



ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING
GRADUATE PROGRAM IN RAILWAY ENGINEERING

**Reducing Energy Consumption of ADDIS ABABA Light RAIL Train by using
 CO_2 -Controlled ventilation for air Condition**

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A Thesis submitted to the School of Mechanical and Industrial Engineering in partial
fulfilment of the requirements for the Degree of Masters of Science in Mechanical
Engineering

(Railway stream)

ADVISOR: Dr. Ing. Demiss Alemu

June, 2017

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Controlled ventilation for air Condition**

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DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in this or any other universities, and all sources of materials used for the thesis work have been fully acknowledged.

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ABSTRACT

Rail has been recognized as the most energy efficient and compatible transportation mode. In fact, reducing the energy consumption of rail vehicle is a key issue. The Addis Ababa light rail train consumes, in addition to the energy needed for train motion, a share of electricity for comfort purpose. About 20% to 40% of the energy consumed by the vehicle is used for ventilation and air-conditioning. It is known that air-conditioning accounts for the biggest share of comfort energy.

The air-condition controlled by CO₂ controls the amount of supply outdoor fresh air in a train depending on a number of people. People are the main source of CO₂ in train or building. In the coach, if a number of passengers in coach is doubled, the CO₂ level will accordingly double. If one or few people leave the train, the level of CO₂ will proportionally decrease. Thus this system saves energy solely by not heating or cooling unnecessary amount of outdoor air.

The main objective of this research is to reduce the energy consumption of the train by using CO₂-operated ventilation for air-conditioning. In order to achieve this precious goal, this paper proposes to use CO₂-operated ventilation in order to reduce the energy used for comfort purpose. The energy of CO₂-controlled air condition and CAV (conventional system) are simulated and analysed by HAP. While doing this thesis, the weather data are collected from National Metrology Agency and the physical data of the train are gathered from Ethiopia Railway Corporation. Then all data are entered in to the software to run the simulation of the train energy and comparison of CAV (conventional system) and CO₂-operated air condition (VAV) has done based energy cost and energy consumption.

The result of train simulation report has shown clearly that CO₂-operated air condition consume less energy and is the energy cost effective as compared to CAV (conventional system). It has shown that this study system saves 8 Mwh per year which means 194 \$/yr. Hence it is recommended to Addis Ababa Light Rail Train to apply this economic system.

Key words: CO₂, HAP, CAV, VAV and Air-condition

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NOMENCLATURE

CAV	Constant Air volume
VAV	Variable Air Volume
CO2	Carbone Dioxyde
HVAC	Heating Ventilation Air-Condition
DCV	Demande Control Ventilation
LRT	Light Rail Train
AALRT	Addis Ababa Light Rail Train
DBT	Dry Bulb Temperature
MDR	Mean Daily Range
CWB	Coincident Wet Bulb
DP	Dew Point
RH	Relative Humidity
WBT	Wet Bulb Temperature
HAP	Hourly Analysis Program
IAQ	Indoor Air Quality

CHAPTER 1

Introduction

1.1. Theoretical background

This chapter provides clear understanding of the main concept of CO₂-based demand controlled ventilation. The chapter may provide a necessary background to understand how CO₂-based DCV operates and how it is applied under current codes and standards. The given chapter introduces the information about human breathing and the way it influences the air quality in the interior of the train. The chapter also explains the required ventilation rates and CO₂differential.

1.1. 1. CO₂ DCV concept

The concept of DCV has been known for over 20 years. The sensors of the first generation did not provide the required reliability, and the cost of the sensors was high. In recent years, the advances in sensor technologies have made demand controlled ventilation both reliable and cost-effective. The ASHRAE Standard 62.1-2004 indicate that the demand controlled ventilation is acceptable when correctly designed and installed.

CO₂-based demand controlled ventilation is a combination of two technologies:

- ✓ CO₂-sensors monitor carbon dioxide level in the air in the interior of the building.
- ✓ An air-handling system that employs data from the sensors to regulate the amount of supply air.

CO₂-Sensors continually monitor air in a conditioned space. Since people exhale carbon dioxide, the difference between the CO₂ concentration in the interior of the building and the level in the exterior of the building indicates the occupancy and activity level in a space and, thus, its ventilation requirements. The sensors send carbon dioxide data to the ventilation controllers, which automatically increase ventilation when carbon dioxide concentrations exceed a certain level in a space. Ventilation rates can be measured and controlled based on real occupancy. This contradicts the conventional method of ventilating at a fixed rate independent of occupancy. This results in much larger air flow rates coming into buildings than necessary.

That quantity of air must be taken into account, because it increases energy consumption and costs. In humid climates, the excess ventilation also can result in uncomfortable humidity and mould growth, making the indoor air quality quite inappropriate. Furthermore, the lack of

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fresh air can make building occupants drowsy. To avoid the problems of excessive and insufficient fresh air, people can apply demand controlled ventilation.

CO₂-based DCV provides a possibility to monitor both occupancy and ventilation rates in a building all the time. Most ventilation systems are often regulated and adjusted only at the time they are installed. DCV provides a higher level of control when monitoring conditions in the space and constantly adjusts the system to respond to the change of parameters.

1.1.2. CO₂ in the exterior of the train

Clean atmospheric air consists of different gases in the proportions given in Figure 1.

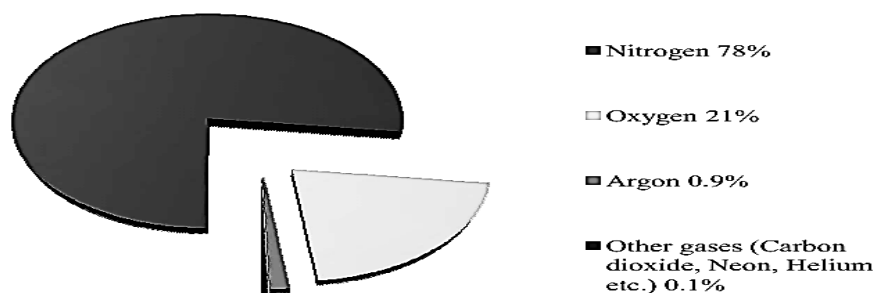


Fig1. 1. Chemical composition of clean and dry atmospheric air.

The given figure illustrates the content of clean atmospheric air. However, due to human activities and natural processes, the real atmospheric air contains the variable amount of water (on average around 1%), dust, pollen, spores, sea spray and volcanic ash.

Various industrial pollutants may also be present such as chlorine (elementary or in compounds), fluorine compounds, elemental mercury, and sulfur compounds such as sulfur dioxide (SO₂).

The carbon dioxide concentration in the atmosphere may alter during a year due to any combustion device or process throughout the world, such as burning of fossil fuels. Yearly the concentration of carbon dioxide increases more and more. Scientists suppose the increase of CO₂ may cause the global warming.

CO₂ has low molecular weight. Therefore carbon dioxide easily occupies the whole open space. It is possible to assume outside CO₂ levels are constant for large geographic regions. Consequently, CO₂ is a baseline reference for outside air for the purpose of measuring and controlling ventilation.

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1.1.3. Carbon dioxide in the interior of the building

There are a number of sources of CO₂ production in the exterior of the train, such as burning of fossil fuels, producing cement and other products, forest combustion and so forth. But humans and their activity is the major source of carbon dioxide in the interior of the train. Plants contribute CO₂ insignificantly in the interior of the building, due to their low level of metabolic activity. Combustion sources can accordingly contribute to carbon dioxide in the interior of the train. The main process of CO₂ production by humans in the interior of the train is respiration. For adults CO₂ production varies from about 10 dm³/h per person when sleeping to about 170 dm³/h per person at high levels of physical activity. CO₂ production is different for children and adults. For instance, in kindergartens an activity level of 157W/m², CO₂ production is 18 dm³/h per person. In schools with children aged from 14 to 16, the CO₂ production is about 19 dm³/h per person. It is equal to CO₂ production of adults during sedentary activity. More information is provided in Table 1.

Table 1.1 The generation of carbon dioxide by humans at six activity levels.

ACTIVITY	Carbon dioxide (dm ³ /h per person)
Adults, sedentary (58-70 w/m ²)	19
Adults, low level of physical exercise (174 w/m ²)	50
Adults, medium level of physical exercise (348 w/m ²)	100
Adults, high level of physical exercise athletes (580 w/m ²)	170
Children of kindergarten age ,3-6 years old (157w/m ²)	18
Children of school age, 14-16 years old (58-70 w/m ²)	19

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The rate of carbon dioxide production by human respiration is related to the metabolic rate by Formula 1:

$$G = 4 \times 10^{-5} \times M \times A \dots\dots\dots (1.1)$$

Where: G - CO₂ production, dm³/s; M - metabolic rate, W/m²; A - body surface area, m²

For example, for an adult person occupied with sedentary activities (M = 70 W/m² and A = 1.8m²), such as office work, the CO₂ production by respiration is about 0.00504 dm³/s (18.1 dm³/h) per person

As people exhale a predictable quantity of carbon dioxide depending on their physical activity, it can be used as a good indicator of CO₂ for ventilation control. It is important to lay emphasis that CO₂ concentration in the interior of the building does not provide enough information of the actual number of people, but it can be used in combination with CO₂ concentration in the exterior of the train.

1.1.4. Carbon Dioxide Generation Rates

While it is not critical to the application of CO₂ DCV, the emission rate of occupant generated CO₂ is certainly a relevant issue in this discussion. This section discusses the rate at which people generate CO₂.

People generate CO₂, and consume oxygen, at a rate that depends primarily on their body size and their level of physical activity. The relationship between activity level and the rates of carbon dioxide generation and oxygen consumption is discussed in the ASHRAE Fundamentals Handbook (ASHRAE 1997). The rate of oxygen consumption ν_{O_2} , in L/s, of a person is given by the following equation

$$\nu_{O_2} = \frac{0,00276 A_D M}{0,23 R Q + 0,77} \dots\dots\dots (1.2)$$

When using inch-pound units, VO₂ is expressed in cfm and Equation (1) takes the form

$$\nu_{O_2} = \frac{0,000543 A_D M}{0,23 R Q + 0,77} \dots\dots\dots (1.3)$$

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where RQ is the respiratory quotient, i.e., the relative volumetric rates of carbon dioxide produced to oxygen consumed. M is the level of physical activity, or the metabolic rate per unit of surface area, in mets (1 met = 58.2 W/m² = 18.5 Btu/h·ft²). AD is the Dubois surface area in m², which can be estimated by the following equation

$$A_D = 0,203H^{0,725} W^{0,425} \dots\dots\dots (1.4)$$

Where **H** is the body height in m and **W** is the body mass in kg. When using inch-pound units, AD is in ft², 0.203 is replaced with 0.660, H is in ft and W is in lb. For an average size adult, A_D equals about 1.8 m² (19 ft²). Additional information on body surface area is available in the EPA Exposure Factors Handbook (EPA 1999). The value of RQ depends on diet, the level of physical activity and the physical condition of the person. It is equal to 0.83 for an average size adult engaged in light or sedentary activities. RQ increases to a value of about 1 for heavy physical activity, about 5 met. Given the expected range of RQ, it has only a secondary effect on carbon dioxide generation rates.

The carbon dioxide generation rate of an individual is therefore equal to vo_2 multiplied by RQ. Figure 1 shows oxygen consumption and carbon dioxide generation rates as a function of physical activity for an average sized adult with a surface area of 1.8 m² (19 ft²) and RQ = 0.83. Based on Equation 1, the carbon dioxide generation rate corresponding to an average size adult engaged in office work (1.2 met) is about 0.0052 L/s (0.011 cfm). However, the generation rate depends strongly on activity level and can cover a range from less than 0.0050 L/s (0.011 cfm) at 1 met to as high as 0.010 L/s (0.021 cfm) at about 2 met for the occupants of an office building. The carbon dioxide generation rate for a child with AD = 1 m² (11 ft²) and a physical activity level of 1.2 met is equal to 0.0029 L/s (0.0061 cfm). When making calculations that use the carbon dioxide generation rate in a building, one must consider the level of physical activity and the size of the building occupants. Chapter 8 of the ASHRAE Fundamentals Handbook, Thermal Comfort, (ASHRAE 1997) contains typical met levels for a variety of activities. Some of these values are reproduced in Table 1.

1.1.5. CO₂ differential and ventilation rates

If the ventilation rate in an occupied space decreases, the carbon dioxide concentration will begin to increase and vice versa. Once people enter at coach of the train, CO₂ concentration will begin to increase. This level will continue to increase until the amount of CO₂ produced

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by the space occupants and the dilution air delivered to the space are in balance. Such a state is called the equilibrium point.

The relation between CO₂ level and outside air ventilation rates can be described using a simple two chamber model. This is illustrated in Figure 3.

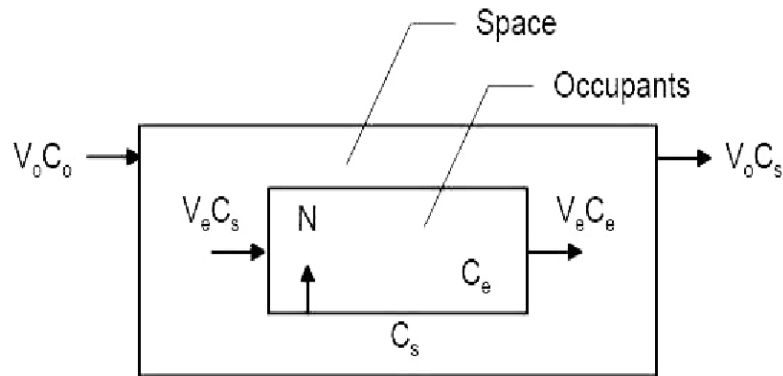


Figure 1.2. Two chamber model

Formula 2 shows the mass-balance equation to predict the difference between indoor and outdoor CO₂-concentrations at steady-state conditions, given a constant ventilation rate per person and a constant CO₂-generation rate:

$$v_D = \frac{N}{c_s - c_o} \dots\dots\dots (1.5)$$

Where: v_D – outdoor airflow rate, dm³/s*person; N - CO₂ generation rate, dm³/s*person;
 c_s - indoor CO₂ concentration, ppm; c_o - outdoor CO₂ concentration, ppm.

The equation can also be restated so that the equilibrium level (C_{eq}) for particular ventilation rate can be calculated using Formula 3:

$$C_{eq} = c_s = c_o + \frac{N}{v_o} \dots\dots\dots (1.6)$$

The correlation between indoor / outdoor CO₂ differential and ventilation rate do not depend on volume of a room. However, the volume of a room will affect the time it takes for CO₂ to build up to an equilibrium level. This equation can be only applied when equilibrium conditions exist. To make an accurate determination of dm³/s*person rates one should take CO₂ measurements when the occupancy has stabilized. Measuring CO₂ concentrations that are

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still in transition to an equilibrium level can result in over estimation of the ventilation rate. Applied properly spot measurements can be extremely useful in helping to qualify if a space is over ventilated.

The ANSI/ASHRAE Standard 62.1-2004 states that comfort (odor) criteria with respect to human bio effluents are likely to be satisfied if the ventilation results in indoor CO₂ concentrations are less than 700 ppm above the outdoor air concentration.

1.1.6. BENEFITS OF CO₂-BASED DCV

Compared to conventional ventilation, DCV provides considerable advantages. The three major benefits of demand controlled ventilation should be mentioned in connection herewith: First of all, demand controlled ventilation saves energy by avoiding the heating, cooling, and dehumidification of more ventilation air than it is needed. According to the observations, the savings range from 5 to 80 percent in contrast to the conventional ventilation system. The payback can vary from several months to two years and can often be significant enough to facilitate to pay for other building systems. The payback from CO₂-based DCV will be retail establishments, and meeting and conference areas).

In spaces with more static occupancies (e.g. offices) DCV can provide control and verification that adequate ventilation provided to all spaces. For example, a building operator may arbitrarily and accidentally establish a fixed air intake damper position that results in over- or under ventilation of all or some parts of space. A CO₂control strategy can ensure the position of the intake air dampers is appropriate for the ventilation needs and occupancy of the space at all times.

Secondly, active control of ventilation system can provide the opportunity to control indoor air quality. Demand controlled ventilation creates improved IAQ by increasing ventilation if CO₂level rise to an unacceptable level. And the last advantage is simplicity and reliability of DCV.

A CO₂control strategy can be used to maintain any per person ventilation rate. As a result this approach is highly adaptable to changing building uses and any changes that may occurs in future recommended ventilation rates.

1.1.7. CO₂ MEASUREMENT TECHNOLOGY

Although relation between CO₂ and controlled ventilation has been known to the general public from 1916, CO₂ as a reliable and economic method of control ventilation began to be used not long ago. The first sensor used for controlling ventilation in HVAC application appeared on the market only in 1990. CO₂ measurements in HVAC applications are based exclusively on the Infrared (IR) absorption principle. This is because different gases absorb infrared energy at specific and unique wavelengths in the infrared spectrum. There are two types of sensors to measure CO₂ concentration with help of the IR absorption method:

1. Non-Dispersive Infrared (NDIR) absorption sensor
2. Photo-acoustic sensor these technologies can be cost-efficient, but have different operational characteristics.

1.1.7.1 Non-Dispersive Infrared (NDIR) CO₂ sensor

Sensors based on non-dispersive infrared detection search the net increase or decrease of light that occurs at the wavelength where CO₂ absorption takes place. The light intensity change depends on the concentration of carbon dioxide.

Figure 4 shows an example of a typical NDIR sensor where air is penetrating into a sample chamber that contains a light source on the one end and a light detector on the other.

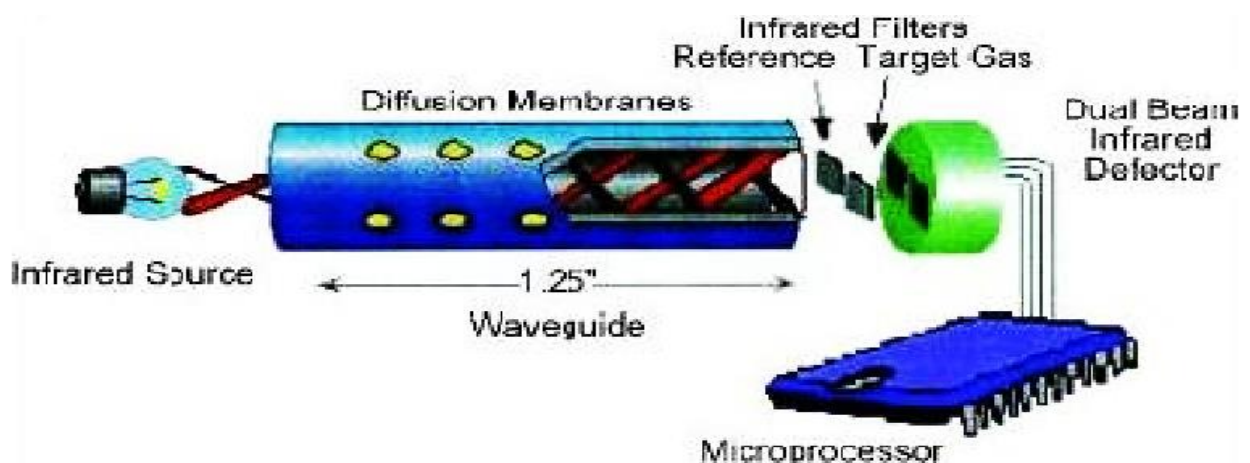


Figure 1.3. Basic parts of non-dispersive infrared detection (NDIR) CO₂ sensor

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A selective optical filter is fixed over the light detector to allow light at the specific wavelength where CO₂ absorbs light. This figure also illustrates the second detector and filter, although it is not always applied. The second optical filter is adjusted at the wavelength where there is no gas absorption. This second detector and filter are used as a reference to correct changes in the sensor optics that may be the result of sensor deviation over a time period. One of the important parts in the design of this sensor type is to minimize or remove sensor deviations that may occur because of accumulation of particles in the sensor and aging of a light source. One method of minimizing accumulation of particles is to use a gas penetrable membrane that facilitates penetration of gas molecules but locks larger particles that may change the sensor optics.

