

**ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY
SCHOOL OF MECHANICAL, CHEMICAL AND MATERIALS ENGINEERING
DEPARTMENT OF MECHANICAL AND VEHICLE SYSTEM ENGINEERING**



**Development of Optimized Vehicle Body of the Ethiopian Train under
Crosswind Conditions for Energy Efficiency and Dynamic Stability**

*A thesis submitted in partial fulfillment of the requirements for the
award of Degree of*

Master of Science in
Automotive and Vehicle System Engineering

By

Kibret Yilak

Department of Mechanical and Vehicle System Engineering

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Adama

CANDIDATE'S DECLARATION

I hereby declare that the thesis work which is being presented in the paper entitled “Development of Optimized Vehicle Body of the Ethiopian Train under the Crosswinds Condition for Energy Efficiency and Dynamic Stability.” in partial fulfillment of the requirements for Graduate Independent Thesis of the degree of master of science in Automotive Engineering is an authentic record of my own work carried out from July 2016 to January 2017 under the supervision of **Professor Chul-Ho Kim** and **Professor N.Ramesh Babu**, Department of Mechanical and Vehicle System Engineering, Adama Science and Technology University, Adama, Ethiopia.

The matter embodied in this paper has not been submitted by me for the award of any other degree or diploma. All relevant resources of information used in this paper have been duly acknowledged.

Kibret Yilak

Student

Signature

Date

This is to certify that the above declaration made by candidate is correct to the best of my/our knowledge and belief. This thesis has been submitted for examination with my approval.

1. _____

Supervisor

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2. _____

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Kibret Yilak

Approved by board of Examiners

Chairman, Department graduate committee

Signature

Supervisor

Signature

Supervisor

Signature

Internal Examiner

Signature

External Examiner

Signature

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DEDICATION

*To my wife **Tadila Fekade Endalew** and my son **Simon Kibret***

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ACRONYMS AND ABBREVIATIONS

Having given precedence of the listed acronyms and abbreviations to the use of the standard notation in each of the different fields addressed in this work.

CSR	China South Locomotive & Rolling Stock Corporation Limited
REVM	Radiused-Edges Vehicle Model
SEVM	Sharp-Edges Vehicle Model
SWERA	Solar and Wind Energy Resource Assessment
PHOENICS	Parabolic Hyperbolic or Elliptic Numerical Integration Code
Series	
CHAM	Concentration, Heat and Momentum limit
CATIA	Computer aided Three-dimensional Interactive Application
LRT	Light Railway Transit
km	kilometer
ERT	Ethiopian Railway Cooperation
DC	Direct Current
AC	Alternative Current
FVM	Finite Volume Method
FEM	Finite Element Method
BEM	Boundary Element Method
V_{wind}	cross-wind speed
F_{cr}	curve resistance
F_g	gravitational force
M_r	rolling moment
M_y	yawing moment
M_p	pitching moment
M_{rr}	rolling resistance
M_{yr}	yawing resistance
M_{pr}	pitching resistance
C_f	force coefficient
C_m	moment coefficient
F_p	pressure drag
F_f	friction drag
F_s	side force

OCS	overhead contact system
kv	kilovolt
P_{sav}	saving power
E	energy
t	time
CG	Center of Gravity
CP	Center of Pressure
W	weight of train
M	mass of train
h	height of center of gravity
Z	height of center of pressure
R	Radius of curvature
X	base distance between wheels at center of contact
R_F	Reaction force
F_C	centrifugal force
C_C	centrifugal couple
Q	inner or outer wheels vertical reaction due to centrifugal moment
P	inner or outer wheels vertical reaction due to gyroscopic couple
U	inner or outer wheels vertical reaction due to horizontal force
V	inner or outer wheels vertical reaction due to vertical force
C	Gyroscopic couple
C_w	wheel couple
ω_p	precession angular velocity
ω_w	angular velocity of wheel
I_w	mass moment of inertia of wheel
R_o	total vertical reaction on each outer wheel
R_i	total vertical reaction on each inner wheel
A	reference Area
CAD	Computer Aided Drafting
CFD	Computational Fluid Dynamics
C_L	Lift Coefficient
C_p	Pressure Coefficient
C_D	Drag Coefficient

DNS	Direct Numerical Simulation
F_L	Lift Force
F_D	Drag Force
Km/h	kilometer per hour
m/s	meter per second
g	gravity
ρ	Density
ω	Omega
ϵ	Epsilon
P	Pressure
RANS	Reynolds-Averaged Navier-Stokes
3D	Three Dimensional
μ	Viscosity
%	Percentage
V	Speed
V_∞	Free Stream Velocity

ABSTRACT

Nowadays, railway transport is widely used and improving its technology day by day in many countries in the world. Thus, this transportation system brings enormous benefits to society and economical by easily providing access and mobility of mainly passenger and freight transport. Ethiopian government has planned ongoing construction of standard gauge electrified railway system which is covering more than 5000km regional and intercity integration. Three types of Ethiopian trains are regional passengers, freight and Light Railway Transit public transport train have poor aerodynamic shape related their speed. This study has been focused on development of optimized vehicle body of the Ethiopian train under 12 m/s cross-winds speed condition for energy efficiency and dynamic stability of regional train locomotives and Light Railway Transit train. For numerical simulation analysis this study has used PHOENICS software a tool of CFD approaching method, KECHEN standard turbulence model and grid optimization test. In developing of train for power saving and guarantee driving stability of train locomotives at their cruise speed at high-speed under the influence of cross-wind, reduction of aerodynamic force coefficients and center of pressure position with respect to center of gravity were major areas. Which is depend on the modification of train locomotive body shape. Particularly, from a simple aerodynamic body modification of front, top and side parts have significant of power reduction of 23.013%, 17.397% and 7.365% for regional passenger train locomotive at maximum operation speed of 160km/h , freight train locomotive at maximum operation speed of 120km/h and Light Railway Transit public transport train at maximum operation speed of 80km/h respectively. But this paper has excluded headwind effect and considered only pressure drag resistance. This work found that the judgment of stability of Ethiopian regional train locomotives and Light Railway Transit train on straight rail track aerodynamic stability the rotational moment values have less than resistance moment values for all six tested model cases and on curved rail track dynamic stability of regional train locomotives maximum limited speed of 20m/s and Light Railway Transit train maximum limited speed of 12m/s under cross-wind condition. Therefore, from these aerodynamic drag improvement energy efficiency and aerodynamic stability has a high impact on the reduction of annual energy consumption and the stability of Ethiopian train locomotives safety has guaranteed at their maximum operational speeds.

Keywords

Aerodynamic, PHOENICS, CFD, Cross-wind, Dynamic Stability, Optimized, Energy efficiency, Ethiopian Railway.

1. INTRODUCTION

1.1 Background

Railway transport is a means of transportation system for passenger and freight on wheeled vehicles running on rails, which is also called track. It is also commonly referred to as train transport. A train is a form of rail transport consisting of a series of vehicles that usually runs along a rail track to transport freight or passengers. Motive power is provided by a separate locomotive or individual motors in self-propelled multiple unit and has air, hydraulic and hand brake system on both locomotive and cars for more safe to this mass transportation system than other ground transportation systems. In contrast to road transport, where vehicles run on a prepared flat surface, rail vehicles are directionally guided by the tracks on which they run. Tracks usually consist of steel rails, installed on ties or sleepers and ballast, on which the rolling stock, usually fitted with metal wheels, moves.

Recently railway transport is widely used in many countries in the world for transporting more than 9,000 billion freight tonne Kilometers (TKM) are travelled around the world from place to place which more than half of these are travelled in the US, China, and Russia. And also more than 2,000 billion passenger-kilometers travelled across the world, among of this around 1200 billion of these are travelled solely in India. The average Swiss person travels 2,400 km by train each year and the Japanese having the second-highest average kilometers travelled 1,900 km in the world. In 2014 there were around 1 million kilometers of railway in the world. Of this, 350,000 km are in Europe and mainly used for passenger service, 370,000 km are in America and mainly used for freight, and 230,000 km are in Asia and used for both freight and passenger service [1].

During the past years, many wind-induced accidents of railway and road vehicles have been reported. Although a lot of efforts have been spent on investigating the crosswind stability of vehicles, the research of crosswind stability is a great challenge. Hence, in this study the effects of the crosswind speed, the crosswind attack angle, and the vehicle speed on the operational safety of the vehicle examined in detail to prevent such many researchers' indicating direction as show in the Figure 1 below the effect of cross-wind on the running of high speed train.



Figure 1: Driving train overturned by crosswinds.

The combination of modern light weight and high speed railway vehicle design has the new development technology to energy saving, high-speed, economical easy production and so on. But it leads to an increased or exposed to instability at cross-wind, sudden powerful wind gusts and affected by high-speed itself. Therefore acquiring detail and correct data is quite important for to optimized new model vehicles body design of Ethiopian train from bad conditions due to prevent risk of accidents as indicated by different scholars in the world.

Thus, this transportation system is indispensable element of development and socio-economic growth which provide easily access passengers and freight transportation that is a major form has more than two cars and locomotives of mass passenger and freight transport system for long distance and high-speed traveling capacity. Railways are the most cost-effective mode of transport for moving bulk cargo for long distances over land. They are also suited to container traffic between ports and capitals. The relative importance of the rail system compared to other modes is the advantage it has gained from recent economic and technological trends including higher energy prices, the growth of container stations and new increases in flows of bulk trade and traffic. However, the railways in Africa carry only 1% of the global railway passenger traffic and 2% of the freight traffic. The major investments in Africa made over the 1970s and 1980s in infrastructure and railway system for the transport of passengers and freight has continued to decline nationally and sub regionally due to the poor maintenance of rail infrastructure and the paucity of available railway have contributed to the deterioration of rail service quality [2]. We can see that the railway history of our country Ethiopia had started railway transportation system at the time of 1897 by Emperor Minelik the II. But without improving, maintaining and keeping the transportation system

had got the chance to deteriorated and finally after 1985 had stopped. Even at the time of train on function there were no any research activity done on it.

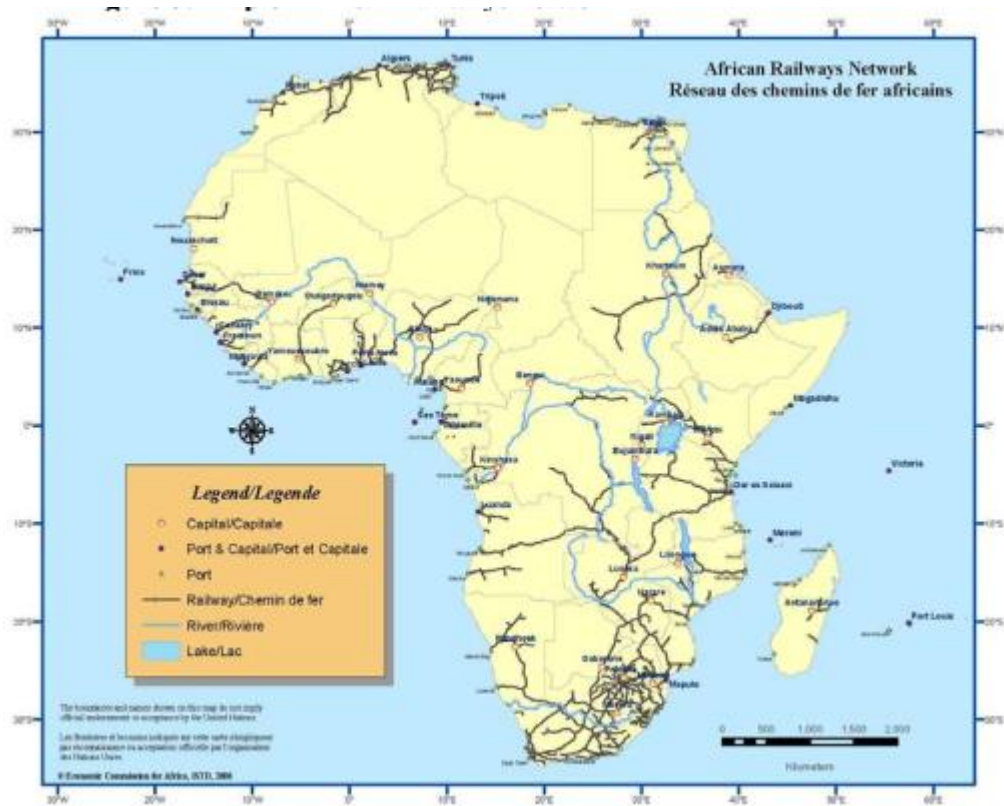


Figure 2: Map of African railways network

African Railway lines use nine different gauges. Among of these three widely used are

- The 1435 mm gauge representing 14.5% of the total railway in Africa network (dominating in Northern Africa).
- The 1067 mm gauge is the most widely used gauge, representing 61.3% of the total railway in Africa network (mainly in Sub Sahara African countries).
- The 1000 mm gauge representing 19.2 % of the total railway in Africa network [2].

The first Ethiopia Railway construction was starting in October 1897 from Djibouti in the period of Emperor Minelik II and service began in July 1901, from Djibout to Dire Dawa then in 1915, the line reached Akaki and after two years it had been reached all the way to Addis Ababa. It was

single-track, a 1,000 mm gauge with covered 781 km Addis Ababa to Djibouti and pass through in the Ethiopian regions as looking the infrastructure on the ground below Figure 3.



Figure 3: The previous Ethiopian Railway infrastructure looks like this.

