DYNAMIC COOLING LOAD ANALYSIS ON INDOOR THERMAL COMFORT STATE IN PASSENGER TRAINS

Thusantha Palangasinghe Kodituwakku

(158284G)

Dissertation submitted in partial fulfillment of the requirements for the degree

Master of Engineering in Energy Technology

Department of Mechanical Engineering

University of Moratuwa

Sri Lanka

March 2020

DECLARATION

Declaration by the candidate

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: …………………….. Date: …………………….

Name of the candidate: T.P.Kodituwakku
Reg.No : 158284G

Declaration of the supervisors

The above candidate has carried out research for the Master of Engineering in Energy Technology and the Dissertation under my supervision.

Signature of the supervisor: ……………………… Date: …………………...

Dr. M. M. I. D. Manthilake,
Senior Lecturer,
Department of Mechanical Engineering,
University of Moratuwa

ACKNOWLEDGMENT

I would like to offer my deepest gratitude to, Prof. R. A. Attalage, Professor in Mechanical Engineering & Dr. M. M. I. D. Manthilake, Seiner lecturer of the Department of Mechanical Engineering, University of Moratuwa, for their professional guidance, valuable suggestions, encouragement and the support given as supervisors from initial to the final level of the thesis, enabled me to develop an understanding of the subject.

Also, I am heartily thankful to the course coordinator of the Energy Master Programme Dr. H. K. Punchihewa, for his continuous guidance, valuable reviews and encouragement given to complete this work. Beside I would like to thank all the lecturers and the staff members of Energy Group of Department of Mechanical Engineering University of Moratuwa by giving the encouragement, criticism and continuous support for successfully completing this study.

Specially, I am extremely grateful to the persons supported by filling questionnaire during the study and to the Staff of Sri Lanka Railway Department & Department of Meteorology of Sri Lanka who have given support for collecting data.

I acknowledge the continuous support and encouragement given by my colleagues and I also thank my wife for her patience and understanding with my overwhelmingly busy schedule.

ABSTRACT

Increasing passenger density makes indoor state of train compartments not thermally comfortable. Air conditioned train compartments have been introduced to provide comfortable pleasant interior environment to the passengers. However the trains consume in a high share of electricity for thermal comfort purposes thereby reducing their fuel economy and increasing emissions. Before adopting more air conditioned train compartments to the railway system, it is necessary to understand indoor thermal comfort state expected by passengers and the energy saving potential. This study discusses the acceptable indoor thermal comfort conditions and the variation in cooling load due to fluctuation of outdoor ambient conditions in moving train compartments. It was based on the Fangers thermal comfort model and a mathematical model was built to simulate this dynamic cooling load. Indoor thermal comfort parameters were examined by surveying of passengers travelled in air conditioned trains. The survey was conducted in trains run through the Colombo-Badulla main line and the northern line in Sri Lanka by interviewing 186 numbers of passengers using standard questionnaire. As independent variables, it was considered three main indoor thermal comfort parameters: temperature, relative humidity and air velocity. Analyzing the survey data using descriptive method, a comfort zone on psychometric chart was defined and accordingly indoor temperature and relative humidity of 26˚C & 55%RH were obtained as appropriate indoor thermal comfort parameters for railway passengers in Sri Lanka. On the other hand, energy saving potential was estimated through simulating dynamic cooling load values for the selected stations in both railway lines considered. Significant differences in dynamic cooling loads of train compartment were found between different stations and between different periods of time. The steady cooling load calculated according to the usual standard method was comparatively higher than the dynamic cooling load. Application of actual maximum dynamic cooling loads of a moving train compartment has been shown 10.9 kW & 5.9 kW of power reduction in train air condition system for mainline & northern line respectively. Thus the application of dynamic cooling load with reference to the time and space can lead to a significant energy saving in passenger trains.

Keywords: Air-conditioned trains**,** Passenger thermal comfort**,** Dynamic cooling load**,** Energy saving

Table of Contents

LIST OF FIGURES

LIST OF TABLES

STRUCTURE OF THE THESIS

The main body of the study reviews the analyzing of the indoor thermal comfort parameters and variation of dynamic cooling load in moving passenger train compartments. Mainly most effective indoor thermal comfort parameters in passenger trains were investigated and factors influencing the variation of dynamic cooling load in moving train compartments were discussed in deep. This thesis began with an abstract which briefs the total story of the research study. The chapter one is the introduction of the thesis. It reviews the background of the research area of focus, overview and current status of the situation, motives for the study, research problem, aim & objectives, research significance. This chapter describes the conceptual framework of the research and the structure of the model. Chapter two consists with theoretical foundations & empirical results abstract from existing literatures which were mainly based on journal research papers. It presents the research approach and methodology used. All the referred literatures were relevant to the subject area of research focus. The literature review illustrated the expecting research gap which was to be filled.

Chapter three, it also discusses methods of data collection, questionnaire used for the survey of railway passengers, formulation of mathematical model, preparation of collected data for calculation and estimations, and analytical methods to be used. Collection of all the primary and secondary data prepared and presented in this chapter. Chapter four which reviews data analysis & the results is the most important part of this thesis. Thermal comfort zone was defined according to the estimated neutral temperature value and it was extended & validated by the questionnaire survey data. Then the indoor thermal comfort parameters were analyzed and acceptable indoor conditions were determined accordingly. Dynamic cooling load values of the selected stations were estimated using finalized indoor conditions and tabulated outdoor ambient conditions which varied with time and space. Data and calculated values have been examined in logically to obtain the required results. Static steady cooling load values were calculated by using usual standard method with reference to the existing standard data and the hourly maximum outdoor ambient conditions obtained relevant to Colombo area. Data were analyzed using descriptive method and results were statistically analyzed to observe the effect of ambient conditions on train cooling load by application of linear multiple regression method using MS Excel software. Also the trends of conduction cooling load, when using standard steady and dynamic unsteady methods respectively were analyzed and highlighted in plotted graphs.

The chapter five discusses the results and comparatively analyzes the results obtained in previous chapter using tables and plotted graphs. It explains deeply the required thermal comfort conditions and the energy saving potential of air conditioned passenger train compartments. Finally, chapter six covers the summery of key findings, conclusions, recommendations and the policy implications. This chapter summarized the main results of the study. Important findings have been briefed as key findings and conclusions presented the outcomes which achieved the objectives. Several numbers of limitations met during the study mentioned in this chapter. Also three important future works related with the results of this study have been proposed and a summery included at the end of the chapter six. Under the References, all sources of literature used have been listed with descriptions written according to the IEEE standard. At the end of the thesis, the format of the questionnaire used in this study included as an appendix.

Chapter 1

INTRODUCTION

1.1 Background

The railway passenger demand is exceeding the existing train capacity of Sri Lanka Railways due to the increasing urban traffic congestion in roads. Thus trains become one of the most important means of passenger transportation not only for the long distances but also for the Colombo suburb. Increasing passenger density makes indoor condition of train compartments thermally discomfort. Air conditioning units are installed in some train compartments to provide thermally comfortable indoor environment. However previous studies show that the energy consumption of the train with air conditioned compartments is large as almost 70% [***1***] of the total energy in addition to the traction energy, is consumed by the air conditioning units in a train compartments [***1***]. Also higher expectations of individual thermal comfort of passengers limit the energy saving potential of train compartment [***2***]. Significant energy consumption in air conditioned rail passenger compartments negatively influence to develop railway transport system as modern one. Popularizing the public transport systems, a significant saving of national energy and time can be achieved by reducing the number of private vehicles on roads [***1***].

In view of the above Public transportation vehicles present a great energy saving potential for their comfort installations. The cooling demand highly affects the distance range of vehicle. By means of thermal simulation, it is possible to calculate the energy demand of the comfort facilities of these transportation vehicles in detail and to assess different energy efficiency measures. Also it is important to defined an appropriate “comfort zone” on the psychometric chart for delivering acceptable thermal comfort to 70% of the passengers in conditioned space of rail vehicles. This will lead to optimize thermal comfort parameters inside rail compartment minimizing energy consumption without any detrimental impact on passenger thermal comfort. The cooling load significantly effect on the energy consumption of air condition system due to the state of indoor thermal comfort conditions and the fluctuation of outdoor ambient conditions in moving train compartments. In this study, the passenger preferences of indoor thermal comfort parameters and the variation in cooling load in the train compartment are investigated during long distance travel of passenger trains which travel in Main Line (Colombo to Badulla) and Northern Line (Colombo to Jaffna) in Sri Lanka. The results can be useful in further studies, designing, operation & maintenance of rolling stock and controlling air conditioning systems in train compartments for energy consumption & better thermal comfort.

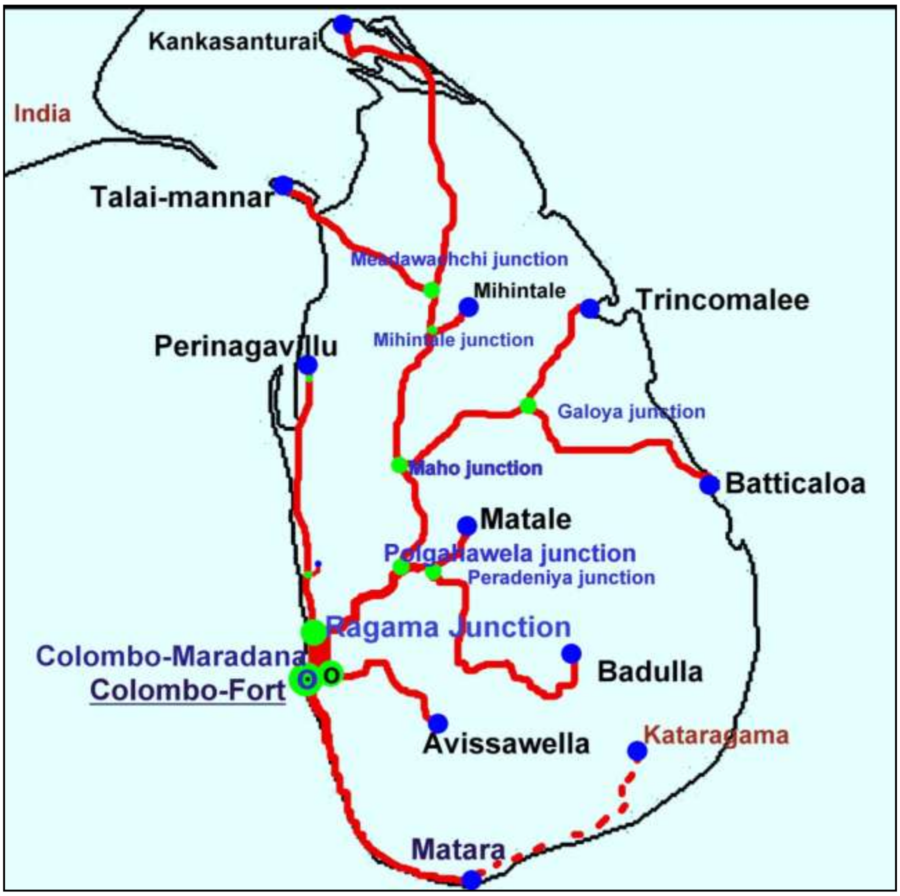

Figure1.1: Sri Lanka Railway Network [3]

1.2 Overview and the current status

Vehicle air conditioning for thermal comfort in passenger cabin is now things of necessity rather than luxury, and cooling is especially needed when travelling in summer or throughout the year in countries of hot and humid climate. The cost of installation of this air conditioning system is generally affordable but the extra weight added and the system operation both course energy consumption to increase. HVAC systems of vehicles have been gradually developed by improving thermal comfort and reducing energy consumption for nearly ninety years by inventors, researchers and industrials. Use of air conditioner reduces fuel economy and increases emissions by considerable amount. Thus vehicle industry has been developed by establishing innovative solutions to improve the quality of thermal comfort of passengers and the urban environment, and to reduce the energy consumption to drive both the compressor air conditioner and the climatic control system together.

Basically air conditioned systems of passenger vehicles discussed under three categories as: private use cars, public use buses and rail vehicles, and private and public use aircrafts. The vehicle HVAC system is intended to provide a comfortable pleasant interior thermal environment to the passengers in all expected external ambient environmental conditions. According to the existing literatures most of researches have been carried out by building up models, simulating the models and calibrating the models up to that of matching simulation results with survey data. The specific factors which influence the energy efficiency of HVAC systems of vehicles are: Heat gain by solar radiation, insulation system of surfaces, variation of outdoor climatic conditions, inhomogeneous air temperature zone inside the vehicle cabin, variation of indoor air velocity, position and angle of air vents, number of air vents, carbon dioxide concentration in air flows, passenger density, clothing and passenger activities etc. Application of advance thermal comfort facilities with improved energy saving measures in public vehicles will positively affected for popularization of public transport sector. Thus further studies are needed for the assessment of energy saving potential of different measures in air conditioned vehicular cabins improving thermal comfort facilities.

Figure1.2: A/C Train compartment considered for the study

Observing increased passenger density, it is highlighted that the public acceptance of air conditioned passenger coaches is increasing. Considering Sri Lankan context, all most all imported cars and vans are consisted with air conditioners. Population of private air conditioned vehicles has been increasing rapidly. There is high demand for the air conditioned intercity road passenger coaches (buses). As a public transport service Sri Lanka Railways have only about 32 numbers of air conditioned passenger compartments up to the end of year 2018 (only 3.5% of total passenger carriages) to fulfill huge demand of rail passengers. All these compartments consist with electrical air conditioning systems which are energized by using separate diesel engine generator unit fixed on under frame or inside end of the same compartment. While most of them are imported factory fitted air conditioned carriages, other few of them have been locally converted from normal carriages to air conditioned carriages. Two types of air conditioning systems are available in existing train compartments as central compact type air conditioners and split type air conditioners. One complete air conditioned intercity train is operated in between Colombo and Jaffna in daily and all tickets for this journey are booked before a month to the date of journey witnessing high passenger demand. There is another air conditioned intercity train service in main line Colombo to Kandy and it is only for weekends. Other than that, all first class rail compartments travel in mainline Colombo to Badulla are consisted with air conditioned carriages. Today in Sri Lanka railway electrification is on debate. Thus requirement of highly demand thermal comfort facilities of rail passenger coaches with energy efficiency improvements are highlighted.

While air conditioning has already been installed in almost all main line rolling stock (with very few exceptions) in developed countries, it still cannot be adapted to the urban and suburban rail transport system in developed countries and under developed countries. However, due to the global climate change and rising passenger expectations of comfort and partly due to the ease of comparison with the passengers' air conditioned private cars, the demand for air conditioned urban and suburban rolling stock can be expected to increase sharply in the near future. This study gives an overview of the current requirement for adding air conditioning system in rail vehicles. In detailed analysis of the comfort parameters and possible ways of improving thermal comfort with energy savings are essential. To success these improvements, combine effort of railway operators, rail vehicle manufacturers, and manufacturers of air conditioning systems to be achieved towards a common goal.

1.3 Justification of the research

This study will be a significant endeavor in promoting useful work. The potential extending building air conditioning to moving air conditioned train compartments which are not well investigated. Thus this research analyzes energy saving potential of train compartments for maintaining indoor thermal comfort parameters which can be accepted by the passengers. Mainly considered indoor conditions are temperature, relative humidity and air velocity because thermal comfort status can be achieved faster through manipulating these three comfort parameters. Furthermore thermal comfort zone for railway passengers can be developed using the data collected by surveying of railway passengers who travel in air conditioned train compartments. This will lead to define more acceptable indoor thermal comfort conditions for air conditioned train compartments in Sri Lanka.

Usually the cooling load of a train compartment is calculated as a steady value under specific ambient condition according to the standard which is the base for building air conditioning. However the cooling load of an air conditioned moving rail compartment is unsteady due to variation of outdoor ambient conditions (Temperature, Humidity, Solar radiation, Velocity & direction of wind, etc.) evidently with space and time. Although it is difficult to estimate the dynamic cooling load directly when train is running, it can be simulated effectively by using approximate mathematical model developed based on theoretical & empirical foundations with reference to the unsteady heat transfer process in an existing air conditioned train compartments considering the thermal storage of train compartment body under variable ambient conditions. The comfort zone established based on the climatic data & questionnaire survey data can be used to determine most acceptable indoor parameters for the moving train compartment in Sri Lanka. Thus it will be possible to evaluate approximate actual cooling load precisely using this fixed indoor parameters and varied outdoor ambient conditions.

1.4 Motives for the study

Today people spent a considerable time in vehicles, Because of their busy schedules in daily life. This is the reason why the thermal comfort and optimization of energy consumption in vehicle HVAC systems have more and more paid attention. Always people try to make comfort in vehicles and in other way the thermal conditions in the cabin of vehicles and passenger compartments directly influence on the safety of drivers and passengers respectively. Nowadays air conditioning system as a basic standard equipment of comfortable thermal climate has been installed in almost all automobiles. Hence most of people prefer private cars as a transport media. The demand for more comfortable and modern vehicular thermal environment has led to promote vehicles thermal control systems. Providing air conditioning in rolling stock in railway which presumably present a great energy saving potential for their comport installations can play a significant role in making public transport a viable alternative to the private car. These energy efficiency improvements will also have great importance in future electric vehicles, since the heating and cooling demand highly affects the distance range of the vehicles by means of thermal simulations. It is possible to calculate the energy demand of the comport facilities of these transportation rail vehicles in detail and to assess different energy efficiency measures.

When considering Sri Lankan context, further studies are needed for the assessment of energy saving potential of different cost effective measures in vehicular HVAC systems used for improving thermal comfort facilities. Also it is important to carry out research studies to defined an appropriate "comport zone" on the psychometric chart for delivering acceptable thermal comfort to the passengers (in this study satisfaction of more than 70% out of total passengers considered) in conditioned space of vehicles. Further analysis of factors influencing energy efficiency improvements in air conditioned vehicles without any detrimental impact on passenger thermal comfort is important. By improving positive significant influential factors and mitigating negative significant influential factors (barriers), energy efficiency of air conditioned trains are to be upgraded. There is no any rail vehicle manufacturing industry in Sri Lanka, However these updated knowledge and data can be applied in modifications of rail passenger compartments, in regular operation and maintenance processes of train HVAC systems, and in preparations of suitable ordering specifications in procurement process of rail passenger compartments, and to converting non-air conditioned passenger compartments into air conditioned passenger compartment using some modifications. Also acceptable indoor thermal comfort parameter values and actual cooling load values of rail passenger compartments are needed to maintain existing railway system in a proper standard. Applications of upgrading passenger thermal comfort and reducing energy consumptions of the HVAC systems in rail vehicles will be positively affected for popularizing public transport systems and promoting future electric train system by benefitting both the passengers and the investors.

1.5 Problem statement

The studies indicate that the usage of vehicle air conditioner reduces fuel economy by about 20% and increases emissions by about 70%-80%. Hence energy efficiency improvements of vehicle air conditioning systems make effect to increase fuel economy and to reduce emissions by considerable amount [*4*]. The railway vehicles consume, in addition to the traction energy, a high share of electricity for thermal comport purposes. About 20% to 40% of the electricity consumed by the rail vehicle is used for heating, ventilation, and air-conditioning (HVAC) [*5*]. Thus it is important to study the possibility of improving the energy efficiency of air conditioned passenger coaches to reduce overall energy consumption without any detrimental impact on passenger comport. In private cars the passengers (occupants) often suffer from the relatively small space, local thermal comfort due to the direct contact between the human body and cold or hot seat surface, thermal radiation in hot summer, large or irregular air movement, cold weather or dry sensation. This situation is similar or too worse in public transport vehicles such as buses and rail vehicle. The thermal environments of bus and rail vehicles which are unpredictable and undetermined differ from private cars due to the following factors: (1) Bigger interior space, (2) Larger glazing area, (2) Open or close the doors at stop and, (4) Higher passenger density. The thermal comfort evaluation could be more complex due to these factors.

Prediction of cooling load in moving passenger compartment is also very complicated due to varying outdoor conditions with time and geographical positions which are changed during the journey. Real estimated values of dynamic cooling load in passenger vehicle compartments are needed in energy efficient design, operation and maintenance stages. Further improvement of energy efficiency & thermal comfort conditions are possible in air-conditioned rail passenger compartments. However it is limited by the increasing passenger density and up grading of thermal comfort conditions according to the real expectations of the passengers in modern competitive society.

1.6 Aim and Objectives

Aim of this research is to improve energy efficiency in air conditioned passenger train compartments without any adverse impact on thermal comfort state.

Mainly objectives are as following;

i. To identify indoor thermal comfort parameters (temperature & relative humidity) applicable to air conditioned passenger trains
i. To justify a mathematical model to predict dynamic cooling load in moving air conditioned train compartments
ii. To analyze variation in actual required cooling load of a moving passenger train compartment
iii. To estimate energy saving potential of air conditioned passenger trains

1.7 Methodology

Research problem has been analyzed considering several dimensions which affect to the problem. Accordingly, three important dimensions were considered in detail are as following; 1) Technical dimension: focusing on technical issues, general technical matters were considered for installing & maintenance of train air conditioning systems; reliability, availability, durability and ease of operation. It was important to find out public interest regarding the existing facilities of air conditioned train compartments, 2) Economic and environmental dimensions: focusing on economic and environmental issues, improvement of indoor thermal comfort parameters and energy saving potential measures were selected considering minimum impact on the air conditioning systems and surrounding environment without doing costly replacements and modifications to the existing train systems, 3) Social and institutional dimension: focusing on social issues, it was more relevant to consider social aspects such as availability, public acceptance and socio cultural effect and psychological impact on passenger behaviours, attitudes and intentions of individual thermal comfort states. In this study, assuming relevant significant factors moving air conditioned rail passenger compartments are investigated for indoor thermal comfort states & cooling load demand. This section provides a description of the data and research setting, variables considered, model selection and estimation process.

1.7.1 Questionnaire survey

Design model is to be applicable to review the process until obtaining the final result. Design and the model depend on the available resource and data. The assessment of moving train compartments can be carried out using quantitative and qualitative data obtained from the existing Rail transport system & Meteorological Department in Sri Lanka. This research was based on the famous Fanger's thermal comfort model and basic heat transfer theories on conduction, convection and radiation effect applicable for moving air conditioned space. Requirement for a passenger to be in thermal neutrality was described and evaluated by two indices: Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) with reference to the ASHRAE 55 & EN ISO 7730 standards. The thermal comfort sensation is assured by the parameters that depend on the heat exchange between the human body and the ambient environment. Thermal comfort parameters were considered as three categories: 1) Personal parameters such as degree of activity, clothing and journey time, 2) Spatial parameters such as radiant temperature, temperature of enclosing spaces, 3) Ventilation parameters such as air temperature, relative humidity, and air speed. According to the effectiveness of selected long running intercity express air conditioned train compartments, only Spatial and ventilation parameters were considered as variables for the study. Important thermal comfort parameters were considered as independent variables which were assumed to be varied independently without correlation among each other while acceptable thermal comfort to the 70% of passengers was considered as the dependent variable.

Validity of the result highly depends on the accuracy of the data. For this research, both primary and secondary data are required. Primary data have been measured (T_i & RH_i) and collected through a questionnaire survey of railway passengers in mainline & northern line. About 200 passengers were participated for the survey. However 186 valid answered questionnaires were considered for further analysis. The survey has been carried out within one year duration (from December 2017 to December 2018) for both railway lines in seven stages within different time frames according to the four different climatic seasons (North-east monsoon and North-east inter-monsoon, South-west monsoon and South-west inter-monsoon) effect to the Sri Lankan context (described in detail under chapter 2 of this thesis) and mainly two different climate seasons globally winter & summer.

Considering most effective three thermal comfort parameters; temperature, relative humidity, and air velocity were detected in the indoor conditioned space of train compartments, during the questionnaire survey. Questionnaire (Appendix) consisted with seven numbers of questions including one likert scale question with seven comfort levels such as Very cold (-3), Cold (-2), Slightly cold (-1), Comfortable (0), Slightly warm (+1), warm (+2), Hot (+3) indicating signs from -3 to +3 according to the sensation of comfort level. According to the majority (70%) of the responses collected from the questionnaire survey, most acceptable indoor thermal comfort parameters can be decided for the use of train compartment in Sri Lanka. These appropriate indoor thermal comfort parameters can be used as constant values for the estimation of dynamic cooling load values in moving train compartments for varying out door ambient conditions with time and locations.

Indoor thermal comfort conditions such as temperature, relative humidity and internal air velocity were measured using proper instruments on the spot during the survey. Also digital indicators screening temperature & relative humidity of any instant were available inside the selected air conditioned train compartments. Outdoor ambient conditions such as monthly mean & hourly maximum temperatures, relative humidity, and solar radiation values have been obtained from existing meteorological data of recent four years (2015, 2016, 2017 & 2018).

Comfort zone; Analytical technique of data analysis consisted with descriptive methods. Comfort zone was defined for indoor thermal comfort parameters of temperature and relative humidity which satisfied more than 70% passengers out of total passengers in sample population of questionnaire survey. Standard method of developing comfort zone on the psychometric chart is by considering neutral temperatures of selected stations as center lines, intercept values and boundaries. Neutral temperatures were calculated by using annual mean dry bulb temperature values of each and every meteorological station. Standard comfort zone can be developed based on average neutral temperature by taking it as center point (described in detail under chapter 2 of this thesis). Developed standard comfort zone on the psychometric chart was extended by using responses of the passengers participated on questionnaire survey. Comfort zone obtained from the mean temperature and relative humidity data was validated with the survey data.

1.7.2 Prediction of cooling loads

The determinants of thermal comfort conditions and total cooling load estimation were based on existing validated measures obtained from existing literatures. According to the realistic situation of rail transport service, geographical locations and climatic conditions in Sri Lanka, the measures were properly modified. A mathematical model has been developed to calculate dynamic cooling load of moving train compartments. Formulation of the mathematical model has been described in detail under chapter 2 of this thesis. This model was built up using theoretical equations based on heat transfer processes such as conduction, convection, radiation and sensible & latent heat associated with train carriage envelop. Dynamic cooling load components considered are: 1) Conduction [$Q_C(t)$], 2) Radiation [$Q_R(t)$], 3) Ventilation[$Q_V(t)$], 4) Infiltration[$Q_I(t)$], 5) Occupancy [$Q_O(t)$], 6) Equipment and lighting [$Q_E(t)$]. Total dynamic cooling load is given by the total summation of these components as: $Q_{Total}(t) = Q_C(t) + Q_R(t) + Q_V(t) + Q_I(t) + Q_O(t) + Q_E(t)$. For each and every components of dynamic cooling load, indoor thermal comfort parameters (temperature and relative humidity) kept constant as acceptable values obtained from analyzing questionnaire survey data.

Two types of secondary data have been collected. They are Meteorological data and Railway data. Climatic data collected from Meteorological department. For recent four years (2015, 2016, 2017 & 2018) hourly maximum temperature values per each month, hourly maximum relative humidity values per each month, monthly mean temperature values and hourly maximum intensity of solar radiation were collected. Dimensions and material properties of the selected train compartment were collected from the Sri Lanka Railway Department.

It was assumed that the heat conduction through the immobile train compartment reached steady at start station in each railway line. Hence corresponding steady temperature distribution in across the train body was taken as the initial condition for the unsteady heat conduction simulation for moving train compartment body. Two dimensional unsteady heat transfer equation is used for the analysis of this unsteady body storage heat transfer process. By simulating these conditions for external and internal surfaces of areas of two sunlit walls, roof and floor, internal surface temperatures with time and space for selected stations can be obtained. The boundary conditions were considered as external surface temperatures of other selected stations calculated using ambient conditions and external surface heat transfer coefficient which varied with relevant train velocity at selected stations at times train passed through them (described in detail under chapter 2 of this thesis).

Radiation, ventilation and infiltration cooling load components relevant to the all selected stations were calculated using solar radiant intensities, ambient temperatures and ambient relative humidity values relevant to the selected stations at the time train travelled through them, obtained with reference to the meteorological data. Occupancy cooling load component was estimated assuming the all available 44 seats filled with 44 numbers of passengers. Cooling load due to the equipment (mainly lighting) which was not varied with the time and space and only depend on the type of train compartment, obtained same estimated value for both the usual static steady method and unsteady dynamic method. Calculating above each and every cooling load components separately for the all selected stations at the times when trains passed through them, total dynamic cooling load values of train compartment at each and every selected stations in both rail lines can be estimated. Thus it can be analysis the variation in cooling load components and the total.

Standard Static steady cooling load value for the selected train compartment was estimated by considering standard method used for building air conditioning on outdoor ambient conditions of Colombo. The mathematical model consists with dynamic cooling load estimation method based on heat transfer theoretical calculations. Total dynamic cooling load can be calculated by adding six type of estimated cooling load component values altogether as a total value. These six components of dynamic cooling load can be estimated separately for each and every selected station (locations) with reference to the arrival times at the same station in both railway lines.

1.7.3 Analysis of the variation in cooling load

Variation of the cooling load according to the different time periods of the day and according to the difference of geographical locations can be obtained for both railway lines considered. Dynamic cooling load values and usual standard static cooling load value were plotted against time at the trains reached in selected stations in charts. Maximum, minimum and mean total values of the cooling loads tabulated for both railway lines, mainline and northern line. It leads to make a comparative analysis among them.

1.7.4 Estimation of energy saving potential

Difference between the estimations of cooling loads by using usual standard steady method and by using unsteady dynamic method can be found from the results. Basically this difference gives the amount of energy saving which can be adjusted in the planning, designing or preparation of technical species at procurement stages. If the cooling load difference is significant, then air conditioned unit of comparatively lower refrigerant capacity can be selected for the train compartment.

Also it can be analyzed the effectiveness of the each and every cooling load components to the total cooling load. Then it will lead to identify more effective and more sensitive cooling load components among conduction, radiation, ventilation, infiltration, occupants and equipment to the total cooling load value. These most effective & sensitive components are considered as determinants of the energy savings in air conditioned train compartments. Controlling these determinants as per the demand, considerable energy savings can be achieved.

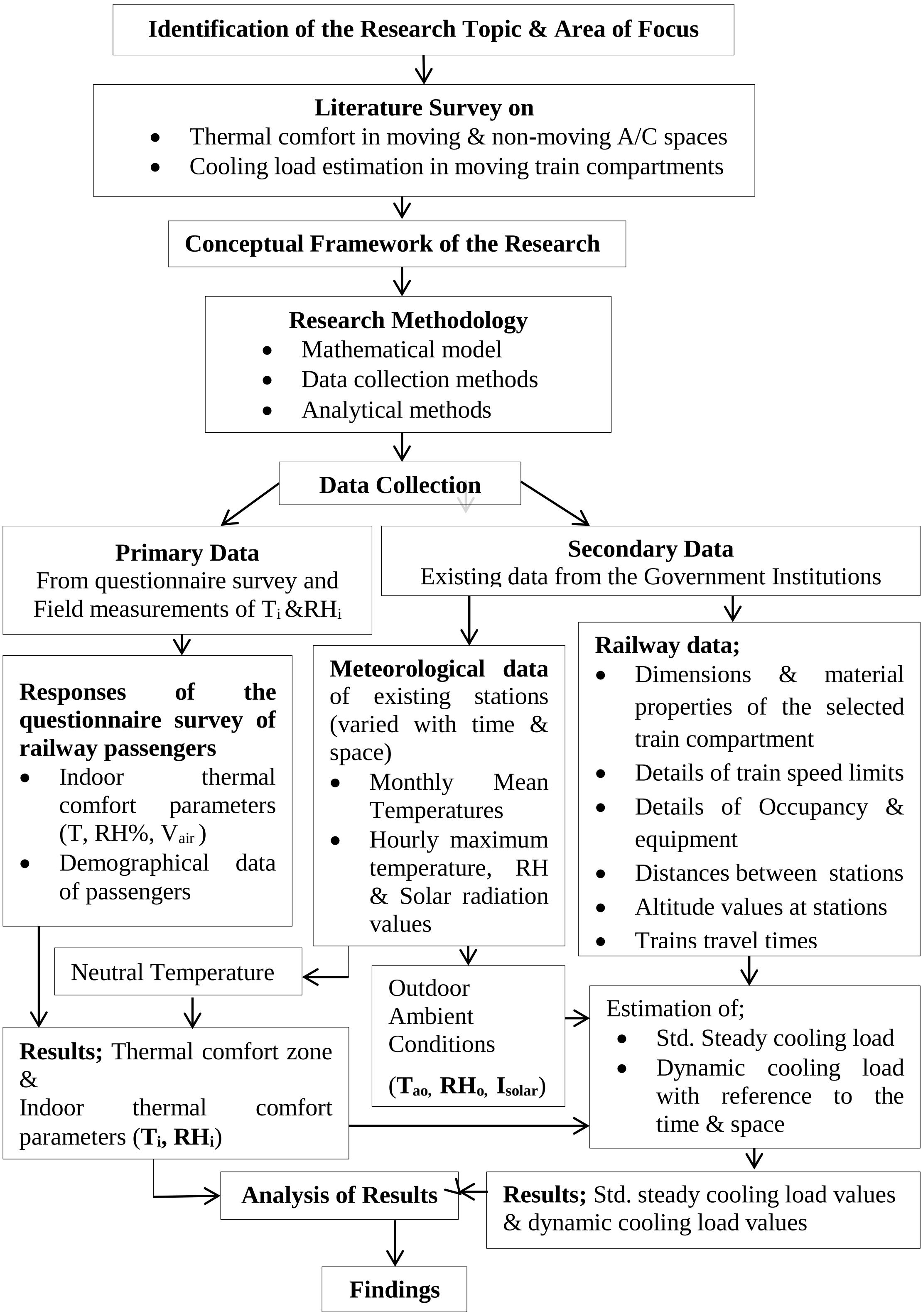

Figure1.3: Research work flow chart

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Theoretical foundations & empirical results relevant to the topic found in existing literatures such as journal research papers, thesis, text books, internet resources, etc. have been reviewed as references to formulate this work within the area of focus. There are plentiful of literatures relevant to the thermal comfort and energy efficiency of air conditioning systems. However the existing literatures regarding the indoor thermal comfort, cooling load analysis and energy efficiency in moving train compartments are rear and very limited. In this case, it was considered only literatures on about the analysis of thermal comfort parameters in indoor vehicular cabin and energy efficiency & the cooling load estimation of vehicular envelop. Specially, it was concerned existing simulation models analyzing of indoor thermal comfort conditions in fixed or moving conditioned spaces & dynamic cooling load in moving vehicle compartments. The conceptual framework of this research based on the Fanger's model of thermal comfort state and basic heat transfer theories applicable to the moving rail compartments.