The second factor of deviation is aging of a light source. It can be minimized by selection of sources with stable characteristics. The method based on dual beam detector application, shown in Figure 4, is one of the methods to compensate both aging and particle accumulation.

Compared with photo-acoustic sensors, NDIR sensors have the following advantages: Firstly, NDIR sensors are less sensitive to pressure changes. Secondly, these sensors are less sensitive to vibrations and acoustic interferences. And the last advantage is that such sensors have a compact design. But photo-acoustic sensors also have benefit, such as no sensitivity to dirt and dust.

1.1.7.2 Photo-acoustic CO₂ sensor.

Another sensor type to measure CO₂ using IR is called photo-acoustic sensors. This type of sensor is designed with a chamber which is open to the atmosphere. Such a sensor exposes air in the chamber to flashes of infrared light specific to the gas absorption wavelength for CO₂. This flashing light produces vibrations of CO₂ molecules as they absorb infrared energy. A small microphone in the chamber monitors this vibration and then microprocessors in the sensor calculate CO₂ concentration.

Figure 5 shows a schematic of a photo-acoustic sensor. This type of sensor is not so sensitive to dirt or dust. But it can also have sensor deviations due to aging of a light source. Photo-acoustic sensor can also be affected by vibration and atmospheric pressure changes. More accurate sensors often use a pressure sensor to correct the range of pressures.

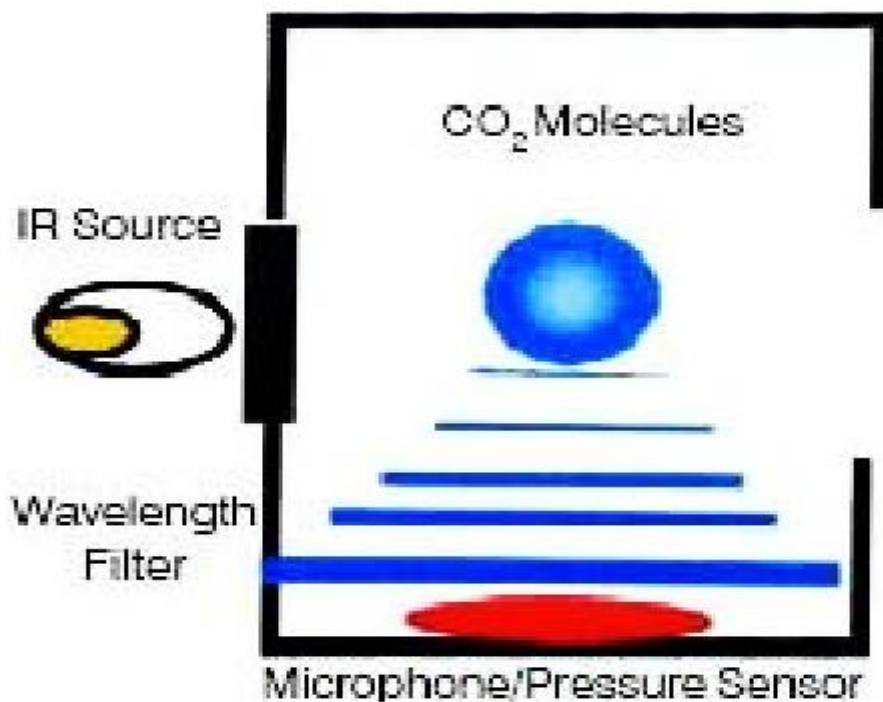


Figure1.4. Basic parts of photo-acoustic CO₂ sensor

1.1.8 APPLICATION OF DCV

DCV has a number of applications in various types of buildings. Firstly, DCV is applied in buildings where the number of people changes continuously during the whole day (24-hour period). It is also applied in places where occupancy is unpredictable and attains a high level. In buildings with a more stable occupancy level, DCV provides enough amount of fresh supply air per person all the time. But this will turn out to be uneconomical. Demand controlled ventilation reduces energy costs in the areas with a high utility level.

Secondly, DCV is used in spaces where heating and cooling for most parts of the year are required. Thirdly, demand controlled ventilation is utilized in the areas with high utility rates, high energy demand and energy costs.

Thirdly, DCV is used in buildings with low average occupancy in comparison with design occupancy. DCV is also applied in such types of buildings as office centers, governmental facilities, banks, shops and shopping malls, cinemas, auditoriums, lecture halls, schools, outpatient areas in hospital, hotel atriums or lobbies, restaurants, bars, nightclubs and so forth. Demand controlled ventilation is used in the areas with warm and humid climates or extreme climate conditions, and buildings which have equipment for automated adjusting of air supply

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(for example, variable speed fans or variable damper arrangement).

DCV is applied in spaces where CO₂ from human respiration and human activity is the main source of pollution. But CO₂-sensors used for DCV are not applied to monitor CO₂ for medical or industrial purposes, because they demand more exact air quality control. And the last point to consider is that DCV may be applied in buildings where there is poor indoor air quality related with under- or over-ventilation or excessive humidity. CO₂-based DCV can operate in combination with a heat recovery or other systems that supply outdoor air in buildings for heating or cooling. However, energy savings may be less where heat exchangers are used depending on climate, occupancy and a building type. Several manufacturers produce CO₂-sensors that can be used in demand controlled ventilation. Most manufacturers of thermostats and air handling units integrate CO₂-sensors into their products. And major manufacturers of HVAC systems offer to install CO₂ sensors at the factories as an option.

1.2. AALRT train Air-condition

DLD25A type air conditioning unit has been supplied and used for Addis Ababa, Ethiopia LRV project. The air conditioning system can perform air treatment in saloon, to achieve dehumidification and refrigerating function, and to create a comfortable environment for passengers. The air conditioning unit casing is made of stainless steel plate, has the advantages of high strength, low weight, corrosion resistance.

CVU550A type ventilation unit is pressurization ventilation equipment that used for cab of metro vehicles, mounted on the vehicle roof, the treated air through the air inlet into the cab, resistant to vibration, impact resistance, suitable for the ground and underground tunnels, and other different operating environment.

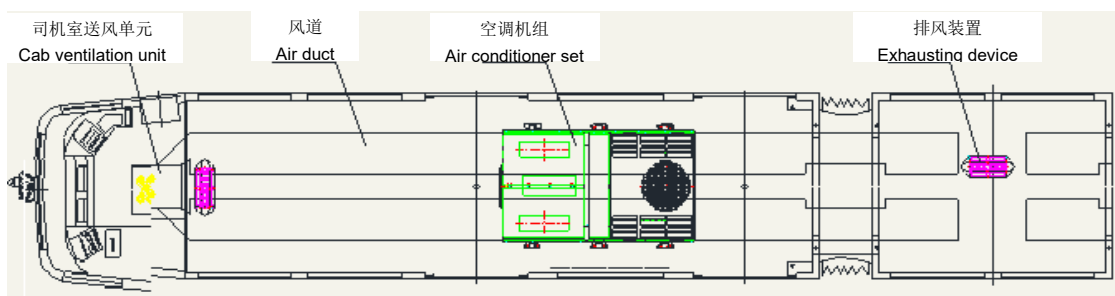


Figure1.5: Layout drawing of air condition

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✓ Technical parameters of saloon air conditioning unit

Model: DLD25A

Type: roof mounted unit

Power supply: main circuit AC380V 3-phase 50Hz

Control circuit: DC24V

Refrigerating capacity: 25kW

Operating condition: The temperature of inlet air dry bulb of evaporator: 27.9°C wet bulb temperature: 22.7°C

The temperature of inlet air dry bulb of condenser: 29.7°C

Heating capacity: 6kW (3+3)

Ventilation rate: 4000m³/h (Fresh air rate 1300m³/h)

Rated power input: 12.7 kW (normal condition)

Refrigerating fluid and filling quantity: R407C 2×2.4kg

Weight of air conditioning unit: 600kg

1.3. Thesis Objective

1.3.1 General objective

The main objective of this research is, as the title already indicates, reducing energy consumption of ADDIS ABBEBA LIGHT RAIL TRAIN by using CO₂-controlled ventilation for air-conditioning

1.3.2 Specific objective

- to define benefits of demand controlled ventilation;
- to investigate the standards which describe the required limits of CO₂ concentration;
- to compare CO₂-based DCV and the conventional ventilation system;
- to explore different types of CO₂ sensors;
- to calculate energy efficiency
- To simulate air-conditioning by HAP software
- Make a comparison of the energy consumption in percentage of the actual air-conditioning and when CO₂-operated ventilation is using for air-conditioning.

1.4. Problem Statement

Nowadays, optimizing the energy used for comfort purpose is a key issue because the air-conditioning accounts the biggest share of comfort energy. The passengers care always their comfort and air quality. At the same time, the operating company needs to conserve the operating energy. It is always difficult to satisfy both at the same time, but there is made balancing between these antagonistic to reduce energy consumption and to satisfy the passenger.

In train, Ventilation is considered to be one of the most important factors for maintaining acceptable indoor air quality in any space. It is used to introduce outside air, control temperature and remove excessive moisture, odors, smoke, heat, dust, airborne bacteria, and carbon dioxide. However, ventilation consumes energy in terms of electrical fan power as well as cooling and heating energy. Energy production also affects negatively on our environment and contributes to CO₂-emissions to the atmosphere.

Many types of ventilation systems encounter problems to control minimum supply air and thus to consume minimum amount of energy. But a ventilation system based on registration of increasing CO₂ concentration can facilitate in solving the given problem. Such a technology is called CO₂-based demand controlled ventilation (DCV).

The experience and field studies have shown that the level of carbon dioxide in any space can be a reliable indicator and quite a cheap instrument of the air quality and ventilation rate. That is why CO₂ is used as an indicator of air quality in demand controlled ventilation systems.

The ADDIS ABABA light rail train which is passenger train consumes, in addition to the energy expected for train motion, a considerable amount of energy for comfort purpose. Air conditioning which deals with the comforts of human beings in an enclosed conditioned space is known as Comfort Air Conditioning. The air-conditioning accounts for the biggest share of comfort energy. In fact, about 20 to 40% of the energy consumed of the train is used for air-conditioning and ventilation. We can reduce some amount of energy consumption by optimizing the air-conditioning energy.

CO₂-based demand controlled ventilation system controls the amount of supply outdoor fresh air in a train depending on a number of people. People are the main source of CO₂ in a train. If

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a number of people in a coach is doubled, the CO₂ level will accordingly double. If one or few people leave a coach or saloon, the level of CO₂ will proportionally decrease. Thus DCV saves energy solely by not heating or cooling unnecessary amount of outdoor air. The benefits of such a ventilation system are maximal when a number of people continuously changes in a train, in the extreme climate conditions or when the electricity cost is quite high. CO₂-concentration in the air is a good indicator for the number of passenger actually present. Installation of CO₂-sensor and a control circuit for ventilation therefor allows a demand-oriented and energy efficient ventilation of passenger coaches.

The main goal of this research is reduce the energy consumption of Addis Ababa light rail train. In order to achieve this precious goal, more strategy has done. It has proposed to reduce energy consumption by light weight of the vehicle, regenerative breaking system and others significant strategy. In this paper the problem has formulated to reduce energy used for comfort function by using CO₂-operated ventilation without compromising the comfort quality for the passengers.

Taking into account the above mentioned, the objectives of the given Master Thesis are as follows:

- to define benefits of demand controlled ventilation;
- to investigate the standards which describe the required limits of CO₂ concentration;
- to compare CO₂-based DCV and the conventional ventilation system;
- to explore different types of CO₂ sensors;
- to analysis energy use by CAV air-condition by HAP
- To analyse VAV air-condition energy use of the train by HAP software

1.5. Scope and limitation of the research

This research was intended to use CO₂-operated ventilation as air-conditioning for the train with the objective to optimize the energy consumption of the train without compromising passenger comfort. The energy of CO₂-controlled HVAC will be analysed by HAP software and it will be compared by the conventional HVAC that AALRT is using in order to show the benefit CO₂-controlled ventilation. Designing CO₂-operated ventilation is not including in this research project. This paper scope only energy analysis and determining cooling load for representative area. Only one saloon of the train will be considered for analysis in order to

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make it simple and easier. Air changing in door opening is considered as infiltration. Accurate study might be required which will not affect the train.

1.6 Organization

This paper contains six chapters. It starts with introductory part which deals with the background about CO₂-based demand controlled ventilation, statement of the problem and objectives of the thesis. The second chapter is a literature review. This chapter summarizes the efforts of previous studies related to the current study. The third chapter deals with HVAC energy analysis soft-wares in which their significance on HVAC energy analysis is discussed. The next chapter which is the main chapter deals with CO₂ -demand HVAC energy analysis by using HAP (Hourly Analysis Program). The fifth chapter is about the discussion and result of the paper, which summarizes the result obtained. Last but not list chapter concludes the paper by putting feature works to be done in relation to the topic. And also there are references and appendices included.

CHAPTER 2

Literature Reviews

2.1. Air-Conditioning System

Most modern passenger vehicles are provided with air conditioning and they will also have heaters in countries where the climate gets cold enough to require it. Here is the basic layout of an air conditioned coach, also equipped with heating equipment.

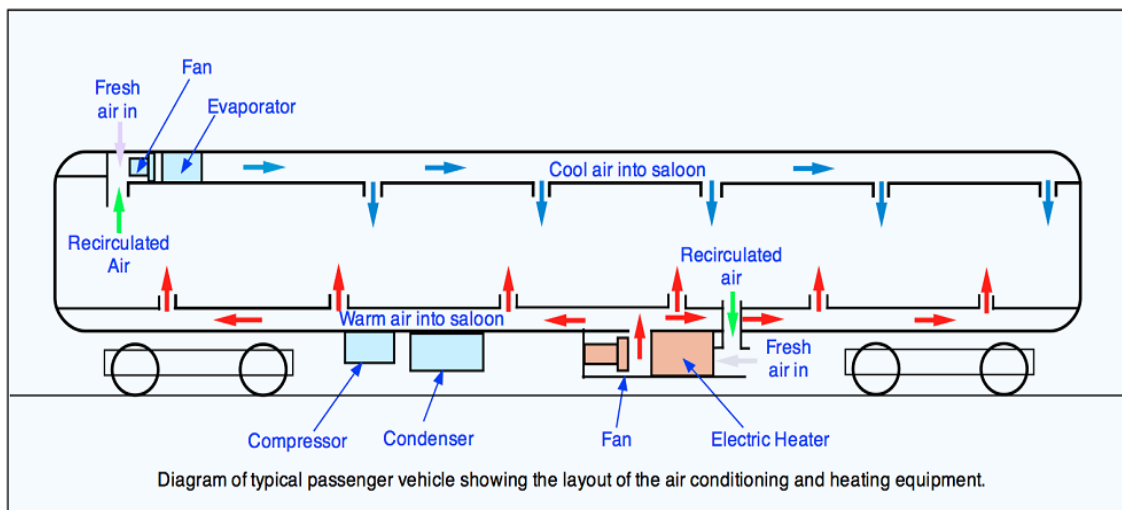


Figure2.1: a diagram showing the air conditioning and heating equipment

The air conditioner is designed to the so-called "split" arrangement, where the condenser and compressor are mounted under the car floor and the evaporator and fans are mounted in the roof. Sometimes there are two sets in the roof. The coolant from the condenser is passed to the evaporator in the roof through a connecting pipe.

The heater is a separate unit under the car floor, consisting of an electric resistance heater and a fan. Hot air is blown into the car by the fan, having passed through the heater from and under-floor intake. This intake collects some fresh air and uses some recirculating air from inside the car. The same air intake arrangement is provided in the roof for the air conditioning fan in the roof.

Some car heaters on EMU trains use resistance grids heated by the dynamic braking system. Waste energy generated by braking is converted into electric energy by the traction motors and this is fed into the heater grids.

2.1.1. Types of air-condition

The specification of a particular air-conditioning system depends upon a number of factors including the size of the space, heat generation within the enclosed area and so on. In general air-conditioning system can be categorized as:

- ✓ window unit systems
- ✓ split unit systems
- ✓ packaged systems
- ✓ chiller systems

These four main types of air conditioning system are divided into several sub-categories that usually depend on system capacity and design, as well as on the heat transfer mechanism of the system. A diagram showing the main types and sub-categories of air-conditioning system is given in Figure 8. The sub-categories will now be described.

Conventional Split Unit System: These systems have two parts: an outdoor unit and an indoor unit. The outdoor unit houses components like the compressor, condenser and expansion valve. The indoor unit comprises the evaporator or cooling coil and the cooling fan [25]. There can be more than one indoor unit per system. These systems are sometimes known as multisplit systems. Normally, they are installed in a small space and require individual control of the air-conditioning system. Further information about this type of system and energy conservation can be found in [26-28]. Figure 1-3 shows a typical schematic drawing of the system.

Split Ducted System: This system is very similar to a conventional split unit system, but instead of having an indoor unit blowing directly into the space, a fan coil unit blows conditioned air into spaces through ducting and diffusers. It is usually installed in a separate room and requires a dedicated control system. It can be installed as a centralized air-conditioning system in a small building. Figure 1-4 shows a typical schematic drawing of the system.

Air Cooled Package System: As the name implies, in a packaged air conditioning system all the important components of the system are enclosed in a single casing like a window unit. Thus the compressor, cooling coil, air handling unit and air filter are all housed in a single casing and assembled at the factory. The condenser of the refrigeration system is cooled by atmospheric air. The cooling unit comprising of an expansion valve, evaporator, an air

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handling blower and filters are located together with the compressor outside a building. From outside, the conditioned air is blown through ducting to the various spaces that are to be cooled [29]. Amount of installation of this system in non-residential buildings has been decreasing year on year due to the availability of higher capacity split ducted systems. This system may also be installed as a centralized airconditioning system in a small building.

Water Cooled Package System: The condenser is of shell and tube type, with refrigerant flowing through the tube side and cooling water flowing through the shell side. The water has to be supplied continuously in these systems to maintain functionality of the air conditioning system. The shell and tube type of condenser is compact in shape and is enclosed in a single casing along with the compressor, expansion valve, and air handling unit including a cooling coil. This whole packaged air conditioning unit looks like a box with the control panel located on the outside [29]. The air handling unit comprising of the centrifugal blower and air filter is located above the cooling coil. The centrifugal blower has the capacity to handle the large volume of air required for cooling a number of spaces. From the top of this packaged system, the duct extends to the various spaces that are to be cooled. As with an air cooled packaged system, it is normally installed as a centralized air-conditioning system in a small building, but with a slightly bigger in cooling capacity demand. Figure 1-5 shows a typical schematic drawing of the system.

Variable Refrigerant Flow System (VRF): VRF systems are larger capacity, more complex versions of ductless multi-split systems, with the additional capability of connecting ducted style fan coil units. They are inherently more sophisticated than multi-splits, with multiple compressors, many evaporators, and complex oil and refrigerant management and control systems. The term variable refrigerant flow refers to the ability of the system to control the amount of refrigerant flowing to each of the evaporators, enabling the use of many evaporators of differing capacities and configurations, individualized comfort control, simultaneous heating and cooling in different zones, and heat recovery from one zone to another. This kind of system is usually installed as a centralized air-conditioning system in a big building which requires an intermittent usage and distributed control system. Further information about this type of system can be found in. Figure 1-6 shows a typical schematic drawing for a variable refrigerant flow air-conditioning system.

