the car by approximately 9% or 2km over the -40°C to 20 °C temperature range for both the driver only and driver and passenger scenario. The results are summarized in Table 5 on page 11.

2.4 Variable Pressure Ratio

Figure 7 on page 13 shows the effects of varying the pressure ratio on the performance of the AirCar. As the pressure ratio increases the efficiency of the vehicle increases, because more mass can be stored in the tank thus more energy that can be converted to be used for the turbine. Low pressures prevent air storage in the tank thereby minimizing the range of the car. Varying pressure ratio has a dramatic effect on the car's performance which is summarized in Table 6 on page 11. Varying the pressure ratio from 0 - 300 causes the kilometre range to vary from 0 - max km, respectively.

2.5 Variable Effectiveness of the Air Cooler

Figure 8 on page 14 describes the effects of varying effectiveness of the air cooler has on the AirCar's performance. The amount of air that can be compressed into the air tank increases non linearly with effectiveness of the cooler. The variation of effectiveness has a big impact on the vehicle's efficiency, as the effectiveness increases the efficiency drops in a linear manner. As the temperature of air in the tank (T_3) approaches the ambient temperature (T_1), the amount of work done by the cooler (Q_{ac}) approaches the amount of work done to compress the air into the tank (W_{comp}). Therefore the energy available for the turbines decreases.

When the effectiveness surpasses 0.9% Q_{ac} becomes greater than the work done by the compressor, thus W_{turb} becomes negative and the surrounding is doing work on the turbines. The results are summarized in Table 7 on page 11.

Table 5: Effects of Varying Ambient Temperature

$T_1(^\circ C)$	W_{comp}(kJ)	Q_{ac}(kJ)	W_{turb}(kJ)	η (%)	Driver(km)	Passenger(km)
-20	75025.178	56830.037	18195.141	24.252	20.677	16.530
-10	75025.178	56620.705	18404.473	24.531	21.033	16.796
0	75025.178	56409.585	18615.593	24.812	21.386	17.060
10	75025.178	56196.949	18828.229	25.096	21.736	17.322
20	75025.178	55983.070	19042.108	25.381	22.083	17.583
30	75025.178	55768.221	19256.957	25.667	22.428	17.842
40	75025.178	55552.674	19472.504	25.955	22.771	18.099

Table 6: Effects of Varying Pressure Ratio P_2/P_1

r_p	W_{comp}(kJ)	Q_{ac}(kJ)	W_{turb}(kJ)	η (%)	Driver(km)	Passenger(km)
50	9165.838	7607.538	1558.300	17.001	2.007	1.562
100	21078.391	16699.714	4378.677	20.773	5.499	4.306
150	33885.779	26218.773	7667.006	22.626	9.417	7.409
200	47239.634	35985.556	11254.078	23.823	13.544	10.702
250	60982.570	45921.503	15061.067	24.697	17.784	14.107
300	75025.178	55983.070	19042.108	25.381	22.083	17.583

Table 7: Effects of Varying Effectiveness of the Air Cooler

ϵ	T_3(K)	m_{FULL}	W_{comp}(kJ)	Q_{ac}(kJ)	W_{turb}(kJ)	η (%)
0.0	1111.932	47.004	47571.100	16089.973	31481.127	66.177
0.25	908.486	57.530	58224.120	31958.558	26265.563	45.111
0.5	705.041	74.130	75025.178	55875.750	19149.428	25.524
0.75	501.595	104.197	105455.143	97354.735	8100.408	7.681
1.0	298.150	175.297	177413.456	192363.456	-14950.000	-8.427