2.2 Contribution of existing literatures

Most of literatures on energy efficiency of rail vehicles in Europe countries have discussed on heating loads than cooling loads due to the cold climatic status they experienced during almost all time over the year. Few literatures have met on energy efficiency and estimation of cooling load in train compartments in Asian countries. According to the existing literatures more thermally comfort standard air conditioned rail facilities were highlighted in developed countries specially, in Europe as modern public transport systems.

Also as Asian countries Japan, South Korea, China and India have developed their railway systems up to a more comfort, efficient and modern one. Therefore this study given more attention on such literatures found related to the Asian hot climatic statuses which are compatible to the Sri Lankan context. Research gap was identified while searching answers to the research problem, going through the existing literatures. Suggestions have been made to improve indoor thermal comfort and the energy efficiency in train compartment economically without adopting expensive changes to the existing systems, according to the theoretical values of passenger rail carriage envelop.

2.3 Thermal comfort

The main purpose of using air conditioning is to provide better thermal comfort. ASHRAE Standard 55 defined it as the "condition of mind that expresses satisfaction with the thermal environment", though the assessment of thermal comfort is a process of gaining facts through thoughts, experiences and the senses. Also it involves in many inputs which influenced by physical, physiological, psychological and other processes. The fundamental of human thermal comfort are useful in operating air conditioning systems and designing conditioned spaces for the comfort and health of occupants. Generally, comfort feel when body temperatures are held within narrow ranges, skin moisture is in low level and the physiological effort of regulation is in minimum level. Thermal comfort depends on behaviours which control thermal and moisture sensation to reduce discomfort conditions. Changing the condition of clothing, altering activity, changing position or location, changing the thermostat setting, opening or closing windows or doors, leaving space are the most usual behaviour among those met in human life. It has been identified that the temperature which choose for a similar thermal comfort state of clothing, activity, humidity and air velocity by people from different climates, living conditions, cultures throughout the world are very similar.

2.3.1 Energy balance

The thermal interaction of the human body with its environment occurs in order to the balance of energy. Energy balance of human body can be explained as following equation. Total metabolic rate (M) within the body consisted with the metabolic rate required for the person's activity (M_{act}) plus the metabolic level required for shivering (M_{shiv}), if shivering occurs ($M = M_{act} + M_{shiv}$). Portion of energy production of human body used is considered as external work (W). Thus the net heat production (M - W) is release to the environment through the skin surface (q_{sk}) and respiratory tract (q_{res}) as surplus or deficit stored (S) by increasing or decreasing the body temperature ($M – W = q_{sk} + q_{res} + s$).

Heat transfer from the human body to the immediate surrounding by several modes of heat exchange can be described as: sensible heat flow from the skin, latent heat flow from sweat evaporation & from evaporation of moisture diffused through the skin, sensible heat flow during respiration and latent heat flow from evaporation of moisture during respiration. Sensible heat transfer from the skin may be a complex process of mixing conduction, convection and radiation for a person wears cloths. Thus it is the sum of convection and radiation heat transfer at the outer clothing surface or exposed human skin. Sensible and latent heat losses from the skin are expressed in terms of environmental factors, skin temperature (t_{sk}) and skin wettedness (w). Also the thermal insulation and moisture permeability of clothing account for heat losses from the skin. The independent environmental variables which effect for the thermal comfort are described as: air temperature, mean radiant temperature, relative air velocity and ambient water vapour pressure. The independent personal variables influencing thermal comfort are activity level and clothing.

The rate of heat storage in the human body and rate of increase in internal energy are in same value in steady condition. The human body can be considered as two thermal compartments as the skin and the core. The heat storage rate of the body can be considered separately for each compartment in terms of thermal capacity and time rate of change of temperature in each compartment. Several studies have been carried out on the thermal comfort of train compartment and energy saving of train air conditioned system. Most of them are limited to specify steady state thermally homogeneous environment. Few of them are discussed on human response on non-uniform and transient conditions. It is more complicated to analyze human response on unsteady or transient conditions. Usually the indoor thermal state of a moving train compartment is inhomogeneous. The human thermo-regulatory system can be strongly described as a non-linear control system, which is activated by internal heat generation by human activity and external thermal disturbances from the heat and cold environments [*6*]. The control variable is an integrated value of internal temperatures. External thermal disturbances are always detected by thermo-receptors in the skin enabling the thermo- regulatory system to activate on disturbances, before them reach the body core. These thermo- receptors in the skin respond not only to the temperature but also to the rate of change of temperature. This autonomic thermoregulation is control by the hypothalamus with different autonomic control actions as adjustment.

2.3.2 Conditions for thermal comfort

Other than the independent environmental and the personal variables influencing thermal response and comfort secondary factors including non-uniformity of the environment, visual stimulation, age, gender, and outer climate may be affected for the indoor thermal comfort. ASHRAE thermal comfort scale developed for analyzing all these influential factors for thermal comfort state. ASHRAE thermal sensation 7^{th} scale ranged from +3 to -3 are: +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly cool), -2 (cool), and -3 (cold) used to indicate the sensitivity and effectiveness of indoor thermal conditions to the human body.

According to the studies women were more sensitive to temperature and less sensitive to the humidity than the men. However in general a 3K change in temperature or a 3KPa change in water vapour pressure is necessary to change a thermal sensation vote by one unit of temperature category. ASHRAE standard specifies thermal comfort condition or comfort zones where 80% of sedentary or slightly active persons accepted thermal indoor environment. Also ASHRAE standard 55 – 2004 defines comfort zones for 0.5 and 1.0 clo as the people wear different levels of clothing depending on the situation and seasonal weather.

2.4 Practical approach in thermal comfort

Literatures in thermal comfort have been extended up to the present status based on research carried out for more than hundreds of years. Accordingly two broad approaches, Engineering and Architectural applications take part in buildup of thermal comfort assessment criteria in practice. Many researchers have contributed to enhance the data base and standards in thermal comfort. Among them an Engineer named P. O. Fanger made influential contribution to the subject by applying the classical psychophysical quantitative research methodology. He has introduced the predicted mean vote and predicted percentage dissatisfied (PMV- PPD) model which describes the relationship of thermal environment to magnitude of subjective discomfort. This Fanger's model can be identified as a better solution to this complex interconnected problem in human thermal comfort. The requirements of the thermal comfort usages are to be compatible or adjusted with the format of Fanger's solution for perfect results [*7*].

Design and operational performance of a building heating, ventilation and air conditioning (HVAC) system can be defined in PMV-PPD terms with the model of the same. Considering four environmental parameters, this PMV- PPD model has been validated by the results of field studies, as expected by the developers. In view of consumer acceptance, HVAC engineering practitioners have become to think for human factors in comfort research which occurred from climate chambers in early times. The thermal comfort is a discipline most directly used by HVAC engineering. However according to the daily routing activities & behaviours of occupants in indoor climate environment, HVAC practitioners used to response with the field based thermal comfort studies rather than the use of conventional climate chamber experimental methods. Thus ASHRAE have made standards based on the results obtained from the series of thermal comfort studies carried out in various climate contexts around the world by field validating the data [*7*].

Comparing with the methodological benefits in between conventional climate chamber research and the field based alternatives some of difficulties and issues identified. Among them sample size and demographics research design, instrumentation and indoor climate parameter measurement procedures, questionnaires, clothing insulation level and metabolic rate assessment techniques are highlighted as important factors to be analyzed. Other than the above determinants, it has been identified that the concept of environmental psychology which highly influence to the thermal comfort of occupants. Presently, the results of thermal comfort researches are directly used by the practitioners. Useful and acceptable predictions of the optimum temperatures for thermal comfort state of occupants are given by using PMV-PPD model in central air conditioning systems specially that beyond the occupant's control. However according to the requirements of the occupants, the architectural approach and related adaptive thermal comfort standard can be used [7].

2.5 Thermal comfort models

Existing literatures reviewed the popular thermal comfort models for buildings & vehicles, and their capabilities and future perspectives. Most of these models and methods are limited to specific thermally steady state and homogeneous environments while few of them built up for analyzing non-uniform and transient conditions using detail thermo- regulation. Some of these models were based on usual international standards existing for more than a decade. Today, it has been proposed a global approach on thermal comfort by considering the physical reaction of the human body in thermal stress conditions and the model implementation accordingly. The physiological base of thermal comfort has been described by the mainly used models and the standards in practice. Also these studies have been focused on thermal manikin experimental methods and numerical methods such as computational fluid dynamics (CFD) as an approach to the future development in this field.

Methods for predicting the degree of thermal comfort of human exposed to a certain environment have been introduced during the past four decades. Among them the most widely accepted two methods are highlighted. They are Fanger's comfort equation, concept of predicted mean vote (PMV) & predicted percentage dissatisfied (PPD), and J. B. Pierce two node model of human thermoregulation. The Fanger's model is an empirical one which uses to predict a thermal vote on empirical equations of heat transferred between human body and environment and based on several parameters. The results obtained from Fanger's model in laboratory steady – state condition on human subject. After considering the unsteady real practical situation and idea of adaptive model, other models have been introduced. Accordingly, human body can adapt from the physiological, behavioral and psychological bases. The physiological models have been used to simulate the thermoregulatory system of the human body.

2.6 Fanger's model of thermal comfort improved by time

The predicted mean vote (PMV) model of thermal comfort, created by Fanger in the late 1960s, is used worldwide to assess thermal comfort. Fanger based his model for use in invariant environmental conditions in air conditioned spaces in moderate thermal climate zones. Existing support and criticism, as well as modifications to the PMV model are discussed in light of the requirements by environmental engineering practice in 21st century. In order, it has been move from a predicted mean vote to comfort for all. Improved prediction of thermal comfort can be achieved through: improving the validity of the PMV model, better specification of the model's input parameters, accounting for outdoor thermal conditions and special groups. The application range of the PMV model can be enlarged by using the model to assess the effects of the thermal environment on productivity and behaviour, and interactions with other indoor environmental parameters, and use of information and communication technologies. Applying such modifications to evaluation of thermal comfort, thermal comfort for all can only be achieved when occupants have effective control over their own thermal environment.

After almost 40 years of practical experience with the PMV model, the foundation of the model and its use, particularly in air conditioning are growing ever more solid [***8***]. In four decades numerous studies have been conducted on thermal comfort in both field, settings and in climate chambers. These studies have provided valuable insight into the principles on which the PMV model is based on. The neutrality is not necessarily the ideal thermal condition as preferences for non-neutral thermal sensations are common. Also very high PMV values do not necessarily reflect discomfort for a substantial number of persons. The PMV model is applied throughout every type of buildings and other spaces such as vehicle compartments all across the globe and its use is prescribed in thermal comfort standards. It was found that, in natural ventilation, indoor temperature increases significantly in warmer climatic contexts and decreases in colder climate zones. This condition of thermal comfort led to the development of an adaptive comfort model which was expressed by the latest round of standard revisions as an optional method in very restricted conditions.

Improvements can be made by correcting or adjusting the model itself or by introducing methods to increasing the accuracy of the model's input parameters. Although many modifications to the original PMV model have been proposed and test to date, these developments have not yet found widespread application. The accuracy of the PMV model and the quality of its predictions gain in strength when users are able to more precisely determine the model's input parameters, particularly clothing and activity levels. This requires more sophisticated tables and tools for use in daily practice. It should also provide accurate data on the insulation of various type chairs, etc.. The current PMV model is used for assessing and predicting thermal comfort in indoor spaces. However it can be used for other applications going beyond the original scope. Thermal comfort plays major role among other indoor environmental parameters which are not yet fully understood and defined. Also it subject of many studies such as transient thermal conditions.

There is a tendency, influenced by the demand of occupants and energy conservation, to set the general indoor climate in accordance with requirement of the PMV model, while on an individual level, people are equipped to control the direct thermal environment by the development of individualized thermal comfort with the computerized thermal comfort environment. In the near future, the thermal environment may be set in compliance with personal preferences stored in an automated user profile that allows for further personal fine-tuning, energy conservation, and coupling with other indoor environmental parameters.

Fanger's PMV model is more than fifty years old and still used as the number one method for evaluating thermal comfort. Even the incorporation of an adaptive model in AHSRAE standard 55 did little harm to the status of the PMV model, as it is still recognized as valid for all type of air conditioned spaces. The quality of the outcomes of the PMV model is as good as that of its input parameters of the comfort equation make PMV an index with great potential for the computerized 21st century in which occupants have increased demands regarding the indoor environment. By considering the means for individual control, Engineers should be able to create indoor environment that provide nearly 100% acceptability and comfort to all, based on the Fanger's method [***8***].

2.7 Effect of variation in relative humidity & temperature on indoor thermal comfort in trains

Temperature and relative humidity (RH%) can be identified as most influential factors which are varied with transient condition of indoor environment, on thermal comfort. The existing literatures discus the effect of controlling relative humidity levels on thermal comfort of passengers. One of the previous studies has investigated the effect of relative humidity and temperature control on in cabin thermal comfort of trains [***9***]. Three different techniques were used to investigate the effect: (1) Thermodynamic and psychometric analysis were used to integrate the influence of change in RH% levels along with the dry bulb temperature on indoor passenger thermal comfort. Effect on heat removal from indoor space of train compartment & occupant's comfort zone by controlling relative humidity levels has been analyzed. The results specify the practical system design consisted with evaporative cooler, (2) Numerical simulations such as 3-D finite difference method are used to predict the effect of relative humidity on the thermal sensation. The Fanger and Berkeley models were used to analyze the occupant's thermal comfort using following four specific approaches: The effect on other environmental conditions, The effect on the temperature of the human body segments in cabin, the cabin local sensation and local comfort for different body segments other than the overall sensation and overall comfort, Measuring the human sensation using the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD) indices for different climate seasons (summer and winter) as per the Fanger's model. (3) Using a set of designed experiments including thermography measurements, vehicular thermal comfort parameters were analyzed [***9***].

2.7.1 Advantage of controlling relative humidity on thermal comfort

To accurately assess the transient and steady state temperature distributions at the test vehicle cabins, the experiments occurred at a full size climate chamber hosting test vehicles. According to the result of empirical and numerical methods, controlling RH% levels along with dry bulb temperature of indoor space lead to achieve thermal comfort state quicker than that of controlling only dry bulb temperature without changing RH% levels. Thus the indoor thermal comfort and the efficiency of the air conditioning systems in trains can be improved by reducing amount of heat removal, controlling relative humidity and dry bulb temperature [***9***].

Previous studies reviewed the development of passenger thermal comfort zone for different climatic seasons by using thermal comfort models based on sensitivity analysis. These studies described the difficulties met in predicting thermal comfort for inside of mobile compartments compared with that of condition in static spaces such as buildings. These difficulties are mainly occurred due to the unsteady heat transfer processes in case of cooling the train compartment after exposing it to a hot environment. Other than that it has been identified following influential factors for vehicular thermal comfort: non uniform indoor thermal environment connected with high localized conditioned air velocity, temperature distribution, solar flux and radiation heat flux reflected from surrounding interior surfaces, clothing level of occupants and journey time duration.

It has been found that the starting of air conditioning system in space with hot & dry air consumed less energy than that of in space with hot & humid conditions.

Increase of the maximum accepted relative humidity value of passenger compartment lead to reduce required amount of heat rejection for thermal comfort state and then it will make the air conditioned system more efficient. However it should be considered to minimize the initial relative humidity value inside the passenger compartment because of higher amount of heat rejection requirement relevant to the higher values of initial relative humidity. Evaporative cooling system can be used with air conditioning system to control the relative humidity value of indoor spaces in passenger compartments [***9***].

Usually at beginning stage of cooling process air conditioning, the higher RH% values make occupants feel hot. However at the end of the cooling process, that higher RH% values make them feel more comfortable in thermally. The comfort level and the local sensation of different body segments are nearly same as that of overall sensation & comfort level. In heating process, at beginning the occupants feel uncomfortable due to cold. However during the heating stage make them feel comfortable by reducing RH% value. It has been found that the temperature ranges on the summer comfort zone is 23.1-27.4 ˚C with 20 -74% RH while the winter comfort zone is 18.6 – 24.6 ˚C with 22 – 79% RH for Fanger's model [***9***]. The duel comfort system with relative humidity along with dry bulb temperature can be used to improve the efficiency of air conditioning system in cooling & heating processes by reducing the amount of heat removal on thermal comfort state (Thermodynamic), and by improving the passenger thermal sensation levels (Psychometric) [***10***]

2.7.2 Possibility of applying evaporative cooling in vehicular air conditioning

The aim of using climate control system in vehicular air conditioning is to provide thermally comfortable indoor environment for passengers with minimum energy consumption. Design of evaporative cooling system for vehicles was analyzed in theoretical stage. However it has not been built. The coefficient of performance (COP) of the evaporative cooling system shows low values in research level. The relative humidity of indoor space in vehicle compartment can be controlled by using this evaporative cooling system. Although it can be identified that the increasing cost, weight & volume due to the sprayed water requirement are major barriers to adopt this more effective evaporative cooling system to the moving compartments. Using evaporative cooling system the dry bulb temperature of indoor space can be reduced in significant amount through phase transformation of liquid water to water vapour. By evaporating, indoor air can be cooled faster using less energy than the energy used in refrigeration process of vapour compressor system. Thus the evaporative cooling system is better than that of vapour compression system economically. However presently, the vapour compressor system is commercially better than the evaporative cooling system [***11***] .

One perspective study done by Guerra described the effect of changing the relative humidity on performance of vehicle air conditioning using evaporative cooling system. The standard of the vehicle air conditioners is the vapour compressor system. However research studies proposed the theoretical evaporative air conditioning system as a solution to the issues arose with the use of vapour compressor system. Theoretically, the evaporative air condition system designed satisfied the two objectives with lower fuel consumption and less environmental pollution than that of the compressor system. However according to the economic analysis it is less commercially feasible than compressor system when comparing with the cost, weight and the volume [***12***].

2.8 The factors influencing passenger thermal comfort in vehicles

The major influential factors of occupant's thermal comfort mainly depend on four environmental variables. They are the dry bulb temperature of air, relative humidity of air, the mean radiant temperature and the relative air velocity in conditioned space. Other two independent relative factors effect thermal comfort are metabolism and the thermal insulation level given due to clothing. Vehicular indoor thermal comfort models are designed based on human physiological and psychological perspectives and other than that it is based on the compartment zone, the human thermal mankins, the subjective observers and infrared thermography. The vehicular thermal comfort depend on fast transient (unsteady) heat transfer process and inhomogeneity in the thermal environment inside passenger compartments in connection with the higher localized air velocity, solar flux and variation of journey time of passenger compartment [***13***]

Presently the vehicular thermal comfort state is predicted or estimated using measurement of each effective environmental parameter (all together six thermal comfort parameters considered): air temperature, air humidity, mean radiant temperature, air velocity, activity level of passengers and clothing insulation. Also indoor thermal comfort levels of vehicles have been optimized by adopting an automatic air conditioning including climate control system. Application of appropriate thermal comfort model and improving measurement method of thermal comfort parameters by analyzing them properly are most important steps to be considered in estimating vehicular indoor thermal comfort precisely [***14***]

The indoor state of vehicles can be described as a moderate thermal environment which is defined by above mentioned six major thermal comfort parameters. Total effect of these parameters on passenger comfort can be calculated by measuring each and every parameter separately. Indoor conditioned of passenger compartment is inhomogeneous. The indoor temperature and relative humidity which are significantly effect on thermal comfort are main parameters of an air conditioning system. However the indoor temperature is correlated with relative humidity of indoor air. It has been found that the effect of relative humidity fluctuates in between 30 - 70% on thermal comfort is low compared with that of dry bulb temperature. Mean radiant temperature occurs due to solar radiation is depend on the size and quality of glass used and influence on passenger thermal comfort [***13***]. Another most effective factor influence on passenger thermal comfort is air velocity. The fluctuations of indoor air velocity depend on the air flow of air conditioning system (including type and quality of air vents) and existing leakages lead to control ventilation and infiltration respectively [***14***]. Minimizing the leakages by tightening the vehicular envelop and maintaining air flow in an acceptable minimum level, passenger thermal comfort can be increased efficiently.

Recently, passenger coaches are generally consisted with air conditioning systems. According to the passenger feedback, there is a great temperature difference between in cabin and external environment highlighted. Poor air conditioning and ventilation lead to make passenger discomfort. One of the recent study to find a method for calculating railway passenger benefits, carried out in China and according to its index adaptation and initial data measurement indoor temperature consider as one of the main objective measurement [***15***].

2.9 The estimation of thermal comfort parameters inside vehicles

The estimation of passenger thermal comfort parameters inside vehicles is more difficult than that of buildings due to the effect of external factors and the subjective matters related to thermal comfort state in vehicles. Additionally limited space and tightness in vehicles cabin and passenger activity in same for a long period of time as seated are effected. There are no any specific international standard to estimate thermal comfort of vehicular indoor spaces. Hence there are so many differences in the theoretical approaches and the experimental methods used to predict thermal comfort in passenger compartments. It is important to use appropriate experimental methods to analyze thermal comfort inside moving train compartments for instant virtually and experimentally. Also it should be developed new appropriate thermal comfort indices for occupied indoor spaces considering local effect of thermal discomfort [***16***].

According to the objective measurements taken in the field in a previous research, the large glazed surface areas which surrounded indoor space allows more natural lights to come inside and result in excessive solar heat gain in indoor space. It leads to discomfort and overheating in occupied areas. Internal temperatures may exceed external ambient temperatures. The mean radiant temperature of indoor space increases due to the solar radiation and convection increases operating temperature in the space which lead to thermal discomfort and overheating. It was found that there is a high probability of accessing significant thermal discomfort in large glazed air conditioned spaces in hot humid climate outdoor conditions [***17***].

Solar radiation cannot be considered as a one of real thermal comfort indices. However it is a local discomfort parameter as it will not only increase the indoor air temperature but also increase the rate of heat transfer. Using anti solar foil is a most reliable solution to minimize the effect of solar radiation. Adopting local ventilation vents to reduce the energy consumption and to ensure the indoor air homogeneous conditions for indoor thermal comfort parameters is another better solution [***16***]. Numerical methods have been applied to study thermal comfort by using CFD simulation in most of past similar studies. A previous study numerically investigated the thermal comfort in passenger compartment by considering spectral solar radiation. A three dimensional computational fluid dynamic (CFD) simulation was applied using commercial software (ANSYS FLUENT V.13.0) to predict thermal and flow field under operating condition. Based on the Fanger's model and equivalent temperature model, thermal comfort was analyzed on numerical predictions. The result shows that estimated temperatures near the passengers increased by 1-2˚C due to spectral solar radiation effect [***18***]. This small temperature difference can create significant variation in indoor thermal comfort. Thus it is important to consider spectral solar radiation effect in thermal comfort evaluations.

A numerical study on air quality and thermal comfort in high speed train compartment was carried out in China. In order to improve the air quality and the thermal comfort, an underflow air supply was introduced instead of traditional sidewall supply and bottom return mode. In this study, the airflow, temperature, CO_2 concentration and humidity field of high speed train were analyzed by CFD simulation. PMV and PPD indices were used as evaluation criteria of indoor comfort state. The result shows that the CO_2 concentration is reduced with under flow air supply and thereby improving air quality. Also the supply air temperature can be increased to improve the thermal comfort & energy efficiency [***19***].

2.10 Weather systems affecting atmospheric ambient conditions in Sri Lanka

Even though Sri Lanka is a tropical Island latitude extent less than 4˚ and land mass area of approximately 65000km^2, there are wide variations in geographical features and thereby significant variation in climate conditions. Accurate prediction of ambient temperature, humidity and incident solar radiation at a given location is of great advantage for determining heat gain of condition space in same location and thereby estimating required cooling load precisely for better thermal comfort with energy saving. It is important for tropical developing countries such as Sri Lanka where annual average solar irradiation is in range of 5.5 $kWhm^{-2}d^{-1}$ and available throughout the year with low seasonal variations. Estimating solar radiation data are less accurate than other weather parameters such as temperature, humidity, sunshine hours etc.. The land of Sri Lanka broadly divided into two regions where the area including the south – west and central hills receiving over 2000mm rain annually as wet region and the combination of the intermediate and the dry zone receiving less than 2000mm of rain per year defined as dry region. The incident terrestrial solar irradiation at a given location varying with geometrical parameters such as latitude & altitude and meteorological parameters such as sunshine duration, relative humidity, ambient temperature and cloud cover amount.

The cloud cover reduces the incoming radiation during the day time and reduces the outgoing radiation at night, therefore the temperature difference between day and night may be reduced. However due to the high atmospheric humidity levels, the possibility of rain events is high. In Sri Lanka as a tropical country where formation of convective low and middle clouds over the surrounding ocean cause frequent raining through out of the year culminating in monsoons and inter-monsoons depending on wind pattern and directions. From March to May as first inter-monsoonal rains and June to September, south – west monsoons set in and just moving low and middle clouds changing sun shine durations and also this period coincide with the summer time in the northern hemisphere with longer daytime periods. During September to November north – east monsoonal winds and rains occur. There are more clear days in the north – east monsoon compared to the south-west monsoon. Thus the areas located in the dry region which depend primarily on north – east monsoon for rain, receives more solar radiation than the site located in wet region. Generally the effect of two inter-monsoonal rains on the solar radiation can be considered as low as there rains mostly occur at evenings for short duration.

The variation of ambient conditions and solar radiation values are influenced by the cloud formation pattern, wind directions and seasonal variation of weather in Sri

Lanka. Although Sri Lanka is located close to the equator and as a country located in the northern hemisphere, it still experiences summer and winter conditions slightly. There are significant differences in relative humidity between day and night, though the variation of humidity levels during day times can be considered as insignificant. However the humidity levels are varied with geographical locations significantly. The ambient temperature values are varied with reference to the time and the locations in considerable amount. Generally, significant differences in ambient temperature and humidity are highlighted in hill country region relevant to the altitude of the locations comparing with other areas of the country. Highest ambient temperatures are indicated in northern and eastern provinces of the country.

2.11 Impact of gender and age of occupants on thermal comfort

Status of thermal comfort condition is very important in air conditioned spaces because of the health and performance of occupants. However it is difficult to add personal factors such as gender and age on thermal sensation when predicting mean vote for comfort assessments. It has been found that a previous study was conducted to analyze significance between females and males as well as several age groups (< 25 years, 25 – 45 years, 46 – 65 years and > 65 years). According to the results the predicted mean vote (PMV) model was applicable for both females and males. It can be verified for the age group of 46-65 years, although it was not applicable for all age groups. Effect of age on thermal comfort was statistically significant while that of gender was not significant [***20***].

The aforementioned previous study assess the effect of gender and age on thermal comfort and the verification of the applicability of the PMV model in worm indoor conditions has been occurred by in situ measurement and a survey. The in situ measurements considered for calculation of predicted mean vote (PMV) values were indoor air temperature, relative humidity, air velocity and mean radiant temperature. Actual mean vote (AMV) values were calculated by using personal data of subject collected from the survey. According to the result, the difference between AMV and PMV values for gender was statistically not significant. Thus the PMV model is applicable for both females and males. However there was a significant statistical difference between PMV and AMV values of population under 25 years old, between 26 – 45 years old and over 65 years old. Thus the PMV model cannot be verified for all age groups except the age group of between 46 – 65 years old [***20***].

Consideration of thermal comfort is essential in design, operation and commissioning of conditioned spaces. Two most generally used standards for thermal comfort are the American Society of Heating, Ventilating, Air conditioning and refrigeration Engineers (ASHRAE) standard 55 and the International Organization of Standardization (ISO) standard 7730:2005 reviewed. Basically, these standards have been prepared to identify safe rangers scientifically, based on practical experiences and the potential of existing technologies [***21***]. Also the past studies described that the thermal comfort standards are useful, though these standards cannot be considered as absolute guidance as the individual thermal comfort requirements which can be varied. Conventional thermal comfort theories may not be incorporated some of the important factors and their effects [***22***]. Most of the studies on thermal comfort have discussed on gender while several studies reviewed based on the age group. It is impossible to defined conclusions on the effect of age groups [***23***].

Past studies which were mainly concerned about the impact of age on thermal comfort revealed that the thermal sensation of the elderly age people is lower than that of younger adults [***24***]. According to the preference of thermal sensation, elder people were found to prefer higher temperatures due to lower activity levels. Also the younger people preferred a higher temperature than older people and the neutral temperature of the younger population between 20 – 25 years old was 26.6 ˚C for cooling season which was higher than the standard value [***25***]. The result of the studies done in previously shows that the difference between indicated values of thermal preferences on age groups was less significant [***20***]. The effect of age groups on thermal sensation has been found to be stronger than that of gender. Thermal comfort acceptability was statistically not significant for gender while it was statistically significant for age group and also it was only significant for the population under 25 years old and over 65 years old.

2.12 Estimation of thermal comfort zone

Accurate information on thermal environment is required to estimate thermal comfort level. The thermal environments can be described in terms of the temperature, humidity and air velocity. When designing and developing HVAC system, it is useful to follow the human thermoregulatory system. Thermal comfort level shows the satisfaction of occupants from ambient conditions. Also conceptual of thermal comfort based on the senses and feelings. The heat balance of the body means the heat generations by activities within the body have to be equal to the heat transfer from the body. Heat balance is one of the requirements to fulfill the thermal comfort. However it is not sufficient to satisfy thermal comfort. It can be described as thermal equilibrium occurred due to energy balance which has a wide range while the thermal comfort zone is a narrow area within that of wide range.

According to the understanding of thermal comfort by humans on sense and feelings, it can be vary with the present states of behaviour and psychology or personality of human. Thus it is appropriate to mention thermal comfort as a range or a zone instead of mentioning as a single point. Naturally it is impossible satisfy all the people in a conditioned space because of their physical or mental state, behaviours and physiology. Accordingly, it is required to define measurement to identify the level of comfort conditions. Presently it is measures as 90% of the occupants must be satisfied with acceptable uncomfortable ratio of 10%. Then it can be considered as comfortable condition space (ASRAE standard 55). With reference to the result of previous studies, generally transient energy balance model and steady – state energy balance model were used to analyze thermal comfort condition. Among them in steady – state energy balance model introduced by Fanger, the human body is considered entirely as overall item assuming heat generated in the human body is equal to the heat transferred to the environment from the body [***26***].

The body heat generation is positively affected by the activity level. When activity level increases, the body heat generated increases and then lower ambient temperature required for thermal comfort condition. However less activity level shows much higher ambient temperature requirement for satisfaction of thermal comfort. It is difficult to keep thermally comfortable state with less activity due to the narrow temperature range relative to that of less activity level [***27***].

Increasing clothing insulations influence the body heat transfer significantly negative. When the clothing insulations of people increasing, the ambient temperature requirement for satisfying thermal comfort to be decreased. Decreasing of clothing insulating positively affects the body heat transfer. Reduction of clothing insulations increases the required value of ambient temperature for thermal comfort satisfaction. However decreasing clothing insulations negatively influences the comfort zone. Thus it is difficult to obtained thermal comfort conditions with lower clothing insulations due to its narrow comfort zone. The convection and evaporative heat transfer coefficients of human body are increased by the increment of air velocity. Then heat transfer from the human body improved with the increase in indoor air velocity. The thermal comfort conditions of indoor environment are reached its satisfactory level faster by increasing indoor air velocity [***27***].