Air Cooled Chiller System: Here, chillers transfer heat from process water (return chilled water) to the surroundings. An air cooled chiller consists of a compressor, evaporator, blower fan, chilled water pumps, control panel and condenser, which are all housed together as a

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package that supplies chilled water to the air handling units located in various floors or locations. The air handling unit then supplies conditioned air to spaces through ducts and diffusers. Warm air in the spaces is drawn back into the air handling unit through return air grills and ducts. Air-cooled chiller systems are generally installed as centralized air conditioning systems in large buildings where the additional heat discharged and optimum efficiency of power consumption are not a significant factor. In return, the system requires less maintenance than water-cooled chiller systems and eliminates the need for a cooling tower and condenser water pump. They generally consume approximately 10% more power than a water-cooled unit as the heat transfer coefficient (h) for water is much better than air.

Water Cooled Chiller System: The chillers in this system absorb heat from process water and transfer it to a separate water source such as a cooling tower, river, pond, etc. Similar to an Air Cooled Chiller System, this system is generally used for large capacity applications. It is more suited to areas with good resources of water and where the client requires optimum power consumption. This system consists of six major parts: chillers, chilled water pumps, condenser water pumps, cooling tower, air handling unit and control panel. The air handling units supply conditioned air to the required spaces through ducts and diffusers. Warm air in the spaces is drawn back into the air handling unit through the return air grills and ducts. Water cooled chiller systems require water treatment to eliminate biological fouling and to reduce corrosion in the system.

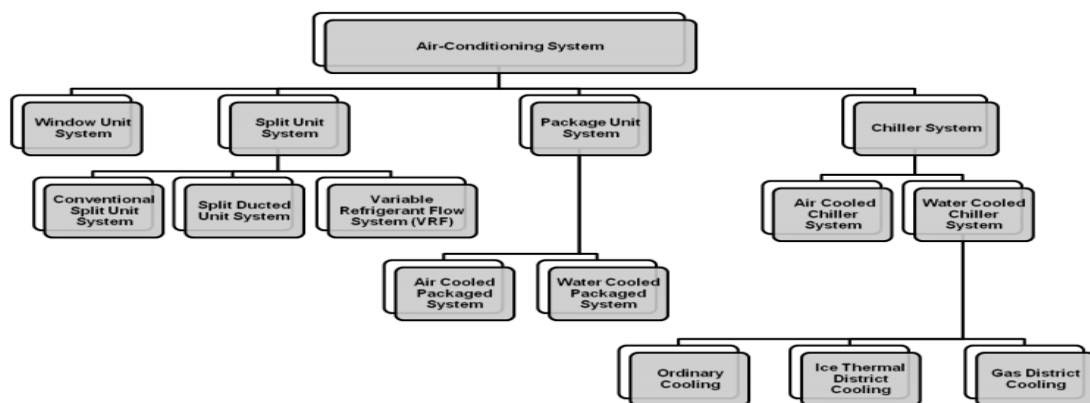


Figure 2.2: the main types and sub-categories of air-conditioning system

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2.1.2. General Comfort Considerations

ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy, may be referenced to determine the railcar interior thermal environmental factors that will provide environmental conditions that will be acceptable to a majority of the passengers. The following factors, typically encountered during rail travel, should also be considered:

- Changes in regional microclimates caused by local geography along the railcar's route.
- Air infiltration, drafts, and rapid temperature changes associated with door openings.
- Thermal Stratification (Vertical Air Temperature Variation).
- Velocity of air at passenger level (seated and standing passengers).
- Radiation effects of windows and structure.
- Solar loading variation due to dynamically changing solar orientation.
- Clothing insulation.
- Temperature recovery capability and pre-conditioning for passenger occupancy.
- Contribution of HVAC system to overall vehicle noise.
- Length of journey.

Thermal comfort is influenced by:

- Personal factors (degree of activity, clothing, journey time)
- Spatial factors (radiant temperature, temperature of enclosing surfaces)
- Ventilation factors (air temperature, air speed, relative humidity).

These factors have complex effects on the heat balance of passengers. Thus all contributing factors must be considered in order to achieve conditions which will be perceived as comfortable by a majority of passengers.

Air Motion: Controlling air motion within an acceptable range in a passenger railcar is an essential element of passenger comfort. Compared to a residential or commercial building HVAC system, the high occupant density and restricted space of a typical rail passenger vehicle make air distribution very challenging. Higher air velocities are normally desirable during high temperature and humidity operation when maximum cooling is required whereas high velocities constitute uncomfortable drafts when in

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heating or low level cooling operation.

Temperature Variation: Depending on the type of service conditions that influence the temperature balance in the passenger compartment can change rapidly. Because it is highly impractical to accurately simulate these dynamic conditions in a test environment, evaluation of these criteria are best made under stabilized conditions with all doors closed for the duration of the evaluation measurements.

Temperature and Humidity Design Range: Actual interior temperatures may be expected to exceed the design range when a combination of extreme environmental conditions, passenger overload, or operation occurs beyond the rating conditions. The limits to which interior temperature may exceed the design range are defined in some cases in the equipment section and may have a specific test or analysis requirement for conformance.

Thermal Recovery Rate: The need for a properly designed passenger rail car HVAC system is to maintain stable interior environmental comfort throughout its specified range of external ambient conditions and changing passenger loads is of primary importance. However, consideration must also be given to the ability of heating and cooling equipment to respond quickly to sudden changes in the thermal load which is a common occurrence in a rail passenger vehicle.

Solar Radiation Mitigation: Glazing specifically designed to reduce the effects of solar thermal radiation and to reduce interior car thermal loads is recommended for all vehicles that operate exposed to the exterior environment.

Spaces Separated From the Main Passenger Compartment: Some vehicles, mostly long distance inter-city type and some used in commuter service, have transient areas that are not intended for prolonged occupancy such as vestibules and toilet rooms and as such have less demanding thermal comfort requirements than the passenger occupied areas. Some are indirectly controlled, relying solely on branch conditioned air ducts from the passenger compartment, while other applications have thermostatically controlled local heaters. Few, if any, have local air conditioning devices or controls for unoccupied areas. The required comfort criteria in these areas can vary widely depending on the level of service and passenger expectations.

Supply Air Temperature: The majority of rail passenger vehicle HVAC systems distribute conditioned air from ceiling mounted grilles or diffusers. Floor and sidewall distribution systems are also used in some applications. Care must be exercised in the

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layout, design, and adjustment of the air distribution devices to assure uniform air distribution and mixing while avoiding uncomfortable drafts.

2.1.3. Factors Affecting Train Air Conditioning Loads

As the intensity of solar heat gain is the major factor for the cooling or heating load in a particular building there are also many factors that influence on the AC load. This includes building materials, building envelopes, orientations, geographical location of the building, the purpose of the building or building type, even the floor level to which the room is located within same building, population size of the room, infiltration and ventilation, room size and etc.

Air conditioning loads arise from energy that flows in to a passenger coach through its envelop, solar gain through windows, infiltration and ventilation which brings in outside air that needs to be cooled and/or dried, plus heat and moisture that are generated within the compartment.

An accurate assessment of rail passenger vehicle heating and cooling loads is required for the selection of HVAC equipment that provides acceptable system performance and comfort. Compared to buildings and other human habitats fixed in a given geographical position, rail passenger vehicles are often subject to significant environmental variation as a result of their motion. These variations include tunnels, changes in elevation, orientation with respect to solar heat gains, heat transfer effects due to wind, etc. These environmental influences affect not only the heating and cooling loads, but also the performance of the HVAC equipment itself.

With the possible exception of building passenger elevators, at design capacity no other form of public transportation exhibits the same degree of passenger loading per unit volume as subway and intra-city rail passenger vehicles.

2.1.4. Climatic and Environmental Design Criteria

Weather related loads arise from direct solar and transmission loads through building glass, walls and roof. The direct solar load component represents the amount of radiant energy transmitted to the space whereas the transmission loads component represent the amount of energy transmitted by conduction to the space due to temperature differences between the inside and the outside surfaces of the space.

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The actual climatologically data conditions were taken from Ethiopian Metrology Service Agency throughout the track alignment but we take the critical hottest region.

a. Cooling Ambient Design Conditions

Cooling dry-bulb temperature/mean coincident wet-bulb temperature data are typically used to determine the required cooling capacity of rail HVAC equipment. The design cooling capacity may be influenced by interior temperature pull-down requirements.

b. Heating Ambient Design Conditions

Heating dry-bulb temperature data is used for determining the required heating capacity of HVAC equipment. The design heating capacity may be influenced by interior temperature pull up requirements.

c. Street/Roadbed Temperatures

If applicable to the specific project, the designer should account for heat gain due to thermal radiation from the street or roadbed to the under-frame and lower sidewalls of the vehicle and resultant localized elevated DB temperatures.

Key factors to consider when this level of accuracy is deemed necessary include:

- Elevated street/roadbed temperature due to solar heating.
- Short distance from street/roadbed to under-frame.
- High surface thermal emissivity.

The net heat flux between the two surfaces depends on the thermal emissivity of the exposed exterior floor area and roadbed, surface areas of the roadbed and floor area, temperatures of the two surfaces, and “view factor” of the two surfaces. Typical thermal emissivity of both surfaces is approximately 0.9. There may be combinations of vehicle design, operation, and environmental conditions that reduce these additional cooling loads to insignificance; however, the designer should consider all of these factors and make an informed judgment as to how they should be addressed in the cooling load assumptions.

d. Roof-Mounted and Under frame-Mounted Equipment

Localized under-frame and roof temperatures may be higher than those calculated from climatological data due to heat rejection from adjacent equipment. These include propulsion motors, braking resistor banks, friction braking systems, HVAC condensing units, and other

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heat-generating equipment. The effect of these combined convective and radiative heat gains must be accounted for as required.

e. Elevation

Reduced air density (increased specific volume) at higher elevations can have a significant effect on the volumetric airflow rate necessary to achieve the desired interior conditions. These effects are usually disregarded at elevations less than 304.8 meters.

f. Train Building Materials

As the heat transfer between the inside and the outside of the coach is through the train envelopes, the properties of these components will have a critical role on heat transfer. In addition to this both indoor and outdoor materials must be durable, resistant to vandalism, easy to maintain, and affordable. Train construction, proper details, and materials are critical components of the heating and cooling load calculations. The R-value of the train wall, roof, and foundation construction components can be accurately calculated using the insulation levels specified combined with the remainder of the components that make up the construction assembly (i.e. drywall, sheathing, exterior siding materials, structural framing system, roofing materials, etc). The window performance, described by the U-value and SHGC, must be known and accurately represented by the data input.

✓ Wall Materials

Stone, concrete, and burnt clay are the most common materials used for buildings walls. Other types of wall materials like wood, steel and structural insulated panels are also sometimes used.

The wall may be composed of either a single wall material or a combination of different layers. The layers include the wall finishing material as well. Their properties like thickness, density, specific heat, R-value and weight are inbuilt in the software. The outside surface color highly affects the absorptivity and the relative humidity of the wall. If the outside surface is light RH will be high. If it is dark, then RH will be low. Factors mainly affect the design are orientation, design supply temperature, roof and wall outside color. For example as the HAP inbuilt data indicates, if the outside wall is dark then the absorptivity of the wall is 0.9, if it is medium the absorptivity will be 0.675, and if the outside color is light, then the absorptivity is 0.45. For this paper the considered building train, the wall is made of steel. The

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materials used for the construction of the building wall are as shown below. (*Source HAP software*).

Table 2.1 Wall Materials and Their Properties

Wall Material	Description	“u” factor
Flat material	0 fiberglass insulation	1.20
	1 fiberglass insulation	0.22
	2 fiberglass insulation	0.12
	3 fiberglass insulation	0,09
	4 fiberglass insulation	0.07
	6 fiberglass insulation	0.05
	8 fiberglass insulation	0.041
	12 fiberglass insulation	0.027
Poured concrete	2”thick	0.99
	4”thick	0.86
	6”thick	0.75
	8”thick	0.67
	10”thick	0.61
	12”thick	0.55

✓ Roof and Ceiling

The materials for the roof are also various. It is depending on the floor to which the room is located. If the room located in the intermediate floor, it will be low weight concrete roof and if it is in the last floor or only one floor case, the layers for the roof may contain ply wood, air space, and steel deck. The roof can have different layers. The HAP software contains the inbuilt roofing materials as in the case of wall material. Some of these materials include: air

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space, ply wood of different sizes, Built-up roofing, Wood siding, 22 gage steel deck, Slate, plasterboard.

✓ Window and Door

Most of the heat transfer in the room through building envelopes is through door and window. Almost all windows and doors are made up of glasses which have high U-value. So the designer should take care to the position of window and door so as not to direct in direction of maximum solar heat gain. The selection of window and door material is mostly depends on the overall heat transfer coefficient U . The overall heat transfer coefficient for some of window and door is given below.

Train Building Location: The train location is described by its latitude and elevation. This location describes the values for the outdoor design conditions such as the elevation of the location, latitude, winter heating dry bulb temperatures, summer cooling dry bulb temperatures and relative humidity (RH) information.

Train Building Type: The type or purpose of the building also affects the air conditioning design. And also the type of the coach has a vital effect. It may be Freight cars or passenger long train for long trip and commuter train type. And the interior structure design of the coach may be different. In this paper, 6-axle double-articulated 70% low-floor Light Rail tramcar will be scoped.

2.2. Related paper reviews

Various researches have been conducted in the previous to come up the reduction of train energy consumption using different techniques such as optimal train movement, regenerative braking system, reduction of train resistance between wheels and tracks, energy efficient locomotives, optimal train front Shape etc. Some of these techniques have disadvantages in case of expensive to apply on work. The main advantage of the current research there is no any Added cost to apply on work. In the last fifteen years, interest in CO₂-based DCV has led to a large body of literature published in journals, conference proceedings, and other forums. This section reviews some of the most important previous works Related to the current work.

2.2.1 Energy consumption

Almost all of today's companies have concerned about reduction of energy consumption. Reduction of energy consumption might refer to the energy consumed during production

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operations, supply chain-transportation and/or the energy consumed during functioning of the products after sales [4].

Concerned about rising energy costs, rail transit operators have implemented energy conservation strategies to maintain sustainability of rail operations. To improve overall operation efficiency, various methods to reduce energy consumption of passenger railway service were made, such as energy efficient locomotives, peak demand control of power supply, and reduction of train resistance between wheels and tracks, and regenerative braking system, which are very expensive [5].

Lambert, M. A., and Jones, B. J. stated that “The A/C power consumption of mid-size cars is estimated to be higher than 12% of the total vehicle power during regular commuting” [6].

Besides emission and fuel efficiency, passengers' comfort is another major factor that should be considered in the design of new vehicles. In fact, auto manufacturers pay a significant attention to driver and passenger comfort which is directly linked to A/C system. This trend is evidenced by new features such as multi-zone climate control and heated/cooled seats that can be found even in recent compact vehicles. Based on these observations, it is of both environmental and economic interest to seek new methods to improve the efficiency and performance of A/C systems of vehicle [7].

Simulation results have shown a saving potential for heating demand as important as 40% for railway vehicles in case of the combined implementation of the measures, control of the air flow rate as a function of the CO₂ concentration, the reduction of the wagon temperature set point by 2K and the night setback of the vestibules. For the whole EWII fleet of the RhB this would represent a possible energy saving potential of about 840 MWh/a.

2.2.2. CO₂-based Demand controlled ventilation

In the last fifteen years, interest in CO₂-based DCV has led to a large body of literature published in journals, conference proceedings, and other forums. The objective of this section is to summarize the literature on CO₂-based DCV.

2.2.2.1. Case Study-Field Test

There have been many demonstration projects in which CO₂-based DCV systems were installed in buildings and some aspects of performance were monitored. These studies vary in many respects, including the detail with which the DCV systems are described. Some reports

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contain detailed descriptions of the DCV control algorithms, while others do not even report the set point. The studies also vary in the impacts that were monitored, which have included fan operation, damper position, indoor CO₂ concentrations, ventilation rates, energy consumption, the concentrations of other pollutants, and occupant perceptions of the indoor environment. Finally, the studies have taken place in a variety of building types including offices, schools, auditoria and retail stores.

The application of CO₂-based DCV is often discussed with reference to office buildings, and occasionally to conference rooms within office buildings. One of the earliest studies of CO₂ control in an office building took place in **Helsinki (Sodergren 1982)**. The outdoor air control algorithm is not described, but the CO₂ set point was 1260 mg/m³ (700 ppm (v)). The CO₂ control system was compared to constant outdoor air and timer-based control, and 24-h plots of CO₂ concentration are presented for each system. Measured concentrations of other pollutants and interviews with occupants did not indicate any IAQ problems.

Davidge (1991) presents a demonstration project in a 30,000 m² (320,000 ft²) Canadian office building. In this building, the system never reduced the ventilation rate because the outdoor temperatures in the winter were never low enough to go off free-cooling. During the summer, damper leakage was more than enough to control CO₂. Davidge also studied a boardroom, where supplemental ventilation was controlled alternatively by a light switch, a motion sensor and a CO₂ controller. In the case of the CO₂ controller, the fan came on at 1440 mg/m³ (800 ppm(v)) and shut off at 1080 mg/m³ (600 ppm(v)). An occupant questionnaire was administered, and it was found that the occupants could not distinguish whether or not the fan was on in terms of air quality. However, they rated the CO₂ system very highly, presumably in terms of indoor air quality though the report does not specify the survey results in any detail.

A fairly comprehensive study of CO₂ control took place on two floors of an office building in Montreal (**Donnini et al. 1991, Haghghat and Donnini 1992**). One floor was equipped with a CO₂ DCV system, while the other floor served as a control. The CO₂ control algorithm was as follows: the damper closed at concentrations below 1080 mg/m³ (600 ppm(v)); as CO₂ increased above 600 ppm(v) the dampers opened with the maximum opening at 1800 mg/m³ (1000 ppm(v)). The study lasted one year, during which indoor concentrations

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of CO₂, formaldehyde, volatile organic compounds and particles, ventilation system performance, thermal comfort, and occupant perception were measured once a month. Energy demand was monitored for the whole year. The outdoor air dampers were closed most of the year, because there were rarely enough people to raise the indoor CO₂ concentration. The indoor air quality measurements revealed no significant contaminant concentration differences between the CO₂ and the control floor. Thermal comfort was generally adequate on both floors. Annual energy savings of 12 % were measured for the floor with DCV. Occupants of the DCV floor complained significantly more about the indoor environment than occupants of the control floor.

One of the most frequently cited demonstration projects took place in a small bank in **Pasco, Washington (Gabel et al. 1986)**. This study involved the measurement of energy consumption, contaminant levels including nitrogen dioxide, formaldehyde, carbon monoxide and particulates, and occupant response based on a questionnaire. The study design included monitoring over the winter, spring and summer seasons, with one week of normal operation followed by one week of CO₂ control. The system's economizer cycle operated normally throughout the test periods. They found that with the CO₂ control system set point at 1800 mg/m³ (100 ppm(v)) to 2160 mg/m³ (1200 ppm(v)), air leakage through the closed damper provided sufficient fresh air for typical occupancy, which was only 10 % to 15 % of design. That is, the indoor CO₂ level never raised to the control set points. All measured contaminants were maintained below indoor standards.

Based on a curve fit of the measured energy consumption to outdoor temperature for the two modes of outdoor air control, average energy savings of 7.8 % for heating and cooling in six climates typical of Oregon and Washington were calculated. Based on the questionnaires, the occupants could not detect differences between background CO₂ levels of 540 mg/m³ (300 ppm(v)) and 1800 mg/m³ (100 ppm(v)). The occupants reported feeling warmer during DCV control, although the measured indoor temperatures were no different.

Zamboni et al. (1991) reported on field measurements in auditoria in Norway and Switzerland. In the Norwegian building, the CO₂ set point was 1800 mg/m³ (1000 ppm(v)), and the reported results include indoor temperature, CO₂ concentration and age of air. In the Swiss building, there was a two-stage controller with the first set point at 1350 mg/m³ (750 ppm(v)) and the second at 2340 mg/m³ (1300 ppm(v)). The researchers monitored energy

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consumption and indoor climate, and administered occupant questionnaires. Heating energy was reduced by 15 % during one week of testing in the winter and by 75 % in the summer. With CO₂ control, there was less draft but more odor in summer.