From expansion of industrialization of one country to economic development needs a huge amount of energy consumption for productivity. And also now a day many researchers identified that industrialization has not only the advantage for development but has negative effect on environment and cost of energy consumed without efficiently and wisely used the technology. Within these and other core reasons, scientists tried to develop new technologies or enhance the performance of already existed technologies for better energy consumption with noticeable economic development in a given sector. For example, railway vehicle body design evolved begins from wagon ways structure design to streamlined shape train design for the aerodynamic effect consideration to be the transportation system energy consumption, safety, excellent driving stability, driving comfort, low environmental pollution, noise reduction, time saving or speedy, and others related benefits can be gain due to this continuous improvement and doing many research activities on this area. To date our country planed policy is expansion of industrialization among of those railway transportation system which is an essential element of economic and social development is needed huge amount of energy consumption for productivity. Practically, greater energy consumption efficiency has an advantage in reduction of environmental pollution and operating cost with increase of profit and sustainability of the project.

The Ethiopian government has given task to the Ethiopian Railways Corporation (ERC) for the developing a national railway network and hence now a day in Ethiopia all other regional railway system is under construction, as shown in the Figure 4. The new Ethiopian nation-wide standard gauge electrified railway passenger and cargo transportation system network currently under construction which will cover about more than 5000 kilometers that connects different regions and with creating the opportunity of a trade routes to neighboring countries; Kenya, Sudan, Somalia and Djibouti. In the beginning, in order to solve Addis Ababa city Public transport problem is constructed about 34.25 km (North-South line 16.9 km and East-West line 17.35 km) Light Railway Transit (LRT) system started service at 2015 and Addis Ababa to Djibouti started service at 2016 [3].

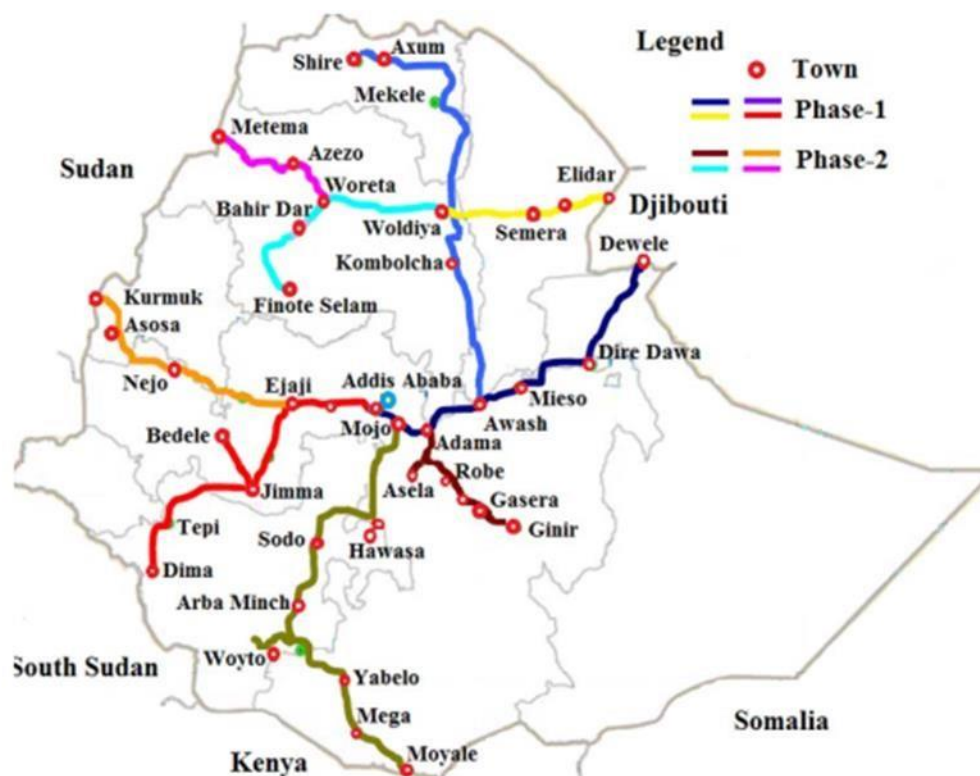


Figure 4: Planned and ongoing railway regional and neighboring countries integration network in Ethiopia.

Today the new standard gauge electrified railway system transportation is a key component of the Ethiopia's government planned to boost economic growth and enhance regional, city public transport and inter-city integrations. While train operating speeds increase, safety and comfort remain paramount concerns to significant social and economic benefit for the country. Compared

with road, air, and sea transportation, railway transportation has the advantages of mass transportation capacity, with rapid, safe, requiring less land resources, with lower energy consumption, less environmental pollution, and the capacity to operate under most weather conditions. Particularly, high-speed railway technology has been growing rapidly. Nevertheless, once dealing with a high speed railway running on straight and curved track, there are factors which has negative impacts on it such as Aerodynamic drag, driving stability, and Cross-wind are forcing to suffer which in critical cases can lead to undesired situations such as energy consumption, lack of comfort and accidents. Consequently, it is extremely important for the railway companies to consider the ride comfort and safety issues during in designing, manufacturing and operation process.

Due to the development of high-speed railways around the world and according to ERC, the new standard gauge electrified train design currently used for with maximum service speed of 160km/h passenger and 120km/h for freight from Addis Ababa to Djibouti and 80km/h for Addis Ababa city Public transport [4]. In high-speed trains the aerodynamic effects has become one of the major concerns of railway current accidents has the catastrophic consequences, therefore, it should be prevent for safety and sustainable system of train as well as other new technology high speed ground vehicles. The magnitude of aerodynamic effects broadly increases as the square of the vehicle speed so that, development of high speed train lines will become more significant with the consideration of design, manufacturing and operation safety and comforts as well. There are a variety of aerodynamic effects associated with train design, test and operation due to the aerodynamic drag, the effect of cross winds on train stability, pressure transient loading on trackside structures. The aerodynamics of railway vehicles influence a wide range areas from the aerodynamic loads acting on the train, the flow characteristics around the train structure the efficiency of mechanical components get effects due to shape of body design of vehicles. Therefore in this study development optimized vehicle body on aerodynamic effect on the Ethiopian railway vehicle, which is constructed by China Company of CSR, under the influence of Cross-wind conditions for energy efficiency and driving stability.

1.2 Description of train types

According to Ethiopian railway corporation (ERC) types of railway locomotive cars and wagon cars are DC locomotives (SS9, SS4), AC locomotives (HXD3C, HXD3B) are used for the LRT in Addis Ababa. SS9 is suggested to be used as passenger locomotive and SS4 is used for freight locomotive. The existing and the optimized vehicle models are intended to be used to test and

verify in detail by using the numerical and computational fluid dynamics method as tools for the calculation of energy consumption and operating conditions in consideration of the Ethiopian weather condition of taking frequently occurred wind speed which is expected to have the stability effect on the running high-speed train under cross-wind condition. There are two general types of trains to consider: Passenger trains and freight trains independently. They can be subdivided into categories:

1) Freight trains

- Post (mail) trains (GP)
- Material trains (GM)
- Regular goods trains (G, GS)

2) Passenger trains

- Regional trains (Re)
- Intercity trains (IC)
- ("Lightning") trains (IC-Lyn)
- Express trains (EP)

There are different study techniques used to predict aerodynamic effects like, in the wind tunnel test and CFD simulation method to determine magnitudes of aerodynamic pressures, velocities, forces etc. acts on the running vehicle body at each speeds. Thus, the aim of this study is to investigate and measure a range of aerodynamic phenomena observed in real Ethiopian train driving operation taking in to consideration the design of train body shapes by optimized the existing one for comparison as well as the state study of at real condition status safety analysis for preventing from accident.

1.3 Definition of Turbulence

According to [5] turbulence is defined as:

“... an irregular motion which in general makes its appearance in fluids, gaseous or liquid, then they flow past solid surfaces or even when neighboring streams of the same fluid flow past or over another.”

According to [6] redefined turbulence more precise manner as:

“Turbulence fluid motion is an irregular condition of flow in which the various quantities show a random variation with time and space coordinates, so that statistically distinct average values can be discerned.”

According to [7] extended the definition of turbulence as:

“... Turbulence has a wide range of scales.”

In general, based on the definitions quoted, it can be said that a turbulent flow exhibit characteristics of irregularity with varying random scales in time and space that refers to time, velocity and length scale, mixing of large and small eddies (shows diffusivity and dissipation) and is three dimensional in nature.

1.4 Methods to approach

From considering of detail design dimensions for the existing as shown in Figure 5 and 6 from the pictures of Ethiopian train have a look and optimized train vehicle either locomotive or cars with CTIA-V5-R20 design drawing data and modeling of needed for the CFD simulations have taken from Ethiopian Railway Corporation (ERC). For optimizing the head shape of the Addis Ababa LRT, Addis Ababa to Djibouti both passenger and freight train, an efficient optimization approach is used. The CFD analysis by solving Navier-Stokes equations is coupled with optimization calculation method, As a result, the efficiency of the optimization calculation is highly improved. After the optimization, an aerodynamic performance comparison between the optimal shape and the original shape of vehicle body models to compared by considering in different running speed for all model types of vehicle design in under cross-wind condition. Better shape developed to use the former at the higher speed. Lastly the drag has compared to check the stability of the train. Finally aerodynamic shape optimization advantages on efficiency of energy utilization analyzed in detail.



Figure 5: Ethiopian Light Railway Transit train in Addis Ababa for Public transportation system.



Figure 6: Ethiopian regional passenger and freight high-speed locomotive vehicles for Addis Ababa to Djibouti respectively.

This work is to increase the understanding of the crosswind sensitivity of a long distance and high-speed Ethiopian railway vehicles to find solutions to the problem of improving the safety with respect to crosswind performance and efficiency of each type train in fluid flow concepts with aerodynamic effects relation to speed, shape, and running condition of train vehicle, by the helping of PHOENICS 2015 CFD licensed software application by the help of CHAM company in the UK. The numerical calculation and 3D simulation analysis conducted to investigate how the running a high-speed Ethiopian train is affected the aerodynamic influence with under cross-wind conditions by Computational Fluid Dynamic approaching method. Under crosswind condition there were a serious reason for the driving stability problem of a high speed railway vehicles such as turnover. Many railway vehicles suddenly gets extreme crosswinds in locations around the world. The crosswind forces consider included the side force, the lift forces, the roll moment, the pitch moment, and the yaw moment.

Generally in this study was consider Ethiopian Light Rail Transit in Addis Ababa the maximum speed of 80km/h it has been starting the service for Public transportation, Passenger train at maximum speed of 160km/h from Addis Ababa to Djibouti and Freight train at maximum speed of 120km/h which are ready to start the service in this year. So, this study consider such maximum speed for detail analysis of the existing condition of train and with comparison of the optimized train models for each types for energy efficiency and dynamic stability in under the side wind conditions. So, rolling and aerodynamic resistance have a greater relative importance. However, from a technical point of view, establishment of modeling principles on the above types of trains is adequate to confirm the general approach and also it is valid for high-speed trains when appropriate data is applied.

1.5 Definition of Computational Fluid dynamics (CFD)

What is CFD? “CFD” is the acronym of Computational Fluid Dynamics. Computational means having to do with mathematics, computation and Fluid Dynamics refers to the dynamics of things that flow. So, CFD is a computational technology that enables to study the fluid flow. CFD not only predicts fluid flow behavior, but also the transfer of heat, mass, phase change, chemical reaction, mechanical movement and stress or deformation of related solid structures. CFD is the art of replacing the differential equation governing the Fluid Flow, with a set of algebraic equations (the process is called discretization), which in turn can be solved with the aid of a digital computer to get an approximate solution. The well-known discretization methods used in CFD are, Finite Volume Method (FVM), Finite Element Method (FEM), and Boundary Element Method (BEM) Computational Fluid Dynamics or simply CFD is concerned with obtaining numerical solution to fluid flow problems by using computers. The advent of high-speed and large-memory computers has enabled CFD to obtain solutions to many flow problems including those that are compressible or incompressible, laminar or turbulent, chemically reacting or non-reacting. Computational Fluid Dynamics (CFD) is the science of predicting fluid flow, heat transfer, mass transfer, chemical reactions, and related phenomena by solving the mathematical equations which govern these processes using computational methods [8].

For the determination of the aerodynamic behavior of railway vehicles still the wind tunnel test is the preferred measure, but to fulfil the requirements for the development of optimized vehicles in a shorter time and computational methods are to be further included in the design process. Nevertheless, following the example of the automotive and aeronautical industries, also in the

design of a railway vehicle the approach of a stronger coupling of the constructional tools with the predictive processes of the train performance is aimed for, in order to get optimized products with less effort, a shorter time and for repeatability and correct comparative measurements when aerodynamic changes are made during the early stages in the design and development process. It has also advantages from wind tunnel test without use of small models allows numerous design features to be tested in a cost effective manner without adequate accuracy from non-dimensionalization and measurement errors. For truly accurate simulation of the full scale flow it is necessary to achieve geometric and dynamic similarity.