Generally thermal comfort conditions are evaluated by using six determinant parameters. As discussed earlier among them four parameters are environmental related and they are temperature, humidity, mean radiant temperature and air velocity while other two are personal parameters called as activity and clothing level. If one of these parameter changes and it influences the thermal comfort state, then it must be changed one or more of other parameters to regain thermal comfort state to the satisfactory level. In a past research, thermal comfort zones were calculated with the ambient parameters. Numerical models of the heat and mass transfer between human body and the environment have been introduced with computer software program [***27***]. Accordingly using these numerical simulation values following parameters and indices can be calculated. Total sensible & latent heat losses, skin temperature & wettedness, predicted mean vote (PMV) and predicted percentage of dissatisfied(PPD), and then it can be obtain the required environmental and personal conditions for the satisfaction of people with thermal comfort state under steady state condition for the PPD less than 10% zone.

One of the important past study was carried out in Sri Lanka to identify indoor thermal comfort and thereby defining a comfort zone applicable to Ratmalana area in the west coast. The neutral temperatures for different areas in Sri Lanka have been established using actual climatic data. Standard comfort zone for each of these locations was identified on the psychrometric chart. Field measurements have been carried out for the validation of comfort zones for Sri Lankan conditions. The influences of physiological cooling at relatively high internal air velocities have been noted. The applicability of standard modification techniques for the standard comfort zone according to the elevated indoor air velocities was investigated using questionnaire survey. The survey was carried out in an air conditioned auditorium and in a seminar room while changing dry bulb temperature, humidity and air velocity in indoor state. The modified comfort zones have shown that higher dry bulb temperatures and humidity ratios can be tolerated within the occupied spaces for the thermal comfort condition. The requirement of additional boundaries to use in standard modifications to be compatible with Sri Lankan context was highlighted. It has been provided a method to extend the boundaries of these comfort zones increasing the level of dry bulb temperature and humidity in the indoor air conditioned state minimizing the energy demand [***28***].

ISO temperature setting standard which requires the temperature range of human thermal comfort is to be 21- 24˚C is widely used in European countries. ASHRAE standard 55-1992 has given the range of thermal comfort temperature to be 20 – 23.6˚C which used in the USA. The predetermined temperature boundaries of human skin feeling for hot and cold condition are considered as 20 - 25˚C. Also as a country in the Asian region, China used the thermal comfort temperature range of 17 - 28˚C comparatively a wider range.

2.13 Field studies on human thermal comfort

The concept of adaptive comfort has been added to the comfort design with reference to the standards like ASHRAE 55 – 2004, ISO 7730 and EN 1925 which are included sections concerning naturally conditioned spaces. Presently designers use clear and recognized standard guidelines relevant to the acceptability and minimal comfort requirements compulsory in thermal applications. According to the ability of occupants to adapt to the different thermal environment and as to restore their comfort, these abilities are categorized into three different levels such as physiological, behavioral and psychological. At all these three levels, that ability of an occupant heavily affected by the weather of conditioned space. Results of using adaptive models in similar climatic zones have shown more similarities than differences. Using this idea of similarities, the results of field study have been validated against the results of comfort surveys carried out in similar climates.

The results of past studies on human thermal comfort carried out in past few decades have been reviewed and presented as an overview by some researches. Accordingly, thermal comfort field studies were separated into groups with reference to the locations where those studies have been performed. The effects on thermal comfort from relevant environmental, physiological, psychological, and other factors have been discussed. The results of field studies highlighted that the people have enough adaptive opportunities and also they are capable of adapting to their surroundings which have been provided. According to the studies air conditioned spaces have narrow comfort zone than that of free ventilated spaces such as buildings with natural ventilation. Adaptation relevant to the modification of air movement (velocity) and clothing are common in meeting of different climate zones [***29***]. One of the past field study on thermal comfort in aircraft cabin conducted with field measurements and collecting questionnaires on aircraft. Local thermal comfort and overall thermal comfort were analyzed. It was found that the spatial differences were not so important to thermal comfort due to the adjustment ability of human [***30***].

As per the major determinants of the adaptive opportunities: ease of application, economy, and effectiveness which are introduced as three E's, mainly contribute to make occupants adapt to their surroundings. According to the studies individuals are willing to perceive same thermal environment in different movements and environments with lack of adaptations which normally gives lower thermal comfort states. However without concern on many people may prefer to use systems like coolers and air conditioners considering their ease and effectiveness. Some of simple adaptive actions like window openings are popular among all climate types while some other actions are limited by climatic and cultural differences. With concerns of environmental effect and depletion of energy sources, there is a trend towards energy efficiency. Thus it is better to have the appropriate standards and design methods based on energy saving without influencing thermal comfort.

Current thermal comfort standards consisted with generalization of global data to use for designers and practitioners. These standards can be improved with the local field surveys on basis of climatic zones and trends in thermal comfort of occupants. Thus, the several concepts relevant to adaptive thermal comfort have been considered to use in recently. It has been upgraded the aspects of thermal comfort surveys using questionnaires, analysis of clo and met values, instruments and measurement locations etc.. Currently there is a trend of examining the result of field studies in order to climate zones where the field studies were conducted [***29***].

As mostly used climate classification system, Koppen – Geiger system with wide spread of application in different field can be used for thermal comfort studies. It divides climates into five main types: Tropical moisture climates, Dry climates, Moist subtropical mid - latitude climates, Moist continental mid – latitude climates and Polar climates. There is no any comfort surveys carried out from polar climates, though several surveys have been carried out across other four main types of climates. Except tropical moisture climate which is much closer to Sri Lankan climate, other climate types have broad ranges of neutral temperatures and comfort zones because of the minimal seasonal variations in tropical moisture climate. Also the neutral temperatures obtained through field surveys are unchangeable over reasonable intervals of time.

According to the existing literature, a past study carried out in Taiwan to investigate passenger thermal perceptions, thermal comfort requirements and adaptation in short haul and long haul vehicles which are normally used for travel lasting less than 30 minutes and longer than 60 minutes respectively [***31***]. This field experiment was conducted in both buses and trains, including short-haul local trains and long-haul limited express trains which travel in urban and suburban areas at speed of 110 – 120 km/h. The study included a field experiment with simultaneous physical measurements and a questionnaire survey. Data were collected from 2,129 numbers of respondents and evaluated for thermal comfort in buses and trains. According to the results, high air temperature, strong solar radiation and low air velocity lead to make passengers feel thermally uncomfortable. The overall clothing insulation and thermal adaptive behaviour of passengers differ from their living and working environments. Passengers travel in short haul trains were more sensitive with the internal air velocity adjustment to increase thermal comfort, while passengers travel in long haul trains were more sensitive with the removal of solar radiation effect to reduce discomfort. Also this study provided valuable results such as neutral temperatures and comfort zones to use as references for practitioners. Accordingly, the neutral temperatures for short and long haul trains are 26.2˚C and 27.4˚C respectively while the comfort zones for short haul and long haul trains are 22.4- 28.9˚C and 22..4- 30.1˚C respectively [***31***]. These results facilitate the operational & management staff of train air conditioning systems to achieve thermal comfort state with significant energy savings.

2.14 Energy efficiency improvements of railway vehicles

The railway vehicles (trains) consume a high share of electricity for comfort purposes rather than the traction energy. About 40% of energy by the total energy consumption of rail vehicle, consumed for heating, ventilation and air conditioning (HVAC). One existing literature reviewed a study of optimizing the HVAC system of the rail vehicle in Switzerland. The aim of that study was to reduce overall energy consumption without any detrimental impact on passenger comfort. For this purpose, models of used rail vehicles have been built up in a simulation program and carried out additional measurements such as heating up experiments, air tightness measurements and thermo-graphic imagery to assess their energy demand and to calibrate the models. The highest heat loss in the rail vehicle could be identified by the results of simulations. Two substantial reasons for high energy demand in rail vehicles revealed to be: the poor insulation of the passenger carriage envelop and the lack of heat recovery in the ventilation system [***32***].

According to the existing literatures the outdoor air flow rate of the ventilation system has a high impact on the accuracy of the simulation models of the vehicles. To assess this variable, tracer gas measurements were performed. The inside space of the vehicle was filled up with a tracer gas until saturation reached. The decay of concentration was observed, when ventilation system was turned off. The decay is cause by wall infiltration or by the supply of outside air through the ventilation system. Then the gas concentration decay and the outdoor air flow rate can be calculated by applying volume of the rail passenger carriage which is known [***32***]

All internal heat sources are to be known as a function of time. For rail passenger coaches the heat gains from lighting and from passengers need to be considered. However heating effect of electronic device used by passengers can be neglected. It was assumed that the lightings in the vehicles are constant as always it is switched on during operation. Passenger occupancy varies during the day and was not available as measured values for the whole time. Hence occupancy was calculated by means of the measured carbon dioxide (CO_2) concentration in the vehicle and the outdoor supply air flow rate of the ventilation. This improved the accuracy of the simulation model than assuming a constant number of passengers over the operation period [***32***]

The vehicles were modeled and simulated using the software program IDA ICE which is widely used in research and engineering applications. The input data put into the model include in the geometrical and physical properties of the carriage especially the vehicle envelop, the HVAC equipment including its control, the internal heat gains and the outside climate conditions such as temperature, solar irradiation and wind. The final model was calibrated using the long term measurements in combination with the stationary heating up and tracer gas measurements and counting of passengers. After calibrating the model, the optimization measures for the HVAC units and the vehicle components hardware could be defined thus the highest energy saving potential in the vehicles could be investigated [***32***].

First, the energy flow diagram was generated. Optimizing method of the rail vehicle envelope and the operation of HVAC system were gathered and evaluated in collaboration with railway companies. The measures were analyzed in three categories: envelope, HVAC system and operation. The measures were obtained according to their energy saving potential and to the required expenditures to implement them on existing vehicle. According to their expenses the measures were categorized into three levels such as low, medium, and high. The lowest expenditure represents measures with small adjustments: control and regulation of the HVAC systems. These measures are cost efficient and can be implemented rapidly. Measures of medium expenditure affect additional or different HVAC components. The third category with the highest expenditure concerns the improvement of the opaque and transparent parts of the envelope to be considered. After implementing these deferent measures the five options representing above measures were considered. Five options considered were: Basic case-the reduction of U value (overall heat transfer coefficient) of windows, the reduction of air temperature of two vestibules, the reduction of indoor air temperature of the train compartment, implementation of heat recovery system in ventilation system and controlling the demand of the outdoor air flow rate as a function of CO_2 concentration [***32***]. Only the heat demand of radiators and air heaters were considered due to the heat gains from lightings, occupants, and solar radiation are identical in all these options.

In the basic case, the U-value of the windows equals 3.1 W/m^{2}K. In the first option, this was reduced to 1.2 W/m^{2}K. This measure results in a 4% reduction of the heating demand. In the second option, the air temperature of the two vestibules is reduced the same way (night set back) as in the passenger room. An anti-freeze protection to a set point of 6°C is assumed. This measure saves up to 10% of the heating demand. The reduction of the indoor air temperature in the wagon from 22.5°C to 20.5°C (option 3) reduces the heating demand by 13%. Another possibility to diminish heating demand is to implement a heat recovery (HR) in the ventilation system. The antifreeze protection for the heat recovery was considered by limiting the exhaust air temperature to 1°C. The installation of a heat recovery system would allow 11’948 kWh or 26% of the heating demand to be saved. The demand control of the outdoor air flow rate as a function of the CO2 concentration (option 5) has shown even a slightly higher potential than the heat recovery system. The set point has been set to a maximum of 1’000 ppm CO2 concentration. This way, the heating demand can be reduced by around 29% [***32***]. These five options are single measures and not cumulated. The combinations of single options given combine measures that lead to further reduction in cumulative total of heating demands relevant to single options which were combined.

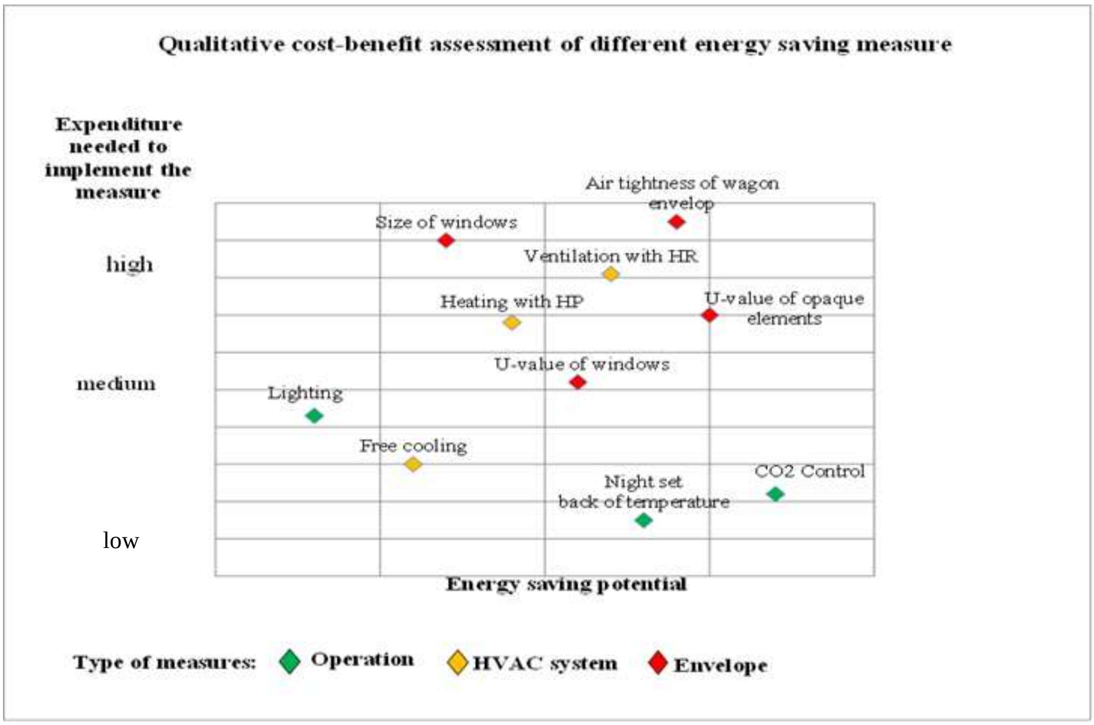

Figure2.1: Qualitative cost-benefit assessment for the different measures (the assessment was performed by railway experts) [*32*]

The heating demand can be reduced further if more than one measure is implemented. The combination of the reduction of the wagon temperature by 2 K (option 2) and the night setback of the vestibules (option 3) can reduce heating demand by 23%. If these two measures are combined with the CO2 control of the air flow rate (option 5) the heating demand can be reduced by 47% which corresponds to a saving potential of 21’000 kWh per year [***32***]. This type of simulations and energy saving estimation can be used for the cooling down experiments to reduce cooling load of the vehicle envelop which present a great energy saving potential for their comfort installations and great importance in future electric vehicles, because the heating and cooling demand highly effects on the distance range vehicles.

2.15 Energy efficiency assessment on thermal comfort in passenger trains

Not only the capacity and efficiency of the components of air condition system but also the estimation of cooling load setup and controlled have a big impact on energy use and levels of comfort provided for passengers. It has been highlighted the significant energy saving potential by predicting the actual required cooling load under variable atmospheric ambient conditions changed with respect to the time and space [***4***]. Energy saving of air conditioned moving passenger compartments can be achieved under control system.

The average predictive mean vote (PMV) shows clear linear correlation with the operative temperature and the neutral temperature. In future, a new thermal comfort prediction model or an improved PMV model should be developed to assess the indoor conditioned space in the hot arid climate environment. Outdoor weather conditions may need to be considered for a better estimation of the occupant indoor thermal comfort sensation in air conditioned spaces [***33***]

The climate control systems have been introduced to integrate the result of vehicle air conditioned in energy consumption, thermal comfort and air quality. According to the existing literature, a previous study carried out on sensitivity analysis of performance indices using mathematical models for moving passenger compartments. Accordingly, controlled variables which influence on energy consumption, thermal comfort and air quality have been identified for functioning climatic control effectively. Considering performance indices related with energy consumption of air conditioning system, predicted mean vote and concentration of carbon dioxide respectively obtained.

The quantitative effect of controlled variables within operating conditions analyzed using mathematical models. Decreasing supply air temperature by a percentage to improve thermal comfort increases energy consumption. Additional energy consumption amount for decreasing supply air temperature by a percentage is less than that of increasing supply air by a same percentage. Increasing amount of supply air will make changes of predicted mean vote index and concentration of carbon dioxide. Thus thermal comfort state and air quality of conditioned space can be improved effectively by increasing the amount of supply air [***34***].

2.16 Heat transfer coefficient estimation for a dynamic thermal model

Heat transfer coefficient and the heat capacity of a thermal model defined for a specific condition usually. When considering a dynamic thermal model, these values are varied with variables other than the material properties of the media of heat transfer. Though dynamic thermal models are state of the art in buildings, road vehicles or rail vehicles, there are no reference values for these parameters. The requirement of the growing population for mobility will increase by number and complexity. In order to fulfill this requirement in sustainably, public transport such as railway should be improved and prioritized. It will reduce energy cost and effort to reach carbon neutrality. The significant energy consumption of train air conditioned system shows the necessity of an efficient design of related components towards a dynamic thermal model of trains. For calculating optimum measures, a mathematical description of the considered systems to be obtained and parameters of this system need to be identified [***35***].

Vehicles are usually air conditioned by using vapour compression refrigeration [***36***]. The same principles can be applied to thermal model of trains [***37***]. In previous studies carried out based on physics, an analytical model of a vehicle with two heat capacities was developed and validated [***38***]. Also an analytical thermal model for an automotive vehicle has been developed and validated. Parameters such as heat capacity & heat transfer coefficient were estimated analytically for this case [***39***]. Thermal simulation software for automotive vehicles is already available and it can be used for the simulation of combined cooling loops [***40***].

Variations in dynamic cooling loads were studied using an analytical thermal model of Chinese mainline trains [***41***]. A mathematical model was built to simulate dynamic cooling load of an air condition train compartment. The effects of ambient conditions and body thermal conditions on the variation in cooling load were investigated. The body conduction heat load was considered as the combined effect of outdoor air temperature and solar radiation. Accordingly, external surface heat transfer coefficient was assumed convective and varied with train velocity while the train compartment moving (given by Equation 17 in Chapter 4 of this thesis). It was taken as constant value of 16 $Wm^{-2}K^{-1}$ when train was at stop position (at zero velocity). According to the existing literatures, almost all vehicle thermal simulation models used to analyze exclusively for only one specific vehicle. However it is difficult to determine every necessary parameter. Therefore it would be useful, if bench marks or reference values for a dynamic thermal simulation model were available.

2.17 Dynamic cooling load analysis for thermal comfort conditions in trains

Most of the existing literature reviewed the indoor thermal comfort analysis of rail vehicles while few of them reviewing the cooling load analysis of passenger trains. It has not been found literatures discussed both of these analysis were in same study as a collective and effective method. However it is important to discussed minimizing the cooling load in order to set indoor thermal comfort state in a more acceptable level. Accordingly, to achieve the target of reaching these two requirements in the same attempt, literatures relevant to the indoor thermal comfort and the dynamic cooling load have been referred separately and made the common model combining both existing model representing indoor thermal comfort and predicting dynamic cooling load respectively.

As an important transport media, condition of air condition train system is proper or not, it effects not only for the indoor comfort state but also for the energy consumption. Thus it should be search for a proper air conditioning system actively towards the energy saving, comfort and clearness [***2***]. Considerable fluctuation on indoor air temperature occurred due to the change of outdoor ambient conditions during long distance travel [***41***]. Uncomfortable indoor thermal environment and significant energy consumption in air conditioned rail passenger compartments negatively influence to develop railway transport system as modern one [***2***].

In view of the above Public transportation vehicles present a great energy saving potential for their comfort installations. The cooling demand highly affects the distance range of trains. By means of thermal simulation, it is possible to calculate the energy demand of the comfort facilities of these transportation rail vehicles in detail and to assess different energy efficiency measures. Also it is important to defined an appropriate "comfort zone" on the psychometric chart for delivering acceptable thermal comfort to 70% of the occupants (passengers) in conditioned space of rail vehicles. This will lead to optimize thermal comfort parameters inside rail compartment minimizing energy consumption without any detrimental impact on passenger thermal comfort. The cooling load significantly effect on the energy consumption of air condition system due to the state of indoor thermal comfort conditions and the fluctuation of outdoor ambient conditions in moving train compartments.

The standard method of modifying the standard comfort zones can be used for Sri Lanka with some additional boundaries. Higher dry bulb temperatures and humidity ratios can be tolerated within the occupancy spaces on thermal comfort state to reduce the capacities of air conditioning system thereby lowering the capital and operating cost and to establish more realistic indoor thermal comfort condition [***28***]. Considering the thermal storage of train body and simulating the unsteady heat transfer process in a moving train compartment under variable outdoor ambient conditions, dynamic cooling load of moving train compartments which varies with time and space can be estimated using an appropriate mathematical model [***41***].

A similar study has been carried out in China to investigate the variation in cooling load of a moving A/C train compartment due to the variable ambient conditions and body thermal storage [***41***]. A mathematical model was built and used to simulate dynamic cooling load which predicted with respect to the changing of time and space. Trains travelled in three main railway lines of China were considered and average ambient conditions during hottest month July were taken to the cooling loads estimation in this study. The effects of the ambient conditions and body thermal storage on variations in the cooling load were analyzed. Significant differences in dynamic cooling load of train compartment highlighted between different regions (north/south and east/west) and between different periods of time during the day (morning, afternoon, night). Comparing with the dynamic cooling load, standard steady cooling load estimated by using traditional method given larger and over estimated value. Thus application of dynamic cooling load and thereby supplying approximately actual required cooling load, a significant energy saving potential with improved thermal comfort state highlighted. The maximum total dynamic cooling loads were between 40.4 and 43.8 kW, while the minimum total were between 4.5 and 33.7 kW. The ventilation cooling load component was the most important and contributed factor to the total cooling load. However contributions of conduction and radiation components were very low comparing with that of ventilation. A linear relationship between the ambient temperature & humidity values with the variable part of dynamic cooling load was observed [***41***].

2.18 Cooling Load reduction strategies and energy saving measures

Space cooling is the rate at which heat must be removed from the space to maintain air temperature at a constant value. Cooling load, on the other hand, is the rate at which energy is removed at the cooling coil that serves one or more conditioned spaces in any central air conditioning systems. It is equal to the instantaneous sum of the space cooling loads for all spaces served by the system plus any additional load imposed on the system external to the conditioned spaces. Items such as from energy, fan location, duct heat gain, duct leakage, heat extraction lighting systems and type of return air systems are all effect component sizing.

The total conditioned space cooling load consists of heat transferred through the conditioned space envelope (walls, roof, floor, windows, doors, etc.) and heat generated by occupants, equipment and lights. The load due to transfer through the envelope is called as external load while all other loads are called as internal loads. The percentage of external versus internal load varies with conditioned space type, site climate and space design. The total cooling load on any conditioned space consists of both sensible as well as latent load components. The sensible load effect the dry bulb temperature while the latent load which effect to the moisture content of the conditioned space. The aim is to find out feasible opportunities which contribute to minimize the cooling load of a conditioned space.

2.18.1 Sensible heat loads through opaque surfaces

Wall insulation: The wall of conditioned space gain heat from the sun by way of conduction the amount of heat depends on the wall material and its alignment with respect to the sun. A train compartment body construction with low U-value will reduce all forms of conduction heat transfer through Styrofoam, etc shall result in a much lower rate of heat transfer through the walls when the outdoor temperatures exceed the indoor temperature. However the added insulation shall also increase the retention of heat generated within the indoor space when the outdoor temperature fall below the indoor temperature.

Wall alignment: If the wall of the conditioned space is exposed to the west direction, it will gain maximum heat between 2 p.m. to 5 p.m. the southern wall will gain maximum heat in the mid-day between 12 p.m. to 2 p.m. The heat gain by the wall facing north direction is the least. The heat gain by the walls in day-time, get stored in them and it is released in to the room at the night time thus causing excessive heating of the indoor space. If the walls of the compartment are insulated the amount of heat gained by them reduces drastically.

Roof insulation: If the roof exposed directly to the sun it absorbs maximum heat, but it is not so the heat gain by the roof will reduces. Compartments with a large amount of roof area, such as a single-story retail facility, reducing heat gain through the roof can be an important consideration and same could be minimized by adding insulation to the roof. The greatest energy savings are typically made when adding insulation to a dark coloured, flat, un-insulated roof directly over air-conditioned space.

Roof/ wall colour: Lighter colors and reflective coatings reflect more of the sun's heat than darker colors. The color of a roof can affect the demand for cooling in vehicles. The savings from applying a light colored or reflective roof treatment vary depending on the orientation of the roof, the ventilation of the space below it, and the roof's insulation levels. The greatest savings are expected on a flat roof with no ventilation below it and no insulation.

Design consideration. In addition to that, heat gain can be reduced by lower CLTD value. Therefore, in order get lower CLTD value, essential to pay due considerations on orientation of the compartment, required internal condition, vehicular body materials and wall thickness etc. at the initial design stage of the rail vehicle.

2.18.2 Sensible heat loads through the transparent surfaces

Window orientation: Solar transmission through windows and skylights can provide free heating during the heating season, but it can cause the space to overheat during the cooling season. Solar transmission through windows and skylights may account for 30% or more of the cooling requirements in rail vehicles. Because the position of the sun in the sky changes throughout the day and from season to season, window orientation has a strong bearing on solar heat gain. Therefore, north and south faces windows are more likely for compartments where skylight and solar gain are not much considered to achieve heat load reduction.

Also the solar gain reduction can be controlled by tilting. Tilting the window glass can significantly reduce solar heat gain through a south facing window. The tilted glass reflects 45% of the radiation when the incident angle is 78° compared with 23% when the glass is vertical.

Type of glazing: In order to provide satisfactory visual effects, better solar heat control and thermal insulation, various types of window glazing is available. Some of the available options are Clear plate or sheet glasses, tinted heat absorbing glasses, reflective quoted glasses, insulating glasses, switch able optics low-emitted glasses. After selecting the correct type for the application, cooling load could be further minimized by increasing the thickness of the glass. That is with the low U-value and low CLF.

Tints & Color: The properties of a given glass can be altered by tinting or by applying various coatings or films to the glass. Glass tints are generally the result of colorants added to the glass during production. The tints absorb a portion of the sunlight and solar heat before it can pass all the way through the window to the vehicle indoor cabin. Tinting is the oldest of all the modern window technologies and, under favorable conditions, can reduce solar heat gain during the cooling season by 25% to 55%.

Coatings & Films: The films are usually in form of metal oxides coatings, which transmit visible light while reflecting the long-wave infrared portion of sunlight. Films are thin layers of polyester, metallic coatings, and adhesives that save energy by limiting both the amount of solar radiation passing through the windows and the amount of internal heat escaping through windows. One layer of film is typically about 1/10,000 the diameter of a human hair generally last 7 to 12 years.

Type of Window Frames: The insulating value of an entire window can be very different from that of the glazing alone. The whole-window U-factor includes the effects of the glazing, the frame, and, if present, the spacer. The spacer is the component in a window frame that separates glazing panes. It often reduces the insulating value at the glazing edges. Window frames can be made of aluminum, steel, wood, vinyl, fiberglass, or composites of these materials. Wood and vinyl frames are far better insulators than metal. Insulated fiberglass can perform better than either wood or vinyl.

Window Shading (Internal Blinds/Curtains etc.): Other ways to reduce the solar cooling load involve physical shading. Exterior and interior shading are among the best ways to keep the sun’s heat out of a compartment. In warm climates, trains run in sunny areas can benefit greatly from a variety of shading techniques. External window shading devices such as awnings, roof overhang, shutters, solar screens, and internal shading devices such as curtains and blinds, can control the entry of solar heat. Exterior shading devices are about 50% more effective than internal devices at blocking solar heat.

Cool roof: Cool roof reduces heat transfer in to the compartment by reflecting solar radiation and less heat transfer leads to minimize cooling load for air conditioning system. Cool roof can have a payback period of a few years. Roof guards also helps to keep roofs cool by absorbing and using solar radiation.

2.18.3 Sensible and latent heat load through ventilation and infiltration

- Control ventilation rates to minimum requirements. The ventilation rate should be calculated based on the actual number of occupancy expected and not on air-changes.
- Avoiding over pressurize the condition space. The recommended level of positive pressurization is 0.03” increasing to 0.05” for critical applications. This would normally equate to 3- 8% of gross room volume.
- The mechanical exhaust systems should be interlocked to the fresh air supply systems.
- Wherever possible, maximize return air re-circulation. Where not possible evaluate possibilities of recovering energy from the exhaust air through heat wheels or heat pipes etc.
- Carbon dioxide-based demand- controlled ventilation systems vary the ventilation rate based on carbon dioxide (CO_2) levels in the space. For spaces with extreme variations in occupancy, such as public transport vehicles or trains, carbon dioxide sensors located in each zone adjacent to the indoor thermostat or in the common return air automatically control the amount of

outside air. The controls are set such that the CO_2 level do not exceed ASHRAE permissible levels of 1000ppm.

- Provide Time Clocks: Time clocks that automatically reduce ventilation rates during unoccupied periods can greatly reduce the energy load in rail vehicles. If the train compartment does not currently have night-time setback of the ventilation system, consider investing in time clocks.
- Use of HVAC automation system to utilize ambient air temperature variations is an effective means of utilizing free energy. At times, many vehicles require air conditioning although the outside air is relatively cool and dry. During these times, increased amounts of outside air can reduce the cooling load.
- In train compartments with mechanical ventilation systems, it is desirable to minimize uncontrolled air leakage to reduce cooling loads. There are several methods to address unwanted infiltration:

a) Caulking and weather-stripping should be in place for doors and windows.

b) For open doorways (such as are often used at rail compartments), clear vinyl strips can be used.

c) Sealing condition space using a cooled air flow (air curtains).

d) Installation of suitable door closers.

e) Minimizing the space being heated by closing doors to unused or unconditioned compartments.

f) The orientation of the compartments, placement of obstacles and structures as windshields, and even the floor-to-floor open corridors will influence infiltration.

- Cooling requirements can be minimized through cycles and user control local environments an economy cycles automatically increases perform of outside air used in the air conditioning systems when cooling is required (when the outside air is cooler than the return air)

2.18.4 Sensible and latent heat due to occupants

Traditionally, cooling loads are calculated based on worst case scenarios. Real occupant loads are seldom as high as design loads. The actual occupant load is usually equal or less than the maximum seating capacity. A rail carriage plan may show seats in each and every row as scheduled, as well as one or two other seats out of order. In most cases, the passenger’s seat will be empty most of the time. Therefore carefully analyzing may reduce the load gain to the account.

2.18.5 Sensible heat through lightings

- Installation of energy efficient fluorescent lamps in place of conventional fluorescent lamps (excellent color rendering properties in addition to the very high luminous efficacy.)
- Installation of Compact Fluorescent Lamps (CFL's) in place of incandescent lamps. As those have light efficacy ranging from 55 to 65 lumens / watt. The average rated lamp life is 10,000 hours, which is 10 times longer than that of normal incandescent lamps.
- Installation of high efficient LEDs. Using LED lamp can achieve additional energy saving by further reducing the cooling load compared to achieve same by CFLs.

2.18.6 Sensible and latent heat due to equipment/appliances

- Always buy equipment with ‘Energy Star’ label. The energy use can be reduced by 50% or more. A typical non-Energy Star-compliant computer and color monitor draw a continuous electrical load of 150 watts or more.
- Effective utilization of machineries by, Using only when it required, Preventing that of leaving the space after switching the machineries, Applying power management features to machineries which will reduce the energy consumption, Assuring machineries are not in stand-by mode.

Above cooling load reduction measures can be used for improving energy efficiency of a moving air conditioned train compartment considering the effectiveness of these measures to the total dynamic cooling load comparatively. The Various methods exist to reduce mechanical cooling demand including of improved insulation in train compartment envelop, high performance window glazing, natural ventilation, external window shading and proper window coverings, painting roof white reduce air conditioning loads by around 20%, controlling internal heat generation from lighting and equipment, and minimizing air leakages can also reduce cooling loads. Numbers of factors influence the cooling load on an air conditioning system.