Chan et al. (1999) address the case of a lecture theater in Hong Kong where radon is known to be of concern. They propose a DCV system controlled by both CO₂ and radon measurements to achieve acceptable IAQ while saving energy. Few details are presented. Finally, **Strindehag et al. (1990)** and **Strindehag and Norell (1991)** reported on a number of examples of how outdoor air intake can be controlled by CO₂ in a conference room, an auditorium, three offices and a school. The report contains descriptions of the buildings and the CO₂ sensors, and notes that the CO₂ set point was 1080 mg/m³ (600 ppm(v)). However, the control algorithms are not described, and no specific performance indicators are discussed. Satisfactory reliability of the system in the auditorium was reported after three years of operation.

The studies cited here show that CO₂ control has been demonstrated in a wide variety of building types including offices, schools, and public. It is apparent in examining these studies that the CO₂ control algorithm is often not described in sufficient detail to understand the system; in fact, some of the studies did not even report CO₂ set points. In several of the demonstration projects, the building occupancy was insufficient to raise the indoor CO₂ concentration enough to activate the CO₂ control system. Several of the studies used occupant questionnaires to evaluate performance, with inconsistent results. In some cases, the occupants perceived the indoor environment with CO₂ control positively. In other cases, there were more complaints, specifically with regards to odor during CO₂ control. Several studies noted a feeling of increased warmth with elevated CO₂ concentration despite the fact that the measured indoor temperatures were no higher. When considering these reports of occupant response, it must be kept in mind that the studies employed different questionnaires.

2.2.2.2. Case Studies-Simulations

Recently, **Brandemuehl and Braun (1999)** investigated the energy impact of various combinations of six economizer and DCV strategies (no economizer, dry bulb economizer, and enthalpy economizer – each with and without DCV) for four types of buildings (office, large retail store, school, and sit-down restaurant) in twenty U.S. climates (including Los

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Angeles and Sacramento). Additional modeling assumptions included a CO₂ set point of 1260 mg/m³ (700 ppm(v)) above ambient, thermostat setup or setback at night, HVAC fan shutdown during unoccupied hours, single-zone buildings with no infiltration, ventilation effectiveness of 0.85, and minimum ventilation flows for non-DCV cases of 9.4 L/s (20 cfm) per person, 4.7 L/s (10 cfm) per person, 7.1 L/s (15 cfm) per person, and 9.4 L/s (20 cfm) per person for the office, retail, school, and restaurant cases, respectively. The DCV system resulted in significant reductions in heating energy use for all buildings and climates. Heating energy use reductions ranged from 40 % for the office to 100 % for the retail building (i.e., the solar and internal loads supplied all necessary heat) in Sacramento and from 75 % for the office to 100 % for the retail building in Los Angeles. The DCV system with enthalpy economizer required the least cooling energy use for all building types and climates. However, in some cases, much of the cooling energy reduction was due to the economizer, and use of DCV without an economizer can actually increase cooling energy use for dry climates. Cooling energy reductions ranged from about 10 % to 20 % for

In an early report of a simulation study for an office, **Knoespel et al. (1991)** investigated the application of a CO₂-based DCV system to a two-zone office space with both constant air volume (CAV) and variable air volume (VAV) HVAC systems. A multiple zone pollutant transport model was used and a ventilation airflow controller model was developed as modules for a transient thermal system simulation program (Klein 1994). Other existing modules of the program were used to calculate building energy consumption. Infiltration to the main zone was assumed constant at 0.2 h⁻¹ and an interzone flow of 12 L/s (24 cfm) from the main office to the conference room was included when the HVAC system was on. Knoespel compared the performance of six ventilation strategies including constant outdoor airflow at the ASHRAE Standard 62-1989 prescribed flow of 10 L/s (20 cfm) per person, constant outdoor airflow at a “typical” rate of 0.7 h⁻¹, minimum outdoor airflow at the typical rate with a temperature-based economizer, DCV with a step-flow control algorithm, DCV with step-flow control and a temperature-based economizer, and DCV with on-off control. In the step-flow control algorithm, the fraction of outdoor air in the circulation flow was changed in 20 % steps depending on whether the measured CO₂ concentration in either zone was above or below the specified limit. On-off control employed an algorithm in which outdoor airflow is set at 100 % if the high CO₂ set point is exceeded and at 0 % if the

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CO₂ concentration drops below the low set point. The set points used were 1440 mg/m³ (800 ppm(v)) and 1800 mg/m³ (1000 ppm(v)). Simulations were performed for Miami, FL and Madison, WI. In Madison, the DCV strategies provided acceptable control of CO₂ levels with coil energy savings from 9 % to 28 % for CAV systems and from 43 % to 46 % for VAV systems compared to the Standard 62-1989 prescribed rate strategy. The savings for Miami were of similar absolute magnitude but smaller percentages. These results did not include fan energy use. Compared to the economizer and constant outdoor airflow strategies at typical rates, the DCV strategies resulted in similar energy use with better control of CO₂ concentrations for both CAV and VAV systems.

In a recent study with a focus on humid climates, **Shirey and Rengarajan (1996)** simulated the impact of a CO₂-based DCV system in a 400 m² (4000 ft²) office located in Miami, Orlando, and Jacksonville to examine the impacts of ASHRAE Standard 62-1989 ventilation rates on indoor humidity levels. The baseline system, a conventional direct expansion (DX) air-conditioning system with a sensible heat ratio (SHR) of 0.78, was unable to keep the indoor humidity below the target of 60 % relative humidity (RH) when the ventilation rate was increased from 2.5 L/s to 10 L/s (5 cfm to 20 cfm) per person. System modifications considered included a low-SHR DX air-conditioner, a high efficiency low-SHR air-conditioner, a conventional air-conditioner with CO₂-based DCV, a conventional air-conditioner with an enthalpy recovery wheel, a heat pipe assisted air-conditioner, and a conventional air-conditioner with a separate 100 % outdoor air DX unit. The operation of the DCV system was simulated by matching ventilation rates to occupancy profiles. Four alternative systems (DCV, enthalpy wheel, heat pipe, and 100 % outdoor air DX unit) maintained acceptable humidity levels for greater than 97 % of occupied hours. Of the systems with acceptable humidity performance, only the DCV and enthalpy wheel options did so with less than 5 % increases in annual HVAC energy use compared to the conventional system with a ventilation rate of 2.5 L/s (5 cfm) per person. The DCV system also significantly lowered the peak heating demand in Orlando and Jacksonville. An economic analysis showed that the DCV system resulted in annual HVAC operating cost increases of 7 % or less, first cost increases of about 14 %, and life cycle cost increases of about 12 % compared to the system with 2.5 L/s (5 cfm) per person. A case with high internal loads was also examined, with the DCV and enthalpy wheel systems again resulting in the best

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performance for the smallest increases in cost.

In a recent follow-up study, **Davanagere et al. (1997)** applied the same methodology with many of the same assumptions as Shirey and Rengarajan (1996) to study HVAC system options including CO₂-based DCV in a Florida school. As in the previous study, the baseline for comparisons was a conventional system with ventilation as required by ASHRAE Standard 62-1981. In addition to DCV, the options simulated included the conventional system with ASHRAE Standard 62-1989 ventilation rates and various combinations of pretreating outdoor air, thermal energy storage, enthalpy recovery wheels, gas-fired desiccant systems, and cold air distribution systems. Results reported included energy use, humidity levels, first costs and lifecycle costs. In general, the DCV system resulted in the smallest or close to the smallest increases in energy costs and installed first costs compared to the baseline system. The thermal energy storage system options generally resulted in the smallest increases (or even decreases) in peak cooling demands and life-cycle costs. DCV was the only option that reduced peak heating demands. Although the DCV system reduced humidity levels compared to the baseline system, many of the other simulated options controlled humidity better.

In addition to offices and schools, public spaces have also been the subject of DCV simulation studies. **Warren and Harper (1991)** evaluated the potential heating energy savings for a CO₂-based DCV system applied to an auditorium in London. Energy simulations were performed using a building energy analysis program (Clarke and McLean 1986) with ventilation rates calculated separately based on occupancy profiles. Assumptions included CO₂ generation of 4.7×10^{-6} m³/s (1.7×10^{-4} ft³/s) per person, auditorium volume of 11,150 m³ (406,000 ft³), high CO₂ set point of 1800 mg/m³ (1000 ppm(v)), peak daily occupancy of 629, and infiltration rate of 0.4 h⁻¹. Three ventilation scenarios were compared including 100 % outdoor airflow at a rate of 5,020 L/s (10,000 cfm), DCV with a minimum outdoor airflow rate of 3,770 L/s (7,500 cfm), and DCV with no minimum. The DCV with minimum outdoor airflow rate rarely exceeded the minimum rate to maintain CO₂ concentrations below 1800 mg/m³ (1000 ppm(v)) and saved 26.4 % in heating energy use compared to the 100 % outdoor airflow case. The DCV with no minimum saved 53.3 %.

The simulation case studies reviewed indicated energy savings for DCV systems between 4 % and over 50 % compared to ASHRAE Standard 62-1989 or other design ventilation rates. The energy savings varied widely depending on type of building, control algorithm, building

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location, assumed occupancy and other assumptions. No parametric or sensitivity analysis has been performed to determine which variables have the most influence on potential energy savings. Also, energy savings are reported with respect to different baseline cases in the different studies. A small number of the studies examined peak demand, economic impacts, humidity and concentrations of other pollutants. These studies verified the concern for increased concentrations of non-occupant generated pollutants, and one study examined potential solutions including scheduled purges. Shortcomings of most of the studies included inadequate treatment of infiltration and interzone airflows and control algorithms.

2.2.2.3. Application

One of the earliest discussions of using CO₂ to control outdoor air intake as a means of saving energy was presented by **Kusuda (1976)**. This paper presented some of the theoretical background of how indoor CO₂ concentrations vary as a ventilation system is turned on and off. Sample calculations showed potential energy savings of 40 % for an office space. Another early discussion of the energy savings potential of CO₂ control was presented by Turiel et al. (1979). This paper discussed a number of DCV control options including water vapor and concluded that CO₂ control appeared to be the most satisfactory approach.

Recently, one of the more detailed discussions of the application of DCV was reported by **Schell et al. 1998**. DCV topics covered include potential energy savings with DCV, determining locations for CO₂ sensors, control strategies (including set point, proportional, and exponential or PID), consideration of outdoor levels of CO₂, estimation of building ventilation rates using CO₂, models for selection of DCV strategy, and benefits of DCV. Additionally, Schell et al. discuss applying CO₂-based DCV in compliance with ASHRAE Standard 62-1989 (ASHRAE 1990).

A general discussion of the principles of DCV in office buildings is presented by **Davidge (1991)** and **Houghton (1995)**. These papers discuss the circumstances under which DCV might be expected to be most effective including the existence of unpredictable variations in occupancy, a building and climate where heating or cooling is required for most of the year, and low pollutant emissions from non-occupant sources. Davidge points out that when such a system is considered, one must address the base ventilation rate that is not controlled by DCV in order to control these non-occupant pollutant sources. The impact of free cooling on DCV

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systems is also discussed, noting that long periods of free cooling will reduce the potential energy savings. The potential for purge ventilation, both before and after occupancy, to control non-occupant sources is also discussed.

Similar discussions of the application of CO₂-based DCV are presented by **Houghton (1995)** and in an application guide published by **Telaire (n.d.)**. These publications contain background information on CO₂ control of ventilation and describe the potential energy savings benefits. Strategies for the use of CO₂-based DCV are also described including simple set point control where the outdoor air intake damper is either open or closed depending on the indoor CO₂ concentration, proportional control in which the intake damper or outdoor air fan flow is proportional to the CO₂ concentration, and PID (proportional-integral-derivative) control which considers the rate of change in the CO₂ concentration. Recommendations are made on the application of these techniques based on the occupancy level. The use of CO₂ control of outdoor air is discussed relative to other approaches of outdoor air control in papers by **Elovitz (1995)** and by **Janu et al. (1995)**. **Elovitz** discusses various options for controlling minimum outdoor air intake rates in VAV systems including: sequencing supply and return fans; controlling return or relief fans based on building pressure; measuring outdoor air intake rates directly; fan tracking; controlling the pressure in the intake plenum; outdoor air injection fans; and, CO₂ control. Advantages and disadvantages of each approach are discussed. Elovitz points out that CO₂ control does not necessarily assure satisfactory indoor air quality, depending on the existence and strength of contaminant sources that are not proportional to the number of occupants. Janu et al. (1995) discuss some of the same methods of outdoor airflow control and raise the same cautions regarding CO₂ control and non-occupant contaminant sources.

In addition to a general discussion of DCV, **Meier (1995)** reports a sensitivity analysis on parameters affecting the payback period for modifying a conventional ventilation system to add DCV capability. Although few details of the calculation are presented, the total airflow rate is reported as the most significant parameter determining payback period. However, operating hours were also found to be significant. More recently, Meier (1998) provided estimated potential energy-cost savings for a range of DCV applications based on case studies and experiences of control companies. These estimates and additional ones from **Mansson (1994)** are presented in Table 2. Mansson provides background information on CO₂DCV

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systems, discusses strategies for base and variable ventilation rates based on application type, and presents a six-step flowchart for determining the feasibility of DCV for an application. As expected, the energy savings in Table 2 are largest for high density spaces with generally variable occupancy, such as the various halls, theatres and cinemas. The lowest savings are seen in the office spaces, which generally have lower occupancy densities with less variation than the other spaces.

Table 2.2: Estimated energy-cost savings from DCV (Meier 1998 and Mansson 1994)

Application	Energy cost saving range		
Schools	20%	to	40%
Day nurseries	20%	to	30%
Restaurant , canteen	20%	to	50%
Lecture halls	20%	to	30%
Open-plan (40% average occupancy)	3%	to	5%
Open-plan (90% average occupancy)	20%	to	60%
Entrance halls, booking halls, airport halls	40%	to	70%
Exhibition halls, sport halls	40%	to	70%
Assembly halls, theatre , cinema	20%	to	60%

2.2.3 The first Metro applied automatic ventilation system using co2 sensor

The Seoul Metro-New Line 2 is the first in the world to apply “automatic ventilation system using CO2 sensor” in its cars to apply “automatic ventilation system using CO2 sensor” in its cars. Each car has two CO2 sensors that detect CO2 gas concentration level in the passenger

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area and then transfer the signals to HVAC's Micom. Once Micom receives the signals, it decides to whether turn on or off the ventilation system based on regulated CO₂ gas concentration data received from the passenger area. When the ventilation system turns on, two supply fans installed in each of HVAC unit car, begin to operate and after 5 seconds, two exhaust fans will turn on until the concentration of CO₂ gas reaches below the regulated concentration level of CO₂ gas. When this survey, six CO₂ measuring sensors were used and three were positioned inside vehicle and two were outside for measuring CO₂ concentration of tunnel.



Fig 2.3: Measurement of co₂ concentration at indoor air



Fig 2.4: Measurement of co₂ concentration at outdoor air

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The vehicles were modelled and simulated in the software program IDA ICE. This software originates from the building sector and is widely used in research and engineering applications. The input data to the model consist in the geometrical and physical properties of the wagon, (especially the housing), the HVAC equipment including its control, the internal heat gains and the outside climate (temperature, solar irradiation and wind). The final model was calibrated with the help of the long term measurements by the University of Basel in combination with the stationary heating-up and tracer gas measurements and passenger counting. Once the models were calibrated, the optimization measures for the HVAC units and the vehicle hardware could be defined and the highest energy saving potential in the vehicles could be identified.

This research paper scope only energy analysis of CO₂-DCV by HAP which is as IDA ICE, software originates from the building sector and widely used in research and engineering application. The input data of this software and IDA ICE are similar:

- ✓ Geometrical properties of the train
- ✓ Physical properties of the train
- ✓ HVAC type
- ✓ The internal heat gain and the outside climate etc.

CHAPTER 3

Tools for HVAC System energy Analysis

3.1. Introduction

Computer programs designed for energy modelling and analysis of buildings are generally known as building energy simulation programs'. These programs are intended for modelling of large, multi-zone building and their HVAC systems (ASHRAE, 1993, Chap. 28). The interactions in buildings are by their nature very complex. While some simplified design tools and guidelines exist to help designers understand the phenomena involved, more elaborate, often computer-based tools are required for detailed analysis.

Most of the building energy analysis programs are developed in USA and Europe; directories and lists of energy analysis software have been published to show people what is available on the market, such as AEE (1991), ASHRAE (1991d), Williams (1992), Degelman (1987) and Weiss and Brown (1989). There are more than 200 programs in USA and 100 programs in Europe and elsewhere (Seth, 1989b), but only a handful of them are frequently used by building designers (Bloomfield, 1989b; BEDTDC, 1988). Table 2.1 gives a list of the programs commonly used nowadays. A list of the programs common in Europe can also be found in Goulder, Lewis and Steemers (1992, pp. 251-254).

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Table 3.1: List of Common Building Energy Simulation Programs

Programme	Reference source	Country	Remarks
QPEC ESP- II	(Wickham, 1985)	USA	D
QSEAM21	(ohadi, ; Meyer , and Pollington , 1989)	USA	S
BESA	(BESA,1993)	Canada	D
BLAST	BLQST , 1991	USA	D,P
BUNYIB	(Moller and Wooldridge, 1985)	Australia	B
Carrier HAP	(carrier corporation 1990)	USA	S,COM
DOE -2	(Birdsall, et al , 1990, LBL, 1981)	USA	D,P
HVACSIM +	(Clarke , 1985)	USA	D,P
TRACE 600	(Trane company , 1992)	USA	S,COM
TRNSYS	(TRNSYS,1988)	USA	D
ESP -r	(Clarke , 1985)	UK	D

In this section we present a summary of currently available and widely used software for performing HVAC design, sizing and simulations. The software tools are designed with the intent to improve the performance of HVAC systems, reduce overall energy consumption, and to meet indoor quality guidelines and requirements. The selected energy tools are a summary based on a review on the web and the literature.

3.2. Hourly Analysis Program (HAP)

In a single software package, the HAP software, developed by Carrier Corporation, offers both a system design tool and an energy simulation tool. HAP's design module uses a system-based approach to HVAC load estimation, by tailoring the sizing procedure and results based on the specific type of system being analyzed. Building heat flow is calculated by using the ASHRAE Transfer Function Method. Furthermore, HAP performs an hour-by-hour simulation of building loads and equipment operation for all 8,760 hours in a year, taking into account the unique weather and operating schedules for each day of the year. This provides superior accuracy versus other methods that use averages or typical days for each month.

Strengths: Technical sophistication is combined with ease of use. HAP can communicate electronically with Carrier to import equipment performance data.

Weaknesses: Limited used for research scientist since the software is closed source.

Safety Factor: A safety factor of 10% for cooling loads and 20% for heating loads is used in calculations [12].

3.3. TRACE 700

Trane's TRACE 700 brings the algorithms recommended by the ASHRAE to the Windows operating environment. This software is used to assess the energy and economic impacts of building-related selections, including HVAC equipment selections. In this software the designer is able to compare up to four scenarios for a single project by modeling different options of the air distribution and mechanical system/control choices. Additionally, the designer can choose from seven different ASHRAE cooling and heating methodologies, including the Exact Transfer Function.

Strengths: Customizable libraries and templates simplify data entry and allow greater modelling accuracy. Documentation includes detailed online Help and a printed modelling guide.

Weaknesses: New users are recommended to take formal training.

Safety Factor: TRACE 700 does not have any one single entry dedicated to providing a factor of safety. The program results can be as moderate or conservative as the user sees fit. It is the user's responsibility to account for safety factors by using conservative information while inputting the values in the different sections of the program. [16].