1.6 Statement of the problem

There is a high demand of railway transportation system in the world including in our country Ethiopia for a long distance transport of passengers and goods. To satisfy such demands in our country, it needs to have a railway transportation system with standard safety, comfort, fast and reliable to customers for the benefit of social and economic aspects. Such a train travel at high speed on straight and curved track at minimum radius of curvature 300m for regional trains and 100m for LRT there are factors which has negative impacts like, aerodynamic drag effects and centrifugal force for dynamic Stability of the moving vehicle under the influence of cross-wind conditions can lead to undesired situations, lack of comfort, noise, unstable driving, environmental pollution and cause of accidents. According to the results of several full scale tests, for the bluff shape train running at a speed of 120 km/h, the aerodynamic drag is about 40% of the total drag, which climbs up to 75% when the speed reaches 160 km/h [9]. Hence, it is extremely important for the Ethiopian railway trains have maximum operational speed 160km/h for regional passenger train, 120km/h for regional freight train and 80 km/h for LRT ongoing construction to consider the aerodynamic drag resistance and safety issues under cross-wind at 12m/s speed conditions. This study could investigate or found the solution of the aerodynamic and dynamic stability of Ethiopian train by using CFD numerical simulation and analytical calculations.

1.7 Objectives of the study

1.7.1 General objective

The general objective of this thesis is to optimize the body shape of a high speed and long-distance travel Ethiopian train under cross-wind conditions for energy efficiency and dynamic stability.

1.7.2 Specific objectives

- To develop optimized high-speed train aerodynamic body design of Ethiopian railway for energy efficiency under the influence of cross-wind conditions.
- To judge aerodynamic and dynamic stability Ethiopian railway locomotives.
- To study the effect of side-wind on centrifugal force for dynamic Stability of the moving vehicle on the curvature.
- To show differences in aerodynamic performance between the two baseline and optimized train models.
- To make numerical and simulation analysis model vehicles using CFD at different driving speeds for Regional Passenger, Regional Freight and Light Railway Transit vehicle models of Ethiopian Railway.

The objectives of the aerodynamic design work outlined above are influenced by the type of vehicle shape design specially focused on frontal area, top part, under body of train develop optimized aerodynamic design under consideration. In this study, during the aerodynamic design of a train the main consideration is drag, lift and side forces and dynamic stability. On a high-speed train, reduction drag load, lift load and side load which is more sensitivity to cross-winds are the primary goal. Various solutions are available depending upon the type of vehicle.

1.8 Significance of the study

The development of the future transport network and the wise use of resources require that network be utilized in an appropriate manner. This work has a great significance for the new under construction Ethiopian railway transportation system. It contributes a lot for evaluate, analysis and applications of aerodynamic and dynamic stability effect on the under construction Ethiopian train with cross-winds condition and optimized of the model vehicle for development planned perspective angle. Especially, the purpose of this study, concerned on evaluation of aerodynamic effect on a long-distance and high-speed Ethiopian train under the influence of cross-winds for development optimized train body to evaluate energy efficiency, driving stability both straight and curved rail track, passenger comfort, safety investigation, and reduce noise due to the shape of particularly train locomotives. Which is undertaking in the straight and curve rail truck conditions to the benefit or better of socio-economic of excellent railway vehicles design to perform improvement in detail by practical observation with comparison the two train models. However, its rapid growth or development of railway transportation system has controversial in terms of quality of design, construction and operational safety. There are different characteristics of modern

trains which is significant for the influence of the crosswind stability such as lightweight construction increases the technical and economic efficiency of the trains, high-speed for time save at driving conditions.

1.9 Scope of the study

The scope of this study is mainly concentrated on aerodynamic and dynamic load effects under consideration of the influence of side wind of a high-speed and long distance cover on the intercity and regional integration Ethiopian Railway transportation system for sustainability and prevent from accidents which focused mainly on aerodynamic drag resistance without head wind consider, lift and side forces under cross-wind condition. In particularly, aerodynamic load effects occurred on the front, inter-car gap, underbody, rear end parts of the train surface as the main part of the total aerodynamic resistance lies on the frontal part of the train surface the main focus of the study is around the train nose, underbody and rear end of the three types of train locomotives such as Light Railway Transit, Regional Passenger locomotive and Regional Freight locomotive vehicles. To find the best approach for detail aerodynamic consideration for between the existing and optimized models trains shape design. Thus, concepts of aerodynamic reliability analysis studied by commercial Software of PHOENICS 2015, CFD method technique numerical and simulation analysis described from completed 3D model CATIA V5R20 and CAD 2015 Software's as considering on different driving speed of train models and some features of cross-wind sensitivity analysis and optimization of body design made.

Generally, this study has evaluated the aerodynamic effect on developing two reliable train 3D models which are the existing Ethiopian railway train and the modify body design one for simulate the models and analyzed the effect of Ethiopian railway vehicles under cross-wind conditions.

1.10 Limitation of the study

The limitations of the studies were mainly first, unavailability of detailed drawing of the train body especially under body part of train locomotive design detail dimension which made difficulty to optimize and to compare the aerodynamic effects on under body parts for both modes easily. Second, 3D model printing machine for preparing the Ethiopian train models to test wind tunnel experiment for comparison of CFD simulation because, numerical methods together with experimental verifications are more and more important for reliability. Thirdly, unavailability of the current wind speed assessment data at the particular areas of Ethiopian under construction railway planned system lines. However, this study main focused on develop aerodynamic shape

optimization for energy efficiency and stability of Ethiopian railway system which does not have much difference on the exact results. And also, other dynamic resistance on train not included here but in the case of comparison of models it does not have effect on this study.

1.11 Organization of the study

This paper has a total of five chapters which contain introduction in the previous chapter and the following four chapters. In the introduction background of train aerodynamics, description of train types and methods to approach how optimized aerodynamic shape design of train body under side wind influence condition. Statement of the study, significant of the study, scope of the study, limitation of the study and objective of the study contained on the first chapter. The second chapter contains literature review parts. There are a lot of works done on this area, railway history in the world, Africa and Ethiopia, overviews of electric railway, aerodynamic running resistance of train, governing equations, lateral dynamic on high-speed train, stability of running train, approaching to train vehicle body design, aerodynamic design and optimization, energy efficiency on Ethiopian train and natural wind assessment in Ethiopia. The third chapter is the main body of the study, which contains aerodynamic drag, lift and side forces and moments, electric locomotive and power efficiency, Ethiopian train locomotive specification, boundary and initial condition for CFD simulation, turbulence model, and dynamic stability, of the train with the cross wind effect, the aerodynamic shape optimization which mainly concentrated on the reduction of drag coefficient and stability of train and at the end of this chapter aspect of energy efficiency of the train is discussed. The fourth chapter contains the results of the analysis and discussed the implications of the results from CFD numerical simulation. The last chapter ends the main works of the study, which contains the conclusion of the paper and suggested future works. At the end of the paper there are references and appendices used in the study.

2.0 LITERATURE REVIEW

2.1 Railway History

The history of rail transport systems is evolved from with man or horse power, and tracks or guides made of stone or wood, dates back to the ancient Greeks. At the time of about 1500 through 1800 Wagon ways transportation were common in Europe (typically in mining) countries. When at 1820s in England the first rail transportation systems appeared. The system was made use of the steam locomotive system, it was critical to the Industrial revolution and to the development of export economies development across the world. They have remained the primary form of long distance land transportation for many bulk materials such as coal, ore, grains, stone and sand and gravel [10].

The worst train disaster recorded on December 12, 1917, had killed 543 people in Modane the Savoie region of the French Alps in France due to overloaded train, the worst American train disaster occurred in Nashville on July 9, 1918, as the reason of a head-on collision of two trains killed 101 and injured 171 and on March 2, 1944, 426 people were killed and 521 were injured by carbon monoxide fumes, and also in the case of an overloaded train in a tunnel in Salerno, Italy, for more than an hour was happening [11].

Indian railway is one of the world largest and has networks about 115,000km which is carried annually 8.398 billion passengers and 1050.17 million tons of freight. Including stoppage average speed of Indian train is 72km/h but the aerodynamic phenomena is depend on train body design of shape, train length, body surface smoothness, environmental condition of cross-winds effect and the inter-gap space between train vehicles which could be indicated as shown in Figure 7 [12].



Figure 7: Inter-car gap in Indian train.

There was train accidents due to the effects of aerodynamic performance of trains under crosswind conditions in 2007, trains derailed with 11 cars under high wind conditions, causing a serious accident on the Xinjiang railway South Line and a train overturned in china as shown Figure 8 and there have been about 30 wind induced accidents which were very serious for passengers as well as train damages which indicated in the Figure 9. However, less attention has been paid to the aerodynamic effects of consider in detail optimization of design and operation under strong rain and crosswind on the aerodynamic characteristics [13].



Figure 8: Train overturning in China in 2007.



Figure 9: Train overturning in Japan in 2007.

2.2 Ethiopian Railway history

One of the worst rail accidents in African history occurred on Sunday afternoon in January 14, 1985. Ethiopian train had got sudden accident into a deep narrow valley in eastern part of Ethiopia from Addis Ababa around 160km, the train was coming in Djibouti to Addis Ababa, it was crossing a bridge outside the town of Awash with a five-car passenger train carrying about 1,000 people among of these 392 were killed and 370 injured. It was third disaster train accident in the world. It was traveling at a high-speed and had failed to slow down around a curve condition the rear car left the track first, crashing through a guard rail and pulling the rest of the train into a dry riverbed more than 10m. There was never happened such a terrible train accident in Ethiopia before [11]. Aerodynamic drag control for ground vehicle is one of the most important research problems about vehicle aerodynamics, which is directly related to the energy efficiency and the drag of a vehicle is proportion to the square of its speed. The aerodynamic drag on ground vehicle typically accounts for about 70% of its total resistance when its speed reaches 90 km/h and more than. The control of aerodynamic drag becomes widely concerned because of to rise extremely energy consumption [14].

For the development train vehicles could be faster, comfort, environmental friendly, less noise, and lower aerodynamic effects. Hence, many scholars are paying much attention on the aerodynamic train optimization design which is aerodynamic characteristics are strongly depend on the speed of train and vehicle body shape. So, aerodynamic resistance problems are very important as the speed of train increases. [15]. In the development of train which is a faster, safe system, less aerodynamic resistance, lower air pollution and noise many scholars paying more attention on the aerodynamic of high-speed railway train [12].

In a high-speed and long distance either straight or a curve way traveling train experiencing crosswind will be subjected to the high aerodynamic load, such as drag, side force and lift force due to effect of train speed and side wind speed as well as wind angle, these aerodynamic loads cause an overturning moment about the lee rail but the restoring moment is only provided through mass of the vehicle itself [16]. The effect of cross-winds on rail vehicles has been investigated since the 1970s by international research, specifically on the railways in Germany, England and Japan. Side wind on rail vehicles is basically determined by different factors such as, vehicle shape, weight, position of center of gravity, radius of curves, track bed, frequency and the direction with which the side wind occur, embankment of truck, etc. Thus these factors should be considered together not individually [17].

The train running speed under strong weather conditions such as, cross-winds, rain when it exposed locations either bridges, tunnels, embankments, the aerodynamic forces and moments may increase significantly and result in the train instability. It was common that the strong crosswind may increase the aerodynamic drag force, side force and yawing moment. Thus, the rain and the crosswind coexist, the aerodynamic performance of train will deteriorate more severely and which may cause train delays, shutdowns, derailments and even overturning.

The effect of side wind on rail vehicles is basically determined in different matter of facts, crosswind stability has become one of the most critical items in the approval procedure of rolling stock system and thus also a crucial boundary condition in the design process of new vehicles. Even though the main attention is often given to high-speed vehicle, lightweight construction, and distributed traction crosswind stability is a relevant topic also for the railway vehicles has been object of large interest by research and industry to improve passenger and freight transportation system which are easily exposed to Aerodynamic effects [18].

When the researchers analyze, evaluate or investigate aerodynamic loads on a railway vehicle is one of the most relevant tasks to be consider for the construction and operation of modern trains. Because, when the train travels a long distance and a speeds the running resistance of a typical high speed train is dominated by the aerodynamic drag, lift forces are causing an unwanted loading especially on the leading vehicle. Additionally cross winds and lift forces result in rolling, pitching and yawing moments which under extreme wind conditions will cause the vehicle to rollover. Therefore, to be guarantee safe and economical operation system the control of the aerodynamic

loads by an optimum design of the railway vehicles is mandatory, respecting the various requirements of infrastructure and driving condition of the train [19].

When the train transportation system evolve a high-speed and long distance travel design railway has been developed hence, at high-speed different aerodynamic pressure loading on surface of vehicle body increases. In particular, the maximum pressure loads occur on around the nose of the Railway vehicles are valid for the open air with a length up to 20m at full-scale lengthen and also different loading patterns have been observed either due to pressure waves presence [20]. The aerodynamic load phenomena can be investigated in different mechanisms which are the predictive numerical equations, computational fluid dynamics (CFD) and wind tunnel test. Thus, wind tunnel is the primary tool for aerodynamic tests and the predictive equations are used for preliminary analysis like, heavy locomotives. But CFD is commonly used for design analysis as an option when fulfilling requirements on suitability and feasibility studies [21].

Therefore these study has given more attention to analyzed, evaluated and optimized the existing Ethiopian train and development of new model train body on rail system under consideration of crosswind influence on the driving stability. This, and similar previous incidents, reveal how railway transportation system considered the aerodynamic effects with influence of cross-wind of severe weather conditions and how this can dangerous of the train accident rather than other transportation system. Thus, the safety of train operations within the different geographical regions and weather condition considered the aerodynamic effects on Ethiopian railway transportation system under the influence of Cross-winds for an optimization of body shape to forecast the safety for minimizing the risk when severe weather conditions occur.