Reducing the demand from any of these factors will reduce the size of the required air conditioning system thus it reduces the delivered cooling load, energy used and cost involved. Main factors that effects the minimizing of cooling load are 1) Design layout and operation of the trains affect how the external environment impact on internal temperature, 2) The heat generated internally by lighting, equipment and people or heat removed by refrigeration equipment and fans, and 3) The amount of temperature difference between a conditioned space and its environment (temperature set points). Thus by controlling these main factors according to the situation of the conditioned space required cooling load can be minimized. In this study, for predicting of unsteady cooling load of moving train compartment due to the variation of outdoor conditions with time and space, a dynamic cooling load estimation method has been proposed. Accordingly, by comparing the results obtained from both methods, sensitivity of using dynamic cooling load predicting method for mobile air conditioned space can be analyzed.

2.18.7 Demand response control in air condition systems

Demand response uses to the technical, operational and market framework allowing investors change their power demand for financial rewards and saving of energy. Also advanced control of air conditioning systems can be adjusted to shift power peaks, reduce energy consumption and associated costs while improving thermal comfort states to an acceptable condition avoiding unnecessary reduction of thermal parameter values. Specific techniques have been identified for space air conditioning as following: Global temperature adjustment, passive thermal storage, fan variable frequency drive limit, temperature adjustment in supply air, etc. Passive thermal storage can be used to reduce thermal loads in peak hours by preheating or pre cooling of spaces leading to total energy savings [***42***].

Demand response control strategies in air condition system operations can be effectively implemented providing acceptable indoor thermal comfort. This is an essential aspect of demand response when thermal comfort is proportional to the occupant's health, satisfaction and productivity. The daily discomfort score is developed to assess demand response and thermal comfort in compartments. As the key input parameters, operative temperature including radiation and air temperature condition in each thermal zone, indicate the daily discomfort score. A penalty mechanism can be introduced to account for temperature deviation of outside the comfort zone and consecutive hours of discomfort. Evaluation of thermal comfort and demand response control are sensitive to the daily discomfort score [***43***].

2.19 Questionnaire survey

This research was based on the famous Fanger's thermal comfort model [***44***] and basic heat transfer theories on conduction, convection and radiation effect applicable for moving air conditioned space. Requirement for a passenger to be in thermal neutrality was described and evaluated by two indices: Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) with reference to the ASHRAE 55 & EN ISO 7730 standard [***45***]. The thermal comfort sensation is assured by the parameters that depend on the heat exchange between the human body and the ambient environment. Important thermal comfort parameters were considered as independent variables which were assumed to be varied independently without correlation among each other while acceptable thermal comfort to 70% of passengers was considered as the dependent variable. Considering most effective two thermal comfort parameters; temperature and relative humidity were detected in the indoor conditioned space of train compartments, during the questionnaire survey. Air velocity is considered as 0.2m/s averagely with reference to the specifications.

Questionnaire consisted with seven numbers of questions including one likert scale question with seven comfort levels such as: Very cold (-3), Cold (-2), Slightly cold (-1), Comfortable (0), Slightly warm (+1), warm (+2), Hot (+3) indicating signs from -3 to +3 according to the sensation of comfort level.

Standard method of developing comfort zone on the psychometric chart is by considering average neutral temperature of available stations as center line, intercept values and boundaries. Neutral temperatures were calculated by using annual mean dry bulb temperature values of each and every meteorological station. Comfort zone was obtained around the neutral temperature using standard method and it was extended & validated by using the survey data (responses for the questionnaire).

2.20 Prediction of cooling load using steady standard method

For estimating cooling load of passenger train compartment usually followed the standard method which is generally used for predicting cooling load of building envelops. Considering the train compartment as a static structure where the cooling load varied only with the time (hour of the day) calculations are done for the passenger carriage envelop using its dimensions, material properties, number of passengers (occupants), lighting & equipment, outdoor ambient conditions and solar intensities. In this case outdoor ambient conditions and solar radiation intensity are taken as that of data referred to Colombo city area as a main hub where all railway maintenance and operation have been controlled. Average values of hourly ambient temperature, relative humidity and solar radiation intensity referred to the Colombo meteorological station have been considered for the calculations assuming cooling load varied only with time. Then it has taken in to account separate possible heat gain measures to estimate cooling load as several components.

Cooling load components: The cooling load components considered are: 1)Conduction [$Q_c(t)$], 2) Radiation [$Q_R(t)$], 3) Ventilation[$Q_v(t)$], 4) Infiltration [$Q_I(t)$], 4) Occupancy [$Q_o(t)$] 5) Equipment and lighting [$Q_E(t)$]. Total dynamic cooling load has been given by the sum of all above component values.

Space heat gains: It is the rate of heat gained when heat enters to the space or heat generated within a space. The methods of how heat enters to the space are following

i. Solar radiation through the windows or any transparent surfaces
ii. Heat conduction through walls, roof and windows of the space
iii. Heat conduction through interior partitions, ceilings and floors.
iv. The generated heat by the occupants such as occupants, lights, appliances, equipment and processors
v. The loads that are results of ventilation and infiltration of outdoor air
vi. Other miscellaneous heat gains

External heat gains: External cooling loads consist of the following,

a) Sensible loads through opaque surfaces (roofs, walls, floors)
b) Sensible loads through transparent or translucent surfaces (skylights, windows, glazed openings)
c) Sensible loads through ventilation and infiltration (air leakage)
d) Latent loads through ventilation and infiltration

Sensible heat loads through Opaque surfaces: The heat flow through the sunlit wall (walls/surfaces which are directly exposed to the sun light) and interior partition (door windows, floor, ceiling, interior walls) are accountable for this. The heat gain is calculated by,

$Q=U * A * CLTD$ ------------------------ (1)

Where, Q= heat gain through sunlit walls), U = Overall heat transfer coefficient, A = Surface area, CLTD = Cooling load temperature difference

$Q=U * A * (T_b-T_i)$ ------------------------ (2)

Where, Q = heat gain through interior walls, T_b= Average air temperature of adjacent area, T_i = Indoor air temperature

U-value describes the rate of heat flow through a train compartment element. It is the reciprocal of the R-value; $U = 1/R_{Total}$, where R_{Total} is the total resistance of the materials used in the construction of wall. The higher the R-value, the higher shall be the insulating value of the material or the lower the U-value. The train body considered as a composite wall of three layers made of steel, glass wool and wood.

The CLTD is determined by the type of wall (assembly construction) and is affected by thermal mass, indoor and outdoor temperatures, daily temperature range, orientation, tilt, month, day, hour, latitude, solar absorbance, wall facing direction and other variables.

Sensible heat loads through the transparent surfaces: Total heat gains through the transparent surfaces are calculated by,

$$Q=U^* A^* (T_o-T_i) \text{ ----------------- } (3)$$

Where, Q= heat transfer by conduction, U = Overall heat transfer coefficient, A = Surface area, To= Outdoor air temperature, Ti = Indoor air temperature

$$Q(\text{through the radiation}) = A_{\text{unshaded area}}{}^* \text{ SHGF}^* \text{ SC}^* \text{ CLF ------------}(4)$$

Where, Q= heat gains through the radiation, SHGF = Solar heat gain factor, SC= Shading coefficient, CLF = Cooling load factor

The U-Factor is a measure of how easily heat travels through a material. The Solar Heat Gain Factor (SHGF) is the fraction of solar heat that enters the window and becomes heat. This includes both directly transmitted and absorbed solar radiation. SHGF is affected by orientation, tilt, time and the location. SC (shading coefficient) is a measure of the shading effectiveness of a glazing product. To determine shading coefficient one must first determine Solar Heat Gain Factor (SHGF).

CLF is the cooling load factor (dimensionless). CLF factors are used to account for the fact that compartment thermal mass creates a time lag between heat generation from internal sources and the corresponding cooling load. CLF factors are presented in a set of tables that account for number of hours the heat has been on thermal mass, type of furnishing or window shading, type of floor covering, number of walls, the indoor air circulation, the solar time, and the facing direction. Therefore, cooling load could be minimized with lower U-value, lower SHGF and lower CLF. Passive solar design techniques can be used to heat areas.

Sensible and latent heat load through ventilation and infiltration: Sensible heat gain through the ventilation and infiltration are calculated by,

Q (ventilation)= m_a*C_{pa}*(1-x)*(To-Ti) --------------- (5)

Q (infiltration)= m_a*C_{pa}*(To-Ti) ----------------------- (6)

Where, m_a= Air mass flow rate, C_{pa}= Specific heat capacity of air at given temperature, X = by-pass factor, To= Outside air temperature, Ti = Inside air temperature

Latent heat gain through ventilation and infiltration are calculated by using following equations,

Q (ventilation) = ma*h_{fg}*(1-x)*(Wo-Wi) ------------------- (7)

Q (infiltration) = ma*h_{fg}*(Wo-Wi) --------------------------- (8)

Where, ma = Air mass flow rate, h_{fg}= Latent heat of water at 1Atm, x= by-pass factor, Wo = Amount of moisture in outside air, Wi=Amount of moisture in inside air

As per the above equations, controlling/regulating air mass flow rate and by-pass factor heat gain by ventilation and infiltration could be reduced.

External Heat Gains

Internal cooling loads consist of the following,

a) Sensible and latent heat due to occupants.
b) Sensible heat through lightings.
c) Sensible and latent heat due to equipment.

Sensible and latent heat due to occupants:

Q (sensible) = N *(SHL/person) ------ (9)   Q (Latent) = N *(LHL/person) ----- (10)

Where, N =Number of occupants

Occupants generate both sensible and latent heat components according to activity level. The sensible heat rate increases slightly with higher activity however latent heat increases dramatically because of greater perspiration rates needed to maintain body temperature.

Sensible heat through lightings: Heat gain by lighting is calculated by,

Q = N * W * BF ------------ (11)

Where, N = No of lights, W = Wattage, BF= Balance factor

Improvements in lighting efficiency shall reduce the heat gain. Therefore type of bulb and the no of bulbs are the considerations for reducing heat gain.

Sensible and Latent heat gain due to equipment/appliances:

Q (Sensible) = N * ($W_{sensible\ load}$) ---- (12)   Q (Latent) = N * ($W_{latent\ load}$) ---- (13)

Where, N = Number of equipment

Reducing equipment heat gain offers very profitable opportunities for cooling load reductions and energy savings.

2.21 Prediction of cooling load using unsteady dynamic method

Prediction of dynamic cooling load is based on unsteady heat transfer process of the moving train compartment. Outdoor ambient conditions are varied with time and space (locations) while train moving across the different geographical areas of the country. Therefore the cooling load may be varied with changing outdoor conditions and number of passengers (occupants) during the train journey. Body conduction heat transfer has become unsteady state due to these rapid changes of outdoor ambient conditions. Also solar radiation effect, condition of ventilation air and infiltration air are changed with these variations of outdoor conditions along the train journey. Considering this situation, the dynamic cooling load can be estimated in component wise separately per each and every moment with reference to these changing outdoor conditions at that stage. Dynamic cooling load components considered are: 1) Conduction [$Q_c(t)$], 2) Radiation [$Q_R(t)$], 3) Ventilation[$Q_v(t)$], 4) Infiltration [$Q_I(t)$], 4) Occupancy [$Q_o(t)$] 5) Equipment and lighting [$Q_E(t)$]. Total dynamic cooling load is given by following equation [***41***],

$$Q_{Total}(t)=Q_C(t)+Q_R(t)+Q_V(t)+Q_I(t)+Q_O(t)+Q_E(t) \text{--- } (14)$$

It was assumed that the heat conduction through the immobile train compartment reached steady at starting station in each railway line. Hence corresponding steady temperature distribution in across the train body was taken as the initial condition for the unsteady heat conduction simulation for moving train compartment body. The two-dimension unsteady heat conduction equation given below was used to describe the heat transfer process of moving train compartment body.

$$\rho c\ \partial T/\partial t= \partial(k\ \partial T/\partial x)/\partial x + \partial(k\ \partial T/\partial y)/\partial y \text{ --- } (15)$$

ρ –Density of body material, c –Specific heat, k –Thermal conductivity, t –Time,

T –Temperature in rail passenger compartment body

Accordingly the internal surface temperatures of train compartment at selected stations were obtained using initial condition and boundary conditions calculated using ambient conditions and train speed of relevant selected station. Initial conditions were considered as external and internal surface temperatures of train compartment at starting station where train was stopped for long time reaching steady state of conduction heat transfer and speed taken zero value (V=0) where external surface heat transfer coefficient can be consider as constant (for this case 16 W/m^2). Thus initial external surface temperature was obtained using this constant value of heat transfer coefficient and ambient conditions (outdoor air temperatures and solar radiation intensities) of the starting station at the departure time of the train. Considering initial steady state conduction heat transfer condition, initial internal surface temperature was calculated. The boundary conditions were considered as external surface temperatures of other selected stations calculated using ambient conditions and external surface heat transfer coefficient which varied with relevant train speed at selected stations at times train passed through them [***41***].

$$\alpha o = 9+3.5V^{0.66}(V>0) \text{ ---------- } (16)$$

$$T_e = Tao + aJ/\alpha_o \text{ ------------ } (17)$$

Where αo - External surface heat transfer coefficient, V- Average velocity of the train, Te - External surface temperature, Tao-outdoor air temperature, a-The absorptance of train body surface for solar radiation, J-Solar radiant intensity

Thus four internal surfaces temperature of Right side wall, Left side wall, Roof and Floor were calculated for all selected stations at train travel times and then the conduction cooling load components of train compartment relevant to the all selected stations were estimated. Solar radiation heat gain on the air conditioned train compartments are varied with time & space. The directions of the sunlit walls, altitude and incident angle are varied with the movement of the train compartment, while the magnitude of the solar radiation & the directions of the sun path varying with the time. Accordingly the conduction heat storage and the radiation heat load were estimated using these changes of solar radiation effect.

Radiation load components relevant to the all selected stations were calculated using solar radiant intensities. Ambient temperatures and ambient relative humidity values relevant to the selected stations at the time train travelled through them, obtained with reference to the meteorological data. Ventilation and infiltration dynamic cooling load components were estimated with respect to the relevant ambient temperature, humidity and air density of selected stations at considered times. Occupancy cooling load components was estimated assuming the all available 44 seats filled with 44 numbers of passengers.

Chapter 3

DATA COLLECTION

3.1 Introduction

The data collection is the most important activity in the research study. However it was the most difficult target to be achieved in this case. Accurate data will make the result more realistic and useful. Hence the data were obtained accurately and adequately as possible as needed. Primary data were collected from railway passengers during their journey in selected type train compartment (S12) in mainline and northern line within one year period. All the required meteorological data have been obtained for recent four years from Meteorological Department of Sri Lanka. Hourly maximum temperatures, hourly maximum relative humidity values and hourly maximum solar radiation values obtained for relevant areas where selected railway stations located and, with reference to the times when selected trains travel through them. Also the dimensions & material properties of the selected train compartment and time table of selected train travels have been obtained from Sri Lanka Railway Department. All these data have been presented in tabulated form in this chapter under the categories of temperature data, steady cooling load estimation by standard method and dynamic cooling load estimation.

3.2 Temperature data collection from all available meteorological stations

It was needed to analyze annual temperature pattern all over the island to have a more realistic idea on average thermal condition in Sri Lanka. However temperature data were available at only 23 meteorological stations. Mean annual temperatures of 23 areas within the country (Table 3.1) have been obtained relevant to those stations where temperature data were available. All annual temperature data were collected from Meteorological department of Sri Lanka, as hourly, daily and monthly basis and average values were calculated up to mean annual temperatures of each and every relevant area. Thus neutral temperature of all these areas have been obtain by using relationship of neutral temperature (T_n) to mean annual temperature (T_o), $T_n=17.6+0.31T_o$, as presented in table 3.1.

Table3.1: Mean annual temperatures and respective neutral Temperatures

Meteorological Station	Mean Annual Temperature (˚C)	Neutral Temperature (˚C)	Meteorological Station	Mean Annual Temperature (˚C)	Neutral Temperature (˚C)
Colombo	28.17	26.33	Katunayake	27.98	26.27
Bandarawela	21.18	24.17	Ratmalana	28.52	26.44
Jaffna	28.42	26.41	Nuwara Eliya	16.48	22.71
Mannar	28.39	26.40	Baddulla	23.50	24.89
Vavuniya	28.28	26.37	Ratnapura	27.74	26.20
Trincomalee	28.72	26.50	Galle	27.54	26.14
Anuradhapura	28.50	26.44	Hambantota	28.30	26.37
Mahailluppallama	28.02	26.29	Pottuvil	28.48	26.43
Puttalam	28.35	26.39	Mattala	27.03	25.98
Batticalo	28.53	26.44	Monaragala	27.01	25.97
Kurunegala	28.15	26.33	Polonnaruwa	28.63	26.48
Katugastota	25.42	25.48	Average Neutral Temperature		26.00

*These mean annual temperature values have been calculated by using daily & monthly mean temperature values obtained from Meteorological Department of Sri Lanka

Selected Railway Stations in Mainline:

Colombo Fort (FOT), Gampaha (GPH), Polgahawella(PLG), Peradeniya (PDA), Nawalapitiya (NVP), Hatton (HTN), Nanu- oya (NOA), Pattipola (PPL), Haputale (HPT), Ella (ELL), Badulla (BAD)

Selected Railway Stations in Northern line:

Mount Lavinia (MLV), Colombo Fort (FOT), Gampaha (GPH), Polgahawella(PLG), Kurunegala (KRN), Anuradhapura (ANP), Vavuniya (VNA), Kilinochchi (KOC), Kodikamam (KKM), Jaffna (JFN), Kankesanthurei (KKS)

3.3 Steady Cooling load estimation using usual standard method

Table3.2: Outdoor climate & solar data used for steady cooling load estimation of train compartment by standard method

Time duration/ (hours)	CLTD/ Roof (K)	CLTD/ Floor (K)	CLTD/ East wall (K)	CLTD/ West wall (K)	SHGF/ East (W/m^2)	SHGF/ West (W/m^2)
5-6	0	0	0	0	0	0
6-7	0	0	7	1	170.37	6.31
7-8	3	1	17	2	422.77	25.24
8-9	10	3	26	3	489.03	25.24
9-10	18	12	30	5	438.55	41.02
10-11	27	14	32	6	309.19	44.17
11-12	34	16	28	8	129.36	44.17
12-13	38	17	22	10	44.17	44.17
13-14	43	18	18	15	44.17	129.36
14-15	44	19	17	23	44.17	309.19
15-16	42	18	16	32	41.02	438.55
16-17	38	17	16	36	34.71	489.03
17-18	33	16	15	38	25.24	422.77
18-19	25	14	14	36	6.31	170.37
19-20	17	12	12	26	0	0
20-21	10	3	8	16	0	0

CLTD – Cooling Load Temperature Difference
SHGF- Solar Heat Gain Factor

Presently, an appropriate cooling load estimation of air conditioned passenger train compartments is not available in Sri Lanka Railways. The existing air conditioned (A/C) rail compartments were imported or locally modified. Among them all central compact type air conditioned compartments were imported. Therefore these A/C train compartments might be designed according to the available international standards of thermal comfort and air conditioning for countries with tropical climate. These air conditioning systems and cooling loads might be overestimated for Sri Lankan context. Thus it can be predicted cooling loads in train compartment by applying usual standard methods assuming steady state condition on train body heat transfer, without considering the movement of the trains. In view of the above standard average climate data were tabulated in Table 3.2 for estimation.

3.4 Dynamic cooling load estimation considering variation of time & space

Table3.3: Directions of sunlit walls of the train compartment at selected stations

Railway Line	Station	Directions of solar facing walls: Travel in Upward – Right side wall	Travel in Upward – Left side wall	Travel in Downward – Right side wall	Travel in Downward – Left side wall
Main line	Colombo Fort	South	North	North	South
	Gampaha	South East	North West	North West	South East
	Polgahawela	South East	North West	North West	South East
	Peradeniya	West	East	East	West
	Nawalapitiya	North West	South East	South East	North West
	Hatton	South West	North East	North East	South West
	Nanuoya	West	East	East	West
	Pattipola	South West	North East	North East	South West
	Haputale	South	North	North	South
	Ella	South East	North West	North West	South East
	Badulla	South West	North East	North East	South West
Northern line	Mount Lavinia	East	West	West	East
	Colombo Fort	South	North	North	South
	Gampaha	South East	North West	North West	South East
	Polgahawela	South East	North West	North West	South East
	Kurunegala	South East	North West	North West	South East
	Anuradhapura	East	West	West	East
	Vavuniya	East	West	West	East
	Kilinochchi	East	West	West	East
	Kodikamam	North	South	South	North
	Jaffna	North East	South West	South West	North East
	Kankesanthurai	South	North	North	South

Averagely mainline is laid in east - west directions while sunlit walls of the trains travel in mainline facing north - south directions respectively. Also the northern line is laid along north – south directions while sunlit walls of the trains travel in northern line facing east – west directions respectively. However, in this case, to obtain possible solar radiation effect on heat gain and thereby to estimate actual radiation cooling load component approximately, directions of the sunlit walls of train compartment when it is at each and every selected stations have considered and tabulated as above. The possible real directions of sunlit walls of the train compartment at the selected stations with travel direction and with travel times were considered to calculate solar radiation values of selected moments.

Table3.4: Outdoor ambient conditions of selected stations with reference to the train travel times in mainline

Altitude (m)	Railway Station	Time	Outdoor Ambient Conditions							
			T_o (˚C)	RHo (%)	h (kJ/kg)	ρ (kg/m^3)	Solar Radiation Intensity (J)(W/m^2)			
							R/wall	L/wall	Roof	Floor
4.87	Colombo Fort	5:55 AM	27.5	78	73.86	1.16	3.15	9.46	3.15	0.79
10.97	Gampaha	6:31 AM	27.4	76.5	72.59	1.16	9.46	3.15	3.15	0.79
74.39	Polgahawela	7:18 AM	26	76	67.57	1.16	246.06	44.16	157.73	39.43
473.47	Peradeniya	8:33 AM	25	78.5	67.56	1.11	72.56	659.3	391.17	97.79
583.23	Nawalapitiya	9:48 AM	24.5	76.5	65.32	1.1	94.64	227.13	640.38	159.31
1262.5	Hatton	11:14 AM	23.5	74.5	63.88	1.01	119.87	369.09	820	205.05
1613.1	Nanuoya	12:45 PM	24	74.5	67.52	0.97	129.34	129.34	873.82	218.46
1897.56	Pattipola	13:24 PM	23.5	65.5	63.1	0.94	170.35	119.87	880.13	220.5
1479.57	Haputale	14:17 PM	26.5	62.5	68.22	0.98	110.41	283.91	725.56	181.39
1041.46	Ella	15:15 PM	28.5	60	71.27	1.02	94.64	589.91	580.44	145.11
652.43	Badulla	16:06 PM	31	68	84.81	1.06	422.72	69.4	397.48	99.37
652.43	Badulla	8:30 AM	23.5	65	56.06	1.09	615.15	75.71	384.86	96.21
1041.46	Ella	9:24 AM	25.5	63	62.95	1.03	94.64	227.13	577.29	144.32
1479.57	Haputale	10:25 AM	25.5	68.5	68.58	0.98	283.91	110.41	725.56	176.66
1897.56	Pattipola	11:19 AM	23.5	74.5	67.21	0.94	337.54	116.72	842.28	210.57
1613.1	Nanuoya	12:02 PM	24	74.5	67.52	0.97	119.87	119.87	946.37	236.59
1262.5	Hatton	13:20 PM	23.5	65.5	58.9	1.01	119.87	170.35	880.13	220.03
583.23	Nawalapitiya	14:52 PM	28.5	68	74.42	1.08	110.41	517.35	725.56	181.39
473.47	Peradeniya	16:16 PM	33	70.5	94.49	1.07	69.4	709.78	397.48	99.37
74.39	Polgahawela	17:38 PM	32	74	90.02	1.13	504.73	44.16	157.73	39.43
10.97	Gampaha	18:23 PM	30	75	81.83	1.15	0	0	0	0
4.87	Colombo Fort	18:57 PM	31	75.5	86.34	1.15	0	0	0	0

T_o - Ambient temperature, RH_o – Relative humidity, ρ –Atmospheric air density, h – Enthalpy of atmospheric air

Table3.5: Outdoor ambient conditions of selected stations with reference to the train travel times in northern line

Altitude (m)	Railway Station	Time	Outdoor Ambient Conditions							
			T_o (˚C)	RHo (%)	h (kJ/k)	ρ (kg/m^3)	Solar Radiation Intensity (J)(W/m^2)			
							R/wall	L/wall	Roof	Floor
4.57	Mount Lavinia	5:10 AM	29.5	75	79.77	1.15	0	0	0	0
4.87	Colombo Fort	5:45 AM	27.5	78	73.86	1.16	3.15	9.46	3.15	0.79
10.97	Gampaha	6:12 AM	27.4	76.5	72.59	1.16	6.3	0	3.15	0.79
74.39	Polgahawela	6:49 AM	26	76	67.53	1.16	9.46	3.15	3.15	0.79
122.86	Kurunegala	7:17AM	26.5	71	66.69	1.15	233.44	44.16	154.57	38.64
79.26	Anuradhapura	9:10 AM	30	63	73.71	1.14	602.53	94.64	580.44	145.11
79.57	Vavuniya	10:03 AM	33	64	86.01	1.13	463.72	110.41	735.02	182.97
23.17	Kilinochchi	11:00 AM	34	68.5	93.86	1.13	258.68	119.87	826.5	206.63
3.65	Kodikamam	11:32 AM	34	73	97.78	1.13	233.44	116.72	842.28	211.36
3.04	Jaffna	11:52 AM	34	73	97.77	1.13	337.54	116.72	842.28	211.36
3.04	Kankesanthurai	12:17 PM	35	73	102.65	1.13	119.87	233.44	873.82	218.46
3.04	Kankesanthurai	13:15PM	34.5	71	98.32	1.13	233.44	116.72	842.28	211.36
3.04	Jaffna	13:45 PM	34.5	71	98.32	1.13	129.34	129.34	826.5	206.63
3.65	Kodikamam	14:01 PM	35.5	70	102.14	1.13	110.41	283.91	725.56	181.39
23.17	Kilinochchi	14:37 PM	36.5	67	104.16	1.12	454.26	110.41	725.56	181.39
79.57	Vavuniya	15:34 PM	38	64	108.81	1.11	602.53	94.64	580.44	145.11
79.26	Anuradhapura	16:27 PM	36	61	72.02	1.12	709.78	69.4	397.48	99.37
122.86	Kurunegala	18:19 PM	31.5	68	83.44	1.13	25.24	3.15	3.15	0.79
74.39	Polgahawela	18:47 PM	31	82	91.78	1.13	0	0	0	0
10.97	Gampaha	19:24 PM	30	79	84.69	1.15	0	0	0	0
4.87	Colombo Fort	20:05 PM	30	87.5	90.71	1.15	0	0	0	0
4.57	Mount Lavinia	20:31PM	30	87	90.37	1.15	0	0	0	0

T_o - Ambient temperature, RHo – Relative humidity, ρ –Atmospheric air density, h – Enthalpy of atmospheric air

Table3.6: Solar-air temperature values of outer surfaces of the train compartment at times trains pass selected stations in mainline

Railway Station	Time	V (ms^{-1})	α◦ (W/m^2K)	Solar-air temperature (Te)/ (˚C)			
				R/wall	L/wall	Roof	Floor
Colombo Fort	5:55 AM	0	16	27.64	27.91	27.64	27.53
Gampaha	6:31 AM	80	72	27.49	27.43	27.43	27.41
Polgahawela	7:18 AM	80	72	28.39	26.43	27.53	26.38
Peradeniya	8:33 AM	40	49	26.04	34.42	30.59	26.4
Nawalapitiya	9:48 AM	40	49	25.85	27.74	33.65	26.78
Hatton	11:14 AM	25	38	25.71	30.3	38.61	27.28
Nanuoya	12:45 PM	25	38	26.38	26.38	40.10	28.02
Pattipola	13:24 PM	20	34	27.01	25.97	41.62	28.04
Haputale	14:17 PM	20	34	28.77	32.35	41.44	30.23
Ella	15:15 PM	20	34	30.45	40.65	40.45	31.49
Badulla	16:06 PM	20	34	39.70	32.43	39.18	33.05
Badulla	8:30 AM	0	16	50.41	26.81	40.34	27.71
Ella	9:24 AM	20	34	27.45	30.18	37.39	28.47
Haputale	10:25 AM	20	34	31.35	27.77	40.44	29.14
Pattipola	11:19 AM	20	34	30.45	25.9	40.84	27.84
Nanuoya	12:02 PM	25	38	26.21	26.21	41.43	28.36
Hatton	13:20 PM	25	38	25.71	26.64	39.71	27.55
Nawalapitiya	14:52 PM	40	49	30.08	35.89	38.87	31.09
Peradeniya	16:16 PM	40	49	33.99	43.14	38.68	34.42
Polgahawela	17:38 PM	80	72	36.91	32.43	33.53	32.38
Gampaha	18:23 PM	80	72	30.00	30.00	30.00	30.00
Colombo Fort	18:57 PM	80	72	31.00	31.00	31.00	31.00

V- Relevant maximum possible train velocity at the selected moments with reference to the latest speed restrictions of Sri Lanka railway department due to the existing condition of rail track &bridges

α◦ - Calculated external surface heat transfer coefficient of the train compartment with reference to the relevant maximum possible train velocity (Equation 16, Page62)

Table3.7: Solar air temperature values of outer surfaces of the train compartment at times trains pass selected stations in northern line

Railway Station	Time	V (ms^{-1})	α◦ (W/m^2K)	Solar-air Temperature (Te)/ (˚C)			
				R/wall	L/wall	Roof	Floor
Mount Lavinia	5:10 AM	0	16	29.50	29.50	29.50	29.50
Colombo Fort	5:45 AM	80	72	27.53	27.59	27.53	27.51
Gampaha	6:12 AM	80	72	27.46	27.40	27.43	27.41
Polgahawela	6:49 AM	80	72	26.09	26.03	26.03	26.01
Kurunegala	7:17AM	60	61	29.18	27.01	28.27	26.94
Anuradhapura	9:10 AM	60	61	36.91	31.09	36.66	31.67
Vavuniya	10:03 AM	100	82	36.96	33.94	39.27	34.56
Kilinochchi	11:00 AM	100	82	36.21	35.02	41.06	35.76
Kodikamam	11:32 AM	100	82	35.99	35.00	41.19	35.80
Jaffna	11:52 AM	100	82	36.88	35.00	41.19	35.80
Kankesanthurai	12:17 PM	60	61	36.38	37.68	45.03	37.51
Kankesanthurai	13:15PM	0	16	44.71	39.61	71.35	43.75
Jaffna	13:45 PM	100	82	35.60	35.60	41.56	36.26
Kodikamam	14:01 PM	100	82	36.44	37.92	41.69	37.05
Kilinochchi	14:37 PM	100	82	40.38	37.44	42.69	38.05
Vavuniya	15:34 PM	100	82	43.14	38.81	42.95	39.24
Anuradhapura	16:27 PM	60	61	44.15	36.8	40.56	37.14
Kurunegala	18:19 PM	60	61	31.79	31.54	31.54	31.51
Polgahawela	18:47 PM	80	72	31.00	31.00	31.00	31.00
Gampaha	19:24 PM	80	72	30.00	30.00	30.00	30.00
Colombo Fort	20:05 PM	80	72	30.00	30.00	30.00	30.00
Mount Lavinia	20:31PM	60	61	30.00	30.00	30.00	30.00

V- Relevant maximum possible train velocity at the selected moments with reference to the latest speed restrictions of Sri Lanka railway department due to the existing condition of rail track &bridges

α◦ - Calculated external surface heat transfer coefficient of the train compartment with reference to the relevant maximum possible train velocity (Equation 16, Page 62)

3.5 Material properties & dimensions of the selected train compartment

S12 type modern Chines-built blue train compartment presently used in Sri Lanka Railway was selected for this study. Totally 25 numbers of this type air conditioned train compartments are available in rolling stock of railway department. That was the highest number of air conditioned train compartments available in same type and also that was the latest modern type model had been added to the service when this type A/C train compartment (S12) selected for this study at the end of the year 2017. The train compartment (2.9m*2.55m*15.24m) consisted with 44 numbers of semi-cushioned seats and central compact type air-condition unit of 35kW rated capacity which has been installed on roof top.