3.4. System Analyser

The System Analyzer develop by TRANE is a comparative analysis tool for preliminary evaluations of HVAC systems based on energy and economic performance [17]. This software package can be used to quickly evaluate any combination of air distribution system(s) and cooling/heating equipment for a specific building type and weather location.

Strengths: The intuitive and user-friendly interface provides built-in templates for creating accurate and comprehensive reports.

Weaknesses: This program lacks some of the features available in the TRACE suite.

Safety Factor: TRANE does not include one single entry dedicated to providing a factor of safety. The program results can be as moderate or conservative as the user sees fit. It is the user's responsibility to account for safety factors by using conservative information while inputting the values in the different sections of the program. [16].

3.5. Energy Pro

Energy Pro is a comprehensive energy analysis program that can be used to perform several type of calculations, including California Title 24 energy analysis of nonresidential buildings, as well as Leadership in Energy & Environmental Design (LEED) and ASHRAE 90.1 calculations. Energy Pro's interface includes a building tree, a set of libraries, and a database of state-certified equipment directories.

Strengths: The extensive use of Wizards allows most users to start creating reports.

Weaknesses: Some advanced concepts encompassed by DOE-2 are not handled by EnergyPro.

Safety Factor: EnergyPro does not have any one single entry dedicated to providing a factor of safety.

3.6. Conclusion

Currently HAP is the commonly used commercial software throughout the world due to its many interesting features like being free application, international, hourly based analysis. It is also common package in our country. Based on a review on the web and the literature, it is the best currently available and widely used software. In fact, I have preferred to use it for my work on this paper. Any information or details about this software will be discussed in the next chapter.

CHAPTER 4

Energy analysis of co₂-controlled HVAC by HAP software

4.1. Hourly Analysis Program (HAP)

HAP is a computer tool which assists engineers in designing HVAC systems for commercial buildings. HAP is two tools in one. First it is a tool for estimating loads and designing systems. Second, it is a tool for simulating energy use and calculating energy costs. This design software uses the ASHRAE-endorsed transfer function method for load calculations and detailed 8,760 hour-by-hour energy simulation techniques for the energy analysis. This program is released as two similar, but separate products. The “*HAP System Design Load*” program provides the system design and load estimating features. The full “*HAP*” program provides the same system design capabilities plus energy analysis features.

4.1.1. HAP System Design Features

HAP estimates design cooling and heating loads for commercial buildings in order to determine required sizes for HVAC system components. Ultimately, the program provides information needed for selecting and specifying equipment. Specifically, the program performs the following tasks:

- ✓ Calculates design cooling and heating loads for spaces, zones, and coils in the HVAC system.
- ✓ Determines required airflow rates for spaces, zones and the system.
- ✓ Sizes cooling and heating coils.
- ✓ Sizes air circulation fans.
- ✓ Sizes chillers and boilers.

4.1.2. HAP Energy Analysis Features

HAP estimates annual energy use and energy costs for HVAC and non-HVAC energy consuming systems in a building by simulating building operation for each of the 8,760 hours in a year. Results of the energy analysis are used to compare the energy use and energy costs of alternate HVAC system designs so the best design can be chosen. Specifically, HAP performs the following tasks during an energy analysis:

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- Simulates hour-by-hour operation of all heating and air conditioning systems in the building.
- Simulates hour-by-hour operation of all plant equipment in the building.
- Simulates hour-by-hour operation of non-HVAC systems including lighting and appliances.
- Uses results of the hour-by-hour simulations to calculate total annual energy use and energy costs. Costs are calculated using actual utility rate features such as stepped, time-of-day and demand charges, if specified
- Generates tabular and graphical reports of hourly, daily, monthly and annual data.

4.1.3. Steps in Using HAP to Energy analysis

The following steps show how to use HAP to energy analysis:

4.1.3.1. Defining the Problem

First define the scope and objectives of the energy analysis. For example, what type of building is involved? What type of systems and equipment are required? What alternate designs or energy conservation measures are being compared in the analysis?

4.1.3.2. Data Gathering

Before energy simulations can be run, information about the building, its environment, HVAC and non-HVAC equipment, and its energy prices must be gathered. This step involves extracting data from building plans, evaluating building usage, studying HVAC system needs and acquiring utility rate schedules. Specific types of information needed include:

- ✓ Climate data for the building site.
- ✓ General information about building size, shape, layout and number of floors.
- ✓ General information about the type of wall, window and roof envelope construction to be used.
- ✓ General information about the space usage in the building which will affect occupant density and lighting and equipment usage levels.
- ✓ General information about the type of air-side systems, equipment and components to be considered.
- ✓ General information about prices for electric service and any fuel sources used in the building.

4.1.3.3. Data Entry in to HAP

Next, use HAP to enter data for the analysis. When using HAP, your base of operation is the main program window. From the main program window, first create a new project or open an existing project. Then use the "Full Wizard Session" feature to rapidly enter all your data for the analysis.

From the main program window choose the "Full Wizard Session" option on the Wizards menu, or click the "Full Wizard Session" button on the toolbar. The Full Wizard Session window provides access to all of the HAP Wizards:

- ✓ The **Weather Wizard** - Used to quickly configure weather data for the building site.
- ✓ The **Building Wizard** - Used to rapidly define the size, shape, layout, envelope and internal
- ✓ Loads for the building spaces.
- ✓ The **Equipment Wizard** - Used to easily create HVAC design alternatives.
- ✓ The **Utility Rate Wizard** - Used to quickly assemble electric and fuel pricing data.

After entering data on the Wizard input screens, press the Finish button in the lower left of the Full Wizard Session window. HAP converts your Wizard data into a full set of detailed HAP inputs and displays them in the HAP main window.

There is another method to enter the Data in to HAP; this method is more detailing than the previous one. In fact, in this method it needs to define the following types of data which are needed for energy analysis work:

4.1.3.3.1. Weather Data

Weather data defines the temperature, humidity and solar radiation conditions the building encounters during the course of a year. These conditions play an important role in influencing loads and system operation throughout the year. Both design and simulation weather data are needed. To define design weather data, a city can be chosen from the program's weather database, or weather parameters can be directly entered. Simulation weather is selected by loading a simulation weather file from the library provided with the program or importing data from an external source. This step is also used to define the calendar for your simulation year. All three types of data are entered using the weather input form.

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4.1.3.3.2. Enter Space Data

A space is a region of the building comprised of one or more heat flow elements and served by one or more air distribution terminals. Usually a space represents a single room. However, the definition of a space is flexible. For some applications, it is more efficient for a space to represent a group of rooms or even an entire building. To define a space, all elements which affect heat flow in the space must be described. Elements include walls, windows, doors, roofs, skylights, floors, occupants, lighting, electrical equipment, miscellaneous heat sources, infiltration, and partitions. While defining a space, information about the construction of walls, roofs, windows, doors and external shading devices is needed, as well as information about the hourly schedules for internal heat gains. This construction and schedule data can be specified directly from the space input form (via links to the construction and schedule forms), or alternately can be defined prior to entering space data.

4.1.3.3.3. Enter Air System Data

An Air System is the equipment and controls used to provide cooling and heating to a region of a building. An air system serves one or more zones. Zones are groups of spaces having a single thermostatic control. Examples of systems include central station air handlers, packaged rooftop units, packaged vertical units, split systems, packaged DX fan coils, hydronic fan coils and water source heat pumps. In all cases, the air system also includes associated ductwork, supply terminals and controls. In the case of packaged DX, split DX, electric resistance heating and combustion heating equipment, the system also encompasses this DX or heating equipment. For example, when dealing with a gas/electric packaged rooftop unit, the "air system" includes the DX cooling equipment and the gas heating equipment. To define an air system, the components, controls and zones associated with the system must be defined as well as the system sizing criteria. For energy analyses, performance information about DX cooling equipment and electric and combustion heating equipment must also be defined. All of this data is entered on the air system input form.

4.1.3.3.4. Enter Plant Data

A Plant is the equipment and controls used to provide cooling via chilled water or heating via hot water or steam to coils in one or more air systems. Examples include chiller, changeover, hot water, service hot water, steam boiler, and remote source cooling and heating plants.

This step is optional; it is only required if chilled water, hot water or steam plants are used in your building. To define a plant for energy analysis purposes, the type of plant and the air

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systems it serves must be defined along with its configuration, controls and distribution system information. This data is entered on the plant input form.

4.1.3.3.5. Enter Utility Rate Data

Utility rate data defines the pricing rules for electrical energy use and fuel use. An electric rate structure must be defined for all energy studies. One fuel rate for each non-electric fuel source must also be defined. Electric rate data is entered using the electric rate form. Fuel rate data is entered using the fuel rate form.

4.1.3.3.6. Enter Building Data

A Building is simply the container for all energy-consuming equipment included in a single energy analysis case. One Building is created for each design alternative being considered in the study. Building data consists of lists of plants and systems included in the building, utility rates used to determine energy costs and data for non-HVAC energy or fuel use. Data is entered using the building form.

4.1.3.4. Use HAP to Generate Simulation Reports

Once all input data has been entered, HAP can be used to generate simulation reports showing energy cost results.

4.1.3.5. Evaluation of result

Finally, use data from the simulation reports you generated to draw conclusions about the most favorable design alternatives.

4.2. Air-condition energy simulation by HAP

4.2.1. Defining the problem

in this paper, the objective is to estimate energy use for AALRT. Normally an energy analysis compares energy use for two or more scenarios. The scope of this paper will be to estimate and compare the energy use of two design scenarios:

- CAV which is deliver comfort to spaces with similar loads.
- VAV which is designed with the supply a quantity of fresh air fitted with the needs in every situation, ensuring the right quantity of fresh air flow. This case describes accurately the quantity of occupant in building or train.

Based on this, equipment like supply fan, space (door, window, wall and roof of train) and the coach interior data will be sized. HAP will be used to simulate the train building load and equipment operation hour-by-hour for one year in order to determine energy use.

4.2.2. Data Gathering

This involves gathering data for the train, its environment and its air system data. These are as follows.

4.2.2.1. Weather Data

The weather data includes monthly maximum and minimum dry bulb and wet bulb temperatures, design DB temperatures for both summer and winter, summer coincident WB, winter coincident WB, region, location, city, latitude, longitude, elevation, and the sunshine hour, for the area of interest which is Addis Ababa, which are collected from the National Metrology Agency (NME).

Dry-bulb Temperature: The temperature of the air measured by the ordinary thermometer, when exposed to the atmosphere, is called as the dry bulb temperature of air, commonly referred as DBT. It is nothing but the atmospheric temperature. In this case the sensing bulb of one of the thermometers is always kept dry .The temperature reading of the dry bulb is called the dry bulb temperature. It is an important consideration when designing a building for a certain climate.

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Wet-bulb Temperature: The wet bulb temperature of air is also measured by the ordinary thermometer, but the only difference is that the bulb of the thermometer is covered by the wet cloth (a piece of cotton wick). Temperature of the ordinary air measured by the thermometer when it is covered by wet cloth or wick is called as the wet bulb temperature, commonly referred to as WBT. When the air comes in contact with the wet cloth it absorbs some moisture and gives up some heat, to which the temperature of the air reduces. It is always less than DBT. The difference between the DBT and WBT is called as wet bulb depression. Unlike the DBT this indicates the amount of moisture in the air. See figure below:

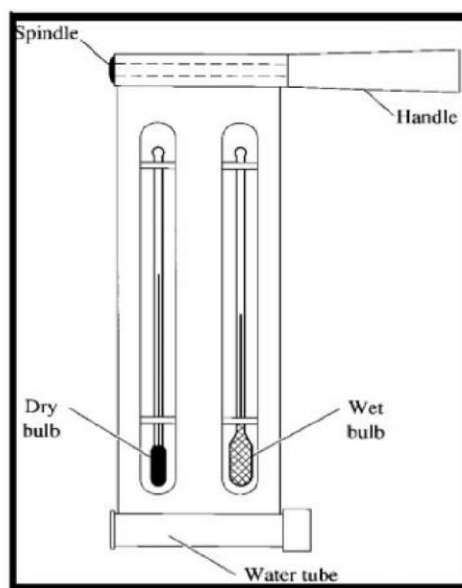


Figure 4.1: Thermometer for Dry-bulb and Wet-bulb

The maximum and minimum dry bulb temperatures as well as maximum and minimum wet bulb temperature are taken from the national metrology agency (NMA). The row data was hourly for each day of the 10 year. Then from that I have get the average values for each month and tabulated as shown in the table 4.1 below. This dry bulb and wet bulb temperature data will be entered in the software under Design Temperature.

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Table 4.1: Maximum and Minimum Wet bulb and Dry bulb Temperature for Addis Ababa

Month/ Temp	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(DB)Max	26.8	28.8	28.8	28.2	28.4	29.2	25.6	23.4	27.2	25.4	25.4	26.2
(DB)Min	10.8	12.6	11.6	12.4	12.4	11.0	10.0	11.2	11.2	12.2	12.6	11.0
(WB)Max	19.0	17.1	24.6	23.6	19.2	24.2	20.2	17.8	19.1	17.6	15.6	19.4
(WB)Min	3.0	6.1	6.8	9.2	9.2	10.4	9.5	9.8	10.6	7.2	6.2	6.0

Dew Point Temperature of Air (DPT): The dew point temperature of the air or DPT is the temperature at which the water vapor within the air at some temperature starts condensing. When the dew is formed the air is said to be in saturated condition. When any object is cooled below the dew point temperature of the air, we can see the formation of sweat on its surface. A glass of water filled with chilled water is an example. The dew point temperature of air depends upon its moisture content. Higher the moisture content of the air, higher is the dew point temperature. For the saturated air, the dry bulb temperature, the wet bulb temperature and dew point temperature are the same.

The Relative Humidity: Humidity is the amount of water vapor in a given space. The humidity ratio or specific humidity is the weight of water vapor per unit weight of dry air; it is given in either grains per pound or pound per pound (kg/kg). The thermal effect of humidity on the comfort of sedentary persons is small, that is, comfort is maintained over a wide range of humidity conditions. In winter, the body feels no discomfort over a range of RH from 50 percent down to 20 percent. In summer, the tolerance range extends even higher, up to 60 percent RH when the temperature is 24°C; above that, the skin feels sweaty. Nevertheless, some types of industrial applications, such as textile manufacturing, optical lens grinding, and food storage, maintain RH above 60 percent because of equipment, manufacturing processes, or product storage requirements. At the other extreme, certain pharmaceutical products, plywood cold pressing, and some other processes require an RH below 20 percent. Hospitals also must carefully control humidity since the level of bacteria

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propagation is lowest between 50 and 55 percent RH. In general Human comfort requires the relative humidity to be in the range 25 - 60% RH. But it may vary depending on the type of applications to which the buildings are used.

Sun Shine Hour

The sunshine hour for Addis Ababa is obtained from the NMA for 10 consecutive years on hourly basis. Then I have calculated the daily value for each day of the 10 years data. Then I have calculated the average value the sunshine hours for each month as shown below.

Table 4.2.Sunshine Hours for Addis Ababa

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sunshine Hr	8.82	8.50	8.30	8.00	8.02	7.68	7.22	6.86	6.77	7.01	7.29	7.55

The design conditions from long term (10 years) hourly observations for some different parts of Ethiopia are shown in the following tables.

Note: DBT= Dry Bulb Temperature, CWB = Coincident Wet Bulb Temperature, DP= Dew Point Temperature, MDR = Mean Daily Range (K)

These weatherdata including the minimum and maximum dry-bulb and wet-bulb temperatures are entered in to the software using the weather column as shown in the figure bellow.

Fig 4.2 : space input data

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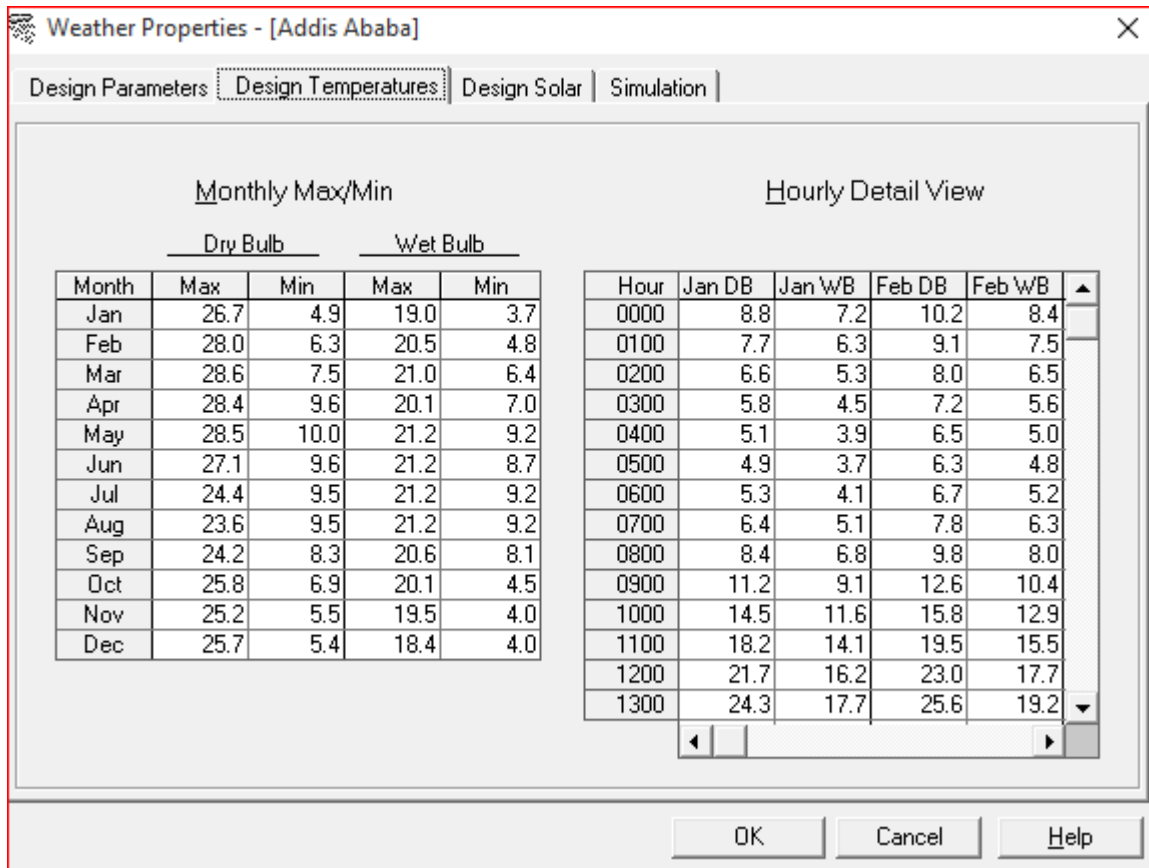


Figure 4.3: input data of weather

Then for each month, the weather parameters and the maximum solar heat gains from each orientation will be obtained from the software. Also the multiplying factor for the design day maximum solar heat gain depends on the presence of cloudy on the day. It can be taken as 1 for clear sky months and can be 0.75, 0.85, 0.9 depending on the strength of the cloud.

We can have the weather data and solar heat gains after entering the data. The following figure shows the design temperature profile for January specifically for Addis.