Generally the knowledge of the aerodynamic forces and moments response of the vehicle is essential for the railway operators in order to provide ecological, social, economic and safe traffic. Special emphasis lies on the determination of the side wind stability of trains as a safety criterion. Technological improvements in areas such as aerodynamics, train weight, rolling resistance, engine efficiency or emission control.

2.3 Overview of Electric Railway Systems

In 1897, Siemens displayed the first electrically powered locomotive at the Berlin Commerce Fair. The maximum speed of this train was 13 km/h, and the output energy came to about 2.2 kW. Since

then, electrified railways have been improved dramatically due to the rapid development of power electronics and manufacturing industries. Nowadays, the transportation capability of a single locomotive has been increased to thousands of tons [22]. Electrification has many advantages for transportation system like train, bus, taxi and subway ground transportation system. Train locomotive electrification system supplies electric power to train without fuel supply. There are different ways to supply power for running ground vehicle locomotive cars or train locomotives with a continuous conductor running along the track such as

- The overhead or catenary wire suspended from poles along the track
- The third-rail system mounted at track level and contacted by a sliding

Hence, electric railway locomotives offer substantially better energy efficiency, lower emissions, quieter, more powerful and lower operating costs, more responsive and reliable than diesels.



Figure 10: This Ethiopian train using overhead or catenary wire suspended from poles along the track.

Electric trains use a similar principle as the diesel electric locomotive. The difference is that the locomotive receives electricity for the electric traction motors directly from the electricity lines along the track. Electrical equipment on the locomotive adapts the electricity to that type used by the traction motors. The Danish ER- train set is equipped with asynchronous A/C motors. They have a better output efficiency (about 90%) than older, more conventional electric motors. This could be accommodated in model calculations by adjusting the electrical locomotive efficiency. Track electrical systems in general, two different current systems are used in European countries. The most common is an alternating current at a frequency of 16 2/3 Hz. In a few countries like Denmark and France a more powerful alternating current at 1500 volt 50 Hertz is used. 50 Hz is a frequency that gives a higher power for the traction motors. This gives a total efficiency of 65%, which is quite higher than that for diesel powered equipment [23]. Therefore, Ethiopian electric train locomotives use for catenary voltage is 25kV, 50Hz direct power feeding with return wire mode.

2.4. Running Resistance of Trains

The fundamental physical processes determining the energy consumption and train movement along the rail suffers from various resistance forces which opposes longitudinal traverse of the train [24]. The magnitude of the forces acting on a train against its direction of travel are known as running resistance. It is a must to know the running resistance of trains for determining power requirements. This study shows that the increase in running resistance is linear due to increasing aerodynamic load due to the geometrical shape of the train body design and load of train. Which can be divided into the following main categories

- **Aerodynamic drag (F_D).**

Air resistance depends on the dimension and cross sectional shape of the train and is independent on the weight of the vehicle. Thus, as shown in the figure which indicates the shape of the train versus the train speed relationships.

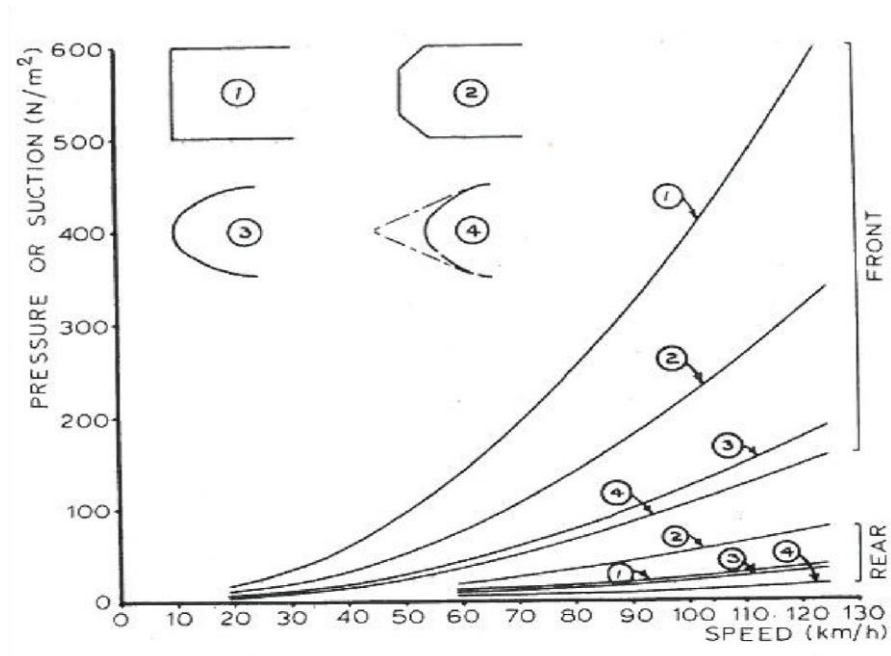


Figure 11: The aerodynamic effect on running vehicle front shape of resistance load versus speed of vehicle.

The aerodynamic force can be estimated:

$$F_D = \frac{1}{2} \cdot \rho \cdot C_D \cdot (V - V_{wind})^2 \cdot A \cdot \cos \theta \quad (1)$$

The projection area (A) of a vehicle from empirical equation [25] is

$$A = 0.82b \cdot h \quad (2)$$

Where ρ is the density of air, C_D is the drag coefficient, V is the train speed, b is the width of train, h is the height of train, V_{wind} is the head on wind, A is the cross sectional area of train front and θ is the angle between wind and driving direction.

- **Curve resistance (F_{Cr})** which is the increment in rolling resistance as a train is rounding a curve. When the vehicle running at a speed V with on the radius of rail R experience for centrifugal force by the reason for undesired effect like passenger discomfort, displacement of wagon load, risk of overturning. Thus, high lateral force on the track which increases curve resistance, risk of rail tilting and risk of lateral displacement of whole track [26].

According to Rockl's Empirical formula [27] for curve resistance can be expressed by

$$F_{cr} = \frac{6.5}{R-55} \cdot g \cdot M_t \quad \text{where } R > 300m \quad (3)$$

$$F_{cr} = \frac{5}{R-30} \cdot g \cdot M_t \quad \text{where } R < 300m \quad (4)$$

Where R is the radius of the rail, M_t is the total mass of the train and g is the gravitational acceleration. A vehicle running in a curve with radius (R), speed (V) experiences a centrifugal lateral acceleration (a) and this results undesirable effects like as shown in the figure below.

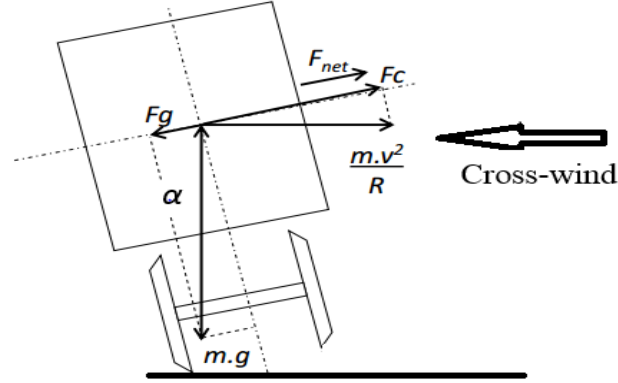


Figure 12: How cross-wind affect the running train and reaction of centrifugal force.

$$F_C = \frac{mV^2}{R} \cdot \cos \alpha = \frac{mV^2}{R}, \quad \text{for small angle} \quad (5)$$

$$F_g = mg \sin \alpha \quad (6)$$

$$F_{net} = F_C - F_g \quad (7)$$

Centrifugal moment (M_C):

$$M_C = \frac{mV^2}{R} h \quad (8)$$

Where g is gravitational acceleration, R is radius of gyration or the rail curvature, V is the speed of train, m is the mass of train, F_C is the centrifugal force, F_g is the gravitational force and α is the tilting angle of the train. Curve resistance is normally not too large but it is one of the smallest driving resistance and it is very complicated and need very detailed calculations.

- **Inertia resistance (F_I)** can be interpreted as the extra tractive effort required for acceleration due to the effect of inertia.
- **Grade resistance (F_g)** when a train will experience a resistive force due to gravity.

$$F_g = M_t \cdot g \cdot \sin \alpha, \text{ or} \quad (9)$$

$$F_g = M_t \cdot g \cdot \frac{\Delta h}{x} \cdot 1000 \quad (10)$$

Where F_g is total gradient resistance in N, M_t is total train mass in kg, g is gravitational acceleration in m/s^2 , α is the angle of gradient and Δh is the height difference in m, over the horizontal distance x in m.

- **Rolling resistance (F_R)** due to mechanical energy dissipation in vehicle, track and the contact areas between wheels and track. Curve resistance is also part of the rolling resistance which is dependent on the curve radius, track gauge and the wheel-rail condition that caused by slipping of wheels and flange resistance.

$$F_R = C_R \cdot M_t \cdot g \quad (11)$$

$$\text{Or } F_R = (0.015 + 0.00016V) \cdot W \quad (12)$$

Where F_R is rolling resistance in N, M_t is total mass of the train in kg, g is gravitational acceleration, V is train locomotive speed in km/h, W is weight of train locomotive and C_R is rolling resistance coefficient. The rolling resistance coefficient is dependent on type of train, as well as the number of axles, speed and weight of the train which has the following effects

- The possible passenger discomfort and noise nuisance
- The possible displacement of wagon loads
- The risk of vehicles overturning
- The risk of derailment by wheel climbing or loosening of rail fastenings
- The high lateral forces on track structure that results
 - High curve resistance
 - Severe wear of rails and wheel flange

- Risk of lateral displacement of the whole track or track shift
- Risk of rail tilting
- Noise nuisance

Expression of C_R is as following

$$C_R = C_0 + C_1 \cdot \left(\frac{V}{V_0}\right) + C_2 \cdot \left(\frac{V}{V_0}\right)^2 \quad (13)$$

Where C_R is rolling resistance coefficient, C_0 , C_1 and C_2 constants in % V is the train speed in m/s. V_0 is a constant reference speed of 100 km/h = 27.78 m/s.

$$C_0 = \frac{F_{SL} \cdot M_L + F_{SV} \cdot M_W}{M_{train}} \quad (14)$$

$$F_{SV} = C_{SV} + \frac{F_{AXW} \cdot n_{AX}}{M_{train} \cdot g} \quad (15)$$

Where F_{SL} and F_{SV} is dimensionless of the initial value for the locomotive driving and wagons resistance respectively, C_{SV} is a constant in %, F_{AXW} the axle weight constant of 100 N, n_{AX} is the number of axles M_{train} is the total weight of the train ($M_L + M_V$) M_L and M_V are the total weights for the locomotive and wagons respectively [28]. In other hand the rolling resistance can be defined the friction between rail and wheel of the train [25]. That expressed as

$$R_R = \mu_R \cdot (W_{car} + W_X) \quad (16)$$

Where μ_R is the rolling resistance coefficient, W_{car} is the gross weight of the vehicle and W_X is induced lift or down force on the running vehicle. In general the total resistance of running train is for open air condition without any cross-wind effect, the total drag on the traveling train can be expressed by formula [29].

$$F_R = A + B \cdot V + C V^2 \quad (17)$$

Where F_R is the total drag, A , B and C are the constants determined by the experiment, and is the train velocity relative to the ground.

Table 1: shows typical values for different types of equipment [28]

Equipment type	constants
4-axle locomotive	$F_{SL} = 25\text{-}35\%$
6-axle locomotive	$F_{SL} = 35\text{-}45\%$
Passenger train cars	$C_{SV} = 40\%$
	$C_1 = 25\%, C_2 = 50\%$
Freight train cars	$C_{SV} = 60\%$
	$C_1 = 50\%, C_2 = 60\%$

2.5 Train Vehicles Aerodynamics and Cross-wind Effects

The aerodynamic load can be mentioned as following methods predictive equations, computational fluid dynamics (CFD) and wind tunnel test. The predictive equations are used for preliminary analysis or conservative assessment. Wind tunnel tests are the primary tool for certification of railway vehicle system engineering, with CFD as an option when fulfilling requirements on suitability. CFD is commonly used for design analysis and feasibility studies [21].

Aerodynamic drag is proportional to the square of speed of train. With the increase of the speed of train, aerodynamic drag plays an important role for high-speed train. Thus, the reduction of aerodynamic drag and energy consumption of high-speed train is one of the essential issues for the development of the desirable train system. Aerodynamic research initially focused upon drag reduction, but it soon became apparent that the lift and side forces were also of great significance in terms of vehicle stability. When a vehicle is moving in a fluid like air, the vehicle interacts with the fluid due to its shape and surface. Assuming a control volume around the vehicle, the law of conversation of mass applies, and thus changes in the curvature of the vehicle surface lead to local changes in the flow velocity and the flow pressure. For a non-viscous and incompressible flow the relation is given by

Bernoulli's equation

$$p + \frac{1}{2} \rho V^2 = \text{const}, \quad (18)$$

Where p is the static pressure, ρ the fluid density and V the flow velocity along a streamline [30].