Table3.8: Material properties and thickness of each layer in train body

Layer	**Material**	**Thickness (mm)**	**Density (kg/m^3)**	**Specific heat (kJ/Kg°K)**	**Thermal conductivity (W/mK)**
Outer wall	Steel	2	7850	0.48	50
Middle	Glass wool	90	200	1.22	0.08
Inner wall	wood	20	300	1.89	0.09

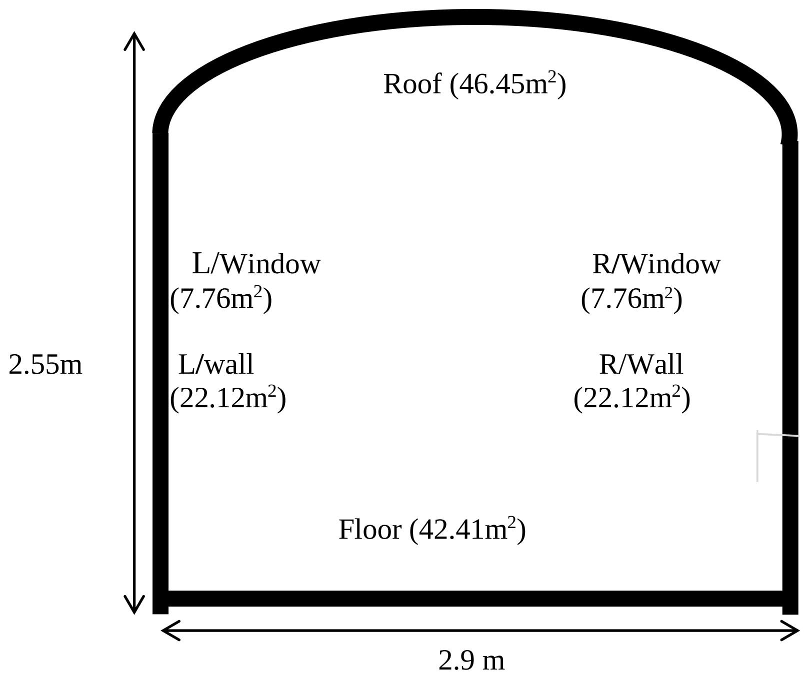

Figure3.1: Body of train compartment (Surface Areas)

Table3.9: Coefficients used for simulation

No:	Coefficient	value
1	Transmittance for window glass	0.6
2	Absorptance for train body surface	0.7
3	Aggregation coefficient	0.955
4	Transfer coefficient for radiation cooling load	0.7
5	Transfer coefficient for occupancy cooling load	0.95
6	Transfer coefficient for equipment cooling load	0.75
7	Thermal conductivity for widow glass (Thickness: 12mm)	0.76 w/mK
8	Shading coefficient for window curtain (no curtain used) [SC]	1
9	Cooling load factor (CLF)	1
10	Convective heat transfer coefficient of moving air- outdoor (h_o)	15w/m^{2}K
11	Convective heat transfer coefficient of still air - indoor (h_i)	10 w/m^{2}K
12	Average heat transfer coefficient for window glass (calculated value for this case)	5.47 w/mK
13	Average heat transfer coefficient through train body (calculated value only used for steady conduction)	0.664 w/mK
14	Ventilation rate per person (as per the specifications)	20m^3/hr
15	Sensible heat emission passenger	69.8 W
16	Latent heat emission passenger	46.5 W
17	Transfer coefficient for occupancy cooling load	0.95
18	Transfer coefficient for equipment cooling load	0.75

Assumptions: Infiltration flow rate = 0.3* (total volume of indoor space) and Total heat emission from the equipment at indoor space is 1.2 kW.

3.6 Summary

Primary data were collected from 186 participants at the questionnaire survey as responses for onsite indoor thermal sensation. Secondary data consisted with meteorological data and material properties & dimensions of the selected train compartment were obtained from Sri Lanka Meteorological Department and Sri Lanka Railway Department respectively. Also the distances among railway stations, altitude, directions of sunlit wall at train travels, time table of selected train travels, train speed limits at relevant stations have been collected.

Chapter 4

ANALYSIS AND RESULTS

4.1 Introduction

All the data were analyzed under three steps. First, the results of questionnaire survey and available annual mean temperatures of different areas in all over the country were analyzed and comfort zone was developed according to the responses of passengers participated in the survey. Second, the steady cooling load for a static rail compartment has been estimated by using usual standard method and the dynamic cooling loads of moving train compartment in mainline & northern line have been estimated separately by components and totally. All these cooling load values were tabulated and plotted graphs separately for upward travel in mainline, downward travel in mainline and upward & downward travel in northern line to observe the variations of cooling loads with respect to the used method of estimation (dynamic or standard steady), time period of traveling and region of traveling. Third, most influential factors of variation in dynamic cooling load were identified by using multiple linear regression analysis in MS Excel software.

4.2 Indoor thermal comfort conditions

4.2.1 Demographic distribution analysis on survey data

Primary data have been collected through a questionnaire survey of railway passengers in main railway line & northern railway line in Sri Lanka. About 200 passengers traveled in air conditioned 1st class compartments were interviewed by using standard questionnaire (Appendix). Out of 200 participants, 80 numbers of passengers participated for the survey from mainline while other 120 numbers of passengers participated from northern line. More numbers of passenger participation from northern line than that of mainline was happened due to the availability of more air conditioned train compartments in northern line comparison with that of in mainline. However among 200 received answered questionnaires, 186 valid answered questionnaires were considered for further analysis. Out of 186 valid answers 74 numbers obtained from mainline while other 112 numbers obtained from northern line. Only 1st class compartments are consisted with air conditioned facilities. Therefore 1st class compartments of train No. 1005 & train No. 1006 travel in mainline and complete air conditioned trains in number 4021 & 4022 which travel in northern line were considered for this study. The survey has been carried out within one year duration (from December 2017 to December 2018) for both railway lines in 7 steps. Details of Survey, Demographical data analysis and thermal comfort responses of participants are presented in table 4.1, table 4.2& table 4.3 respectively.

Table4.1: Details of questionnaire survey

Step	Month	Railway line	Number of participants	Numbers of valid answered questionnaires obtained
1	2017 December	Mainline	20	17
2	2018 February	Northern line	40	36
3	2018 April	Mainline	20	19
4	2018 June	Northern line	40	37
5	2018 August	Mainline	20	18
6	2018 October	Mainline	20	20
7	2018 December	Northern line	40	39
Total			200	186

The demographic characteristics of participants were tabulated in Table 4.2. Age, gender, and residential area (province) were the characteristic considered. As shown in Table 4.2, majority of the participants were male (55.9%), because the most of the travelers were male as usual. However considerable percentage of female was participated (44.1%). Participant came from all nine province of the country, though majority of them were from western, northern and central as percentage of total it has shown 21%, 17% and 15% respectively. It may be due to the selected rail lines were across these areas. However hot, cool and average climate conditions were met in these areas. According to the age levels of participants, it has shown that averagely all age limits represented in the survey. It was highlighted that the passengers of 25- 44 age limits were given the highest percentage of participation and the most sensitive group for the thermal sensation.

Table4.2: Demographical details of passengers participated for the survey

Type	Selection	Numbers of participant	Percent %
Gender	Male	104	55.9
	Female	82	44.1
Age (years)	< 25	42	22.6
	25 - 44	57	30.7
	45 - 60	49	26.3
	> 60	38	20.4
Province of resident	Western	39	21
	Central	28	15
	North Central	16	8.5
	Northern	31	17
	Eastern	7	4
	Southern	23	12
	Sabaragamuwa	11	6
	Uva	19	10
	North western	12	6.5

4.2.2 Passengers responses on indoor thermal condition

Table4.3: Results of questionnaire survey

Dry Bulb Temperature (°C)	R.H%	Comfort		Discomfort	
		Number of responses	Percentage	Number of responses	Percentage
20.0-21.0	60-65	0	0	8	100.00%
23.0-24.0	45-50	7	23.33%	23	76.66%
23.0-24.0	60-65	2	16.67%	10	83.33%
24.0-25.0	45-50	24	80.00%	6	20.00%
24.0-25.0	60-65	11	91.67%	1	8.33%
25.0-26.0	50-55	12	85.71%	2	14.29%
25.0-26.0	70-75	4	40.00%	6	60.00%
26.0-27.0	65-70	8	72.72%	3	27.27%
26.0-27.0	75-80	7	77.78%	2	22.22%
27.0-28.0	70-75	6	60.00%	4	40.00%
27.0-28.0	75-80	3	30.00%	7	70.00%
28.0-29.0	75-80	7	63.64%	4	36.36%
29.0-30.0	70-75	6	66.67%	3	33.33%
30.0-31.0	70-75	4	40.00%	6	60.00%

In this case it is assumed that the indoor conditions are kept as averagely resulting values all over the cabin environment. Thus the PMV/ PPD indices can be calculated in a single point and were supposed to consider the resulting values all over the indoor environment of train compartment.

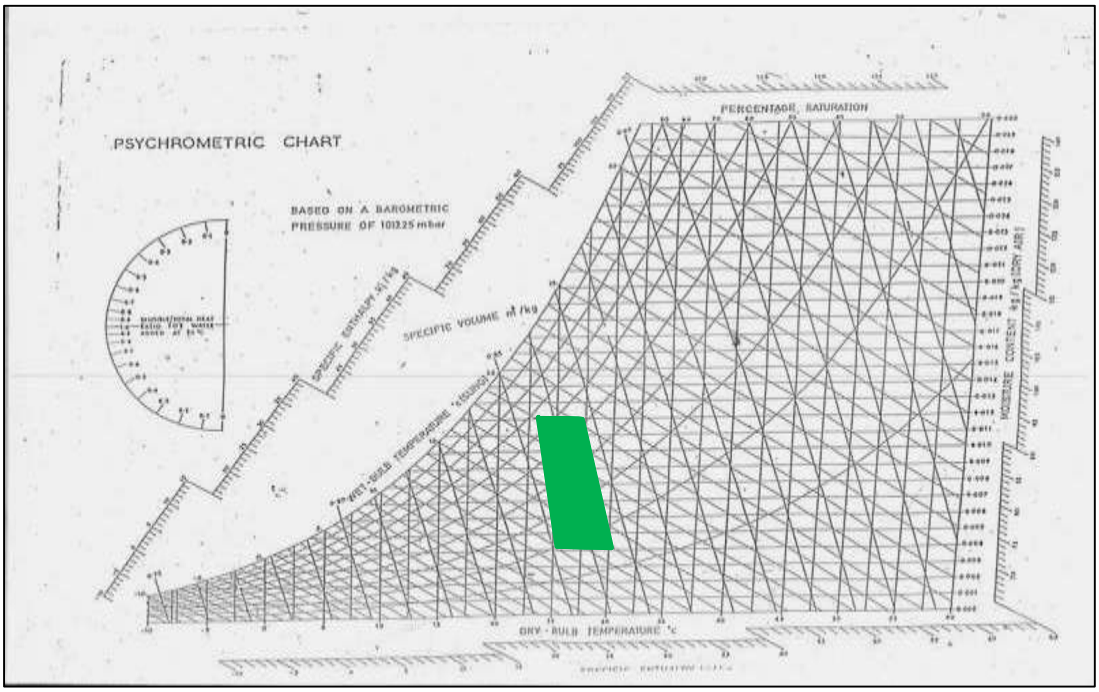

Figure4.1: Standard comfort zone developed for railway passengers

Standard comfort zone for indoor state of train compartments averagely railway passengers in Sri Lanka, can be identified on the psychrometric chart. The indoor air velocity was taken as 0.2 m/s as per the specifications of the selected train compartment. Standard comfort zone (Green colour) has been decided using meteorological data, annual mean dry bulb temperature (To) and then neutral temperature given by [4]: Tn=17.6+0.31To, it was obtained as 26˚C (Tabel 4.1) and it was given that,

$T_{intercept}$ = T+23(T-14)HRt where HRt = humidity ratio (Kgw/Kg,d.a). Boundaries were obtained by using two Standard Effective Temperature (SET) lines corresponding to, $T_1 = T_n - 2˚C$ and $T_2 = T_n + 2˚C$ points on 50% RH curve. The top and bottom boundaries will be at 0.012 and 0.004 humidity ratio levels. This standard comfort zone was extended (Yellow Colour) according to the responses of the questionnaire survey (Table 4.3).

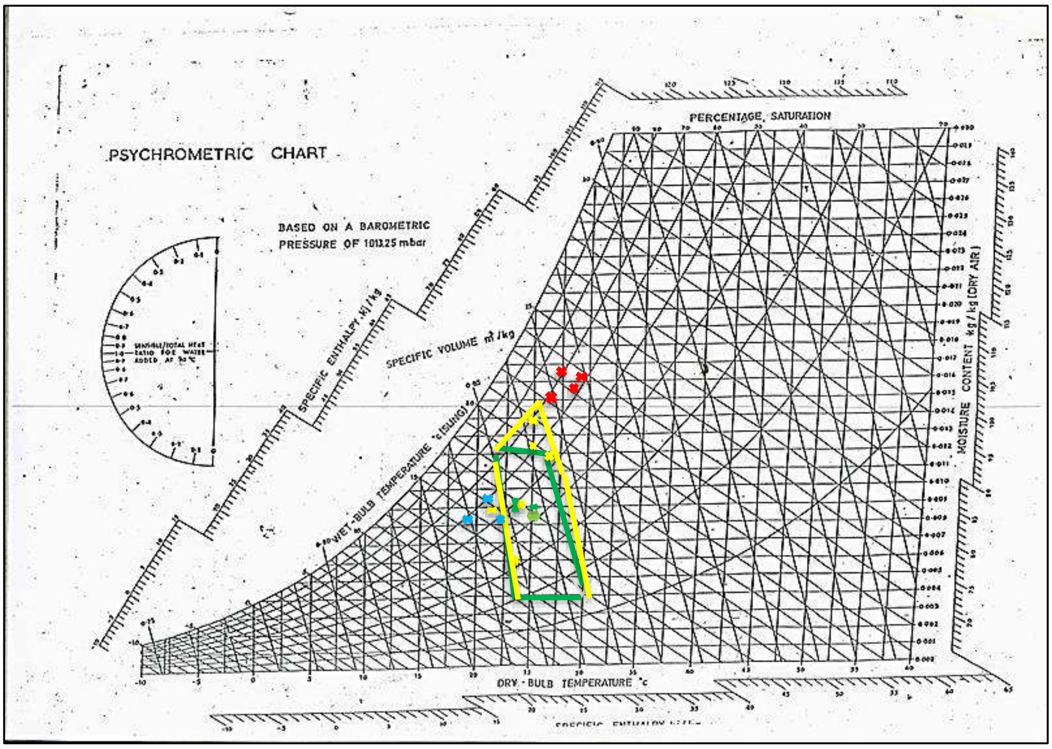

Figure4.2: Extension of standard comfort zone according to the responses of passengers participated for the questionnaire survey

The boundaries of the standard comfort zone were determined using a set of lines called standard effective temperature which represents the combined effects of temperature, humidity, radiation and air velocity for indoor space. Accordingly average standard comfort zone has been developed for Sri Lanka is shown in Figure 4.1, where a neutral temperature of 26˚C was used.

Modification of the standard comfort zone for the responses of the questionnaire survey (as per Table 4.3) is shown in Figure 4.2 and then after completion in Figure 4.3 below. The combination of two environmental variables, dry bulb temperature and humidity of internal air, which form the conditions that around 70% of the population find the whole body thermally comfortable, were considered as comfort zone. It can be seen that the standard modifications which have been taken account of railway passenger's responses, shift the modified comfort zone into very high humidity ratios as the neutral temperatures high as for tropical climates. Therefore it can be appropriate to introduce an upper boundary of humidity ratio level 0.015 higher than that of humidity ratio level of 0.012 in standard comfort zone.

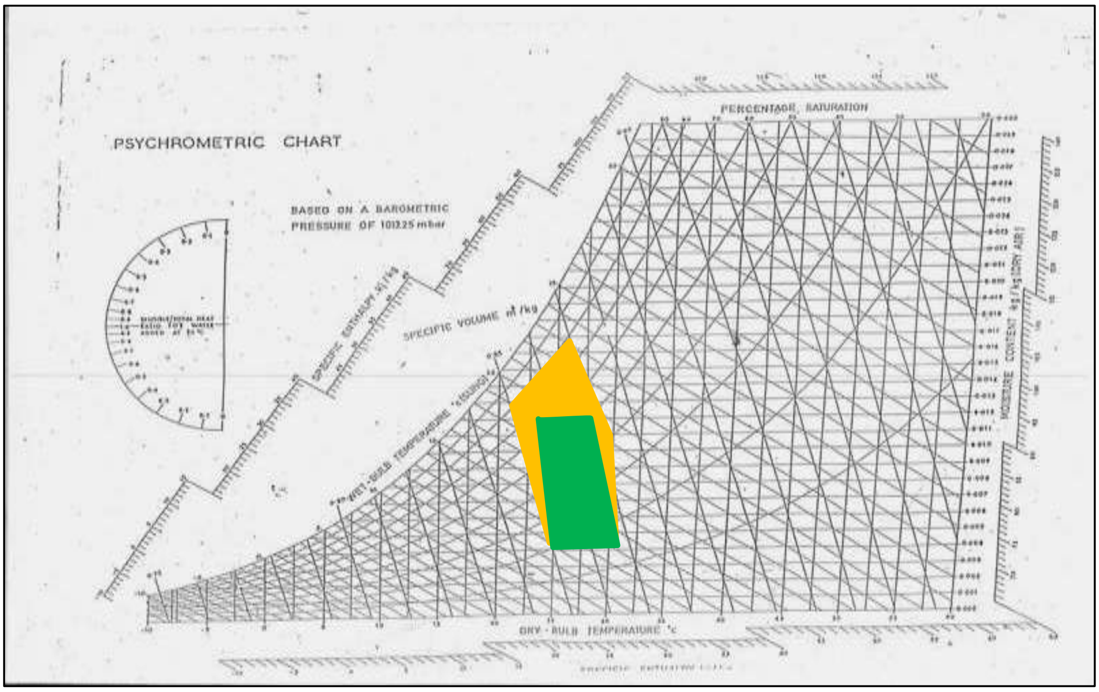

Figure4.3: Extended comfort zone applicable to railway passengers in Sri Lanka

Accordingly indoor thermal conditions of 26˚ C & 55% RH were considered as constant values for predicting dynamic cooling loads. Variation of dynamic cooling load values in between selected stations were assumed as linear. Considering all passengers were seated (activity level) with light to medium clothing (around 0.8 clo), Internal air velocity less than 0.2m/s and without any asymmetrical radiation from surrounding surfaces comfort conditions were decided.

Considering the average value of neutral temperatures of 23 locations around Sri Lanka, with reference to the existing mean temperature data of 23 numbers of meteorological stations standard comfort zone for indoor spaces was defined and it has been extended up to acceptable level using the responses of the questionnaire survey held for railway passengers. Accordingly most effective indoor thermal comfort parameters (26˚C & 55%RH) were selected as fixed values for predicting cooling loads. Using these indoor thermal comfort conditions (26˚C & 55%RH), dynamic cooling load values for selected stations in mainline and northern line were estimated considering the variable outdoor ambient conditions with respect to the time and locations of the travels of the selected trains.

4.3 Estimation of standard steady cooling loads for a train compartment

Steady cooling loads components conduction (body conduction + window conduction), radiation, ventilation, infiltration, occupancy and equipment were estimated using traditional method used for building and non-moving condition spaces. Considering this train compartment located in Colombo. All climatic data and other factors obtain as average values with reference to the ASRAE & meteorological data of Colombo. It was assumed that the body conduction heat transfer process was steady state & outdoor ambient conditions were only varied with time during the day. Estimated total static steady cooling load values **[Q_{ss}]** have been taken to the dynamic cooling loads tables hereafter for comparison purposes.

Table4.4: Standard steady cooling loads for a passenger train compartment

Time (hours)	Conduction cooling load (kW)	Radiation cooling load (kW)	Ventilation cooling load (kW)	Infiltration cooling load (kW)	Occupancy cooling load (kW)	Equipment cooling load (kW)	Total STD steady cooling load [Q_{ss}] (kW)
5-6	0.849	0	17.042	0.602	5.5	1.2	25.193
6-7	0.966	1.371	17.042	0.602	5.5	1.2	26.681
7-8	1.249	3.477	17.042	0.602	5.5	1.2	29.069
8-9	1.668	3.991	17.042	0.602	5.5	1.2	30.002
9-10	2.256	3.721	17.042	0.602	5.5	1.2	30.321
10-11	2.634	2.742	17.042	0.602	5.5	1.2	29.72
11-12	2.877	1.347	17.042	0.602	5.5	1.2	28.567
12-13	2.970	0.659	17.042	0.602	5.5	1.2	27.972
13-14	3.167	1.347	17.042	0.602	5.5	1.2	28.857
14-15	3.329	2.742	17.042	0.602	5.5	1.2	30.414
15-16	3.356	3.721	17.042	0.602	5.5	1.2	31.421
16-17	3.263	4.063	17.042	0.602	5.5	1.2	31.67
17-18	3.096	3.477	17.042	0.602	5.5	1.2	30.916
18-19	2.749	1.371	17.042	0.602	5.5	1.2	28.463
19-20	2.269	0	17.042	0.602	5.5	1.2	26.613
20-21	1.594	0	17.042	0.602	5.5	1.2	25.938

All these cooling load values were estimated using standard steady method for static S12 train compartment using climatic data of Colombo as per the table 3.2 in chapter 3

4.4 Estimation of dynamic unsteady cooling loads for a train compartment

Table4.5: External & Internal train body surface temperatures at times trains pass selected stations in mainline

Railway Station	Time	External surface temperature (Te) / (˚K)				Internal surface temperature (Twi) / (˚K)			
		R/wall	L/wall	Roof	Floor	R/wall	L/wall	Roof	Floor
Colombo Fort	5:55 AM	300.64	300.91	300.64	300.53	299.16	299.19	299.16	299.15
Gampaha	6:31 AM	300.49	300.43	300.43	300.41	299.15	299.14	299.14	299.14
Polgahawela	7:18 AM	301.39	299.43	300.53	299.38	299.23	299.04	299.15	299.04
Peradeniya	8:33 AM	299.04	307.42	303.59	299.4	299	299.83	299.45	299.04
Nawalapitiya	9:48 AM	298.85	300.74	306.65	299.78	298.98	299.17	299.75	299.08
Hatton	11:14 AM	298.71	303.3	311.61	300.28	298.97	299.42	300.24	299.12
Nanuoya	12:45 PM	299.38	299.38	313.1	301.02	299.04	299.04	300.39	299.2
Pattipola	13:24 PM	300.01	298.97	314.62	301.04	299.1	299	300.53	299.2
Haputale	14:17 PM	301.77	305.35	314.44	303.23	299.27	299.62	300.52	299.42
Ella	15:15 PM	303.45	313.65	313.45	304.49	299.44	300.44	300.42	299.54
Badulla	16:06 PM	312.70	305.43	312.18	306.05	300.35	299.63	300.3	299.69
Badulla	8:30 AM	323.41	299.81	313.34	300.71	301.4	299.08	300.41	299.17
Ella	9:24 AM	300.45	303.18	310.39	301.47	299.14	299.41	300.12	299.24
Haputale	10:25 AM	304.35	300.77	313.44	302.14	299.52	299.17	300.42	299.31
Pattipola	11:19 AM	303.45	298.9	313.84	300.84	299.44	298.99	300.46	299.18
Nanuoya	12:02 PM	299.21	299.21	314.43	301.36	299.02	299.02	300.52	299.23
Hatton	13:20 PM	298.71	299.64	312.71	300.55	298.97	299.06	300.35	299.15
Nawalapitiya	14:52 PM	303.08	308.89	311.87	304.09	299.4	299.97	300.26	299.50
Peradeniya	16:16 PM	306.99	316.14	311.68	307.42	299.78	300.68	300.25	299.83
Polgahawela	17:38 PM	309.91	305.43	306.53	305.38	300.07	299.63	299.74	299.63
Gampaha	18:23 PM	303.00	303.00	303.00	303.00	299.39	299.39	299.39	299.39
Colombo Fort	18:57 PM	304.00	304.00	304.00	304.00	299.49	299.49	299.49	299.49

Table4.6: External & Internal train body surface temperatures at times trains pass selected stations in northern line

Railway Station	Time	External surface temperature (Te) / (˚K)				Internal surface temperature (Twi) / (˚K)			
		R/wall	L/wall	Roof	Floor	R/wall	L/wall	Roof	Floor
Mount Lavinia	5:10 AM	302.50	302.50	302.50	302.50	299.34	299.34	299.34	299.34
Colombo Fort	5:45 AM	300.53	300.59	300.53	300.51	299.15	299.16	299.15	299.15
Gampaha	6:12 AM	300.46	300.40	300.43	300.41	299.14	299.14	299.14	299.14
Polgahawela	6:49 AM	299.09	299.03	299.03	299.01	299.01	299.00	299.00	299.00
Kurunegala	7:17AM	302.18	300.01	301.27	299.94	299.31	299.1	299.22	299.09
Anuradhapura	9:10 AM	309.91	304.09	309.66	304.67	300.07	299.5	300.05	299.56
Vavuniya	10:03 AM	309.96	306.94	312.27	307.56	300.08	299.78	300.30	299.84
Kilinochchi	11:00 AM	309.21	308.02	314.06	308.76	300.00	299.89	300.48	299.96
Kodikamam	11:32 AM	308.99	308.00	314.19	308.8	299.98	299.88	300.49	299.96
Jaffna	11:52 AM	309.88	308.00	314.19	308.8	300.07	299.88	300.49	299.96
Kankesanthurai	12:17 PM	309.38	310.68	318.03	310.51	300.02	300.15	300.87	300.13
Kankesanthurai	13:15PM	317.71	312.61	344.35	316.75	300.84	300.34	303.46	300.74
Jaffna	13:45 PM	308.60	308.60	314.56	309.26	299.94	299.94	300.53	300.01
Kodikamam	14:01 PM	309.44	310.92	314.69	310.05	300.03	300.17	300.54	300.09
Kilinochchi	14:37 PM	313.38	310.44	315.69	311.05	300.41	300.12	300.64	300.18
Vavuniya	15:34 PM	316.14	311.81	315.95	312.24	300.68	300.26	300.67	300.30
Anuradhapura	16:27 PM	317.15	309.8	313.56	310.14	300.78	300.06	300.43	300.09
Kurunegala	18:19 PM	304.79	304.54	304.54	304.51	299.57	299.54	299.54	299.54
Polgahawela	18:47 PM	304.00	304.00	304.00	304.00	299.49	299.49	299.49	299.49
Gampaha	19:24 PM	303.00	303.00	303.00	303.00	299.39	299.39	299.39	299.39
Colombo Fort	20:05 PM	303.00	303.00	303.00	303.00	299.39	299.39	299.39	299.39
Mount Lavinia	20:31PM	303.00	303.00	303.00	303.00	299.39	299.39	299.39	299.39

Table4.7: Dynamic cooling load components, total dynamic & standard steady cooling loads at selected stations in mainline (Colombo – Badulla) - Upward

Distance (km)*	Altitude (m)	Railway Station	Time	Cooling Loads of train compartment (kW)							
				Q_C	Q_R	Q_V	Q_I	Q_O	Q_E	Q_{DY}	Q_{SS}
0	4.87	Colombo Fort	5:55 AM	0.299	0.041	5.055	0.178	4.86	1.2	11.634	25.193
28	10.97	Gampaha	6:31 AM	0.268	0.041	4.696	0.166	4.86	1.2	11.23	26.681
74	74.39	Polgahawela	7:18 AM	0.117	0.946	3.275	0.116	4.86	1.2	10.513	29.069
115	473.47	Peradeniya	8:33 AM	0.242	2.385	3.131	0.111	4.86	1.2	11.929	30.002
141	583.23	Nawalapitiya	9:48 AM	0.205	1.049	2.501	0.088	4.86	1.2	9.9032	30.321
175	1262.5	Hatton	11:14 AM	0.36	1.594	1.942	0.069	4.86	1.2	10.024	28.567
207	1613.1	Nanuoya	12:45 PM	0.425	0.843	2.727	0.096	4.86	1.2	10.151	27.972
227	1897.56	Pattipola	13:24 PM	0.442	0.946	1.628	0.057	4.86	1.2	9.1342	28.857
247	1479.57	Haputale	14:17 PM	0.905	1.285	2.922	0.103	4.86	1.2	11.276	30.414
271	1041.46	Ella	15:15 PM	1.254	2.231	3.8	0.134	4.86	1.2	13.48	31.421
292	652.43	Badulla	16:06 PM	1.49	1.604	7.451	0.263	4.86	1.2	16.869	31.67

*Distances are indicated as rail track length to the considered station from Colombo Fort station

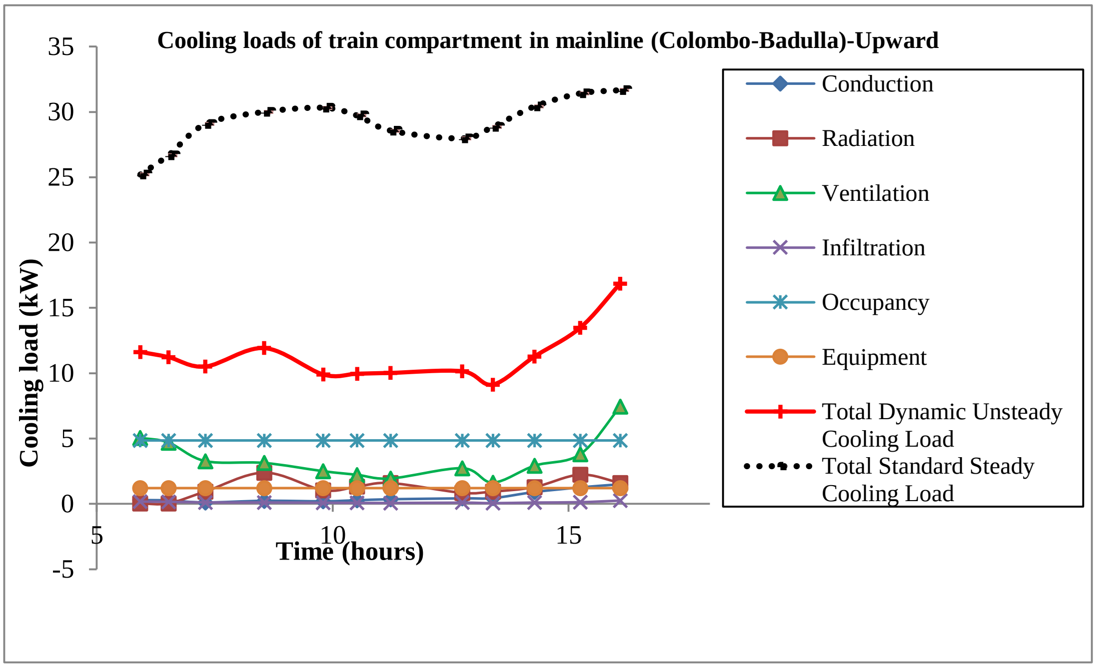

Figure4.4: Variation in dynamic cooling load components, total dynamic cooling load and total standard static steady cooling load of train compartment (At Train No: 1005)

Table4.8: Dynamic cooling load components, total dynamic & standard steady cooling loads at selected stations in mainline (Badulla- Colombo) – Downward

Distance (km)*	Altitude (m)	Railway Station	Time	Cooling Loads of train compartment (kW)							
				Q_C	Q_R	Q_V	Q_I	Q_O	Q_E	Q_{DY}	Q_{SS}
292	652.43	Badulla	8:30 AM	0.806	2.252	0.016	0.001	4.86	1.2	9.135	30.002
271	1041.46	Ella	9:24 AM	0.553	1.049	1.747	0.062	4.86	1.2	9.470	30.321
247	1479.57	Haputale	10:25 AM	0.712	1.285	3.008	0.106	4.86	1.2	11.172	29.72
227	1897.56	Pattipola	11:19 AM	0.466	1.481	2.571	0.091	4.86	1.2	10.668	28.567
207	1613.1	Nanuoya	12:02 PM	0.479	0.781	2.727	0.096	4.86	1.2	10.143	27.972
175	1262.5	Hatton	13:20 PM	0.346	0.946	0.715	0.025	4.86	1.2	8.0913	28.857
141	583.23	Nawalapitiya	14:52 PM	1.094	2.046	4.854	0.171	4.86	1.2	14.226	30.414
115	473.47	Peradeniya	16:16 PM	1.775	2.54	10.05	0.355	4.86	1.2	20.778	31.67
74	74.39	Polgahawela	17:38 PM	1.298	1.789	9.38	0.331	4.86	1.2	18.858	30.916
28	10.97	Gampaha	18:23 PM	0.757	0	7.248	0.256	4.86	1.2	14.321	28.463
0	4.87	Colombo Fort	18:57 PM	0.947	0	8.513	0.301	4.86	1.2	15.821	26.613

*Distances are indicated as rail track length to the considered station from Colombo Fort station