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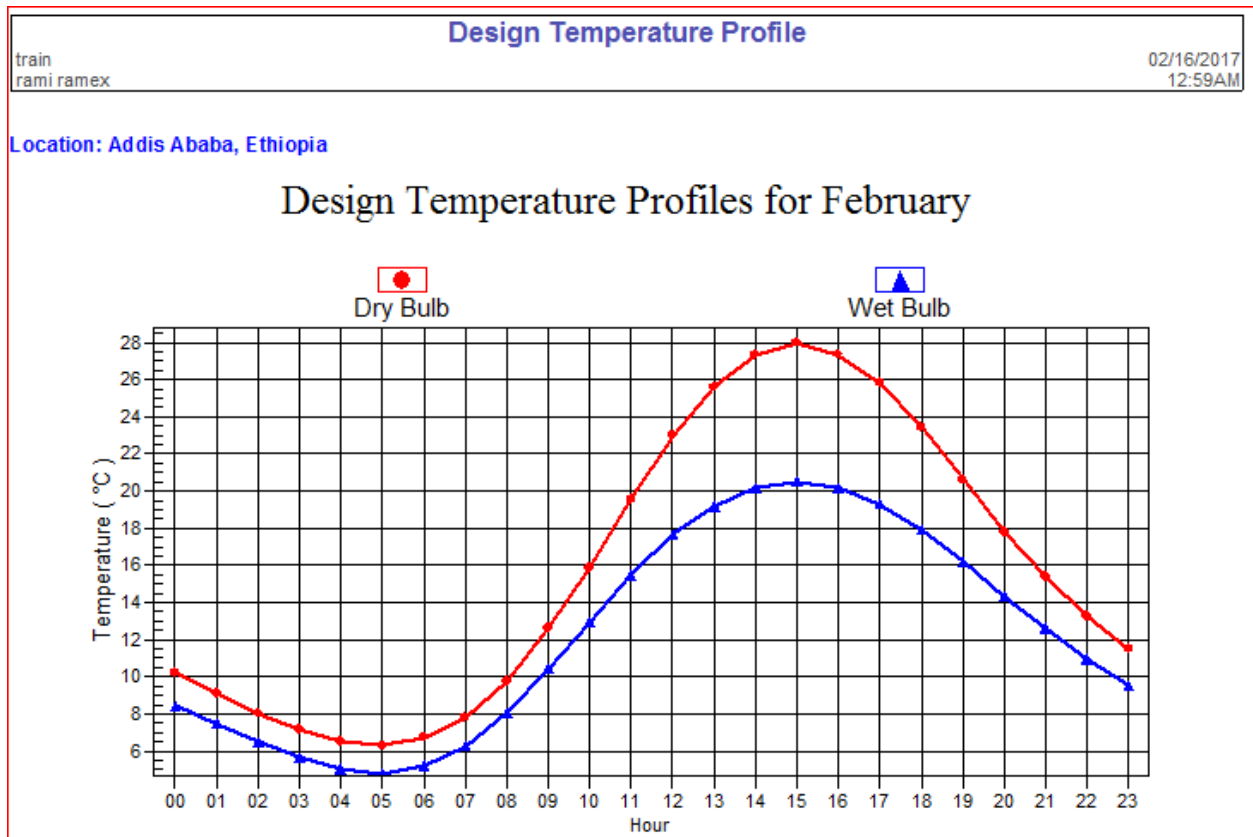


Figure 4.3: Design Temperature Profile for February only

4.2.2.2 Enter Space Data

There are a variety of spaces considered for this project and their characteristics were derived from architectural floor plans and professionals on that area and some of this information are described below.

The coach is heated through windows, sidewalls, roof and floor. The solar application represented by the solar heat which comes into the coach through the windows exposed to the sun (direct actions of the solar rays). The description of interior structure is below.

Walls: Side wall panel: Every seat area is a large block of side wall, and the end part is composed of a large block of wall panel. In Mc car, a lower wall panel at handicapped area shall be provided in Mc car. During installation of side wall panel at seat area, use bolts to connect aluminum profile on the reverse side of side wall and steel installing seat on the top, and use bolts to connect aluminum profile on the reverse side of side wall and steel installing seat on the bottom, and use bolts to connect end profile of side wall and vertical shield plate on the side, to complete the fixing operation for side wall. The lower end of lower wall panel

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at handicapped area shall be connected to steel structure by means of bolts, one side use bolt to connect side wall end and vertical shield plate, and the other side use bolt to connect side wall end profile and compartment partition. The lower wall panel at handicapped area, and lower part of small wall panel assembly at the end has 0.8mm thick skirt board made of stainless steel with drawbench type, the height is 320, and the skirt board and wall panel shall be fixed directly with adhesive. The lower wall panel at handicapped area, small wall panel assembly at end and floor gap will provide sealing adhesive, to convenient to cleaning and maintenance inside of compartment. The upper wall panel of side wall panel is aluminum panel structure; the lower wall panel of the window is GRP structure. The lower wall panel at high floor area has 0.8mm thick skirt board made of stainless steel with drawbench type, the height is 320, and the skirt board and wall panel shall be fixed directly with adhesive. See the attached figure 2.2.3-1 below for detailed layout of side wall panel.

Roofs: The materials for the roof are also various. It is depending on the floor to which the room is located. If the room located in the intermediate floor, it will be low weight concrete roof and if it is in the last floor or only one floor case, the layers for the roof may contain ply wood, air space, and steel deck. The roof can have different layers. The HAP software contains the inbuilt roofing materials as in the case of wall material. Some of these materials include: air space, ply wood of different sizes, Built-up roofing, Wood siding, 22 gage steel deck, Slate, plasterboard. In this paper case, the roof is divided into steel module and aluminum modules are bolt connected. Roof steel module is welded on to end wall and side wall. Aluminum module is bonded to roof. Exterior wall panel of side wall is bonded using composite materials.

Floor: Floor inside passenger saloon is structured with polyurethane rubber. Floor is covered by PVC floor covering. Polyurethane rubber floor is bonded to steel structure of under frame, thereby offering good damping and acoustic insulation. PVC floor covering is bonded to polyurethane rubber floor, and has a minimum life cycle of 15 years. It is 2.5mm thick and can offer good resistance to compression, tension, fire, skid, heat, sound, vibration, acid, alkaline and wear. The length of floor is 23600mm.

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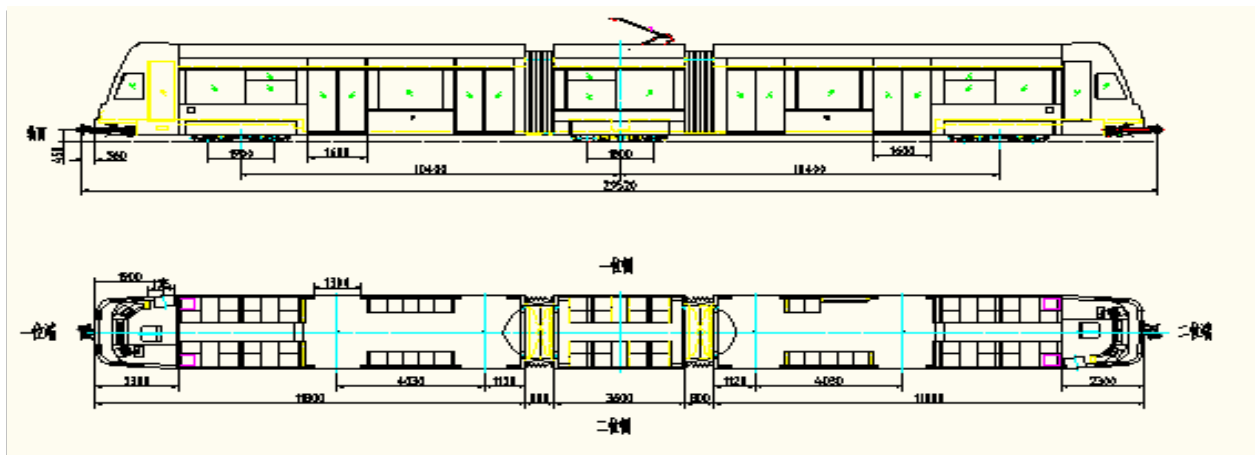


Figure 4.4: body structure dimension

Windows: Windows are installed with safety glazing resistant to scratch, UV radiation, heat and sound. Windows demonstrate good water-tightness and can be quickly replaced to reduce maintenance work. Windows have larger sizes insofar as possible provided car body strength is guaranteed. Windows are mounted and designed to withstand pressure difference between interior and exterior and accommodate all requirements for operations at 70 km/h. Side windows of passenger saloons can be partially opened for ventilation. Both sides of the passenger compartment have windows. The windows in non-frame structure are large without effect the strength, stiffness and effective opening. The windows use safety glass, bonded to the tramcar. The window has heat transfer coefficient $3.2 \text{ w/m}^2 \cdot \text{k}$.

Doors: Each modular articulated tramcar with 6-axis has four doors along the carriage. The doors are electric sliding doors. The effective opening of the door should be no more than 1250mm, and its effective height should be no more than 1850mm. The door adopts high-strength aluminum alloy materials and the interlayer aluminum is in honeycomb structure. The doors and windows use hollow coating toughened glass. The doors maintain many advantages, such as high strength, high stiffness, and low weight, good thermal and sound insulation. The door has heat transfer coefficient $4.5 \text{ w/m}^2 \cdot \text{k}$.

Side doors for passenger saloon are double-leaf electrically operated sliding doors. Side doors for cab are single leaf manual sliding door. Door layout is given as below:

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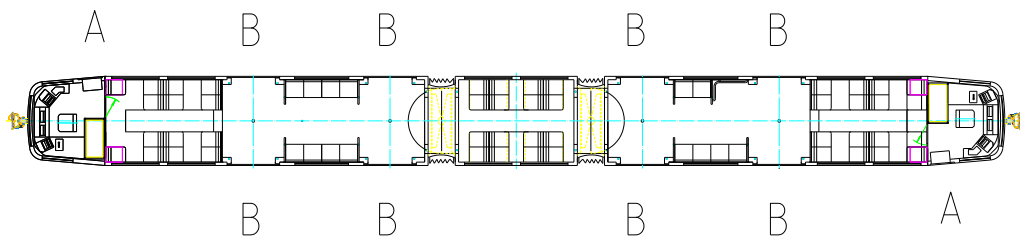


Fig 4.5: Door layout

Door dimension:

Clear height 1900 mm

Clear width 1300 mm

Lighting: Vehicle lighting system includes lighting inside the vehicle, side lamp, headlight, taillight and direction signal light.

Lighting inside the car:

- Fluorescent lamp band is adopted as interior lighting for cars. Lamp tubes should be fluorescent and 36W (DC24V) and 18W (DC24V). Lamp band layout inside passenger saloon is given in figure as below.
- Fluorescent lamp is used as emergency light inside the car. Such lamps form lamp band with lamp band inside passenger saloon. Emergency lamps are located at doorway and arranged staggered.
- Lighting for passenger saloons are subject to central control. Emergency lights and lighting for passenger saloon are independently controlled.
- Mean value for lighting intensity at floors nearby seats and 800mm above the floor should not be less than 200 lux. Minimum value should not be less than 150 lux (without any illumination available outside car)
- Emergency lighting: In case of interruption of normal power supply, emergency lighting should be available with illumination ≥ 10 lx.
- Lighting system should be capable of withstanding vehicle acceleration and vibration.
- Ceiling lamps should be installed in the cab.

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- Instrument lights should be made available at driver console. For normal operation, illumination at central floor inside the cab should be 3~5 lux. Illumination level at driver console should be 5~10 lux. In addition, lighting units with high intensity should be provided to accommodate indoor equipment inspection and maintenance. Lighting should be arranged to avoid shade projected on driver console, and to prevent reflected light from hurting eyesight of train operator. Illuminance should comply with EN 13272: 2001.

The light system of Addis Ababa LRT train is in operation all days after 17h30 up to 22h.

Occupants: The rated passenger are 286 person in one tramcar (width 64 seats and 6 standing person per m^2). Based on the passenger flow of E.W rout in Addis Ababa LRT is 734,4 thousands person/day. We took E.W line because this line goes through city center, and is one of the most important contacting line between city center and city western parts and city western suburbs.

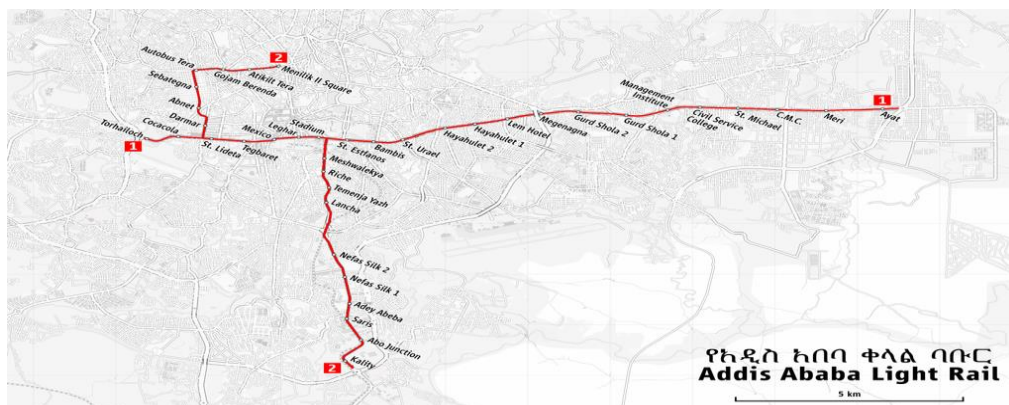


Figure 4.6: Map of Addis Ababa light Rail

The HAP software needs as input data the number of occupants or passenger in the train per hour. Based on my observation and estimation per percentage after used the train all hour per day (5h to 22h) during one months and interviewing passengers, the number of passenger per hour is as follows.

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Table 4.3.Number of passenger per hour at Works days

Hours (h)	Number of LRT passengers in percentage (%)
5h	30 %
6h	50 %
7h	100 %
8h	100 %
9h	80 %
10h	80 %
11h	80 %
12h	80 %
13h	80 %
14h	70 %
15h	80 %
16h	100 %
17h	100 %
18h	100 %
19h	100 %
21h	60 %
22h	10 %

Passenger flow is not same for work days and holidays, for holidays the most of passengers are using the train after 10h.

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Table 4.4: Number of passengers per hour at Sunday / holiday's

Hours (h)	Number of LRT passengers in percentage (%)
5h	5 %
6h	5 %
7h	10 %
8h	10 %
9h	30 %
10h	40%
11h	50 %
12h	50 %
13h	50 %
14h	50%
15h	70%
16h	80 %
17h	100 %
18h	100 %
19h	100 %
21h	30 %
22h	10 %

Spaces: after entering those data in HAP program, it will look like as follows:

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Space Input Data																
train rami ramex	05/28/2017 12:33PM															
Coach																
1. General Details:																
Floor Area	75.6 m ²															
Avg. Ceiling Height	3.0 m															
Building Weight	151.4 kg/m ²															
1.1. OA Ventilation Requirements:																
Space Usage	User-Defined															
OA Requirement 1	2.5 L/s/person															
OA Requirement 2	0.00 L/(s·m ²)															
Space Usage Defaults	ASHRAE Standard 62.1-2007															
2. Internals:																
2.1. Overhead Lighting:																
Fixture Type	Recessed (Unvented)															
Wattage	10.00 W/m ²															
Ballast Multiplier	1.00															
Schedule	Office															
2.2. Task Lighting:																
Wattage	0.00 W/m ²															
Schedule	None															
2.3. Electrical Equipment:																
Wattage	0.0 Watts															
Schedule	None															
3. Walls, Windows, Doors:																
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th>Exp.</th> <th>Wall Gross Area (m²)</th> <th>Window1 Qty.</th> <th>Window2 Qty.</th> <th>Door 1 Qty.</th> </tr> </thead> <tbody> <tr> <td>E</td> <td style="text-align: center;">85.2</td> <td style="text-align: center;">10</td> <td style="text-align: center;">0</td> <td style="text-align: center;">0</td> </tr> <tr> <td>W</td> <td style="text-align: center;">85.2</td> <td style="text-align: center;">10</td> <td style="text-align: center;">0</td> <td style="text-align: center;">0</td> </tr> </tbody> </table>		Exp.	Wall Gross Area (m ²)	Window1 Qty.	Window2 Qty.	Door 1 Qty.	E	85.2	10	0	0	W	85.2	10	0	0
Exp.	Wall Gross Area (m ²)	Window1 Qty.	Window2 Qty.	Door 1 Qty.												
E	85.2	10	0	0												
W	85.2	10	0	0												
3.1. Construction Types for Exposure E																
Wall Type	Wall1															
1st Window Type	Window1															

4. Roofs, Skylights:											
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th>Exp.</th> <th>Roof Gross Area (m²)</th> <th>Roof Slope (deg.)</th> <th>Skylight Qty.</th> </tr> </thead> <tbody> <tr> <td>H</td> <td style="text-align: center;">75.6</td> <td style="text-align: center;">0</td> <td style="text-align: center;">0</td> </tr> </tbody> </table>				Exp.	Roof Gross Area (m ²)	Roof Slope (deg.)	Skylight Qty.	H	75.6	0	0
Exp.	Roof Gross Area (m ²)	Roof Slope (deg.)	Skylight Qty.								
H	75.6	0	0								
4.1. Construction Types for Exposure H											
Roof Type											
5. Infiltration:											
Design Cooling	0.50	ACH									
Design Heating	0.00	L/s									
Energy Analysis	0.00	L/s									
Infiltration occurs at all hours.											
6. Floors:											
Type	Floor Above Unconditioned Space										
Floor Area	75.6	m ²									
Total Floor U-Value	0.568	W/(m ² ·K)									
Unconditioned Space Max Temp.	26.0	°C									
Ambient at Space Max Temp.	28.0	°C									
Unconditioned Space Min Temp.	10.0	°C									
Ambient at Space Min Temp.	6.0	°C									
7. Partitions:											
7.1. 1st Partition Details:											
Partition Type	Wall Partition	Area	183.5 m ²								
		U-Value	2.839 W/(m ² ·K)								

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Space Input Data	
train rami ramex	05/28/2017 12:33PM
Uncondit. Space Max Temp	26.0 °C
Ambient at Space Max Temp	28.5 °C
Uncondit. Space Min Temp	10.0 °C
Ambient at Space Min Temp	6.0 °C
7.2. 2nd Partition Details:	
(No partition data).	

Fig 4.7: space input Data for train

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4.2.2.3 Air System Data

The air system used in this case is Package Rooftop Units. The analysis will be done when the air system is constant air volume (CAV) and when it is variable air volume (VAV). The energy analysis is done for a single coach or passenger saloon then it will be applied to many coaches having the same condition.

All data will be entered in to HAP software and indeed next step is to generate simulation reports.

There are two type of HVAC air system:

➤ *Constant Air Volume (CAV)*

Ventilation with constant air flow. This type of ventilation system is characterized by one or two manual operations (e.g. ON/OFF), chronological management or control of supply/extract temperature.

➤ *Variable Air Volume (VAV)*

In this case the control is managed in a manual or continuous mode with prefixed models or time steps. A variable air volume system with automatic control based on the real need, that automatically adapts the supply air temperature, and supply airflow to keep the target conditions inside a building is defined as **demand controlled ventilation (DCV)**. In other words, a DCV system is designed with the aim of supply a quantity of fresh air fitted with the need in every situation, ensuring the right quantity of fresh airflow and right environmental conditions. Carbon dioxide is one of parameters that could control a DCV system and can accurately describe the quantity of occupants in a building or the pollution emitted by new furniture or manufacturing inside a building. This solution ensures that there is always the right indoor air quality.

4.2.3. Use HAP to Generate Design Reports

The design reports includes system sizing summary, zone sizing summary, system load summary, zone load summary, space load summary, hourly system and zone loads and system psychometrics for the train. We generate two design reports after changing the number of passenger (design capacity and overload capacity).

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Seating capacity is given in following table:

Table 4.5 : seating and standing capacity

Number of passengers (persons)	Seated	Standing	Total
Seats (AW ₁)	65	0	65
Seating capacity (AW ₂) (standing: 6 persons/m ²)	65	189	254
Overload capacity (AW ₃)(standing: 8 persons/m ²)	65	252	317

In this part, the cooling load and outdoor air of the two generated design reports will be compared.