2.5.1 Approaching of Governing Equation

The equations governing the fluid motion are called the Navier-Stokes equations for incompressible, compressible, viscous flow and inviscid flow of fluid. In this study considered the air flow on the running train. These equations are derived from first principles of conservation of mass (continuity equation), momentum and energy. These equations are shown below

The conservation mass equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho V) = 0 \quad (19)$$

The conservation of momentum equation:

$$\rho \frac{\partial V}{\partial t} + \rho(V \cdot \nabla V) = -\nabla p + \rho g + \nabla \tau_{ij} \quad (20)$$

The conservation of energy equation:

$$\frac{\partial}{\partial t} \int e \cdot \rho dV + \int \left(\dot{u} + \frac{p}{\rho} + \frac{V^2}{2} + gz \right) \rho \cdot V \cdot \hat{n} \cdot dA = Q_{\text{net in}} + W_{\text{net in}} \quad (21)$$

The turbulent kinetic energy:

$$K = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad (22)$$

The turbulent energy dissipation rate (ϵ):

$$\epsilon = \nu \left[\left(\frac{\partial u'}{\partial x} \right)^2 + \left(\frac{\partial u'}{\partial y} \right)^2 + \left(\frac{\partial u'}{\partial z} \right)^2 + \left(\frac{\partial v'}{\partial x} \right)^2 + \left(\frac{\partial v'}{\partial y} \right)^2 + \left(\frac{\partial v'}{\partial z} \right)^2 + \left(\frac{\partial w'}{\partial x} \right)^2 + \left(\frac{\partial w'}{\partial y} \right)^2 + \left(\frac{\partial w'}{\partial z} \right)^2 \right] \quad (23)$$

A ways of modeling and analyzing fluid flow was through turbulence modeling k- ϵ . The incompressible Navier-Stokes equations in Cartesian coordinates are shown in Equations below.

X-direction:

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{p}{\rho} \rho g_x + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (24)$$

Y-direction:

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{p}{\partial y} \rho g_y + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (25)$$

Z-direction:

$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{p}{\partial z} \rho g_z + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad (26)$$

Train speed in particular has a great impact on the aerodynamic force since these forces increase with the square of the train speed. Thus, the aerodynamic forces greatly affected by the geometry of the train nose and a slender nose produces weaker aerodynamic force than a bluff nose. Train geometry, particularly the shape of the train nose, has a significant influence on the strength of the aerodynamic forces. There are sufficient variations in the strength of the aerodynamic forces due to a train's design, such that a streamlined train with a slender nose, traveling at 240km/h, creates aerodynamic forces that are no more severe than a train with a bluff nose traveling at a speed of 170 km/h [31].

Although the aerodynamics of trains is obviously related to the aerodynamics of other ground vehicles, there are various important differences. For example, the aerodynamics of airplanes also involves consideration of more streamlined bodies, but trains operate near the ground, have much greater length-to-diameter ratios, and pass close to adjacent structures and each other, and modern high-speed trains are more subject to crosswinds. Crosswinds have many important effects on the aerodynamics of trains, one might expect that the increase in operating speed of modern high-speed trains would reduce the effective yaw angle that corresponds to a given crosswind component, so that the effects would be reduced. However, high-speed operation of modern trains has been accompanied by a significant reduction in train weight as a result of better structural design and improved materials, so the net effect has been an increase in the importance of crosswind effects. Thus, on the effects of a crosswind not only on drag but also on lift, side force, and moments are very important for assessing vehicle stability [32].

Crosswind stability of rail vehicles has been a research topic during the last decades, mainly motivated by overturning accidents. Reports on crosswind accidents of rail vehicles in fact date back to the 19th century to the current decade [33]. Two examples of accidents of the current

decade can be seen in Figure.13 showing the most common crosswind accident type for a rail vehicle, which is overturning among one of the trains in the world. In comparison, crosswind accidents of road vehicles are mostly of a different kind, since an initial deviation from the direction of travel is most common.



Figure 13: Rollover accidents of rail vehicles, (a) on curved track at Uttendorf (Austria) in 2002, (b) on tangent track at Wasserauen (Switzerland) in 2007 [18].

In recent times the motivation of studies of crosswind stability of rail vehicles has been extended. The operational speed of trains has increased, also leading to higher aerodynamic loads on the vehicle. Heavier vehicles could improve the crosswind stability and increase energy consumption but on the contrary issues like lower energy consumption demand lighter vehicles, which at the same time would lead to benefits regarding track deterioration and track maintenance and instability. Furthermore, the traction layout of passenger trains, especially high speed ones, is changing in recent years going from loco-trains to multiple units with distributed traction. Since the aerodynamic forces are most critical on the leading vehicle of a train, the weight change from a locomotive - as the leading and heaviest vehicle of a loco-train - to a vehicle of a multiple unit increases the demands on crosswind stability of trains. In addition, unsteady crosswind like various gusts is becoming a major concern [18].

The forces may be considered to act along three, mutually perpendicular axes. Those forces are the drag, which is a measure of on head aerodynamic force that resists the forward motion of the car, the lift which may act upwards or downwards, and the side force which only occurs in the event of a cross-wind or when the vehicle is in close proximity to another. The lift, drag and pitching moments are a measure of the tendency of those three forces to cause the car to rotate

about some datum, usually the center of gravity. The changes in the aerodynamic forces were small above Re-numbers of $Re > 1.7 \times 10^5$ [34]. Generally the aerodynamic forces and moments that act upon a vehicle are shown in coefficient form are the force and moment coefficients are defined respectively as

$$C_f = \frac{F}{\frac{1}{2} \rho A V^2} \quad (27)$$

$$C_m = \frac{M}{\frac{1}{2} \rho A l V^2} \quad (28)$$

Where F is force (lift, drag or side), M is a moment, ρ is air density, V is velocity, A is reference area and l is a wheel base (reference) length. Since the aerodynamic forces acting on a vehicle at any given speed are proportional to both the appropriate coefficient and to the reference area or usually frontal cross section area.

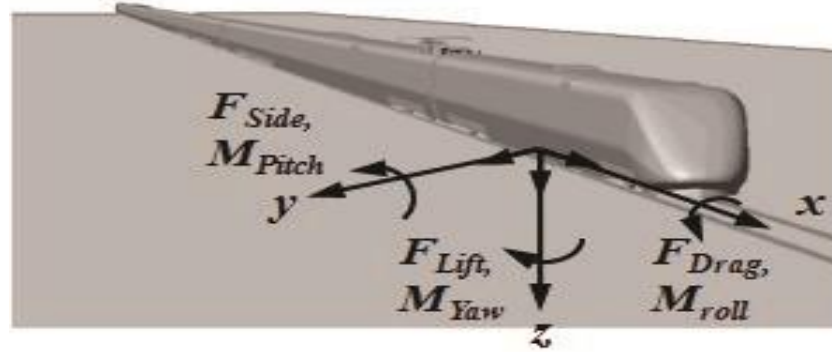


Figure 14: Force coefficients: lift (C_L), drag (C_D), side force (C_S) and Moment coefficients: pitch (C_{mp}), roll (C_{mr}), yaw (C_{my})

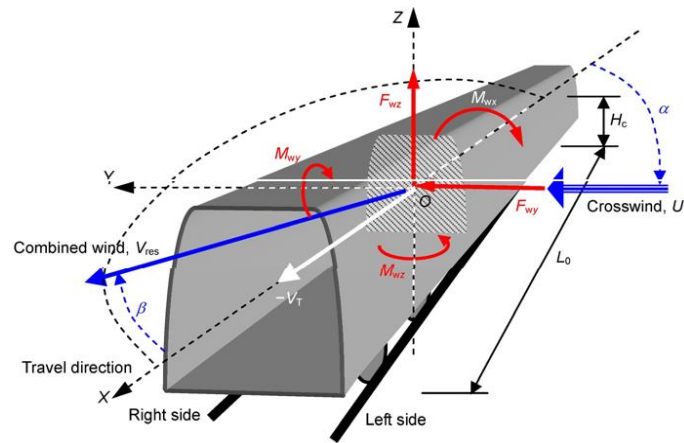


Figure 15: Aerodynamic forces effects on moving railway vehicle under the influence of cross-wind.

2.5.2 Lateral dynamics on high-speed train

Both on straight and curve track a vehicle is beside the track irregularities affected by lateral impacts due to the running behavior of the vehicle itself. Vehicle ride instability can occur at high speed and in some cases this could also affect the vehicle ability to withstand crosswind. The increase in resistance due to curves is significant and increases as the curve radius decreases [35]. Due to side strong winds appear over running vehicles and on bridge structures which were built very long and tall. So, the new Ethiopian railway lines are currently under construction in regions with very deep valleys and mountains so these bridges have a very low lateral stiffness and lateral dynamic effects that may endanger safety of transportation could easily appear.

2.5.3 Pressure Drag on the Running train vehicles

In automotive aerodynamics drag is a major concern of investigation and also drag is a sum of mechanical forces generated on the surface of an object due to the interaction with the fluid. Since, the magnitude of it is largely affect the vehicle characteristics such as energy consumption and stability. Acting drag force can be divided into two source, but the physical origin makes them dependent to each other. The drag consist a pressure source term normal to the surface (pressure drag), and a viscosity originated shear stress term parallel to the surface (friction drag). In other approach the aerodynamic drag is an integral of static pressure, friction and turbulence stresses over the surface of the vehicle [36]. Aerodynamic drag is a major component of train resistance, particularly at high speeds [37].

$$F_D = \frac{1}{2} \rho A C_D V^2 \quad (29)$$

Where F_D is the pressure drag force, A is the reference area of train, C_D is the drag coefficient and V is the train speed.

According to so many findings the pressure drag is the dominant source for automotive flows, compared to the friction drag from the shear stresses. Generally the pressure distribution along a bluff body or a vehicle consist a high pressure area in front (stagnation), and a low pressure area at the rear in the separation zone (wake). The flow separation is highly determines the pressure drag, thus it is important to understand the detachment of the flow. Flow separation which governs the pressure drag component can be divided into two types. The first type is where the separation

line is perpendicular to the flow direction. The separation zone is unsteady and vortices are generated with a rotational axis perpendicular to the flow and parallel to the separation line.

2.5.3.1 Formation mechanism of train aerodynamic drag

The aerodynamics drag force is most constituent into five elements which are

- The form drag or pressure drag which is the component that is most closely identified with the external shape of the vehicle.
- The surface drag or skin friction drag which is a frictional forces generated when air flows across the surface of the vehicle.
- The induced drag force which is a profile which in most situations is found to generate a force with a vertical component due to passenger space and mechanical design requirements which is lift, whether positive (upwards) or negative(downward) induces.
- The excrescence drag is a consequence of components that disturb like, wheels and wheel arches, wing mirrors, door handles, rain gutters and windscreen wiper blades.
- The interference drag which is the interactions between the main flow and the flows about external devices such as door mirrors can further add to the drag and.
- The internal drag which is arising from the cooling of the engine, the cooling of other mechanical components such as the brakes and from cabin ventilation flows.

Generally the vehicle size and shape, the frontal area of train locomotive car, the inter-car space and underbody shape and structure were determined by the design requirements, and efforts to reduce drag are concentrated on reducing the drag coefficient. Therefore, the aerodynamic drag on the traveling train is categorized into two main category pressure drag and friction drag. But this study only considered the pressure drag for the train taken as bluff body.

$$F_D = F_P + F_f \quad (30)$$

Where F_D is the aerodynamic drag, F_P is the pressure drag, and F_f is the friction drag.

$$F_D = \frac{1}{2} \rho C_D A (V \pm V_{wind})^2 = \frac{1}{2} \rho A (C_P + C_f L_T) (V \pm V_{wind})^2 = \frac{1}{2} \rho C_D \cdot A (V \pm V_{wind})^2 \quad (31)$$

Where ρ is air density of air, V is train velocity, V_{wind} is the (head) wind speed and A the frontal area of train model railway car. C_D is the air drag coefficient, C_P pressure drag coefficient, C_f friction drag coefficient and L_T is the total train length.

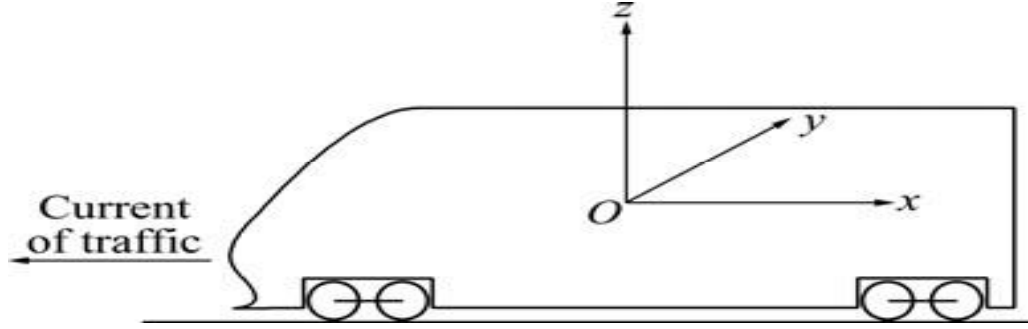


Figure 16: Train locomotive definition of coordination.