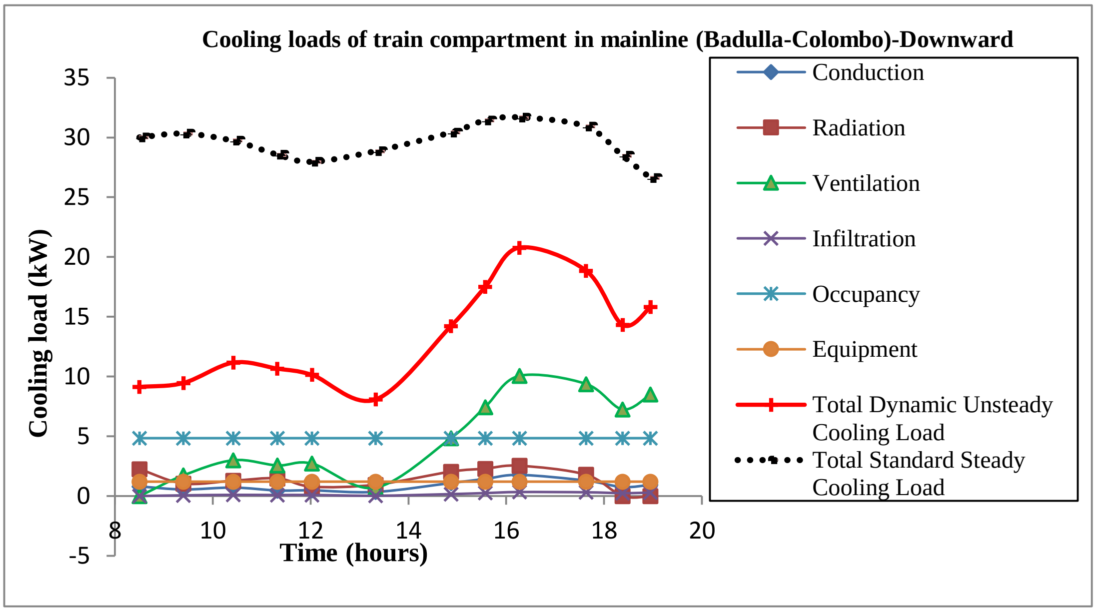

Figure4.5: Variation in dynamic cooling load components, total dynamic cooling load and total standard static steady cooling load of train compartment (At Train No: 1006)

Table4.9: Dynamic cooling load components, total dynamic & standard steady cooling loads at selected stations in northern line - Upward & Downward

Distance (km)*	Altitude (m)	Railway Station	Time	Cooling Loads of train compartment(kW)							
				Q_C	Q_R	Q_V	Q_I	Q_O	Q_E	Q_{DY}	Q_{SS}
14	4.57	Mount Lavinia	5:10 AM	0.662	0	6.6699	0.235	4.86	1.2	13.628	25.193
0	4.87	Colombo Fort	5:45 AM	0.287	0.041	5.0551	0.178	4.86	1.2	11.621	25.193
28	10.97	Gampaha	6:12 AM	0.267	0.021	4.6956	0.166	4.86	1.2	11.209	26.681
74	74.39	Polgahawela	6:49 AM	0.002	0.041	3.2635	0.115	4.86	1.2	9.4822	26.681
94	122.86	Kurunegala	7:17AM	0.229	0.905	2.9996	0.106	4.86	1.2	10.299	29.069
207	79.26	Anuradhapura	9:10 AM	1.195	2.272	4.9262	0.174	4.86	1.2	14.628	30.321
252	79.57	Vavuniya	10:03 AM	1.693	1.871	8.2744	0.292	4.86	1.2	18.19	29.72
328	23.17	Kilinochchi	11:00 AM	1.889	1.234	10.439	0.369	4.86	1.2	19.99	28.567
370	3.65	Kodikamam	11:32 AM	1.891	1.141	11.52	0.407	4.86	1.2	21.018	28.567
393	3.04	Jaffna	11:52 AM	1.906	1.481	11.517	0.407	4.86	1.2	21.37	28.567
411	3.04	Kankesanthurai	12:17 PM	2.226	1.152	12.862	0.454	4.86	1.2	22.754	27.972
411	3.04	Kankesanthurai	13:15PM	3.532	1.141	11.668	0.412	4.86	1.2	22.814	28.857
393	3.04	Jaffna	13:45 PM	1.965	0.843	11.668	0.412	4.86	1.2	20.949	28.857
370	3.65	Kodikamam	14:01 PM	2.137	1.285	12.722	0.449	4.86	1.2	22.653	30.414
328	23.17	Kilinochchi	14:37 PM	2.351	1.84	13.161	0.465	4.86	1.2	23.878	30.414
252	79.57	Vavuniya	15:34 PM	2.6	2.272	14.303	0.505	4.86	1.2	25.74	31.421
207	79.26	Anuradhapura	16:27 PM	2.255	2.54	4.3779	0.155	4.86	1.2	15.387	31.67
94	122.86	Kurunegala	18:19 PM	1.049	0.093	7.5658	0.267	4.86	1.2	15.034	28.463
74	74.39	Polgahawela	18:47 PM	0.947	0	9.8653	0.348	4.86	1.2	17.22	28.463
28	10.97	Gampaha	19:24 PM	0.757	0	8.0504	0.284	4.86	1.2	15.152	26.613
0	4.87	Colombo Fort	20:05 PM	0.757	0	9.7396	0.344	4.86	1.2	16.901	25.938
14	4.57	Mount Lavinia	20:31PM	0.757	0	9.6442	0.341	4.86	1.2	16.802	25.938

*Distances are indicated as rail track length to the considered station from Colombo Fort station

Note: During the time in between 12:17 PM to 13:15 PM, the train was at stop position and it can be considered as an unoccupied period without using air conditioning (no requirement of cooling load)

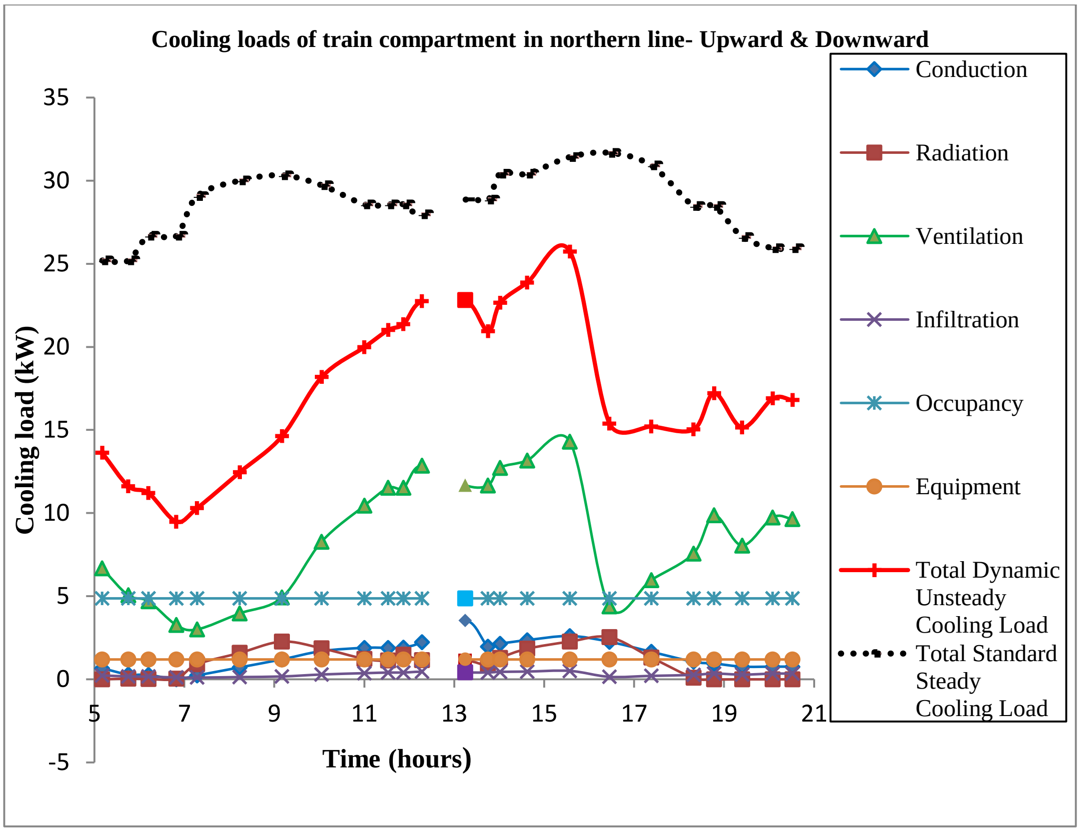

Figure4.6: Variation in dynamic cooling load components, total dynamic cooling load and total standard static steady cooling load of train compartment (At Train No: 4021& 4022)

For Mainline (Colombo-Badulla), two passenger trains which consisted with air conditioned compartments and traveled in day time were considered for the study. One train (Train no.1005) starting from Colombo Fort station at 5:55 AM and ended journey at 16:06 PM in Badulla station on the same day. The other one (Train no.1006) started from Badulla station at 8:30 AM and ended journey at 18:57 PM in Colombo Fort Station on the same day. Both trains passed through the hill country at the afternoon (Figure 4.4 & figure 4.5). For Northern line two passenger trains (Trains numbered 4021 & 4022 as per two turns of the same set of train compartments) were selected. This set of train compartments is completely air conditioned which started from Mount Lavinia at 5:10 AM as train no.4021 and ended its journey in Kankesanthurai at 12:17 PM and returned (as train no.4022) from Kankesanthurai at 13:15 PM and ended in Mount Lavinia at 20.31 PM (Figure 4.6). This trains passed Northern area at the afternoon & early evening hours when cooling load requirements at its highest values.

4.5 Numerical estimation of dynamic cooling load at any moment based on the calculated values at selected stations & times trains pass through them

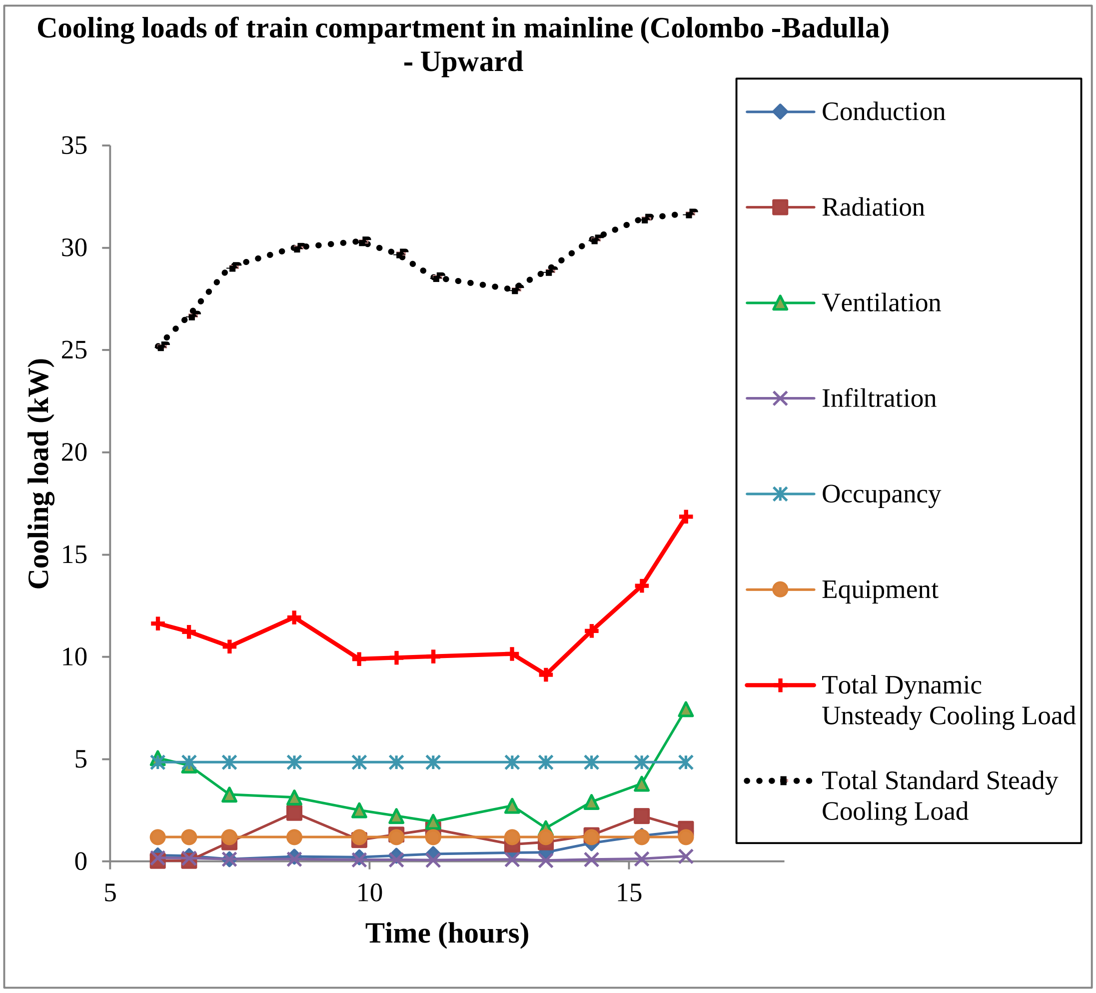

Figure4.7: Variation of cooling loads are assumed linear in between two adjacent selected stations in mainline - upward

It was assumed that the variation of cooling loads were linear in between two adjacent selected stations in both railway lines to estimate cooling load values at any point numerically. Differences in total cooling loads with estimated methods, periods of time, geographical regions and contribution of each dynamic cooling load components to the total are presented in the graph (Figure 4.7) above. Significant variation and reduction in total value of dynamic cooling load than that of standard static steady cooling load has been highlighted. Ventilation and occupancy components are significantly higher than others.

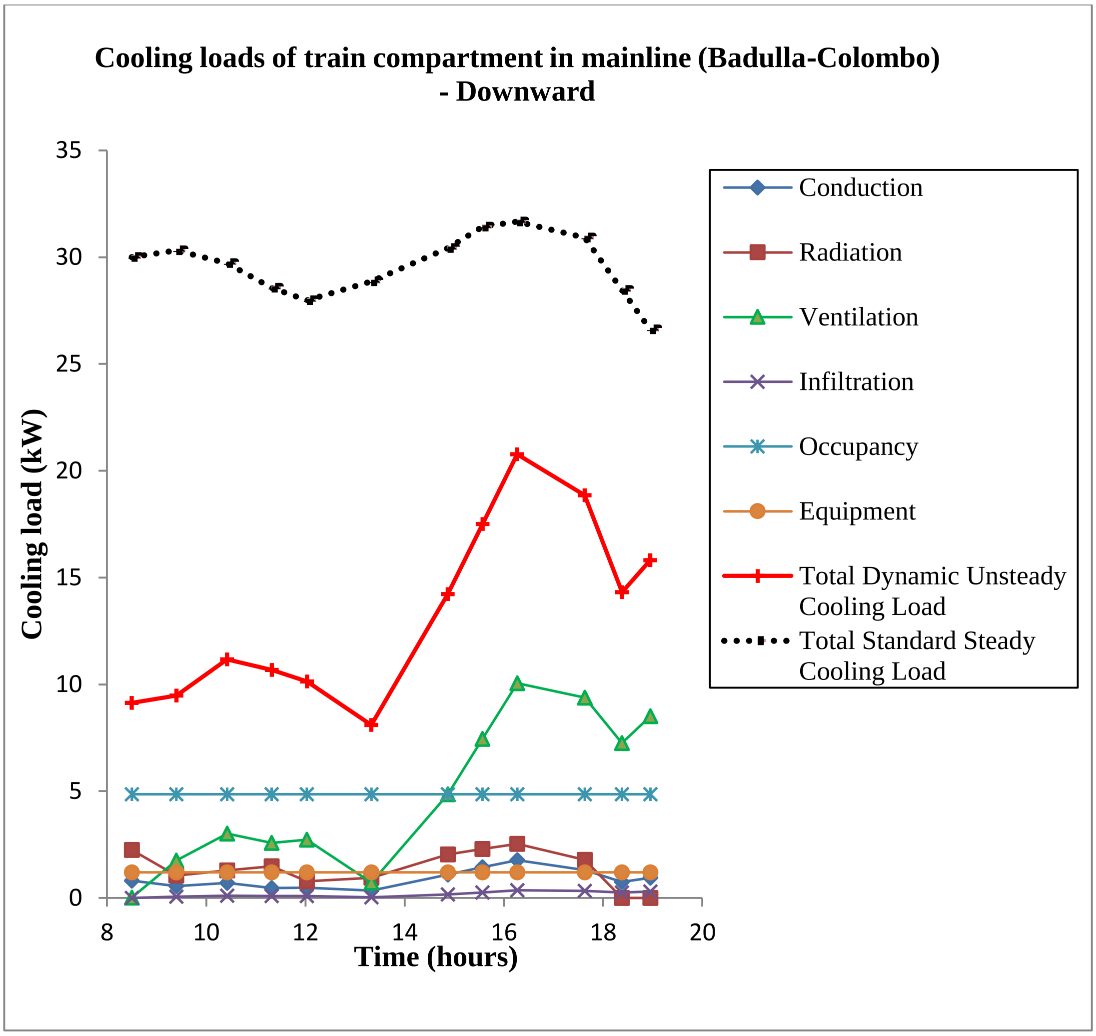

Figure4.8: Variation of cooling loads are assumed linear in between two adjacent selected stations in mainline - downward

Differences in total cooling loads with estimated methods, periods of time, geographical regions and contribution of each dynamic cooling load components to the total for the mainline down ward direction are presented in the graph (Figure 4.8) above. Contribution of ventilation & occupancy components to the total cooling load were significantly higher than that of other cooling load components, while the effect of other cooling load components were seem to be insignificant. Comparing with the conduction and radiation components, the variation of ventilation components was lager and it was closely similar to the variation of the total dynamic cooling load. The value of conduction cooling load component was varied between 0.3 – 2 kW and the radiation cooling load component varied between 0 – 2.5 kW, while the ventilation cooling load component varied between 0.02 – 10 kW (as per the Table 4.8 and the Figure 4.8).

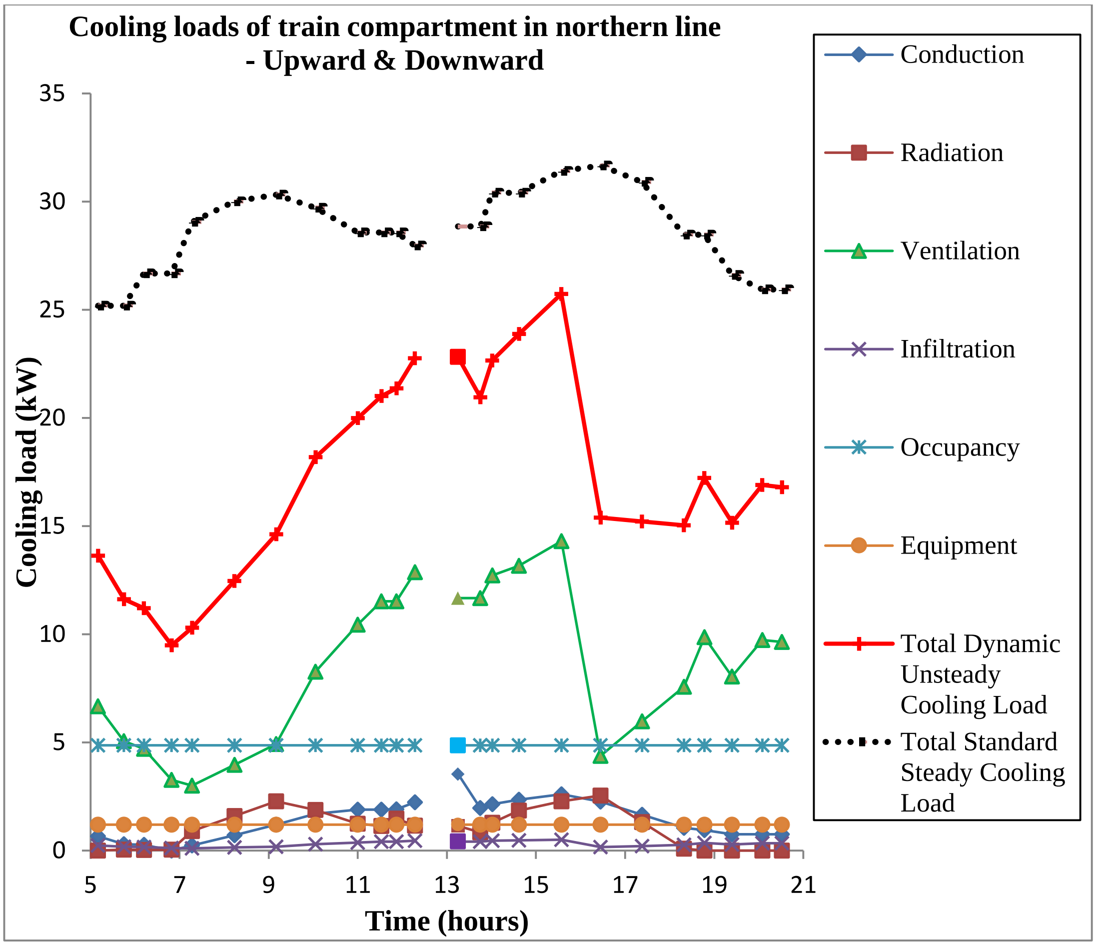

Figure4.9: Variation of cooling loads are assumed linear in between two adjacent selected stations in northern line – upward & downward

Differences in total cooling loads with estimated methods, periods of time, geographical regions and contribution of each dynamic cooling load components to the total for the northern line are presented in the graph (Figure 4.9) above. The dynamic cooling loads for upward and downward directions in two rail lines considered are shown in Figure 4.7, Figure 4.8, and Figure 4.9 separately. It can be observed that the conduction, radiation, ventilation and infiltration cooling loads varied with the time and space (with the railway stations), which lead to change the total cooling load, though the occupancy and equipment cooling load components kept constant due to the steady indoor air temperature. Compared with the conduction and radiation cooling loads, the variation and the amount of ventilation cooling loads were significantly larger (According to the above Table 4.7, Table 4.8 & Table 4.9 and relevant graphs in Figure 4.4, Figure 4.5 & Figure 4.6 respectively).

4.6 Analysis of variation in conduction components of cooling loads of a moving train compartment with time & space

Table4.10: Variation in conduction cooling load components with time and space when the train compartment moving in mainline upward direction

Railway Station	Time	Dynamic unsteady conduction cooling load (kW)**	Standard static steady conduction cooling load(kW)*
Colombo Fort	5:55 AM	0.299	0.849
Gampaha	6:31 AM	0.268	0.966
Polgahawela	7:18 AM	0.117	1.249
Peradeniya	8:33 AM	0.242	1.668
Nawalapitiya	9:48 AM	0.205	2.256
Hatton	11:14 AM	0.36	2.877
Nanuoya	12:45 PM	0.425	2.97
Pattipola	13:24 PM	0.442	3.167
Haputale	14:17 PM	0.905	3.329
Ella	15:15 PM	1.254	3.356
Badulla	16:06 PM	1.49	3.263

*Standard steady values have been calculated considering the one-dimension steady condition using overall heat transfer coefficient.

**Dynamic Unsteady values have been calculated considering the two-dimension unsteady condition using corresponding heat transfer coefficients estimated according to the relevant train velocities

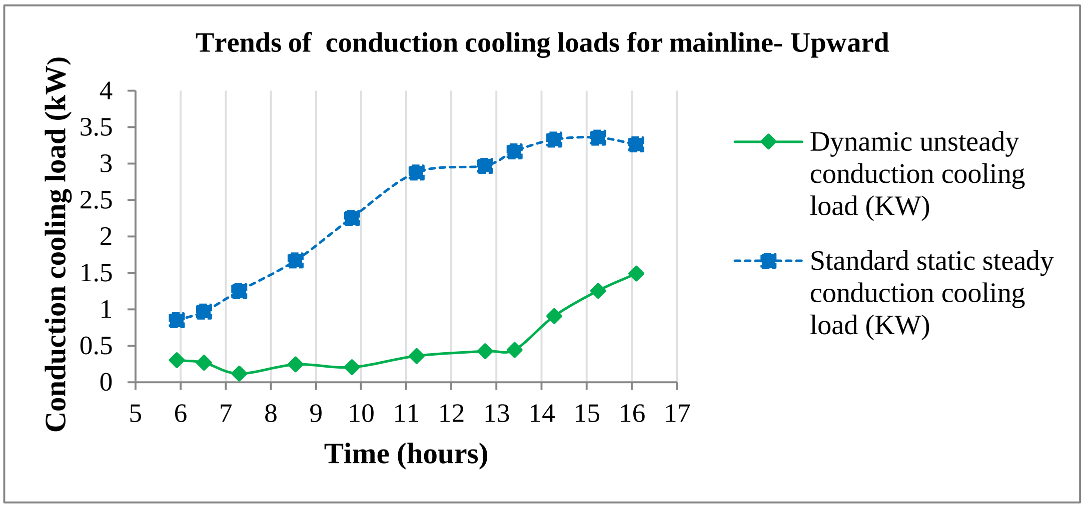

Figure4.10: Trends of the conduction cooling load components when the train moving in mainline upward

Table4.11: Variation in conduction cooling load components with time and space when the train compartment moving in mainline downward direction

Railway Station	Time	Dynamic unsteady conduction cooling load (kW)**	Standard static steady conduction cooling load (kW)*
Badulla	8:30 AM	0.806	1.668
Ella	9:24 AM	0.553	2.256
Haputale	10:25 AM	0.712	2.634
Pattipola	11:19 AM	0.466	2.877
Nanuoya	12:02 PM	0.479	2.97
Hatton	13:20 PM	0.346	3.167
Nawalapitiya	14:52 PM	1.094	3.329
Peradeniya	16:16 PM	1.775	3.263
Polgahawela	17:38 PM	1.298	3.096
Gampaha	18:23 PM	0.757	2.749
Colombo Fort	18:57 PM	0.947	2.269

*Standard steady values have been calculated considering the one-dimension steady condition using overall heat transfer coefficient.

**Dynamic Unsteady values have been calculated considering the two-dimension unsteady condition using corresponding heat transfer coefficients estimated according to the relevant train velocities

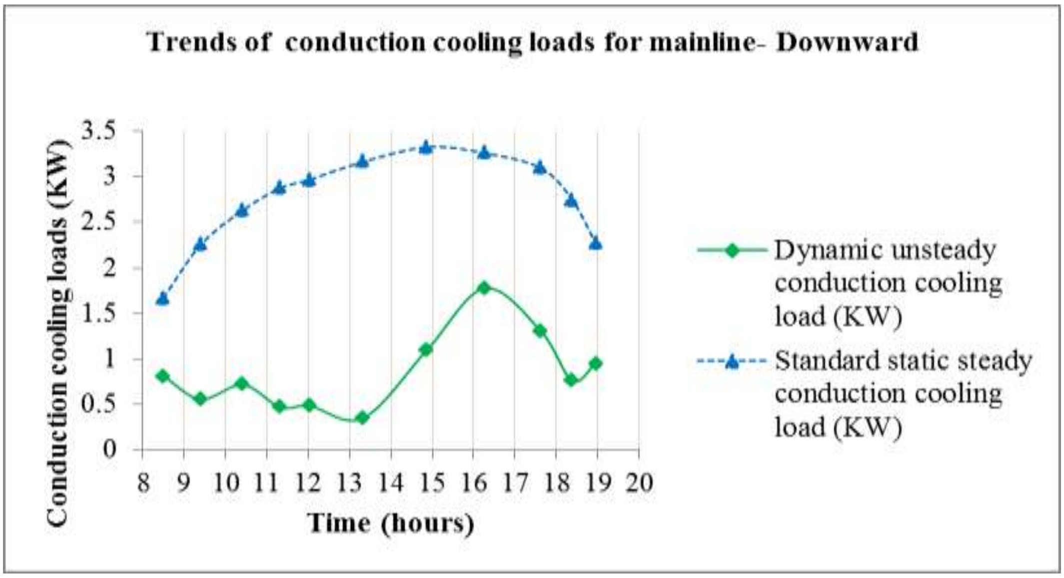

Figure4.11: Trends of the conduction cooling load components when the train moving in mainline downward

According to the Figure 4.11 the peak conduction load with the dynamic unsteady method lags behind that with the standard steady method by about more than one hour and its value was lower in significant amount with dynamic unsteady method than that of standard steady method.

Table4.12: Variation in conduction cooling load components with time and space when the train compartment moving in northern line upward & downward directions

Railway Station	Time	Dynamic unsteady conduction cooling load (kW)	Standard static steady conduction cooling load (kW)
Mount Lavinia	5:10 AM	0.662	0.849
Colombo Fort	5:45 AM	0.287	0.849
Gampaha	6:12 AM	0.267	0.966
Polgahawela	6:49 AM	0.002	0.966
Kurunegala	7:17AM	0.229	1.249
Anuradhapura	9:10 AM	1.195	2.256
Vavuniya	10:03 AM	1.693	2.634
Kilinochchi	11:00 AM	1.889	2.634
Kodikamam	11:32 AM	1.891	2.877
Jaffna	11:52 AM	1.906	2.877
Kankesanthurai	12:17 PM	2.226	2.97
Kankesanthurai	From12:17 PM To 13:15 PM	Train at Stop position	Train at Stop position
Kankesanthurai	13:15PM	3.532	3.167
Jaffna	13:45 PM	1.965	3.167
Kodikamam	14:01 PM	2.137	3.329
Kilinochchi	14:37 PM	2.351	3.329
Vavuniya	15:34 PM	2.600	3.356
Anuradhapura	16:27 PM	2.255	3.263
Kurunegala	18:19 PM	1.049	2.749
Polgahawela	18:47 PM	0.947	2.749
Gampaha	19:24 PM	0.757	2.269
Colombo Fort	20:05 PM	0.757	1.594
Mount Lavinia	20:31PM	0.757	1.594

*Standard steady values have been calculated considering the one-dimension steady condition using overall heat transfer coefficient.

**Dynamic Unsteady values have been calculated considering the two-dimension unsteady condition using corresponding heat transfer coefficients estimated according to the relevant train velocities

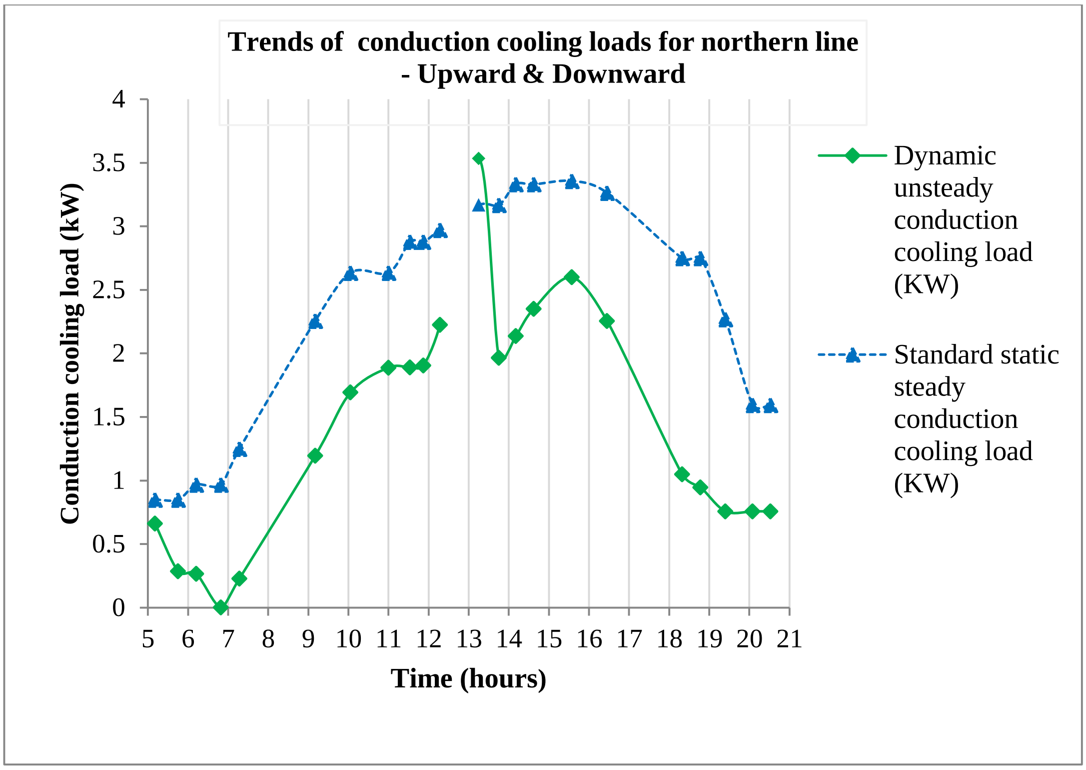

Figure4.12: Trends of the conduction cooling load components when the train moving in northern line upward & downward

The train body thermal storage lead to transfer the effect from heat to cooling load with a delay. In a moving train the train body thermal storage influence by conduction, radiation, occupancy and equipment cooling loads while ventilation load is handle by in train air conditioned unit. The effect of body thermal storage on the conduction cooling load shown by the comparison between the standard steady and dynamic unsteady conduction cooling load values. In Figure 4.12, it was found that the unexpected sudden increase after a break in dynamic unsteady conduction load at afternoon (at about 13:15 PM). This value exceeded the standard steady cooling load value at the moment. The train was at the stop position for about one hour period (12:17-13:15 PM) in Kankesanthri with the effect of highest temperature difference at afternoon and then it reached to the standard steady cooling load value when started at 13:15 PM. After starting the return journey of the train, it has become to the normal expected pattern of conduction cooling load component. The peak dynamic conduction load lags behind that of standard method with lower value.