4.2.3.1 Design reports for design (normal) capacity

Air System Sizing Summary for RPGU			
Project Name: train Prepared by: rami ramex		06/01/2017 12:55AM	
Air System Information			
Air System Name	RPGU	Number of zones	1
Equipment Class	PKG ROOF	Floor Area	75.6 m ²
Air System Type	SZCAV	Location	Addis Ababa, Ethiopia
Sizing Calculation Information			
Calculation Months	Jan to Dec	Zone L/s Sizing	Sum of space airflow rates
Sizing Data	Calculated	Space L/s Sizing	Individual peak space loads
Central Cooling Coil Sizing Data			
Total coil load	50.7 kW	Load occurs at	May 1700
Sensible coil load	29.7 kW	OA DB / WB	26.7 / 20.2 °C
Coil L/s at May 1700	3540 L/s	Entering DB / WB	25.0 / 19.5 °C
Max block L/s	3540 L/s	Leaving DB / WB	15.6 / 15.1 °C
Sum of peak zone L/s	3540 L/s	Coil ADP	14.6 °C
Sensible heat ratio	0.586	Bypass Factor	0.100
m ² /kW	1.5	Resulting RH	64 %
W/m ²	670.4	Design supply temp.	14.4 °C
Water flow@ 5.6 °K rise	N/A	Zone T-stat Check	1 of 1 OK
		Max zone temperature deviation	0.0 °K
Central Heating Coil Sizing Data			
Max coil load	21.1 kW	Load occurs at	Des Htg
Coil L/s at Des Htg	3540 L/s	W/m ²	279.6
Max coil L/s	3540 L/s	Ent. DB / Lvg DB	18.1 / 24.8 °C
Water flow@ 11.1 °K drop	N/A		
Supply Fan Sizing Data			
Actual max L/s	3540 L/s	Fan motor BHP	0.00 BHP
Standard L/s	2626 L/s	Fan motor kW	0.00 kW
Actual max L/(s·m ²)	46.83 L/(s·m ²)	Fan static	0 Pa
Outdoor Ventilation Air Data			
Design airflow L/s	635 L/s	L/s/person	2.50 L/s/person
L/(s·m ²)	8.40 L/(s·m ²)		

Fig 4.8: air system sizing summary on normal load

Reducing energy consumption of ADDIS ABABA LIGHT RAIL TRAIN by using co2 -controlled ventilation for Air-condition

4.2.3.2 Design reports for overload capacity

Air System Sizing Summary for RPGU			
Project Name: train Prepared by: rami ramex		06/01/2017 01:18AM	
Air System Information			
Air System Name	RPGU	Number of zones	1
Equipment Class	PKG ROOF	Floor Area	75.6 m ²
Air System Type	SZCAV	Location	Addis Ababa, Ethiopia
Sizing Calculation Information			
Calculation Months	Jan to Dec	Zone L/s Sizing	Sum of space airflow rates
Sizing Data	Calculated	Space L/s Sizing	Individual peak space loads
Central Cooling Coil Sizing Data			
Total coil load	61.7 kW	Load occurs at	May 1600
Sensible coil load	34.7 kW	OA DB / WB	27.9 / 20.9 °C
Coil L/s at May 1600	4068 L/s	Entering DB / WB	25.1 / 19.7 °C
Max block L/s	4068 L/s	Leaving DB / WB	15.6 / 15.1 °C
Sum of peak zone L/s	4068 L/s	Coil ADP	14.5 °C
Sensible heat ratio	0.563	Bypass Factor	0.100
m ² /kW	1.2	Resulting RH	66 %
W/m ²	816.1	Design supply temp.	14.4 °C
Water flow@ 5.6 °K rise	N/A	Zone T-stat Check	1 of 1 OK
		Max zone temperature deviation	0.0 °K
Central Heating Coil Sizing Data			
Max coil load	23.1 kW	Load occurs at	Des Htg
Coil L/s at Des Htg	4068 L/s	W/m ²	305.6
Max coil L/s	4068 L/s	Ent. DB / Lvg DB	17.8 / 24.2 °C
Water flow@ 11.1 °K drop	N/A		
Supply Fan Sizing Data			
Actual max L/s	4068 L/s	Fan motor BHP	0.00 BHP
Standard L/s	3017 L/s	Fan motor kW	0.00 kW
Actual max L/(s-m ²)	53.81 L/(s-m ²)	Fan static	0 Pa
Outdoor Ventilation Air Data			
Design airflow/L/s	793 L/s	L/s/person	2.50 L/s/person
L/(s-m ²)	10.48 L/(s-m ²)		

Fig 4.9: air system sizing summary for RPGU on overload

4.2.3.3 Conclusion

After compare the two design reports to AALRT air-condition design based on:

- ✓ Cooling load
- ✓ Design airflow

It is concluded that AALRT air-condition is suitable when the train is on design capacity (254 passenger). At over load capacity, the train demands more cooling load and air flow and the air flow is insufficient.

As the objective of this paper is to optimize the AALRT air-condition energy and showing the benefit VAV which is controlled by CO₂ sensor, in the next chapter the energy simulation report of VAV which is controlled by CO₂ sensor and CAV will be compared and discussed.

CHAPTER 5

Result and Discussion

5.1. Result

5.1.1. Train simulation report

5.1.1.1. CAV system

The results of building simulation when the system is CAV (constant air volume) are as follows:

✓ **Annual Energy Consumption**

Table 5.1: Annual energy consumption

Component	train locomotive
HVAC Components	
Electric (kWh)	33,322
Non-HVAC Components	
Electric (kWh)	4,691
Totals	
Electric (kWh)	38,013

After running the simulation with the HAP software, the Annual energy consumption is summarized in the above table. CAV system which is the conventional system consumes 38,013 kwh annually. This amount of energy consumption concluded from CAV scenarios will be compared with VAV system one.

Reducing energy consumption of ADDIS ABABA LIGHT RAIL TRAIN by using co2 -controlled ventilation for Air-condition

Table 5.2: Annual energy cost

Component	Annual Cost (\$/yr)	(\$/m ²)	Percent of Total (%)
HVAC Components			
Electric	836	11.054	87.7
HVAC Sub-Total	836	11.054	87.7
Non-HVAC Components			
Electric	118	1.556	12.3
Non-HVAC Sub-Total	118	1.556	12.3
Grand Total	953	12.610	100.0

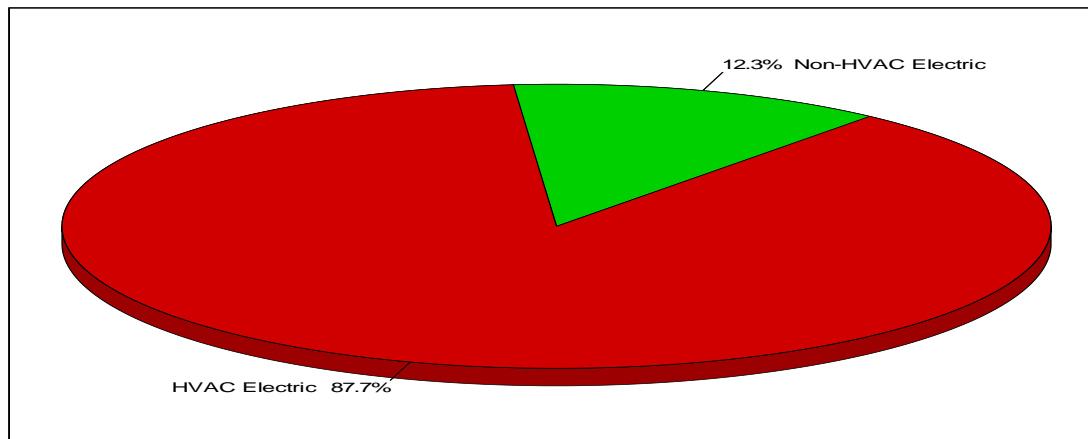


Fig 5.1: percentage total

Reducing energy consumption of ADDIS ABABA LIGHT RAIL TRAIN by using co2 -controlled ventilation for Air-condition

✓ Monthly energy cost

Table 5.3: HVAC Costs

Month	Electric (\$)
January	75
February	67
March	71
April	66
May	70
June	66
July	62
August	64
September	68
October	71
November	76
December	80
Total	836

**Reducing energy consumption of ADDIS ABABA LIGHT RAIL TRAIN by using
co2 -controlled ventilation for Air-condition**

Table 5.4.Non-HVAC cost

Month	Electric (\$)
January	10
February	9
March	10
April	10
May	10
June	10
July	10
August	10
September	10
October	10
November	10
December	10
Total	118

Reducing energy consumption of ADDIS ABABA LIGHT RAIL TRAIN by using co2 -controlled ventilation for Air-condition

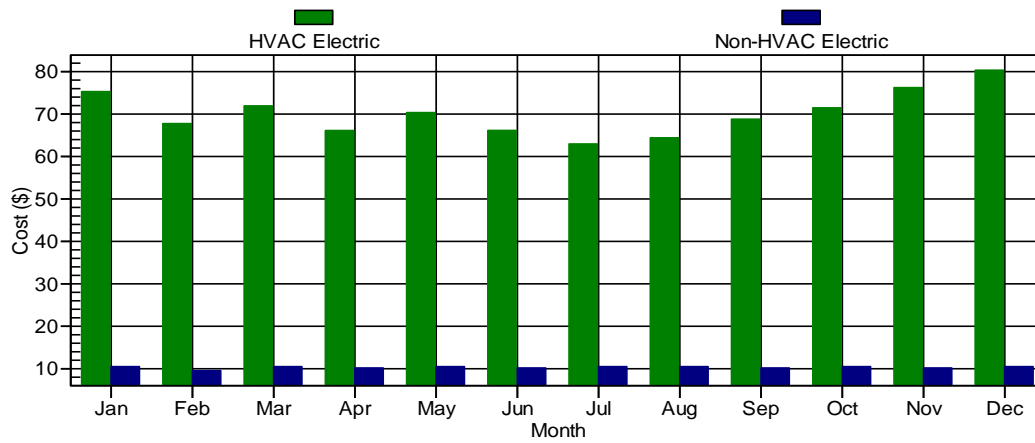


Fig 5.2: Monthly Energy Cost

Even if the cost analysis isn't the scope of this paper, energy evaluation and the economic assessment are always related. The energy cost of this conventional system will clearly compared with VAV system.

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5.1.2. VAV system (controlled by CO₂) result

The results of building simulation when the system is VAV (constant air volume) are as follows:

✓ **Annual Energy Consumption**

Table 5.5: Annual Energy Consumption

Component	train locomotive
HVAC Components	
Electric (kWh)	25,535
Non-HVAC Components	
Electric (kWh)	4,691
Totals	
Electric (kWh)	30,226

This table summarizes the energy consumption of VAV system which is controlled by CO₂. As it is noticeable from the table, this system consumes 30,226 kWh per year in the same train. Compared with the conventional system, this system which is controlled by CO₂ and giving the load based on the number of passenger in the train saves some amount of energy.

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✓ Annual Energy Cost

Table 5.6: Annual Costs

Component	Annual Cost		Percent of Total (%)
	(\$/yr)	(\$/m ²)	
HVAC Components			
Electric	641	8.478	84.5
HVAC Sub-Total	641	8.478	84.5
Non-HVAC Components			
Electric	118	1.557	15.5
Non-HVAC Sub-Total	118	1.557	15.5
Grand Total	759	10.035	100.0

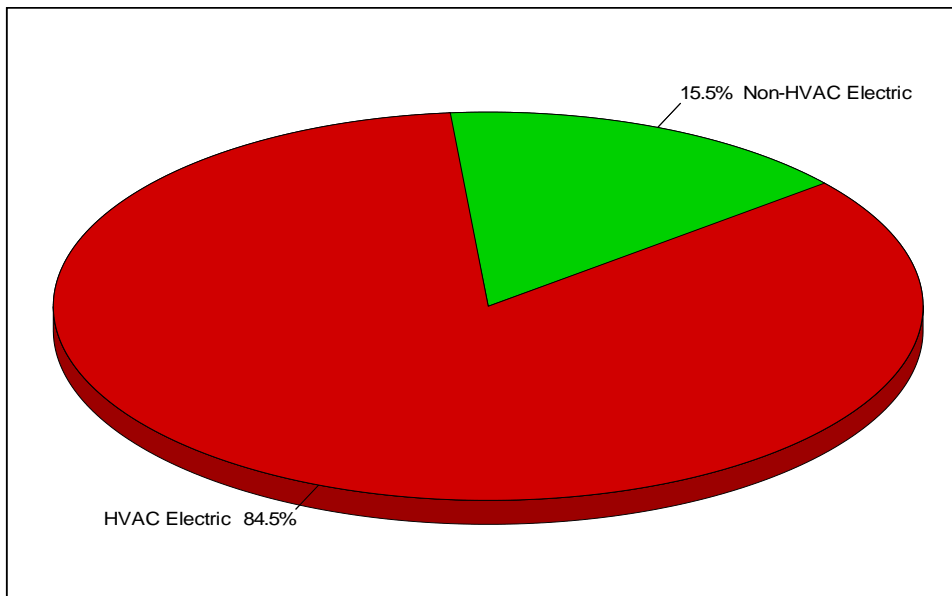


Fig 5.3: percentage of total diagram

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✓ Monthly Energy Cost

Table 5.7: HVAC Costs

Month	Electric (\$)
January	49
February	48
March	61
April	59
May	64
June	54
July	49
August	49
September	53
October	54
November	50
December	51
Total	641

Reducing energy consumption of ADDIS ABABA LIGHT RAIL TRAIN by using co2 -controlled ventilation for Air-condition

Table 5.8.Non-HVAC Costs

Month	Electric (\$)
January	10
February	9
March	10
April	10
May	10
June	10
July	10
August	10
September	10
October	10
November	10
December	10
Total	118

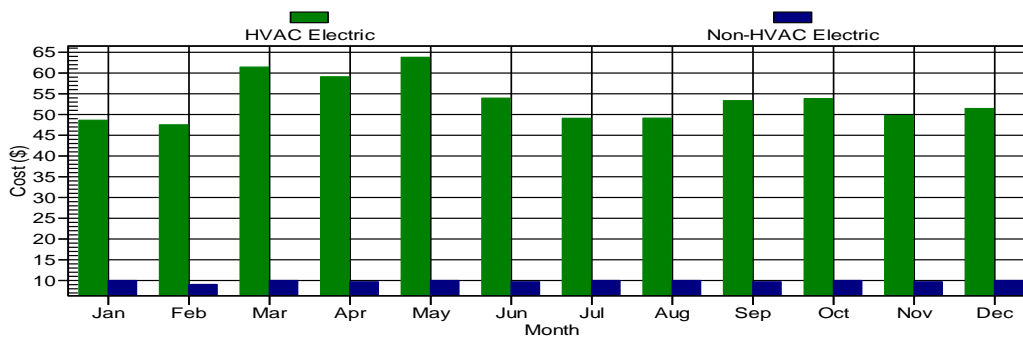


Fig 5.4: Monthly Cost

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Table 5.9. Consumption Totals

Billing Period	Peak (kWh)	Mid-Peak (kWh)	Normal Peak (kWh)	Off-Peak (kWh)	Overall (kWh)
Jan	793	722	412	407	2,335
Feb	799	697	392	364	2,252
Mar	1,047	903	505	392	2,847
Apr	1,028	878	465	369	2,740
May	1,088	952	525	376	2,941
Jun	888	809	443	394	2,535
Jul	804	734	407	408	2,353
Aug	788	718	418	430	2,355
Sep	873	805	436	396	2,510
Oct	898	814	473	358	2,543
Nov	778	747	453	388	2,367
Dec	832	755	446	415	2,448
Totals	10,616	9,535	5,376	4,698	30,226

Saving the energy consumption is not only advantage of this system but also this system is energy cost effective. After the analysis it has concluded that the annual cost of this system is 759 \$/yr.

Reducing energy consumption of ADDIS ABABA LIGHT RAIL TRAIN by using co₂-controlled ventilation for Air-condition

5.2. Discussion

This study shows the importance of employing advanced simulation of HAP software in the comparison of CAV (conventional HVAC) and VAV (which is controlled by CO₂) in a train that otherwise wouldn't be possible to compare with each other's.

CO₂-controlled air condition, when applied in spaces subject to variable or intermittent occupancy (such as our study train) or in space where actual occupancies are below design occupancy, can reduce unnecessary over ventilation while ensuring that target person ventilation are met.

In fact, our train simulation report has shown so far, show that VAV system which is controlled by CO₂, save some amount of energy instead of using CAV in train.

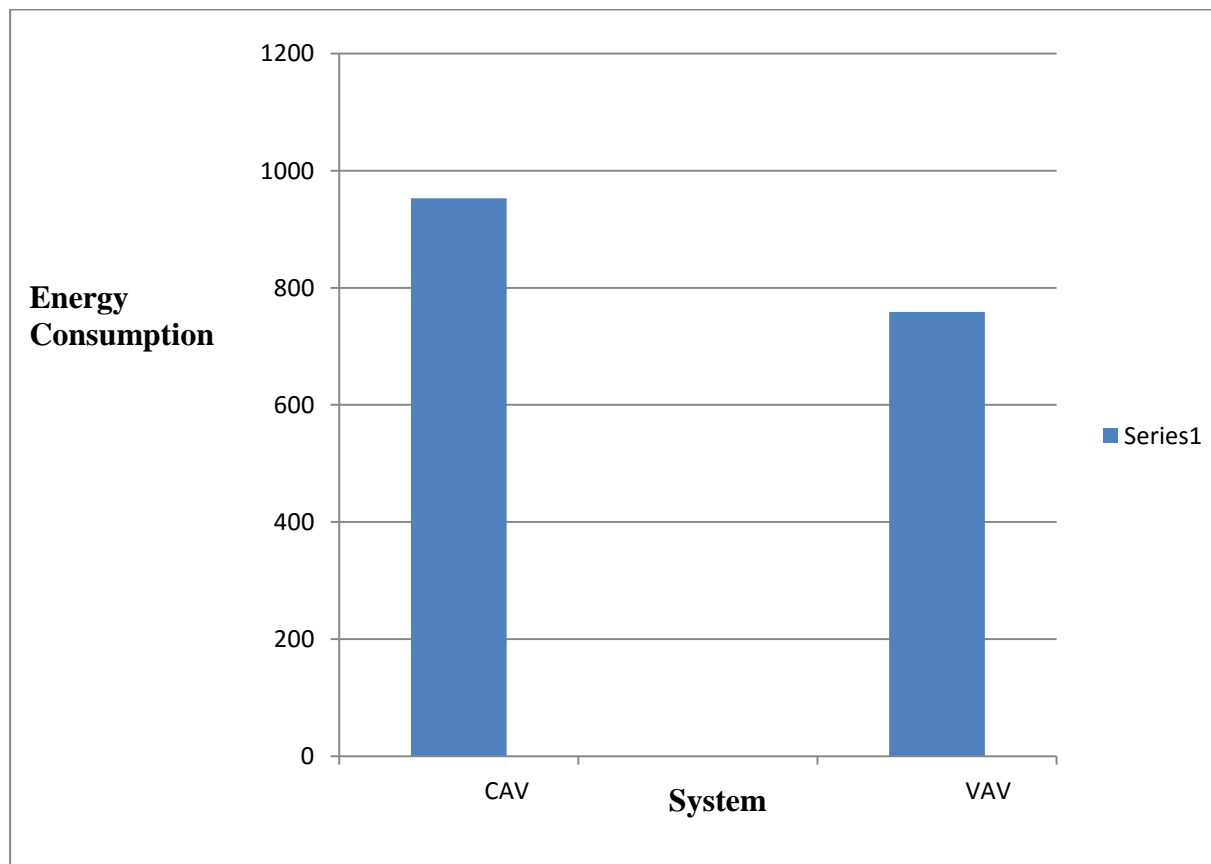


Fig 5.5: Energy consumption diagram

The Energy evaluation, or rather how much energy is employed to reach indoor set points, cannot be separated from an economic assessment that has to evaluate the expense for the purchased energy to reach the purpose. In other words, the aim is to evaluate the operating

Reducing energy consumption of ADDIS ABABA LIGHT RAIL TRAIN by using co₂ -controlled ventilation for Air-condition

cost for choosing VAV system which is controlled by CO₂ instead of CAV system (conventional one).