The aerodynamic drag of the train is composed of the drag of each carriage. The drag force can be written as shown here

$$F_X = F_{LX} + \sum_{i=1}^n F_{XZ}(i) + F_{TX} \quad (32)$$

Where F_X is the total aerodynamic drag; F_{LX} is the drag of the leading car or locomotive; F_{TX} is the drag of the tail car; $F_{XZ}(i)$ is the friction along the train, which includes the bogies, wheels, interference, and bottom structure of the train; and n is the number of middle carriages. So, the total aerodynamic drag coefficient (C_X) can be written as shown

$$C_X = C_{LX} + \sum_{i=1}^n C_{XZ}(i) + C_{TX} \quad (33)$$

Where C_{LX} is the drag coefficient of the leading car or locomotive; C_{TX} is the drag of the tail car; and $C_{XZ}(i)$ is the friction coefficient along the train. In the case of high speed train, there would a stagnation region with high pressure on both the windward face of the train nose and the flow speed decreased. At the same time, the flow moves at high velocity along the tail car and the pressure decreased. The pressure drag can be obtained by integrating along the whole car as shown.

$$F_{PD} = \oint_{A_f} P_{Sx} dA_f \quad (34)$$

Where P_{sx} is the skin pressure of the train along x axis, and A_f is the area of the train wall surface

When a train is moving at high-speed due to the viscosity of the air, boundary layer occurs on the wall of train when the air flows along the train surface [38]. Friction drag of the train is the sum of shear stress, which is in the reverse direction of the train running direction. Friction drag can be obtained by integrating along the whole train as

$$F_{\tau x} = \oint_{A_f} \tau_{ix} dA_f \quad (35)$$

Where τ_{ix} is the shear stress on the train along x axis, A_f is the area of the train wall surface.

2.5.4 Pressure Coefficient

The pressure coefficient is the dimensionless number, describes the relative pressures throughout a fluid flow in fluid dynamics, which can be defined as the ratio of the difference between static and reference pressure ($p - p_\infty$) over dynamic pressure ($\frac{1}{2} \rho u^2$). Therefore every point in a fluid flow field has its own unique pressure coefficient. At different case in aerodynamics and hydrodynamics, the pressure coefficient at a point near a body is independent of body size and so, pressure coefficients can be determined at critical locations around the model, and these pressure coefficients can be used to predict the fluid pressure at those critical locations around a full-size of model train vehicles.

$$C_p = \frac{p - p_\infty}{\frac{1}{2} \rho u^2} \quad (36)$$

Where: p is static pressure in pa, p_∞ is reference pressure in pa, ρ is density of air in kg/m^3 and u is velocity of air in m/s.

2.5.5 Lift Force

Aerodynamic lift is the component of aerodynamic force perpendicular to the free stream velocity. It is mainly created by the pressure difference on the top and bottom surface of a vehicle. Aerodynamic lift has a strong influence on driving stability and it is very important not to negatively affect it so that the vehicle remains stable. If aerodynamic lift increases too much then it will cause the vehicle wheels to have less traction force with the road, and this will cause the vehicle to become very unstable and risk rollover. The lift force is a result of the asymmetrical

flow of air above and below the vehicle. The lift force affects the vehicle driving stability. The lift force is measured at the centerline of the vehicle at the center of the wheel base. Lift forces are causing an unwanted de-loading of the wheel-sets, especially on the leading vehicle. In the presence of cross winds side and lift forces result in rolling, pitching and yawing moments which under extreme wind conditions might cause the vehicle to derail or overturn [34].

$$F_L = \frac{1}{2} \rho A C_L V^2 \quad (37)$$

Where F_L is the pressure lift force, A is the reference area of train, C_L is the lift coefficient and V is the train speed.

2.5.6 Aerodynamic moments

The moment method calculates moments about the leeward/outer rail and compares the stabilizing moment due to the gravitational forces of the vehicle with the overturning moment due to the aerodynamic and centrifugal loads. If these moments are equal, the vehicle begins to overturn, thus real vehicle overturning is considered. The method does not usually take dynamic effects from track irregularities into account. General for all moments can be formulated as shown below

$$M = \frac{1}{2} \rho A L C_m V^2 \quad (37)$$

Where: ρ is density of air in kg/m^3 , A is frontal reference area of vehicle in m^2 , L is total length of vehicle in m , C_m is non-dimensional moment coefficient of vehicle, v is the speed of vehicle in m/s .

2.5.7 Cross-wind effects on the running train

Cross-wind effects are now routinely considered by designer's experimental techniques and computational flow prediction methods still require substantial development if a sufficient understanding of the flow physics is to be achieved. The moment effect is most easily observed in cross-wind conditions when the effective aerodynamic side force acts forward of the center of gravity, resulting in the vehicle tending to steer away from the wind. In extreme, gusting conditions the steering correction made by the driver can lead to a loss of control. Lift forces are causing an unwanted de-loading of the wheel-sets, especially on the leading vehicle. In the presence of cross winds side- and lift forces result in rolling, pitching and yawing moments which under extreme

wind conditions might cause the vehicle to derail or overturn. The side force and rolling moment coefficients have increased with the increase of yaw angles. The highest side force coefficient was generated in between 75° and 90° yaw angles [39].

The side force is formed by the asymmetric flow of air around the body of the vehicle due to cross wind flow (forces). The lateral wind components impose a side force on the vehicle to change its direction. Side force acts on the body on the center of pressure.

$$F_s = \frac{1}{2} \rho A C_s V^2 \quad (38)$$

Where F_s is the side force, A is the reference area of train, C_s is the side coefficient and V is the speed of side wind.

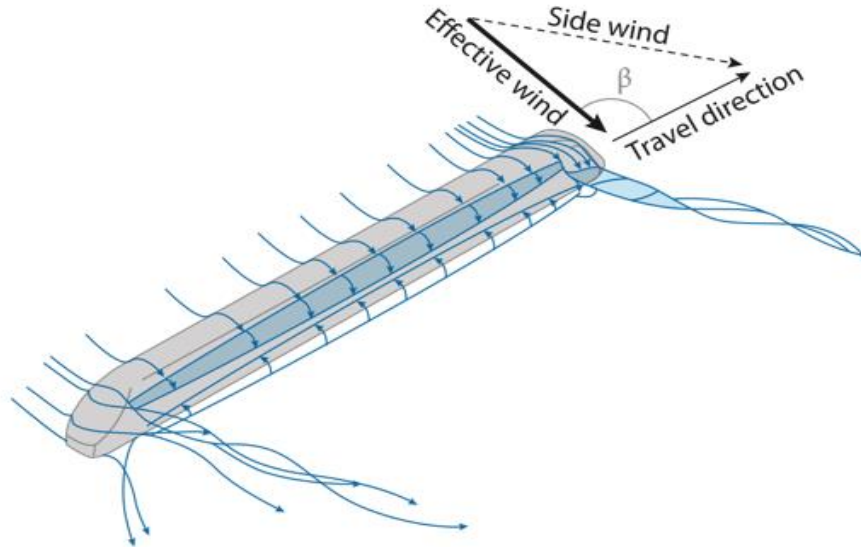


Figure 17: This shows how the cross-wind effects and the side wind flow stream

The turbulence intensity with respect to the train is defined as the atmospheric turbulence level divided by the wind velocity relative to the train. It can be clearly seen that at low train speeds, the velocity profile takes on the appropriate boundary layer form, with a significant velocity variation across the train, the yaw angle is close to 90 degrees and the turbulence intensity is high. At high train speeds, the velocity profile is more uniform, and the yaw angle is low and varies somewhat over the height of the train. The turbulence intensity is low – of the order of a few percent [40].

As a result of cross wind the lateral stability of running train is an important safety issue as it largely depends on aerodynamic forces caused by crosswinds, centrifugal force, and gravitational force due to curving and track cant. However, aerodynamic forces are considered to have significant influence on roll over problems. The critical wind velocity of overturning can be obtained from the static equilibrium of external forces acting on the carriage. In order to predict the rollover moments due to aerodynamic input, a comprehensive study of steady and unsteady aerodynamic forces and moments under range of yaw angles is required [41].

Generally in this study, the crosswind was assumed to be steady, and the mean wind speed was assumed to be in the horizontal direction. The aerodynamic forces due to the crosswinds were exerted on modeled train vehicle body and only aerodynamic forces acting on the car body were taken into account. The crosswind forces F applied to the vehicle body include the side force F_S , the lift force F_L , the roll moment M_R , the pitch moment M_P , and the yaw moment M_Y , as shown in Figure 15.

The cross-wind force can account the transient response of the vehicle in a crosswind scenario, the crosswind forces F can be calculated as

$$F = \begin{cases} \frac{L_W}{L_V} * F_0, & 0 \leq L_W \leq L_0; \\ F_0, & L_V < L_W; \end{cases} \quad (39)$$

Where L_V is the vehicle length, and L_W is the length of the wagon car body immersed in the crosswind scenario.

According to the quasi-steady approach, the force vector $F_0 = [F_P, F_L, M_R, M_P, M_Y]$ can be expressed as

$$F_S = \frac{1}{2} \rho A C_s \beta V_{rel}^2 \quad (40)$$

$$F_L = \frac{1}{2} \rho A C_L \beta V_{rel}^2 \quad (41)$$

$$M_R = \frac{1}{2} \rho A H C_R \beta V_{rel}^2 \quad (42)$$

$$M_P = \frac{1}{2} \rho A H C_P \beta V_{rel}^2 \quad (43)$$

$$M_Y = \frac{1}{2} \rho A H C_Y \beta V_{rel}^2 \quad (44)$$

Where ρ is the air density, A is the reference area, and H is the reference height. C_S , C_L , C_R , C_P , and C_Y correspond to the aerodynamic force and moment's coefficients respectively, which depend on the crosswind attack angle β were used in the calculation of the crosswind forces, as shown in Figure 15. And also V_{rel} corresponds to the resulting squared wind speed. The terms β and V_{rel} correspond to spatial averages with respect to the surface of the vehicle. The resulting wind speed V_{rel} is defined as follow

$$V_{rel}^2 = U^2 + V_T^2 - 2UV_T \cos(\pi - \alpha_W) \quad (45)$$

$$\beta = \tan^{-1} \frac{U \sin \alpha_W}{V_T + U \cos \alpha_W} \quad (46)$$

Where V_T is the vehicle speed, U is the crosswind velocity and the crosswind attack angle (α_W) is defined as the relative angle between the direction of the crosswind.

2.6 Dynamic behavior of train under crosswinds

Through the aerodynamic investigations which have been carried out by many scholars, it has become clear that train design parameters have a significant influence on the resulting dynamic response of the body. The highly coupled nature of these effects has made it difficult for researchers to isolate and fully understand the individual contributions of the train vehicle parameters on the observed dynamic behavior. In this study, from the train design observations regarding several key train vehicle parameters presented. From this, further insight will be gained regarding the underlying physical phenomenon of dynamic stability. To investigate the effect of crosswinds on the dynamic responses and running safety of high-speed railways but normal track irregularity was neglected in this study because its effects on the dynamic behavior of the vehicle-track system is very small compared to the effect of crosswind. The effects of the crosswind speed, the crosswind attack angle, and the vehicle speed on the running safety of the vehicle were examined in detail.

2.7 Stability of running train

Stability concerns also relate to the lift forces and side wind force the changes in those forces that may arise under typical atmospheric wind conditions and train speed. Flow separation is most likely to occur around sharp corners such as those at around front face, top roof part, inter-car gap, underbody, rear end vehicle. Because of the close relationship between drag and noise generation it is not surprising that drag reduction programs have a direct and generally beneficial effect upon wind noise. Such mutual benefits are not true of the second related concern, that of dynamic stability. The rounded shapes that have come to characterize modern, low drag designs are particularly sensitive to cross-winds both in terms of the side forces that are generated and the yawing moments [42]. To evaluate the transient behavior of a vehicle at a much earlier stage of its design it is necessary not only to develop model wind tunnel techniques to provide accurate and reliable data but most importantly to fully understand the flow mechanisms that give rise to the transient aerodynamic forces and moments. Initial results from recent developments in wind tunnel testing suggest that the side forces and yawing moments [43].

Railway vehicles that are exposed to crosswind capable of causing a vehicle failure to instability, most commonly overturn about the leeward rail. Hence, when assessing crosswind stability, the phenomenon of vehicle overturning is often what is considered. Several measures and criteria are available to describe the crosswind stability of a rail vehicle that take the overturning process into account. Vehicle crosswind stability is influenced by the four factors wind excitation, aerodynamics, vehicle dynamics and driver [44].

The aerodynamic stability of vehicles have been broadly addressed as two independent concerns

- It travels in a straight line at high speed and to lane change manoevrability
- The effects of steady cross-winds and transient gusts that are associated with atmospheric conditions and which may be exaggerated by local topographical influences such as embankments and bridges

The sources of straight line instability in calm conditions has proved to be one of the most difficult aerodynamic influences to identify. New evidence suggests that stability and particularly lane change stability degrade with increases in the overall lift and with differences in lift between the front and rear axles [45]. Generally wind induced forces and moments especially the side force generally acting perpendicular to the lateral side of the carriage contributes most to the overturning

of the carriage. Lift force also has some contributions to this process. In order to assess the carriage lateral stability (over turning or roll over) under crosswinds, three aerodynamic parameters such as side force, lift force and their coefficients, and rolling moment (and its coefficient) are important and need to be measured.

2.8 Train Speeds

Similar to the gust frequency, vehicles are exposed to crosswind gusts at a wide range of driving speeds. Hence, in the following the occurrence and variation of the unsteady phenomena is investigated over a range of vehicle speeds from 70 km/h to 220 km/h. Again, the aim is to understand the influence of the vehicle speed on the unsteady effects. In order to keep the minimum and maximum yaw angles constant over the range of vehicle speeds, the lateral crosswind velocity is adjusted accordingly. Railway and road vehicles can be seen during normal operation as slender bodies because regions of separated flow are comparatively small and do not have a large influence on the overall flow. However, in the presence of crosswind, railway vehicles must be seen as bluff bodies, because large separated regions with strange flow patterns appear on the lee side. The separated, strongly turbulent flow between underbelly and track, which is always present and has large influence on drag, as well as the wake after the last car of the convoy [46].