4.7 The effect of ambient conditions on the dynamic cooling loads of trains

Variation of dynamic cooling load with changes of ambient conditions was analyzed. Accordingly, 44 numbers of estimated dynamic cooling load values with respective to the ambient conditions at the same time & location were tabulated and statistically analyzed for multiple regression using MS Excel software.

Table4.13: Variation in variable part of dynamic cooling load with changes of ambient temperature & humidity

Railway Station	Time	∆T (˚C)	∆RH %	VPQ_{DY} (kW)	Time	∆T (˚C)	∆RH %	VPQ_{DY} (kW)
Colombo Fort	5:55 AM	1.5	23	5.574	18:57 PM	5	20.5	9.761
Gampaha	6:31 AM	1.4	21.5	5.170	18:23 PM	4	20	8.261
Polgahawela	7:18 AM	0	21	4.453	17:38 PM	6	19	12.798
Peradeniya	8:33 AM	-1	23.5	5.869	16.:16 PM	7	15.5	14.718
Nawalapitiya	9:48 AM	-1.5	21.5	3.843	14:52 PM	2.5	13	8.166
Hatton	11:14 AM	-2.5	19.5	3.964	13:20 PM	-2.5	10.5	2.031
Nanuoya	12:45 PM	-2	19.5	4.091	12:02 PM	-2	19.5	4.083
Pattipola	13:24 PM	-2.5	10.5	3.074	11:19 AM	-2.5	19.5	4.608
Haputale	14:17 PM	0.5	7.5	5.216	10:25 AM	-0.5	13.5	5.112
Ella	15:15 PM	2.5	5	7.420	9:24 AM	-0.5	8	3.41
Badulla	16:06 PM	5	13	10.809	8:30 AM	-2.5	10	3.075
Mount Lavinia	5:10 AM	3.5	20	7.568	20:31 PM	4	32	10.742
Colombo Fort	5:45 AM	1.5	23	5.562	20:05 PM	4	32.5	10.841
Gampaha	6:12 AM	1.4	21.5	5.149	19:24 PM	4	24	9.091
Polgahawela	6:49 AM	0	21	3.422	18:47 PM	5	27	11.160
Kurunegala	7:17AM	0.5	16	4.239	18:19 PM	5.5	13	8.974
Anuradhapura	9:10 AM	4	8	8.568	16:27 PM	10	6	9,327
Vavuniya	10:03 AM	7	9	12.130	15:34 PM	12	9	19.680
Kilinochchi	11:00 AM	8	13.5	13.930	14:37 PM	10.5	12	17.818
Kodikamam	11:32 AM	8	18	14.958	14:01 PM	9.5	15	16.593
Jaffna	11:52 AM	8	18	15.310	13:45 PM	8.5	16	14.889
Kankesanthurai	12:17 PM	9	18	16.694	13:15 PM	8.5	16	16.754

∆T – Temperature difference in between outdoor air and indoor air
∆RH% -- Relative humidity difference in between indoor & outdoor air
VPQ_{DY} – Variable part of dynamic cooling load in moving train compartment

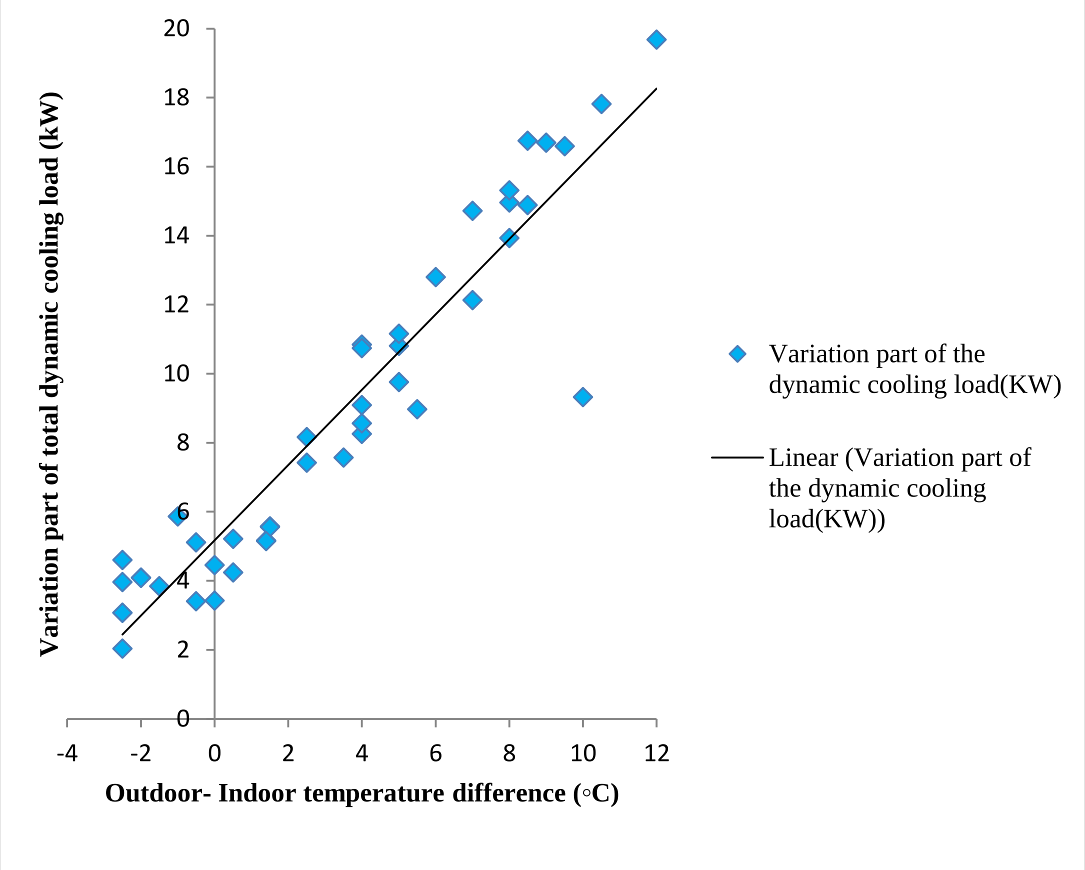

Figure4.13: Linear relationship between outdoor – indoor temperature difference and variable part of dynamic cooling load

The variation part of the dynamic cooling load consisted only with conduction, radiation, ventilation & infiltration only as per the occupants and equipment components were considered as constants. Thus the total of these variable cooling load components were taken as the variable part of dynamic cooling load for 44 numbers of considered positions at which the dynamic cooling loads have been predicted already. According to the above Figure 4.13, the quantitative linear relationship between outdoor – indoor temperature difference and variable part of dynamic cooling load has been found. Thus the significant effect of ambient conditions on the dynamic cooling load highlighted. The trend of the variable part of dynamic cooling load with the outdoor – indoor temperature difference was almost linear with a positive correlation. According to the Table 4.14, the regression equation and its determination coefficient R square were given in Equation (18).

Table4.14: Regression analysis explaining the variation in variable part of dynamic cooling load with the change of ambient temperature (indoor condition was steady)

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.944							
R Square	0.891							
Adjusted R Square	0.889							
Standard Error	1.621							
Observations	44							
ANOVA								
	df	*SS*	*MS*	*F*	*Sig. F*			
Regression	1	905.9	905.88	344.888	7.3E-22			
Residual	42	110.3	2.6266					
Total	43	1016						
	Coeff.	*Std. Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	5.175	0.314	16.479	6.1E-20	4.54112	5.809	4.541	5.809
To-Ti =ΔT (˚C)	1.091	0.059	18.571	7.3E-22	0.9722	1.209	0.972	1.209

Table4.15: Regression analysis explaining the variation in variable part of dynamic cooling load with the change of ambient temperature & humidity (indoor condition was steady)

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.948							
R Square	0.898							
Adjusted R Square	0.893							
Standard Error	1.587							
Observations	44							
ANOVA								
	df	*SS*	*MS*	*F*	*Sig. F*			
Regression	2	912.94	456.5	181.245	4E-21			
Residual	41	103.26	2.519					
Total	43	1016.2						
	Coeff.	*Std. Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	4.05	0.7391	5.479	2.4E-06	2.557	5.542	2.557	5.542
To - Ti =ΔT (˚C)	1.105	0.0581	19.01	6.1E-22	0.987	1.222	0.987	1.222
RHo - RHi=ΔRH%	0.064	0.0381	1.674	0.10174	-0.01	0.141	-0.013	0.141

Accordingly, Equation(18) the high value of R square shows that the change of ambient temperature when indoor condition was steady, can explain about 89% of the variation in the variable part of dynamic cooling load;

$VPQ_{DY} = 5.175 + 1.091*\Delta T$ (R square = 0.891, Sig < 0.001) ------------------- (18)

The unexplained part of the above single parameter regression equation is associated with the effects of ambient humidity, solar radiation and thermal storage of the train compartment. As shown in the Table 4.15 and the Equation (19), the value of determination coefficient R square increased to 90%, when the outdoor-indoor temperature and relative humidity differences were considered together, shows that the humidity is another effective factor to the variable cooling load. Also Sig <0.001 means the regression equation was significant.

$VPQ_{DY} = 4.05 + 1.105*\Delta T + 0.064*\Delta RH$ (R square = 0.9, Sig < 0.001) ------ (19)

Thus the total dynamic cooling load can be taken as: $Q_{DY} = Q_o + Q_E + VPQ_{DY}$

Total Dynamic cooling load; $Q_{DY} = Q_o + Q_E + 4.05 + 1.105*\Delta T + 0.064*\Delta RH$

Q_{DY} (kW) $= 10.11 + 1.105*\Delta T + 0.064*\Delta RH$ ------ (20)

When considering acceptable major indoor thermal comfort conditions obtained in this study as indoor dry bulb temperature & relative humidity are 26 ˚C & 55% RH respectively, above equation can be simplified with outdoor ambient temperature & relative humidity as two linear variables instead of indoor – outdoor differences of temperature & relative humidity, as follows; $Q_{DY} = 10.11 + 1.105*(T_{ao} – 26) + 0.064*(RH_{ao} – 55)$

Q_{DY} (kW) $= - 22.14 + 1.105*T_{ao} + 0.064*RH_{ao}$ ------ (21)

In view of the linear relationship of Equation (20) or Equation (21), it can be considered that these equations provide simple and quick models to predict dynamic cooling load which lead to improve energy efficiency in A/C train compartments. By application of these relationship and models, a linear climatic control system can be designed to control air conditioned unit of passenger trains in Sri Lanka.

Chapter 5

DISCUSSION AND A COMPARATIVE ANALYSIS

5.1 Validation of indoor thermal comfort parameters

Figure: (4.3) shows the end result of the questionnaire survey. Modified comfort zone shows that the comfort zone defined for indoor state (temperature & humidity) of moving passenger train compartments at specific internal air velocity of 0.2 m/s averagely maintained in train air conditioned system. It was found that the acceptable comfortable level exists in and around the periphery of the standard comfort zone which has been indicated in green and yellow colours respectively. The low percentages obtained within the standard comfort zone were due to the passengers feeling of discomfort because of too low temperatures and humidity ratios. This situation in inside of train compartment may occur due to the excess cooling load supplied over the decreasing demands by changing outdoor ambient conditions with the movements of the train. However, by setting indoor temperature and humidity to acceptable average higher values and controlling the supply of cooling load according to the demand this situation can be avoided.

Feeling like comfortable of majority of passengers who participated for the questionnaire survey, represent the modified comfort zone. There were few responses as discomfort due to too cold or too hot, have been ignored in to the analysis reasonably. When the neutral temperature are high as tropical climate such as in Sri Lanka and considering the ventilation effects, standard modification to the comfort zone can be applied by elevating humidity ratios up to possible highest level beyond 0.015 in psychrometric chart. Thus it is possible to introduce new upper boundary giving high humidity ratios.

It can be included more acceptable point which represent slightly higher values of temperature and humidity by increasing upper limits on humidity ratio beyond the 0.012 in psychrometric chart. However, it is important to maintain indoor state of thermal comfort parameters specially, temperature and humidity in more thermally comfortable slightly higher values which accepted by higher percentage of passengers (more than 70%). In this case it has been obtained as 26˚C and 55% as fixed values for indoor temperature and relative humidity respectively. According to the average neutral temperature estimated for Sri Lankan context from mean temperature data available (Table: 3.1) and also the responses of the questionnaire survey these indoor parameters are more acceptable for passengers while applicable to reduce required cooling load. Thus maintaining elevated indoor temperature and humidity, it will make the moving air conditioned indoor space steady and make the train air conditioning system more energy efficient.

5.2 Differences of cooling loads with respect to the railway lines & estimated methods

The trend of the variation in total cooling load in each railway line was distinct. The maximum, minimum, and mean were used to analyze the change of the total cooling load for each line. According to the Table 5.1, Table 5.2 & Table 5.3 relevant graphs at Figure 5.1, Figure 5.2 & Figure 5.3 respectively, it has been shown that the variation of cooling load components and the total cooling loads with respective to the methods of standard steady and dynamic unsteady for mainline and northern line separately. Maximum dynamic cooling loads for both lines were taken significant lower values than the maximum total standard steady cooling load value which was over estimated. The differences between dynamic cooling load and the steady cooling load for maximum, minimum and average values were higher in mainline than that of in northern line. Maximum total standard steady cooling load , maximum total dynamic unsteady cooling load in northern line and maximum dynamic unsteady cooling load in mainline were 31kW, 25kW and 20kW respectively. All these maximum cooling load values were significantly lower than the rated capacity of train air conditioning system (35 kW) presently used. Therefore it can be used separate air conditioned systems for mainline and northern line with relevant to the maximum capacities instead of using 35kW capacity air conditioned systems for both lines. Also minimum cooling loads for mainline & northern line were 8 kW & 9 kW respectively (both were nearly 10 kW).

Table5.1: Maximum cooling load values obtained using standard static steady method & unsteady dynamic method and the differences in the results of both methods

Method		Maximum cooling Load (kW)						
		Conduction	Radiation	Ventilation	Infiltration	Occupation	Equipment	Total
Standard Static Steady		3.26	4.06	17.04	0.60	5.50	1.2	31.67
Dynamic Unsteady	M/L	1.77	2.54	10.05	0.36	4.86	1.2	20.78
	N/L	2.60	2.27	14.30	0.51	4.86	1.2	25.74
Difference	M/L	1.49	1.52	6.99	0.24	0.64	0	10.89
	N/L	0.66	1.79	2.74	0.09	0.64	0	5.93

M/L-Main line (Colombo-Badulla)
N/L-Northern line (Colombo-Jaffna)

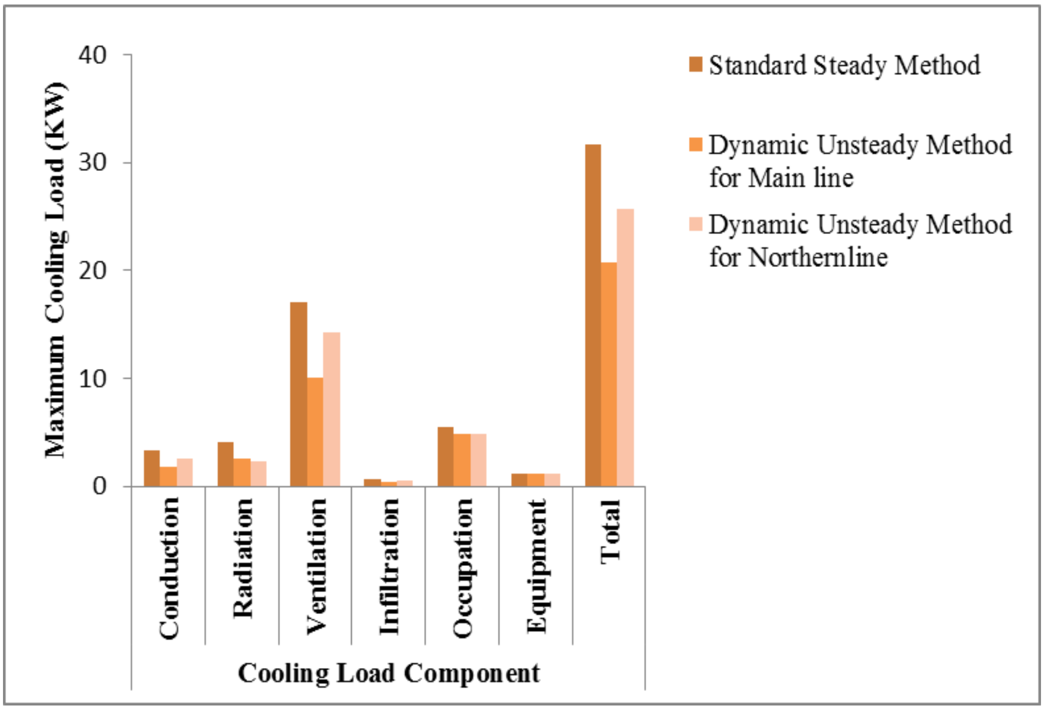

Figure5.1: Maximum cooling load values predicted by using Standard static steady method and Dynamic unsteady method

Table5.2: Minimum cooling load values obtained using standard static steady method & unsteady dynamic method and the differences in the results of both methods

Method		Minimum cooling Load (kW)						
		Conduction	Radiation	Ventilation	Infiltration	Occupation	Equipment	Total
Standard Static Steady		0.85	0.00	17.04	0.60	5.50	1.20	25.19
Dynamic Unsteady	**M/L**	0.35	0.95	0.71	0.02	4.86	1.2	8.09
	N/L	0.00	0.04	3.26	0.12	4.86	1.2	9.48
Difference	**M/L**	0.50	-0.95	16.33	0.58	0.64	0	17.10
	N/L	0.85	-0.04	13.78	0.48	0.64	0	15.71

M/L-Main line (Colombo-Badulla)
N/L-Northern line (Colombo-Jaffna)

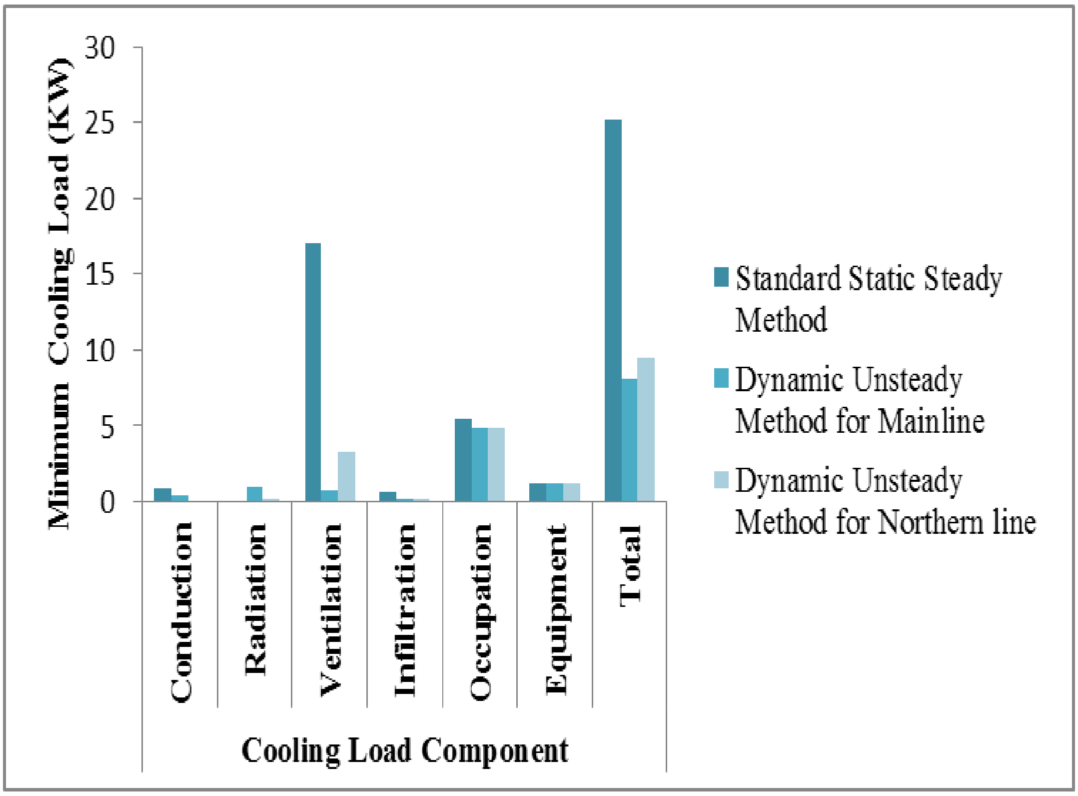

Figure5.2: Minimum cooling load values predicted by using Standard static steady method and Dynamic unsteady method

Table5.3: Average values of cooling load obtained using standard static steady method & unsteady dynamic method and the differences in the results of both methods

Method		Average values of cooling Load (kW)						
		Conduction	Radiation	Ventilation	Infiltration	Occupation	Equipment	Total
Standard Static Steady		2.39	2.13.	17.04	0.60	5.50	1.20	28.86
Dynamic Unsteady	**M/L**	0.68	1.36	3.89	0.14	4.86	1.2	12.13
	N/L	1.49.	1.14	9.21	0.29	4.86	1.2	17.19
Difference	**M/L**	1.71	0.77	13.15	0.46	0.64	0	16.73
	N/L	0.90	0.99	7.83.	0.31	0.64	0	11.67

M/L-Main line (Colombo-Badulla)
N/L-Northern line (Colombo-Jaffna)

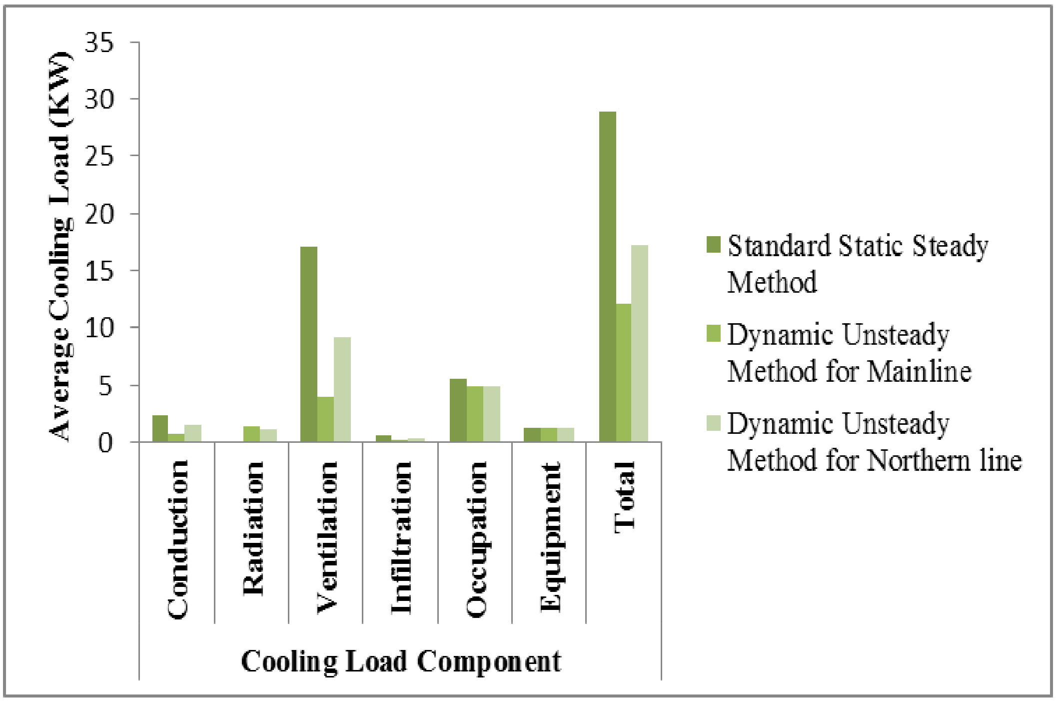

Figure5.3: Average cooling load values predicted by using Standard static steady method and Dynamic unsteady method

5.3 Proportion of each cooling load component to the total

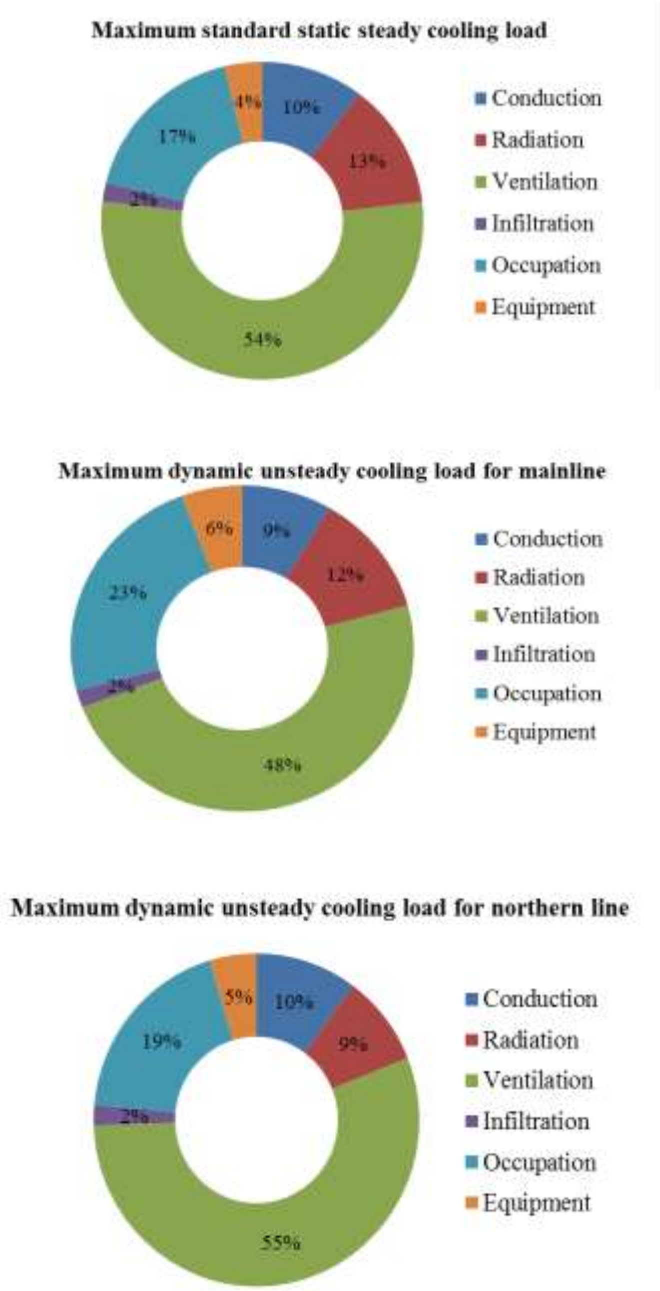

Figure5.4: Contribution of components in maximum cooling loads

It can be seen that the contribution of ventilation and occupants components to the total respectively, were significantly higher than that of other components because of the higher ambient temperature & humidity values at the maximum positions of the dynamic cooling loads at the main line and the northern line.

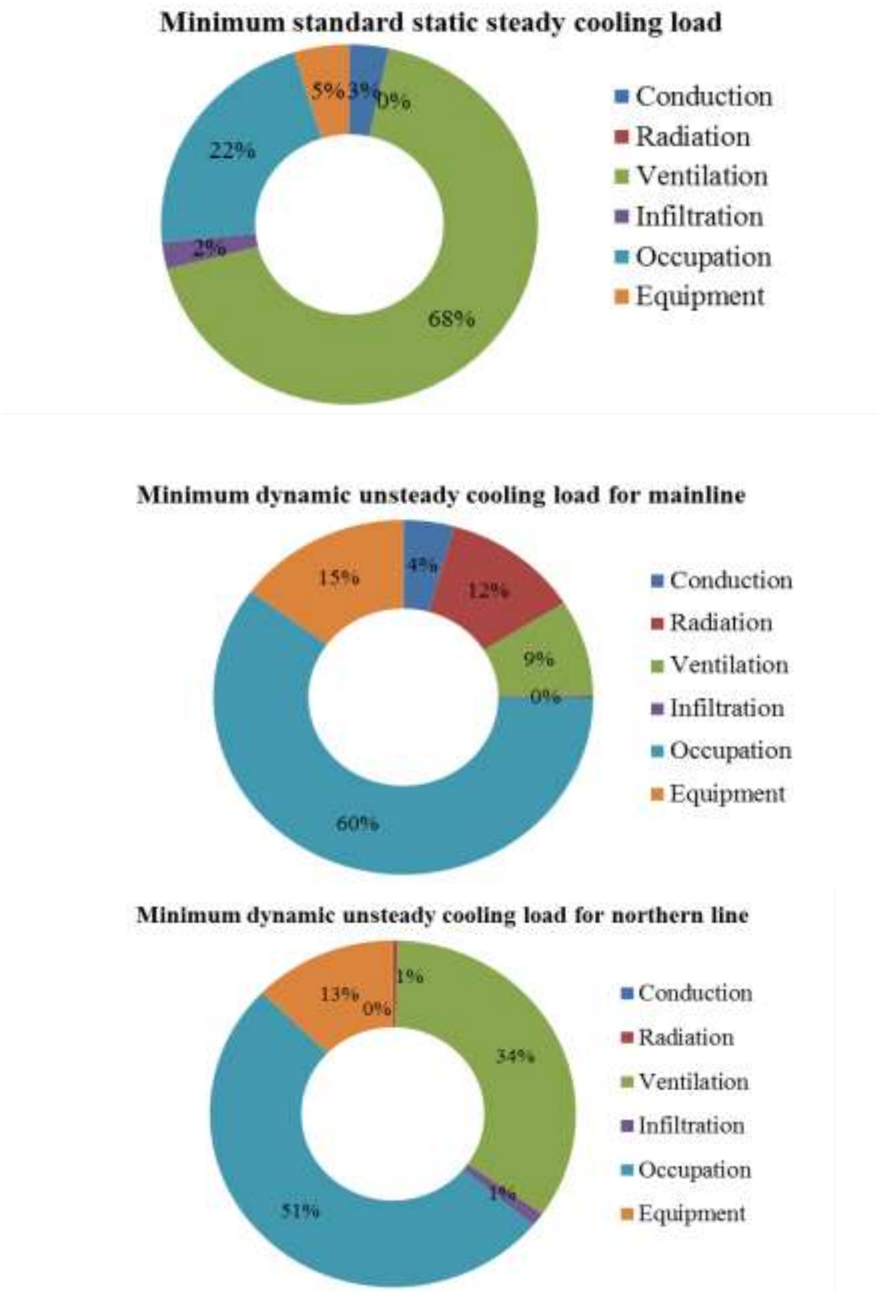

Figure5.5: Contribution of components in minimum cooling loads

When minimum dynamic cooling load occurred, occupation components have been shown the highest contribution for the total cooling load due to the lower ventilation load with relevant to the lower ambient temperature & humidity values at the minimum positions of dynamic cooling load in both railway lines. Among them in mainline contribution of ventilation load was lower than that of in northern line.