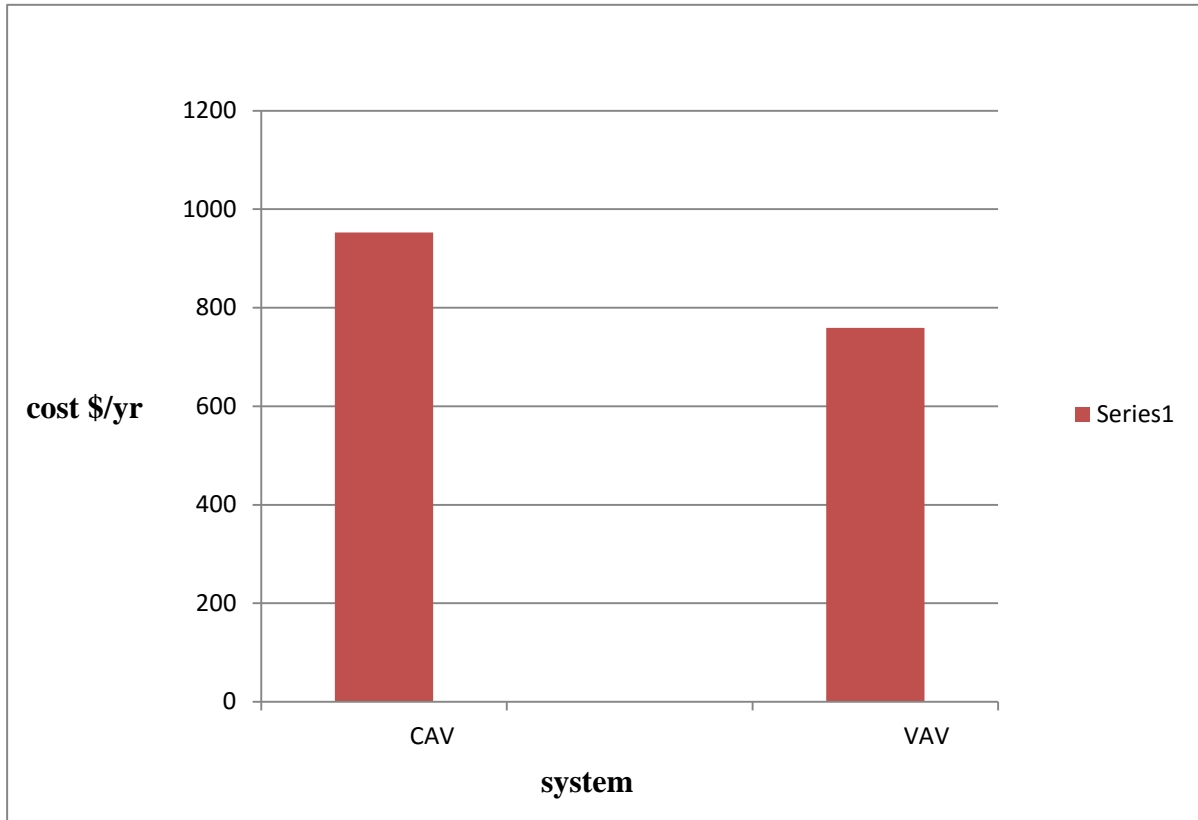


Fig 5.6: annual cost diagram

This study has shown as result that it can be saved logically 8Mwh and 194 \$/yr by VAV which is controlled by CO₂ instead of using CAV in train.

In train, where the numbers of passengers change hour by hour, the air-condition controlled by CO₂ is Energy cost effective.

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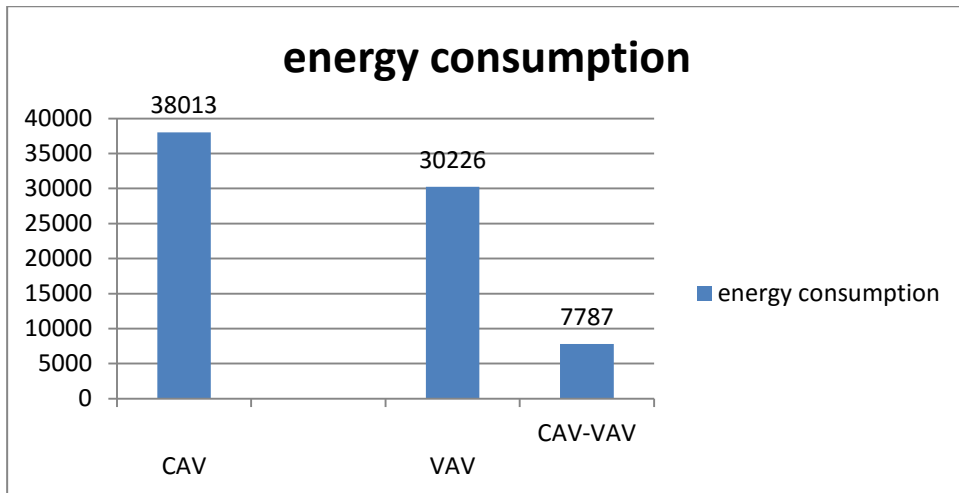


Fig 5.7: Annual Energy consumption save

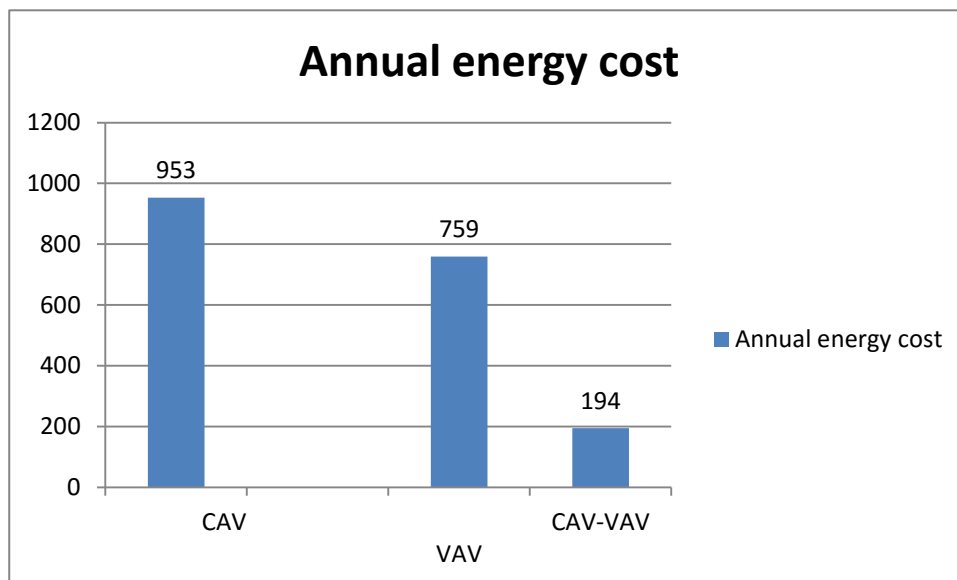


Fig 5.7: Annual energy save cost.

CHAPITRE 6

Conclusion, Recommendation and Future works

6.1 Conclusion

This study showed that air-condition controlled by CO₂ controls the amount of outdoor fresh, depending on the number of passenger in the train. Such system benefits both the train operator and the passengers.

Rooftop package unit controlled by CO₂ is benefit to apply on train, where the passenger occupancies change greatly. This system reduces unnecessary over ventilation while ensuring that target per person ventilation rates is met. It use CO₂ as a control input to modulate ventilation below the maximum total outdoor air intake rate while still maintaining the requested ventilation rate per person.

In practical, this system requires a CO₂-sensor, and this sensor will detect the amount of passenger in the train. The air-condition controlled by CO₂ which has a variable speed fan will be modulated by sensors and will control outdoor fresh based on number of passengers.

The system which is belong our study, is economic and energy efficacy. It reduces electricity requirements when an actual occupancy level is below than the design occupancy level during the demanded periods. It creates also improved indoor air quality by increasing ventilation, when CO₂ level rises to an unacceptable level.

6.2 Recommendation

As it is shown, demonstrated and analysed before, the air-condition controlled by CO₂ is energy cost effective and consume less energy in terms of electric than the conventional one. This paper recommend to AALRT to apply this technology system and absolutely CO₂-sensor which is a very important auxiliary for the system. In fact, the overall cost for implanting DCV has dropped substantially in recent years.

Nowadays, use of CO₂-sensors for demand controlled ventilation has dramatically increased over the past 10 years, which has stimulated a significant drop in sensor pricing. A typical contractor price for CO₂ sensor has dropped approximately 50%. It is likely that this trend in

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price reduction will continue as the use of CO₂-sensors are expanded. CO₂ are now priced below US\$ 200 (compared to over \$ 500 a decades ago). Today's sensors can self-calibrate, so the need far less maintenance than their processors. This paper recommends the cost analysis of this system to be done as future works.

6. 3 Future works

The following are suggested for future works as extension and elaboration of this research:

- ✓ Demonstration of the efficiency of CO₂-operated air condition by experimentation
- ✓ Using Carbon Dioxide Measurements to Determine Occupancy for Ventilation Controls
- ✓ AALRT train HVAC optimization in order to reduce energy consumption
- ✓ Test of DCV in AALRT train
- ✓ Cost- analysis of CO₂-demand control ventilation

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Appendix A

Table: U-value for Window and Glass Materials

Windows with wood or PVC-U frames	U-value W/m²k	windows with metal frames	U-value W/m²k
Single	4.8	Single	5.7
Double	2.8	Double	3.4
Double, low-E glass	2.3	Double, low-E glass	2.8
Double, low-E glass, argon filled	2.1	Double, low-E glass, argon filled	2.6
Triple	2.1	Triple	2.6
Triple, low-E glass	1.7	Triple, low-E glass	2.1
Triple, low-E glass, argon filled	1.6	Triple, low-E glass, argon filled	2.0
Single glazed window with secondary Glazing doors		U-Value W/m²k	
Solid wood door to outside		3.0	
Solid wood door to unheated corridor		1.4	
Triple, low-E glass, argon filled		2.0	

Reducing energy consumption of ADDIS ABABA LIGHT RAIL TRAIN by using co2 -controlled ventilation for Air-condition

Appendix B

Table : outdoor design for different location of Ethiopia for cooling load design

		Location			Annual cumulative frequency of occurrence (%)											
					0.4				1				2.5			
Region	City/Town	Latitude	Longitude	Elevation	DBT (°C)	CWB (°C)	DPT (°C)	MDR	DBT (°C)	CWB (°C)	DPT (°C)	MDR	DBT (°C)	CWB (°C)	DPT (°C)	MDR
Oromia	Adama	08°55'N	38°55'E	2485m	39.9	28.03	21.25	19.71	33.5	23.43	18.25	19.71	32.6	24.54	20.82	19.71
Addis Ababa	Addis Ababa	09°02'N	39°42'E	2355m	29	23.07	20.35	18.46	28.5	22.59	19.81	18.46	28	21.19	17.73	18.46
Benishangul-Gumuz	Assosa	10°04'N	34°32'E	1570m	35	22.86	14.56	22.84	34.5	21.7	14.16	22.84	34	22.94	17.02	22.84
Amhara	Bahirdar	11°37'N	37°10'E	1800m	33	21.48	14.72	23.59	32.6	19.73	11.3	23.59	32.2	21.09	14.52	23.59
Dire Dawa	Dire Dawa	09°35'N	41°45'E	1200m	38.5	25.88	19.8	20.31	38	27.4	22.75	20.31	37.6	25.99	20.53	20.31
Gambella	Gambella	08°15'N	34°34'E	514m	42.5	29.92	24.92	23.50	42	30.08	25.38	23.50	41.5	29.78	25.11	23.50
Somali	Gode	05°57'N	43°27'E	254m	39.6	34.78	33.13	17.89	39.2	33.94	32.1	17.89	38.7	33.33	31.44	17.89
Somali	Jijiga	09°20'N	42°50'E	1609m	32.5	24.12	20.1	26.72	32.2	22.53	17.45	26.72	31.7	23.64	19.72	26.72
Tigray	Mekelle	13°33'N	39°30'E	2084m	30	27.97	27.18	18.95	29.8	27.48	26.57	18.95	29.4	27.28	26.44	18.95
Afar	semera	11°30'N	41°12'E	633m	44.5	28.71	21.81	25.85	44	28.62	21.99	25.85	43.8	31.65	27.1	25.85

Table : Outdoor Design Conditions for Different Locations of Ethiopia

		Location			Annual cumulative frequency of occurrence (%)					
					99.6		99		97.5	
Region	City/Town	Latitude	Longitude	Elevation	DBT (°C)	CWB (°C)	DBT (°C)	CWB (°C)	DBT (°C)	CWB (°C)
Oromia	Adama	08055'N	38055'E	2485m	6	2.52	7.7	5.19	9.4	6.7
Addis Ababa	Addis	09002'N	39042'E	2355m	4.5	0.66	5	1.57	5.6	2.09

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	Ababa	N									
Benishangul-Gumuz	Assosa	10004' N	34032'E	1570m	8.4	4.92	9	5.62	10	5.4	
Amhara	Bahirdar	11037' N	37010'E	1800m	3.5	0.54	4.1	1.33	5	2.77	
Dire Dawa	Dire Dawa	09035' N	41045'E	1200m	11.1	8.14	12	9.32	12.8	9.9	
Gambella	Gambella	08015' N	34034'E	514m	17	14.99	17.5	15.51	18.5	16.3	
Somali	Gode	05057' N	43027'E	254m	17.3	14.11	18.5	14.5	19.6	16.29	
Somali	Jijiga	09020' N	420 50'E	1609m	1	-0.16	2	0.2	3.5	1.84	
Tigray	Mekelle	13033' N	39030'E	2084m	5	2.9	6	3.9	7.3	5.3	
Afar	Semera	11030' N	410 12'E	633m	13.5	11.82	14.5	11.16	15.3	13.38	

Table : Monthly Maximum and Minimum Temperature Values for Different Locations.

Month	Location										
	DBT	Adam a	Addi s Aba ba	Assos a	Bahird ar	Dire Dawa	Gambell a	God e	Jijig a	Mekelle	Semera
January	Max . DBT	30.1	26.6 7	33.28	29.53	31.91	40.90	37.7 0	30.25	26.16	34.62

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	(°C)										
	Min. DBT (°C)	7.61	4.87	9.60	4.55	11.71	17.50	18.1 2	2.91	5.44	14.66
	MD R (°C)	22.45	21.8	23.68	24.98	20.20	23.40	19.5 8	27.34	20.72	19.96
Febr uary	Max . DBT (°C)	32.09	28.1 3	34.07	30.92	34.71	42.20	38.5 3	31.95	27.91	37.13
	Min. DBT (°C)	10.11	6.27	10.93	6.26	12.17	18.60	19.3 2	3.85	6.99	15.86
	MD R (°C)	21.98	21.8 6	23.14	24.66	22.54	23.60	19.2 1	28.11	20.92	21.27
Marc h	Max . DBT (°C)	32.71	28.6 2	34.53	32.16	36.65	43.00	39.2 9	32.44	28.42	40.30
	Min. DBT (°C)	10.92	7.54	11.69	7.66	14.07	19.50	21.4 0	5.72	8.11	16.73
	MD R (°C)	21.79	21.0 8	22.84	24.49	22.58	23.50	17.8 9	26.72	20.31	23.57

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April	Max . DBT (°C)	32.5	28.3 9	33.85	32.39	37.12	42.20	39.3 4	32.14	28.73	41.90
	Min. DBT (°C)	12.42	9.55	13.17	8.80	16.42	21.20	21.6 4	8.60	9.65	18.30
	MD R (°C)	20.08	18.8 4	20.68	23.59	20.70	21.00	17.7 0	23.54	19.08	23.60
May	Max . DBT (°C)	33.38	28.4 6	32.29	31.89	38.17	39.50	36.9 7	31.74	29.66	43.84
	Min. DBT (°C)	13.67	10.0 0	13.22	11.45	17.86	20.90	21.7 0	10.03	11.26	23.60
	MD R (°C)	19.71	18.4 6	19.07	20.44	20.31	18.60	15.2 7	21.71	18.40	20.24
June	Max . DBT (°C)	32.68	27.1 1	28.21	29.99	38.05	38.02	36.4 8	30.93	29.97	45.25
	Min. DBT (°C)	12.99	9.60	14.15	12.06	17.60	19.90	22.6 7	11.98	11.02	22.35
	MD R (°C)	19.69	17.5 1	14.06	17.93	20.45	18.12	13.8 1	18.95	18.95	22.90

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July	Max . DBT (0C)	29.54	24.3 6	26.59	26.67	36.85	36.50	35.5 6	30.36	27.06	45.55
	Min. DBT (0C)	13.81	9.49	13.80	11.87	16.89	20.10	22.1 1	13.56	10.96	19.70
	MD R (0C)	15.73	14.8 7	12.79	14.80	19.96	16.40	13.4 4	16.80	16.10	25.85
Augu st	Max . DBT (0C)	28.47	23.6 1	27.25	26.48	35.84	35.43	36.0 9	30.02	25.52	42.68
	Min. DBT (0C)	13.61	9.54	13.70	12.01	16.92	19.30	22.0 4	12.78	11.10	18.48
	MD R (0C)	14.86	14.0 7	13.55	14.46	18.92	16.13	14.0 4	17.24	14.42	24.20
Septe mber	Max . DBT (0C)	29.46	24.2 44	27.74	26.92	35.69	36.07	37.1 6	30.58	26.36	42.93
	Min. DBT (0C)	12.29	8.92	13.70	11.07	16.64	20.30	22.4 6	11.03	9.20	19.80
	MD R (0C)	17.17	15.3 22 2	14.04	15.85	19.04	15.77	14.7 0	19.55	17.16	23.13
Otber	Max . DBT (0C)	29.7	25.8	28.77	27.95	35.53	37.67	37.3	30.09	26.19	40.25

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	DBT (0C)							6			
	Min.	9.83	6.92	11.80	9.85	14.63	20.30	21.1 8	5.83	7.02	18.20

	DB T (⁰ C)										
	MD R (⁰ C)	19.87	18.877 8	16.9 7	18.10	20.90	17.37	16.1 8	24.26	19.17	22.05
Novembe r	Max . DB T (⁰ C)	29.22	25.19	30.0 3	28.53	33.84	38.33	36.5 1	29.88	25.40	37.65
	Min. DB T (⁰ C)	9.31	4.26	9.98	5.27	12.44	18.17	18.6 0	3.11	6.99	17.20
	MD R (⁰ C)	19.91	20.93	20.0 5	23.26	21.40	20.17	17.9 1	26.76	18.41	20.45
Decembe r	Max . DB T (⁰ C)	28.7	25.7	31.2 5	28.59	31.78	38.73	36.7 8	30.26	25.23	35.20

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	Min. DB T (°C)	8.02	5.37	9.26	4.44	12.2 1	17.63	18.4 0	2.84	5.76	17.20
	MD R (°C)	20.68	20.333 3	21.9 9	24.14	19.56	21.10	18.3 8	27.42	19.46	18.00
Annual	Max . DB T (°C)	33.38	28.5	34.5 3	32.39	38.17	43.00	39.2 9	32.44	29.97	45.55
	Min. DB T (°C)	13.67	10.00	11.6 9	8.80	17.86	19.50	21.4 0	5.72	11.02	19.70
	MD R (°C)	19.71	18.46	22.8 4	23.59	20.31	23.50	17.8 9	26.72	18.95	25.85