2.9 Properties of incompressible air

The density of any material is defined as its mass per unit volume. In fluids this property depends on the pressure p and on the temperature T . The highest speeds achieved by land-vehicles during record attempts are in the order of the speed of sound, which is for air $a = 340$ m/s. In the flow field of a body exposed to such a free stream the compressibility of the air, i.e. the variation of density due to changes of pressure and temperature, is very important. On the other hand, most vehicles including racing cars are operated at speeds u which is lower than one-third of the speed of sound. For this speed range the variations of pressure and temperature in the flow field vary little from those of the free stream values, and therefore the corresponding density changes can be neglected. Thus the fluid can be regarded as incompressible. In this study the air density took a constant property, the numerical value of which is, according to US standard atmosphere sea-level conditions ($p = 1 \text{ atm}$, $T = 288 \text{ K}$, $\rho = 1.2250 \text{ kg/m}^3$) [47].

2.10 Approaches to train vehicle body design

As considering many researchers states two simplified vehicle geometries with the same dimensions and based on a sharp edges vehicle model (SEVM) and a radius edges vehicle model (REVM) are subjected to an unsteady gust that has a special extension of $5L$, L being the vehicle length [48]. Throughout the history of the motor car there have been individual vehicles that have demonstrated strong aerodynamic influence upon their design. Until recently their flowing lines were primarily a statement of style and fashion with little regard for the economic benefits. It was only rising energy prices, triggered by the energy crisis of the early 1970s that provided a serious drive towards energy-efficient aerodynamic design. The three primary influences upon energy efficiency are the weight of the train vehicle, the efficiency of the engine and the aerodynamic drag. So, in order to reduce the aerodynamic drag, adapting streamline shape of train is the most effective measure. And also considering the velocity of the train is related to its length and shape. The outer wind shields can reduce train's air drag by about 15%. At the same time, the train with bottom cover can reduce the air drag by about 50%, compared with the train without bottom plate or skirt structure specially under on the train bogie parts [49]. Therefore, in this study the overall structure of train locomotive and its components indicated as following diagram.

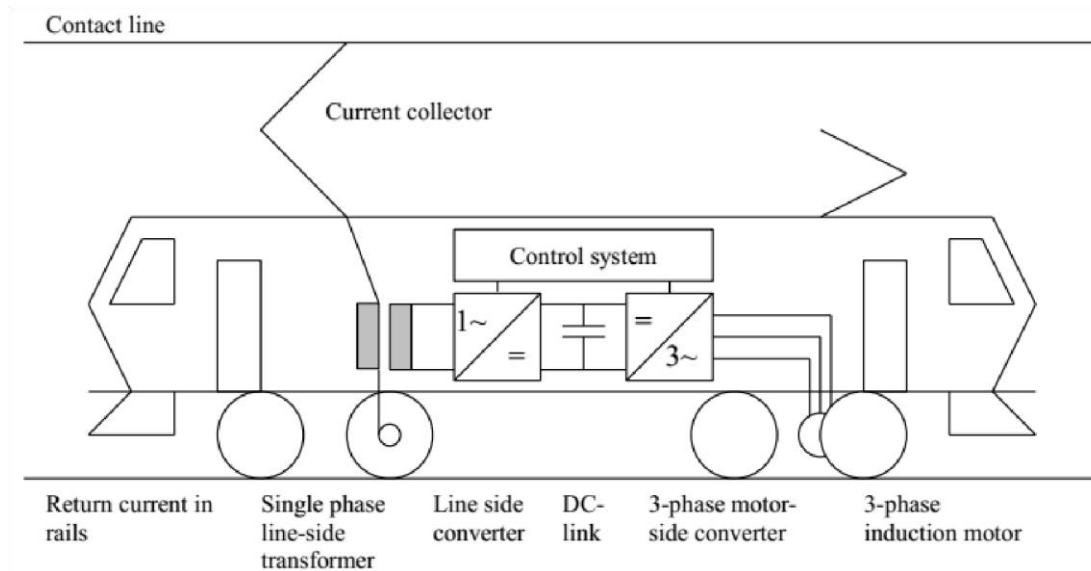


Figure 18: Electric Locomotive Block Diagram and its Basic Components

2.11 Aerodynamic Design and Optimization

Optimization of multiple trains lead to more efficient loading overall if complete information on all trains and loads is available at the time of optimization. Large expenditure has to be carried out by the railway operators to guarantee safe and economical operation of the train and thus, the control of the aerodynamic loads by an optimum design of the coaches is mandatory, respecting the various requirements of infrastructure and running behavior of the train [34]. From optimization concepts train study considering the main focused parts are as shown below such as, major drag source which have more significant pressure loads.

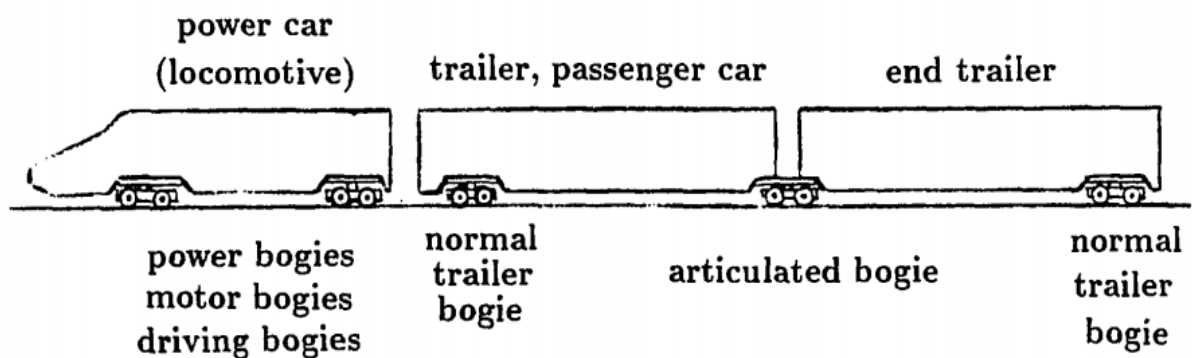


Figure 19: Train sets and bogie types

A major drag source occurs on the train parts are:

- At the very front where the maximum pressure is recorded around the front, upper corner of train.
- At the base of the windscreen of train.
- Due to the speed of the locomotive vehicle and the height and width of the tail end.
- A very different flow structure arises on train vehicles shape if the rear surface slopes more gently as is the case for hatchback, fastback and most notchback shapes.

The airflow over the rear surfaces of the vehicle is more complex occurs for 'squareback' shapes and is characterized by a large, low pressure wake. Here the airflow is unable to follow the body surface around the sharp, rear corners, the drag that is associated with such flows depends upon

the cross-sectional area at the tail and if the rear surface slopes more gently as is the case for hatchback, fastback and most notchback shapes [42].

The low pressure over the upper surface draws the relatively higher pressure air along the sides of the car upwards and leads to the creation of intense, conical vortices at the end tail. These vortices increase the likelihood of the upper surface flow remaining attached to the surface even at backlight angles of over 30 degrees. Air is thus drawn down over the rear of the car resulting in a reacting force that has components in both the lift and the drag directions. As the angle increases from zero (typical squareback) towards 15 degrees there is initially a slight drag reduction as the effective base area is reduced. Further increase in backlight angle reverses this trend as the drag inducing influence of the upper surface pressures and trailing vortex creation increase. As 30° is approached the drag is observed to increase particularly rapidly as these effects become stronger until at approximately 30° the drag dramatically drops to a much lower value. This sudden drop corresponds to the backlight angle at which the upper surface flow is no longer able to remain attached around the increasingly sharp top, rear corner and the flow reverts to a structure more akin to that of the initial squareback as shown in the Figure 20 [42].

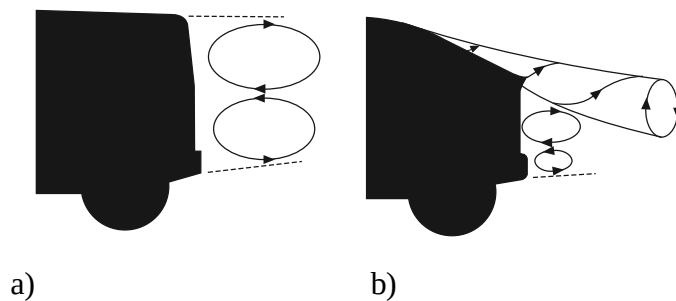


Figure 20: a) 'Squareback' large scale flow separation. b) 'Hatchback/Fastback' vortex generation

There are different mechanisms of drag reduction approaches:

- One of the most effective drag reduction techniques is the adoption of boat-tailing which reduces the effective cross-sectional area at the rear of the car and hence reduces the volume enclosed within the wake [50].
- The lowering and rounding of the sharp, front corner together with the reduction or elimination of the flat, forward facing surface at the very front of the car addresses both of these drag sources [30].

A comparison of pressures can be made between slender-nose locomotives having nose shape ratios which is ratio of nose length to body width of 0.8 to 1.25, and bluff-nose locomotives whose nose shape ratios range from 0.1 to 0.5. The measurements indicated that the slender-nose shapes of the high-speed train produced pressure effects that are half those of bluff-nose trains, and therefore, a slender-nose train can travel at a 40% higher speed for the same effect as a bluff-nose train. Tests performed with container trains generated pressure pulses that are up to 20% higher than those of bluff-nose trains. Generally the external profile of the train can have an important effect on the induced airflow. Measurements indicate that the induced airflow speed of a slender-nose high-speed passenger train is 0.78 times lower than for a bluff-nose train, while for freight trains, it can be 1.9 to 3.5 times higher than for a bluff-nose train. Therefore, the high-speed train can travel at 25% to 30% faster than a bluff-nose train and still produce the same maximum flow disturbance [31]. Therefore from consideration of above optimization approaching mechanism the train locomotive leading shape could introduce as follow.

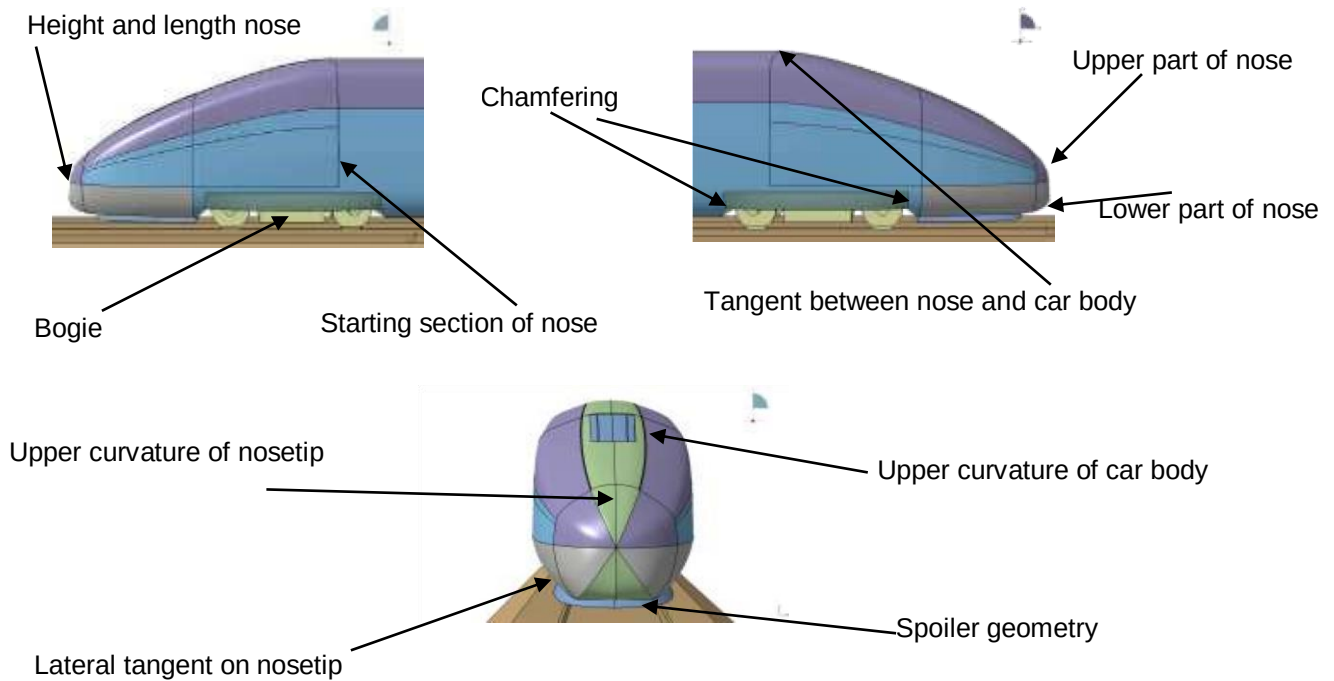


Figure 21: The figure indicate the main possibility of optimization of design faces on the front of high-speed train

Many scholars have evaluated the effects of modifying external body shape on railway to reduce aerodynamic drag. Replacing exposed external ribs with smooth sides is particularly effective and offers the advantages of being low cost and easy to install [51].