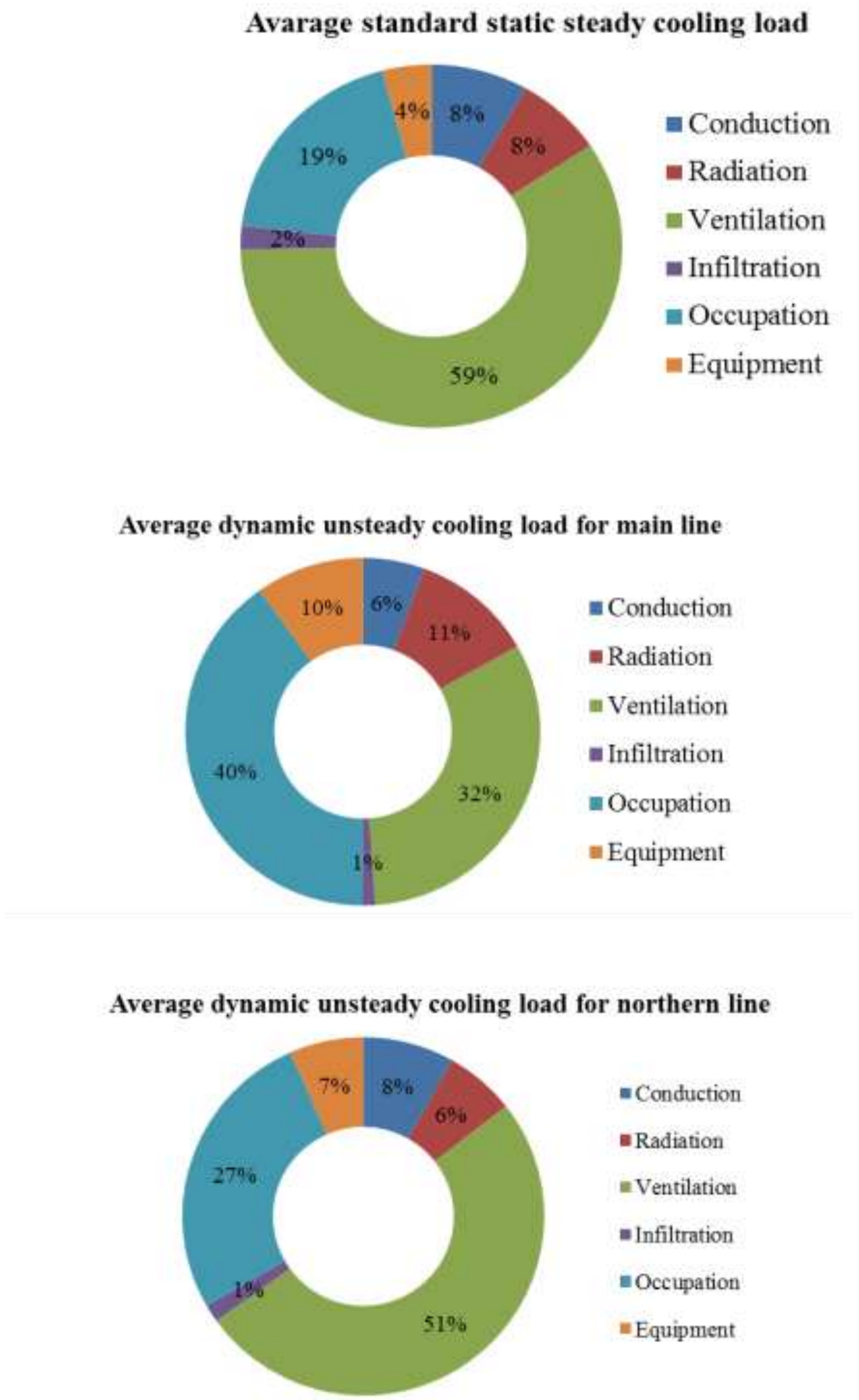

Figure5.6: Contribution of components in average cooling loads

It has been shown that average values of ventilation and occupation cooling loads were significantly higher than that of other cooling load components.

5.4 Variation of dynamic cooling loads between different geographical areas & different times during the day

Table5.4: Comparison on mean total cooling loads between different divisions and different periods of time

Rail line	Mean total dynamic cooling load (kW)						
	Division*			Period of time**			
	Central	Upper	Northern	Morning	Afternoon	Evening	Late Evening
Main	14.567	11.295	-	10.636	9.960	15.878	15.231
Northern	13.818	-	19.817	12.952	27.909	19.853	16.106

** Time periods taken; Morning – 5 am to 10 am, Afternoon – 10 am to 14 pm,
Evening – 14 pm to 18 pm and Late Evening – 18 pm to 21 pm

*Division; Central – Colombo to Peradeniya and Colombo to Anuradhapura
Upper – Peradeniya to Badulla
Northern – Anuradhapura to Kankesanthurai

The main reason to the divisional differences on the mean total dynamic cooling load was the regional weather and climates in different divisions of Sri Lanka. The ambient humidity in the stations in the upper division were lower than that in northern and central divisions, resulting in a low ventilation cooling load component which significantly effect for the total cooling load. Also the ambient temperature in northern division was highest that of central and upper divisions. This may be affected for the increase in conduction & ventilation cooling load components, resulting highest total dynamic cooling load at northern division while the lowest at upper division. For northern line minimum cooling load appeared at morning and the mean total cooling load in afternoon which was higher than that of in morning and evening because of the higher ambient temperature and solar radiation. For mainline the mean total cooling load in afternoon was slightly lower than that of morning and evening due to the train traveled in hill country region during the afternoon obtaining very ambient temperatures and humidity levels.

5.5 Findings

Appropriate and realistic values of indoor thermal comfort parameters (26˚C & 55%RH) in passenger train compartment were obtained for Sri Lankan context (Table 1, Figure 2). However according to the requirements indoor conditions can be modified within the comfort zone obtained (Figure 4.4). Variation in cooling load on constant acceptable indoor thermal comfort state (26˚C & 55%RH) of trains running in two major railway lines of Sri Lanka under varying outdoor ambient conditions was observed. Dynamic cooling load value of locations in between two stations can be obtain using known values of two relevant stations assuming variation of dynamic cooling load is linear in between two stations.

The effect of the outdoor ambient conditions (air temperature and humidity) on dynamic cooling load of train compartment was significantly high while the effect of solar radiation on the cooling load was comparatively low (Figure 4.4, Figure 4.5 and Figure 4.6). Also the effect of velocity of train compartment on total dynamic cooling load was significantly low due to the lower body thermal storage values obtained for all train journeys in both rail lines considered. The difference of total cooling load with reference to the geographical area was highlighted. Total cooling load for train running in East- west direction was significantly lower than that in South -North direction because of the significant differences in outdoor ambient conditions in between both lines due to different geographical changes and also due to the sunlit wall facing directions of the train compartment. When train running in south-north direction, sunlit walls faced to east–west direction where more heat gain by conduction and radiation. Train compartments consisted without curtains were considered for the study because of the preference of majority of the passengers. However by using curtains approximately 30% reduction of radiation cooling load can be achieved. The difference of total cooling load with reference to the different periods of time during train traveling was highlighted. Total cooling load for train traveling in afternoon and evening was higher than those at morning and in late evening. According to this study, only cooling loads were applicable and heating loads were not applicable.

Comparing with the conduction and radiation cooling load components, the variation and the quantity of the ventilation cooling load component was significantly larger. Ventilation and occupancy cooling load components were highlighted as most significant and effective parts of the total cooling load. All train compartments were built within construction gauge and variations of the width and the height of the compartments are insignificant comparing with its length. Hence based on these results, approximate cooling load values for any other train compartment can be estimated proportionately with respect to its length and numbers of seats (occupants). Comparing with the maximum of static steady cooling load (about 31 kW) estimated based on traditional standard method, the maximum of the dynamic cooling loads (20 kW & 25 kW per mainline and northern line respectively) were given significantly lower values (Table 5.1 & Figure 5.1). These differences highlighted 10.9kW & 5.9kW of energy savings for mainline & northern line respectively. Thus using actual dynamic cooling load of moving train compartment significant energy savings can be achieved.

Presently 35 kW capacity air conditioned units are used in train compartments travel in both mainline & northern line. However it is obvious that the capacity 20 kW & 25 kW air conditioned units are sufficient enough to supply maximum possible cooling loads at mainline & northern line respectively. This will lead to save considerable amount of capital cost and operational cost with a significant energy saving. Considering the minimum cooling load values, it has been shown that the minimum standard steady cooling load (25 kW) taken significantly higher value than the minimum dynamic cooling load values 8 kW & 9 kW for mainline & northern line respectively (Table 5.2 & Figure 5.2). Assuming that the cooling load variations in between two adjacent selected stations are linear, it can be estimated the average dynamic cooling load values in between two adjacent stations. Considering travel time in between two adjacent stations and dynamic cooling load values of relevant two stations, average dynamic cooling load value applicable in between the same adjacent two stations can be calculated. Considering all of these average dynamic cooling load values obtained in between each and every adjacent two selected stations (from starting to the end station), and total travel time it can be calculated the total average dynamic cooling load per rail line. Thus, in this case it has been obtained average dynamic cooling load values of 12 kW and 17 kW for the mainline and the northern line respectively. Those values were significantly lower than that of standard steady cooling load average of 29 kW (Table 5.3 & Figure 5.3). In view of the above, it can be used appropriate climatic control system to control cooling load supply of train compartment according to the actual cooling load demand (as per the variation of dynamic cooling load) to obtain a significant energy saving. By controlling the supply of dynamic cooling load with respect to the demand, it can be achieved around 750 kWh of average energy saving per day and then 274 MWh per annum per one train compartment only from these two complete train journeys in both rail lines as per the approximate estimation of savings by considering average cooling loads with effective journey times respectively for both rail lines.

5.6 Current need of controlling actual dynamic cooling load supply in moving air conditioned passenger train compartments

Today demand for railway passenger transport has been increased due to the rapid increment of road traffic in Sri Lanka. Considering the condition of the railway system in the past years, present situation is more complicated though it has been developed by adding more rolling stock, expanding its track length and improving infrastructure facilities such as stations and passenger platforms. During the study it was found that the cooling load requirement in trains traveling in mainline (Colombo to Badulla) was significantly lower than that in Northern line. Train traveling from Colombo to Polgahawela junction has been analyzed in both cases mainline and northern line as this track length is common for both lines. However cooling load values of this Colombo suburb (Colombo-Polgahawela) region were in between maximum and minimum cooling load values which have been found in northern area and hill country area respectively.

During the day times, passenger density of this Colombo- Polgahawela region has reached to the highest level which cannot be satisfied comparatively with the existing capacity of train service. Also the situation of other Colombo suburb train services of Colombo-kaluthara, Colombo-Negombo and Colombo-Awissawella are same. However the geographical and climatic conditions changes among these four Colombo suburb regions are not varied significantly. Therefore it can be considered that the dynamic cooling load values of these four regions varied significantly with time only. The required cooling load values for Colombo suburb region were shown an average values lower than the estimated maximum. This means the actual energy consumption for supplying thermally comfort air conditioned train service in these Colombo suburb regions will obtained significantly lower value than the estimated maximum value.

Trains running in short time period during morning and evening with higher passenger density in Colombo Suburb region highly effect for the daily road traffic and passenger transportation in the country. Also according to this study during the long distance train traveling in mainline and northern line showed huge variation in cooling load with respect to the variation of the time and the variation of space (outdoor environment). In main line, upward and downward train traveling passed hill country at afternoon that lead to reduce the expected higher cooling load of afternoon due to the comparatively cooler outdoor condition of the hill county than the other areas of the country. In northern line, trains traveling through northern area at the afternoon that lead to increase the expected higher cooling load of afternoon due to the comparatively hot outdoor condition of northern area than the other areas of the country. Variation of the cooling load of moving train compartment during the long distances of its travel were highly significant due to the rapid variation of its outdoor ambient conditions, direction of solar radiation, intensity of solar radiation and train speed with respect to the variation of the time and space. Thus the prediction of dynamic cooling loads precisely provides an adequate basis to determine the actual cooling loads for passenger train traveling in different regions and different periods of time approximately.

The usual static steady method of cooling load estimation might overestimate the actual cooling load requirement of train compartment during its traveling. Therefore neglecting the outdoor ambient conditions and acceptable indoor thermal comfort conditions, using traditional standard cooling load predictions, it is likely to induce significant discrepancy under the present situation of railway transport in the country which can lead to waste of energy and discomfort of indoor thermal environment. It is important that these significant differences in the cooling load should be seriously considered when designing or selecting the refrigeration capacity of air conditioning units for moving train compartments.

During this study basic and important measures were considered to simulate dynamic cooling load of a moving train compartment. However, in order to improve the method of predicting dynamic cooling loads, it is to be further considered the variation of occupancy load during the travel due to the changing of number of passengers. In this case it was assumed that the number of passengers was constant at full capacity as long distance intercity train traveling. The effect of infiltration on the dynamic cooling load to be considered with the effect of the velocity pressure associated with the train movement. However in this case, it was only considered the possible leakages of the train body and door openings at the stations. However the result of this study reflected that the steady cooling load predicted using usual standard method might over-estimate the actual dynamic cooling load of train compartment. That might be the main reason to considerable energy consumption of train air conditioning unit and the uncomfortable thermal environment causing passengers' feelings of cool or cold.

A model should be built to add variations of ambient conditions and solar radiation effects with time and space for different railway lines in Sri Lanka and the train system should be adopted with appropriate climatic control system to adjusting and controlling the cooling load supply in its traveling according to the demand of actual dynamic cooling load. The result of this study shows that the body conduction cooling load was significantly lower value comparing with the total dynamic cooling load. The limited effect of body thermal storage has been highlighted that the estimation of dynamic cooling load using this model (without applying CFD simulation for unsteady body conduction heat transfer) is adequate enough to obtained numerically appropriate results.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the important key findings. Also it briefs the achievements of the objectives in conclusions. Based on the results, recommendations and policy implications are given to overcome the research problem. Limitations met during the study are mentioned and as continuation of this study, three concepts for future woks have been suggested at the end.

6.1 Key Findings

- Appropriate comfort zone and realistic values of indoor thermal comfort parameters (26˚C & 55%RH) in passenger train compartment were obtained for Sri Lankan context.
- The effect of the outdoor ambient conditions (air temperature and humidity) on dynamic cooling load of train compartment was significantly high while the effect of solar radiation on the cooling load was comparatively low.
- Also the effect of velocity of train compartment on total dynamic cooling load was significantly low due to the lower body thermal storage values obtained for all train journeys in both rail lines considered.
- The difference of total cooling load with reference to the geographical area was highlighted. Total cooling load for train running in East - west direction (mainline) was significantly lower than that in South-North direction (northern line).
- The difference of total cooling load with reference to the different periods of time during train traveling was highlighted. Usually total cooling load for train traveling at afternoon and evening was higher than those at morning and late evening except that for train traveling at afternoon in hill country.
- According to this study, only cooling loads were applicable and heating loads were not applicable for both mainline and northern line.
- Comparing with the conduction and radiation cooling load components, the variation and the quantity of the ventilation cooling load component was

significantly larger. Ventilation and occupancy cooling load components were highlighted as most significant and effective parts of the total cooling load.

- Using these total dynamic cooling load values, approximate cooling load values for any other type of air conditioned train compartment can be calculated with respect to its length and numbers of seats (occupants) proportionately.
- Comparing with the maximum of static steady cooling load estimated based on traditional standard method, the maximum of the dynamic cooling loads were given significantly lower values. These differences highlighted 10.9 kW & 5.9kW of reduction in cooling demand per a train compartment for mainline & northern line respectively. This will lead to give 315 kWh of energy saving per day and then 115 MWh per annum per one train compartment only for two complete train journeys considered for both lines. Thus using these maximum dynamic cooling loads for selecting capacity of train air conditioning systems and accordingly by installing lower capacity air conditioning systems with relevant equipment, saving of capital expenditure and significant energy savings can be achieved.
- Assuming that the cooling load variations in between two adjacent selected stations are linear, average value of dynamic unsteady cooling load in mainline and average value of dynamic unsteady cooling load in northern line and rated capacity of the air conditioning system per one existing train compartment were obtained as 12 kW, 17 kW and 35 kW respectively. Accordingly controlling the supply of dynamic cooling load with respect to the demand, it can be achieved around 750 kWh of average energy saving per day and then 274 MWh per annum per one train compartment only from these two complete train journeys in both rail lines. Thus the results of this study shows that the application of climatic control system to control cooling load supply of train compartment, in according to the fluctuation of dynamic of cooling load demand due to the variation of outdoor ambient conditions, is more advantageous.

6.2 Conclusions

Based on the results, following main conclusions were achieved.

1) Indoor temperature and relative humidity of 26˚C & 55%RH respectively can be accepted for passenger train compartment in Sri Lanka.
2) Dynamic cooling load prediction model used for this study is more precise than usual standard steady method to predict cooling load of moving air conditioned train compartments.
3) Actual required cooling load of moving train compartments significantly varied with time and space in order to the variation of outdoor ambient conditions, occupants, solar radiations and train velocity respectively. Ventilation component was the most effective determinant of the total dynamic cooling load among six numbers of cooling load components considered. Thus the demand control of the outdoor fresh air flow rate has shown significant energy saving potential for the air conditioned moving train compartments.
4) Maximum values of the dynamic cooling load of train compartment obtained for both rail lines was significantly lower than the maximum of estimated static steady cooling load value. Thus when designing a cooling system for a train compartment, considering this maximum dynamic cooling load value as the required total capacity, it will save considerable amount of expenditure by selecting lower capacity air conditioning systems (20 kW & 25 kW for mainline and northern line respectively) instead of existing train air conditioning system (35 kW) used for both rail lines. Other than that it will also lead to save significant amount of energy due to the reduction of required cooling loads, only from these considered two complete daily travelled train journeys.
5) Application of actual dynamic cooling loads of a moving train compartment has been shown 23 kW & 18 kW of average reductions in cooling demand for mainline & northern line respectively comparing with rated total capacity of the existing air condition system per one train compartment (35 kW). It will lead to save approximately 274 MWh of energy per one train compartment per annum only from these two complete daily train journeys considered for this study, in both rail lines. This can be achieved by adding a linear climatic control system designed based on the dynamic total cooling load depend on the variation of outdoor ambient temperature

& relative humidity with reference to the model given in regression equation obtained from the results of this study.

6.3 Policy Implications & Recommendations

The determinant factors of indoor thermal comfort state and the dynamic cooling load of passenger train compartments have important theoretical and practical implications. Based on the theory of thermal comfort & heat transfer methods and using famous Fanger’s indoor thermal comfort model & mathematical models of estimating cooling load of train compartments, this study predicted acceptable indoor thermal conditions then the comport zone for railway passengers and key influential energy saving measures to improve and develop existing air conditioned train service in Sri Lanka as a modern, more comfortable and more economical one.

Outdoor air quality is not so polluted in Sri Lanka comparing with other countries which are industrially developed. Therefore fresh air requirement for moving air conditioned trains can be reduced further determining the existing CO_2 percentage of indoor carriage space. Minimizing the supply air flow rate, requirement of the cooling load can be reduced up to a considerable amount which will lead to save total energy consumption economically. When considering the requirement of air conditioned train compartments in future, for designs, modifications, and preparing specifications for procurement process, it can be adopted acceptable indoor conditions (set possible maximum values of temperature and relative humidity) and other energy saving measures identified during this study such as controlling supply cooling load according to the variation of outdoor ambient conditions, minimizing the required rate of fresh air supply, optimizing glazing area, and reducing possibilities for leakages.

The result of this study provides a basis for future scholarly research and policy implications. Also these results can be used by others in future conversion studies as well as policy makers, rail operation & maintenance staff, project managers in their effort to popularize public transport system in the society.

Uncomfortable indoor thermal environment and significant energy consumption of air conditioned rail passenger compartments negatively influence development and the popularity of railway transport system. Popularizing the public transport systems, a significant saving of national energy and time can be achieved by reducing the number of private vehicles on roads. Thus considering the huge socio-economic benefit of using thermally comfortable rail transport system, it is social responsibility to developed existing Sri Lankan Railway system to a comfortable, reliable and attractive one for public use.

6.4 Limitations

Questionnaire survey population was limited to the sample of 186 respondents among passengers travel in northern line and main line. Only two most influential indoor thermal comfort parameters (temperature and relative humidity) were considered as independent variables for the analysis. The period of primary data collection was limited to one year duration and only 22 numbers of stations were considered for both railway lines**.**

6.5 Future works

In view of the current requirements highlighted in the railway system following future works have been proposed as continuation of this study.

1) By fixing indoor parameters (temperature & relative humidity) to the acceptable values within comfort zone introduced in this study for passenger thermal comfort, considering the variation of outdoor ambient conditions (mainly temperature & relative humidity as the two most influential parameters) as independent variables and variations in dynamic cooling load values as a dependent variable, a climatic control system for train air conditioning units can be designed to control energy consumption of moving train compartments on demand which is varied with time and space. It can be used the multiple regression equation which constrains to two

independent variables (ambient temperature & relative humidity) linearly varied with cooling load, obtained as the result of this study.

2) As a future work, it can be developed an Artificial Neural Network (ANN) Model using developed software MATLAB for the prediction of dynamic cooling load in a moving train compartment at station anywhere in the country according to the geographical data (latitude, longitude and altitude) which are represented their outdoor conditions. The dynamic cooling load values of the selected stations and other relevant climatic and geographical data can be used to formulate the algorithm for the ANN model. Considering nine numbers of neurons as input layer: Latitude, Longitude, Altitude, Hour of the day, Hourly outdoor air temperature, Hourly relative humidity of the outdoor air, Hourly solar radiation, Length of the train compartment and the Number of passengers. An appropriate ANN model is to be trained while the cooling load of required station is considered as the only one neuron at the output layer. The developed ANN model will be more useful for practitioners.
3) Further study on thermal comfort evaluation for railway passengers can be done by increasing the survey population and considering the transient nature of indoor environment of moving train compartment. More accurate results can be obtained by using numerical model with applicable CFD software for the simulation process.

6.6 Summary

Ten numbers of valuable key findings were highlighted. Under the conclusions it has been described briefly that the research objectives have been achieved by the results. Based on the results discussed, recommendations and policy implications were made to minimize the problem. It was pointed out few limitations which occupied the research towards useful result in a feasible way. Finally, it was suggested three important future woks which can be carried out using the results of this study.

REFERENCES

[1] Z. Ouyang, M. Cai H. Chen, "Investigation and analysis of the energy consumption in traveling air-conditioned trains," *Energy Conservation Technology* , vol. 21, no. 1, pp. 18-20, 2003.

[2] H. Duan, Ch. Han G. Zang, "Investigation of comfort level of air-conditioner in passenger train after speed-up of Chinees railways," *Chinees Railways*, vol. 7, pp. 54-56, 2009.

[3] Sri Lanka Railways. (2011) www.railway.gov.lk.

[4] Qihong Deng, Wenjie Huang, Rui Liu Weiwei Liu, "Variation in cooling load of a moving air-conditioned train compartment under the effect s of ambient conditions and body thermal storage," *Applied Thermal Engineering*, pp. 1150-1162, 2011.

[5] U.P. Menti, F.Sider, E. Thaler, G. Zweifel Nadege Vetterli, "Energy Efficiency in Railway Vehicles," *CISBAT*, pp. 955-960, september 2015.

[6] J.L.M. Hensen, "Literature review on thermal comfort in transient conditions ," *Build Environment*, vol. 25, no. 4, pp. 309-316, 1990.

[7] R. de Dear, "Thermal comfort in practice," *Indoor Air* , vol. 14, no. 7, pp. 32 - 39, 2004.

[8] J. Van Hoof, "Forty years of Fanger,s model of thermal comfort: comfort for all ?," *Indoor Air*, vol. 18, pp. 182 - 201, 2008.

[9] Alahmer. A., "Effect of relative humidity and temperature control on in cabin thermal comfort state," Clemson University, South Carolina, Dissertation 2011.

[10] M. Omar, A. Mayyas, S. Dongri, A. Alahmer, "Effect of relative humidity and temperature control on in-cabin thermal comfort state: thermodynamic and psychometric analysis," *Applied Thermal Engineering*, vol. 31, no. 14-15, pp. 2636 - 2644, 2011.

[11] A. Alahmer, "Thermal analysis of direct eveporative cooling system enhancement with desiccant dehumidification for vehicular air conditioning,"

Applied Thermal Engineering, vol. 98, pp. 1273 - 1285, 2016.

[12] Zuimdie Guerra, "Evaporative air conditioner for automotive application," Massachusetts Institute of Technology, USA, Master Dissertation 1994.

[13] A. Mayyas, M. A. Omar, S. Dongri A. Alahmer, "Vehicular thermal comfort models; a comprehensive review," *Applied Thermal Engineering*, vol. 31, pp. 995 - 1002, 2011.

[14] E. Helerea, R. Musat, "Parameters and models of the vehicle thermal comfort," *Acta Universitatis Sapientiae, Electrical and Mechanical Engineering*, pp. 215 - 226, 2009.

[15] B. Shuai W. Huang, "A methodology for calculating the passenger comfort benefits of railway travel," *J. Mod. Transport*, vol. 26, no. 2, pp. 107 - 118, February 2018.

[16] Andreea Vartires, Angel Dogeanu Paula Danca, "An overview of current methods for thermal comfort assessment in vehicular cabin," *Energy Procedia*, vol. 85, pp. 162 - 169, 2016.

[17] F. Wang, S. Roaf K. Pichatwatana, "Thermal comfort evaluation of an existing glazed airfort terminal in Thailand," *Engineering sustainability- Proceedings of the Institution of Civil Engineers* , vol. 172, no. 4, pp. 184 - 197, 2019.

[18] J. W. Lee, C. H. Jeong, S. H. Lee J. H. Moon, "Thermal comfort analysis in a passenger compartment considering the solar radiation effect," *International Journal of Thermal Sciences*, vol. 107, pp. 77 - 88, September 2016.

[19] Yalin Lu Xu Zhang, "Numerical study on air quality and thermal comfort in high speed train compartment with underflow air supply," in *2nd International Conference on Industrial Aerodynamics*, 2017, pp. 716 - 722.

[20] M. Kuru G. Calis, "Statistical significance of gender and age on thermal comfort: a case study in Turkey," *Proceedings of Institution of Civil Engineers-Engineering Sustainability* , vol. 172, no. ES1, pp. 40 - 51, 2019.

[21] W. Rose J. Brown, "Humidity and moisture in historic buildings or origins of building and object conservation," *APT Bulletin*, vol. 27, no. 3, pp. 12 -24, 1996.

[22] R. Dear, J. Hensen, W. D'haesleer L. Peeters, "Thermal comfort in residential buildings: comfort values and scales for building energy simulation," *Applied Energy*, vol. 86, no. 5, pp. 772 - 780, 2009.

[23] Y. Feng, Y. Tochihara N. Hashiguchi, "Gender differences in thermal comfort and mental performance at different vertical air temperatures," *European Journal of Applied Physiology*, vol. 109, no. 1, pp. 4 - 48, 2009.

[24] T. Ogawa, J. Sugenoya, , N. Ohnishi and K. Imai K. Natsume, "Preferred ambient temperature for old and young men in summer and winter," *International Journal of Biometeorology*, vol. 36, no. 1, pp. 1 - 4, 1992.

[25] M. Kuru G. Calis, "Assessing user thermal sensation in the Aegean region against standards," *Sustainable Cities Cities and Society*, vol. 29, pp. 77 - 85, 2017.

[26] ASHRAE,. Atlanta, USA: American Society of Heating, Refrigeration and Air Conditioning Engineers, 1989.

[27] Umit Unver, Muhsin Kilic O. Kaynakli, "Calculation of thermal comfort zones with the ambient parameters," in *IEEE - 1 The first international exergy, energy and environmental symposium*, Izmir, Turkey, 2003.

[28] R.A. Attalage M.T.R. Jayasinghe, "Comfort Conditions for Built Environments in Sri Lanka," *ENGINEER, Journal of the Institute of Engineers, Sri Lanka*, 1999.

[29] M. Ramgopal A. K. Mishra, "Field studies on human thermal comfort - An overview," *Building and Environment*, pp. 1 - 35, June 2013.

[30] Q. Ouyang, Y. Zhu W. cui, "Field study on thermal environment spatial distribution and passenger local thermal comfort in aircraft cabin," *Building and Environment*, vol. 80, pp. 213 - 220, 2014.

[31] R. L. Hwang, K. T. Huang, C. Y. Sun, Y. C. Huang T. P. Lin, "Passenger thermal perceptions, thermal comfort requirements, and adaptations in short - and long- haul vehicles ," *International Journal of Biometeorology*, vol. 54, pp. 221 - 230, October 2009.

[32] U.P.Menti, F.Sidler, E.Thaler, G.Zweifel Nadege Vetterli, "Energy Efficiency

of Railway Vehicles," *CISBAT 2015*, pp. 955-960, September 2015.

[33] Mahdi Houchati, Abdl Monemi Beitelmal Zhidan Zhao, "An energy efficiency assessment of the thermal comfort in office building," *Energy Proceedia*, vol. 134, pp. 885 - 893, 2017.

[34] Thananchchi Leephakpreeda Daniel Kristanto, "Sensitivity analysis of energy conservation for effective energy consumption, thermal comfort, and air quality within car cabin," *Energy Procedia*, vol. 138, pp. 552 - 557, 2017.

[35] Thomas Zero, Christian Dullinger, Gregor Richter, Martin Kozek Raphael N. Hofstadter, "Heat capacity and heat transfer coefficient estimation for a dynamic thermal model of rail vehicles," *Mathematical and Computer Modelling of Dynamical systems*, vol. 23, no. 5, pp. 439-452, August 2017.

[36] P. A. Domanski J. S. Brown, "Review of alternative cooling technologies," *Applied Thermal Engineering*, vol. 64, pp. 252 - 262, 2014.

[37] S. Liu, L.Tian Z. Zhang, "Thermodynamic analysis of air cycle refrigeration system for chinese train air conditioning," *System Engineering proceedings - Engineering and Risk Management*, vol. 1, pp. 16 - 22, 2011.

[38] F. J. Pino, C. Bordons, J. J. Guerra D. Marcos, "The development and validation of a thermal model for the cabin of a vehicle," *Applied Thermal Engineering*, vol. 66, pp. 646 - 656, 2014.

[39] F. Bjurling, J. M. Corberan, F. Di Sciullo, J. Paya B. Torregrosa-Jaime, "Transient thermal model of a vehicle's cabin validated under variable ambient conditions," *Applied Thermal Engineering*, vol. 75, pp. 45 - 53, 2014.

[40] K. Bennion, A. Brooker, J. Langewisch, K. Smith, J. Meyer J. Rugh, "PHEV/EV integrated vehicle thermal management - development of a KULI model to assess combine cooling loops," in *Vehicle Thermal Management System Conference and Exhibition (VTMS 10), I Mech E, woodhead publishing*, 2011, pp. 649 - 660.

[41] Qihong Deng, Wenjie Huang, Rui Liu Wei wei Liu, "Variation in cooling load of a moving air-conditioned train compartment under the effects of ambient conditions and body thermal storage," *Applied Thermal Engineering*, vol. 31,

pp. 1150-1162, 2011.

[42] A. Ferrante, D. Kolokotsa, K. Gobakis, L. Standardi, C. Cristalli N. Kampelis, "Thermal comfort evaluation in HVAC demand response control," *Energy Procedia*, vol. 134, pp. 675 - 682, 2017.

[43] M. A. Piete, D. S. Watson, S. Kiliccote, P. Xu N. Motegi, *Introduction to commercial building control strategies and techniques for demand response*. California: Berkeley, 2017.

[44] Ilinca Nastase, Florin Bode, Amina Meslem, Angel Dogeanu Cristiana Croitoru, "Thermal comfort models for indoor spaces and vehicles- Current capabilities and future perspectives," *Renewable and Sustainable Energy Reviews* , vol. 44, pp. 304-318, 2015.

[45] ANSI/ASHRAE Standard 55, Thermal and Environmental Condition for Human Occupancy, 2013, Approved American national Standard, Atlanta.

[46] ISO International standard 7730, Ergonomics of the thermal environment, 2005

[47] Deying Li Pin Liu, "Issues & Factors of Train Air Conditioning System Design & Operation," in *Comference for Enhanced Building Operations*, Shenzhen, China, 2006, pp. 6-11.

[48] Gabriel Haller, "Thermal Comfort in Rail Vehicles," *RTA Rail Tec Arsenal*, pp. 01-12, September 2006.

APPENDIX: Survey of railway passengers carried out using following questionnaire:

COMFORT IN AIR CONDITIONED PASSENGER TRAINS

NO: ______________ RAILWAY LINE: ________________________

DATE: ________________________ TIME: ______________

LOCATION (NEAREST STATION): __________________________

Indoor Air flow Velocity (m/s): -------------
Indoor Relative Humidity (RH%) : ------------
Indoor Temperature, T_i (^oC): -------------------
----

01. What is your gender? Female ----- Male ------

02. What is your age? ____________

03. Where is your permanent resident (District)? _______________________

04. At the moment, Activity level: Seated ----- Standing -----

05. How do you feel?

    Very Cold (-3) ----

    Cold (-2) ---------

    Slightly cool (-1) ---

    Comfortable (0) ----

    Slightly warm (1) ---

    Warm (2) ---------

    Hot (3) -----------

06. How long are you here?
    Less than 15 minutes -----
    ½ an hour--------------
    More than ½ an hour-----

07. What is your preference to overcome above problem? ____________________