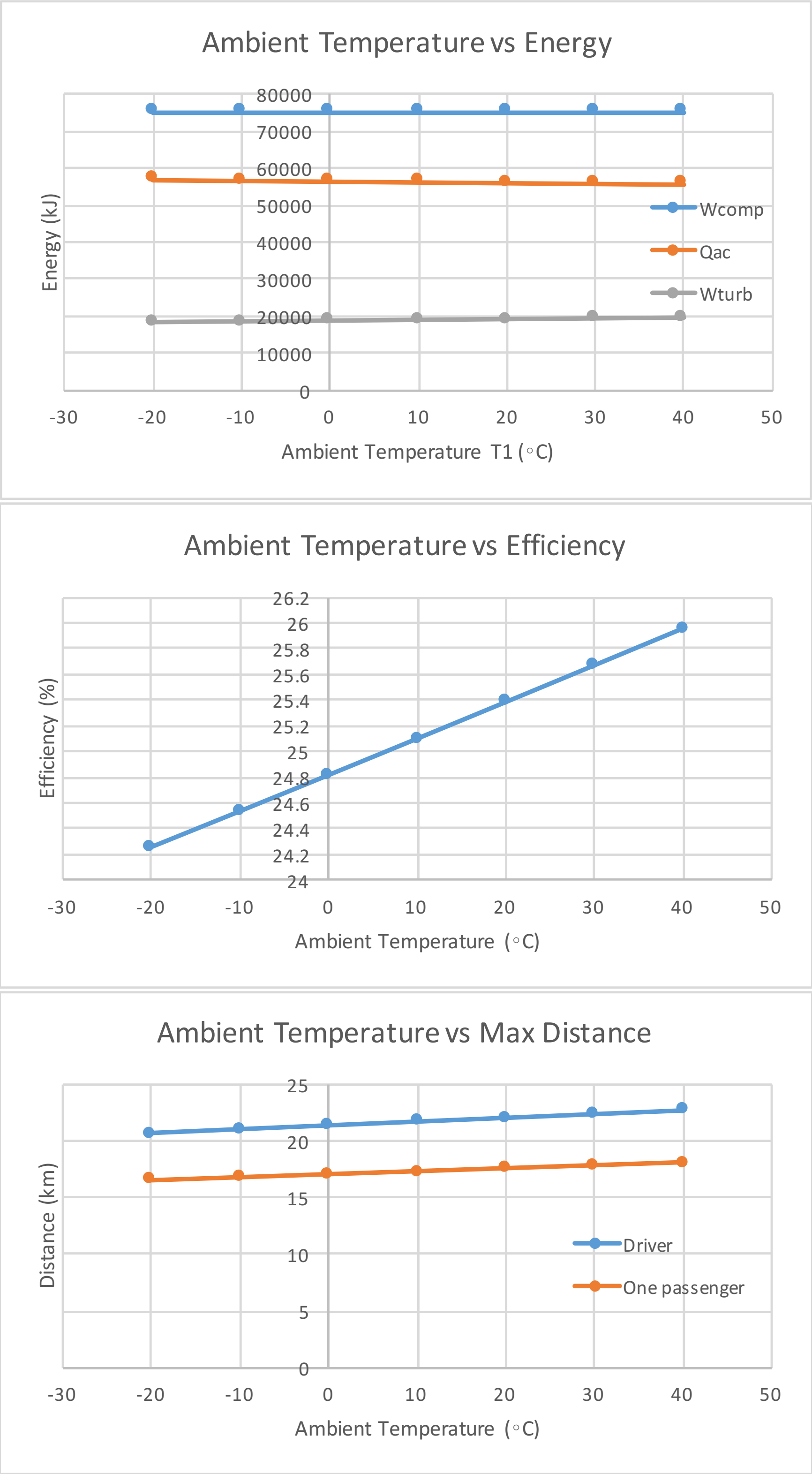

Figure 6: Effects of Varying Ambient Temperature

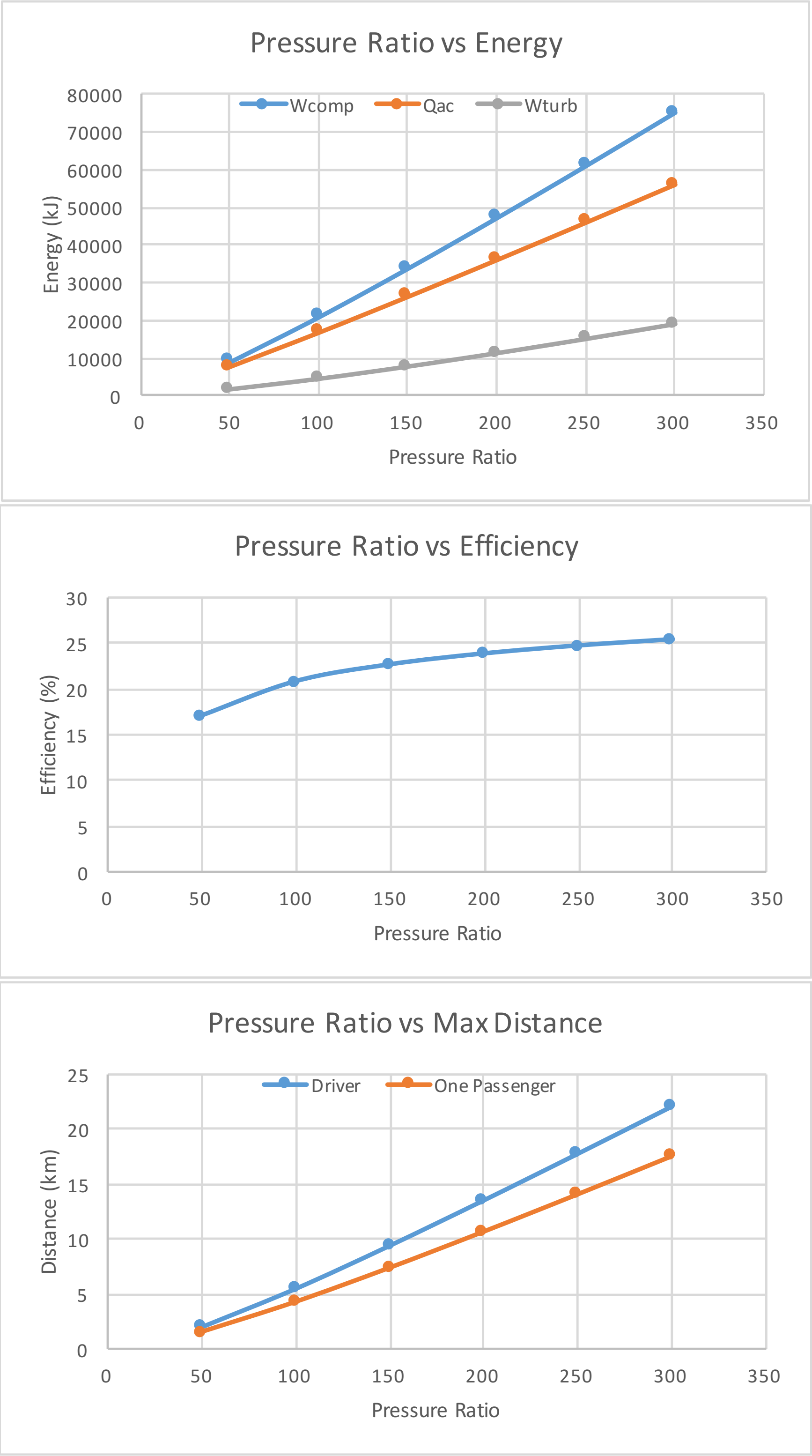

Figure 7: Effects of Varying Pressure Ratio P_2/P_1

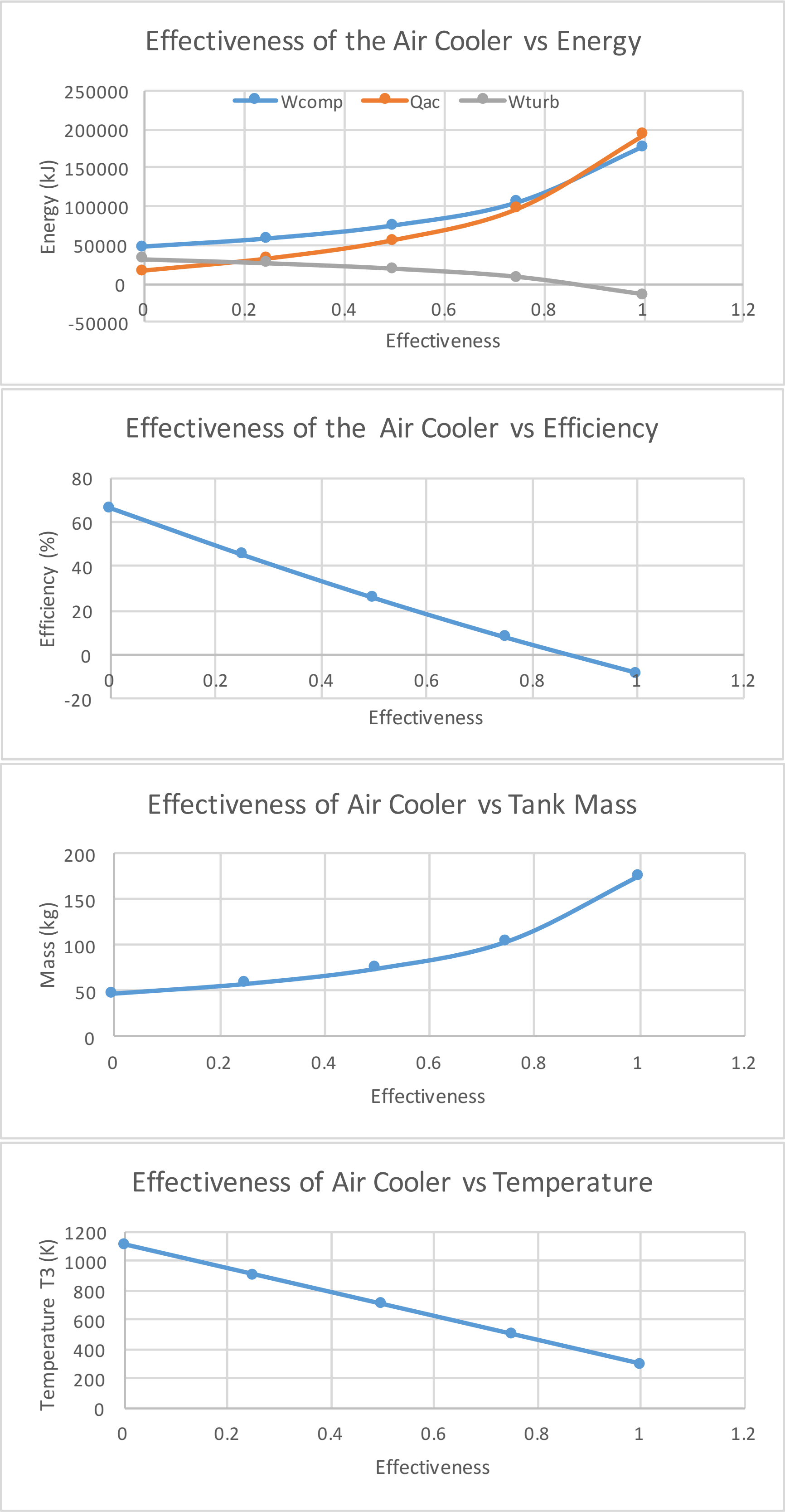

Figure 8: Effects of Varying Pressure Ratio P_2/P_1

2.6 Discussion and Recommendations

Ambient temperature has little effect on the AirCar's efficiency and range. Therefore the vehicle can operate in temperature ranges of -20 to 40°C and have a reasonable performance, although decreasing by 10% at the temperature reaches 40°C.

The pressure ratio between ambient pressure and the pressure of air stored in the tank should be maximized for maximum range and efficiency of the vehicle. The current existing technology allows for pressure ratios of 300, therefore the design is sound with regards to pressure.

The effectiveness of the air cooler has the greatest effect on the efficiency of the vehicle. Although the amount of air mass stored (energy) in the tank increases with air cooler effectiveness, the energy output by the turbines decreases dramatically. From results, its deduced that the efficiency is at its maximum when the temperature of the air inside the tank is approximately T_2, thus the effectiveness of the cooler is zero. However, realistically that is impossible to design a thermally insulated tank that must withhold 30MPa of air at the temperature of 830°C.

From the ideal case described throughout the report, the AirCar design is approximately 20% efficient, which is 10% than diesel engines and about the same at petrol engines, with dramatically less range. Although the vehicle is environmentally friendly in term of its operation, it will not replace gas driver automobiles.

The AirCar is recommended for small range travels and without load. An example application could be a warehouse supervisor, that must get from A to B in a quick manner.