2.12 Effects of Inter-Car Spacing on the train vehicles

For the case of small gaps between adjacent train vehicles, the flow appears to move smoothly from the rear of the upstream car to the front of the downstream car. The flow in the gap region is a trapped vortex that does not interact substantially with the free-stream as show below in the Figure 22 between two cars.



Figure 22: The Ethiopian train inter car gap is looks like as shown in the figure

Adjacent cars with narrow inter-car gaps thus act as a single body. In other hand larger gaps between train vehicles result in a higher aerodynamic coefficient and greater resistance. The front of the train experiences the greatest aerodynamic resistance due to high-speed of train related to the geometrical shape of train and headwind impact by itself. Therefore, to incorporate both the gap length and position-in-train effect, the objective function of the model is to minimize the adjusted gap length within the train. Adjusted gap length is equal to the adjustment factor time's gap length. The adjustment factor associated with each gap is computed by dividing the drag area of a given unit by the drag area of the 100th unit (Table 2) to account for position-in-train effect.

Table 2: Adjustment factor for each gap in the train [52]

Number of locomotives	Drag Area(ft ²)	Adjustment factor
1	31.618	1.5449
2	28.801	1.4073
3	26.700	1.3046
4	25.133	1.2209

5	23.963	1.1709
6	23.091	1.1283
7	22.440	1.0964
8	21.954	1.0727
9	21.591	1.0550
10	21.320	1.0418
100	20.466	1.0000

The wind tunnel tests results showed that the lead locomotive experiences the highest drag due to headwind impact. After the head end, resistance declines until about the 10th unit in the train, after which drag remains nearly constant for the remaining units. Therefore, minimizing the total gap length and placing loads with shorter gaps near the front of the train will result in lower aerodynamic resistance [53].

Table 3: Effects on Aerodynamic Drag of Railway Vehicles Due to Modification of Exposed External Ribs (Zero Degrees Yaw, Center Location in Train Consist) [51]

Train vehicles type	External surface Configuration	Modification	Drag Reduction
Passenger Car	External Ribs and Structure	Smooth Side	6%
ISO Container	External Ribs	Smooth Side	10%
Hopper Car	External Ribs	Smooth Side	20%
Gondola Car	External Ribs	Smooth Side	13%
Well Type Intermodal	External Ribs on Trailers	Smooth Side	10%
Skeleton Type Intermodal	Platform Support Ribs	Shielded Ribs	15%
Gondola Car	External Ribs	Shielded Ribcaps	17%
Open Top Hopper Car	External Ribs	Smooth Side	30%

2.13 Energy efficiency of high-speed trains

In the study of automotive aerodynamics by different researchers have concluded that, it is known that over 70% of the brake power of a vehicle engine is consumed to overcome aerodynamic drag on the front and rear side of the vehicle at 100 km/h [54]. The potential for energy savings by reducing the aerodynamic drag of rail cars is significant. A previous study of aerodynamic drag of coal cars suggests that a 25% reduction in drag of empty cars would correspond to a 5% fuel savings for a round trip [55]. Train mass and shape are the most important factors to influence energy consumption. Thus, the way that the energy consumption is calculated in train motion studies varies regarding both to the approach that is used and in the precision of the formulas used given the approach. Tractive force is the total train force required from traction drive system to overcome total train resistances and provide sufficient acceleration for the moving train. Newton's Second Law of motion states that the change in kinetic energy of a moving object used to do a useful work. This could be shown by taking the derivative of kinetic energy of a moving object with respect to time. The power demand for any vehicle driven by an engine increases with increase in speed, weight, rate of acceleration and reacting drag forces as indicate state of equation below.

$$T = \frac{1}{2}mV^2 \quad (47)$$

$$\frac{dE}{dt} = \frac{dT}{dt} = mV\frac{dV}{dt} \quad (48)$$

According to Newton's second law states that, $F = ma = m\frac{dV}{dt}$

$$\frac{dE}{dt} = F.V = P \quad (49)$$

$$E = \int_1^2 F.Vdt = \int_2^2 Pdt \quad (50)$$

$$dE = F.dS \quad (51)$$

$$\Delta E = \Delta W = \Delta T = \int_1^2 F.dS \quad (52)$$

Where ΔE is the total consumption energy, m is the total mass of train, V is the speed of train, P is the power of train, dt is the small interval time, ds is the small interval distance, ΔW is the total change of work done and ΔT is the total change of kinetic energy.

The main power consumer in the train are traction motors, especially during acceleration. In train operation, energy required during free-running or constant speed regime is low compared to acceleration regime and must balance all the drag forces at the line section to keep the maximum speed attained at the up to the end of acceleration [56].

Table 4: Standardized Voltage Levels for Railway Power System

DC Voltage				AC Voltage	
600V	750V	1500V	3000V	15kV, 16.7Hz	25kV, 50/60Hz

The voltage levels from 50 V up to 50 kV have been used to propel railroad vehicles around the world. The low voltage DC system is used for light rails usually supplied at 750 Volts (metro transit) and for commuter and intercity trains usually supplied at 3000 Volts. In addition non-standard voltage levels such as 50kV and 2x25 kV, 50 Hz are also available options proven to be practical in high capacity railway lines [57].

2.14 Natural wind Assessments in Ethiopia

The first national-level study on wind energy potential assessment was done by Italian company CESEN-ANSALDO corporation group at mid-1980s in Ethiopian. The assessment was mainly based on the original wind speed data collected and recorded by Ethiopia National Meteorological Services Agency at that time, Ethiopian Meteorological stations mainly served for aviation. The nationwide resource assessment has been conducted twice in Ethiopia. The first was for wind and solar resource assessment by CESEN-ANSALDO in 1980s, and the second was the wind and solar energy resource assessment by SWERA in 2007. In the project, based on spatial correspondence between elements (altitude, land type) and on the basis, a high-resolution atlas is built concerning seasonal and average annual situation of solar radiation and wind energy distribution & evolution in each province about 30 years [61]. From 2009 to 2012 annual wind speed distribution study the most frequent maximum wind speed at the height of 2m is 10 m/s almost same for all the years

[62]. And also there are some Ethiopian meteorology station has been recorded wind speed values at the height of 10 meter studied as shown in the Table 5.

Table 5: This is some Ethiopian areas which are meteorology station wind speed has been recorded [56].

Area	Height in m	Observed Wind Velocity in m/s
Sululta	10	3.8
Ashegoda	10	6.8
Bahir Dar	10	3.8
Nazert	10	7.73
Gode station	10	11.34
Dire Dawa	10	3.4
Mosobo	10	5.3
Gondar	10	5.51
Negele Borena	10	5.1
Aysha	10	7.8

In general wind speed in Ethiopia in different metrology station areas indicated according of the two corporation groups studied for 30 years estimation and forecasting for future at the height of 2m and 10m are more sensitive to quickly-varying atmospheric motions on boundary layer that are produced by dynamic and thermodynamic effect of local environment. So, the Ethiopian railway vehicles have got this wind effect at the running condition. Therefore, this study has used aerodynamics characteristics of moving train locomotives at different speed rang and under the influence of cross-wind condition of frequently occur at the maximum speed of 12 m/s based on the above studies and some Ethiopian meteorology station have been recorded data as shown on the Table 5. But in this study was not considering gusty winds which has more than this speed value and occur for long and at unexpected time.

3. METHODOLOGY

To investigate the aerodynamics performance of the ground vehicles for more accuracy result wind tunnel and road tests are required. However, Full-scale wind tunnel and road tests are very expensive and time consuming to operate as multiple tests are usually required in achieving the desired aerodynamic shape or characteristic during the design process of vehicles. Further validation of the this study procedure is provided through numerical simulations to predict the overall drag, lift and side coefficients for six models three of the baseline models and other three models are optimized Ethiopian train at different speed under cross- wind condition. Aerodynamic evaluation of air flow over a moving train locomotive can be performed using analytical method or CFD approach. On one hand, analytical method of solving air flow over a train locomotive can be done only for simple flows over simple geometries like laminar flow over a flat plate. If air flow gets complex as in flows over a bluff body, the flow becomes turbulent and it is impossible to solve Navier- Stokes and continuity equations analytically. On the other hand, obtaining direct numerical solution of Navier-stoke equation is not yet possible even with modern day computers. With the reduction on computational cost today, aerodynamic simulation using CFD have a faster turnaround time.

In railway and ground vehicle design especially the high-speed one geometry manipulation is particular importance in aerodynamic design. The pressure for automated approaches has led to the invention of Computer-Aided Design packages. CATIA (computer aided three dimensional interactive application) uses a Dassault Systems computer language system that enables to model especially for its 3D model feature applications for standard railway vehicle dimensions of LRT, high-speed passenger and Freight train locomotive and cars such as part design, and assembly design so, for this study used CATIA V5 R20, which are now seen as the fundamental tool for academic institutes and industries.

Table 6: General Specification of Ethiopian train locomotives vehicle body.

Regional Passenger locomotive	Values
Length	22,216mm
width	3,100mm

height	4,754mm
Gross mass	109,000kg
Regional Freight locomotive	
Length	22,670mm
width	3,160mm
height	4,750mm
Gross mass	150,000kg
Light Railway Transit train	
Length	28,000mm
width	2,650mm
height	3,500mm
Gross mass	41,000kg

3.1 General aerodynamic specification guide points

Table 7: Dimension for Optimize Model trains [63]

S.no	Aerodynamics specification for ground vehicle
1	Minimum front corner radius of 100mm
2	Smooth and curved underbody from 11.5° to 15°
3	Minimum trailing edge radius of 100mm
4	Minimum side panel tapering length is 100mm
5	Increase rake angle is 30° to 45°
6	Maximum effective curved length from nose is 10m
7	Rear roof tapering around 1000mm
8	Rear roof tapering of 1000 mm
9	Curved front end and Roof end lowering

3.2 Train body aerodynamic optimization Process

As many researchers indicated that when ground vehicle length is too long like train the aerodynamic resistance is dominated on the leading vehicle front part of nose height, nose length, nose angle, nose smoothness, nose sharpness, top part, underbody and side edge for cross-wind stability. For such a vehicle optimize of front part of train locomotive has significant aerodynamic

drag reduction and cross-wind stability effects. Thus, this work has been used some design constraint variables such as nose length, height and angle of train nose slanted surface to make smooth flow of air on the leading edge of high-speed train locomotives as shown in Figure 23 and this made sure the has freedom possible in relation to aerodynamic parameters to choose with in the optimization process by aerodynamic ideal concepts including general aerodynamic specification as listed on Table 7. This study has considered all impacts on the front end design requirements which included space for driver seat, standing, visibility, floor height coupler, gauge profiles and crash worthiness described in detail as shown on Appendix-B 2D detail drawing.

In order to represent realistic nose length (**b**), height (**h**), angle (**α**) and roundness of cross section of train locomotives for improving of drag resistance and side wind effects the range of length optimize $0.64h \leq b \leq 1.28h$ and front upstream slanted angle $24^\circ \leq \alpha \leq 46^\circ$ of geometry parameterization [64] and high speed train can easily penetrate the aerodynamic pressure with the leading vehicle nose geometry range of $1.186\text{m} \leq h \leq 2.50\text{m}$, $1.164\text{m} \leq b \leq 2.164\text{m}$ at the top and $0.225 \leq b \leq 1.225\text{m}$ at the bottom [65].

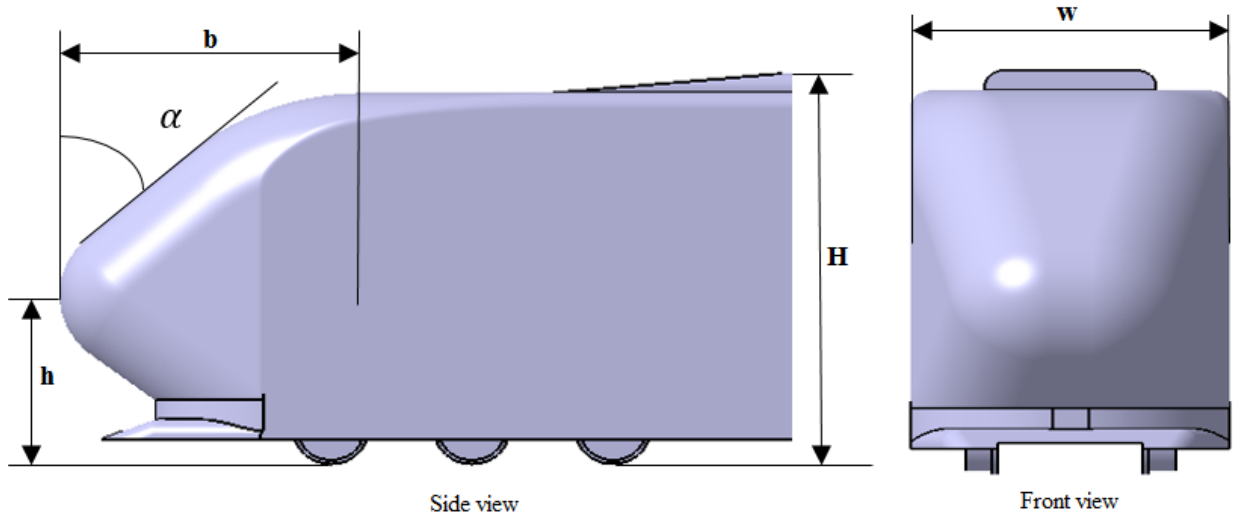


Figure 23: The train locomotives shape from the side and front for cross-wind influence of 90° yaw angle condition.

Therefore, in this study to improve energy efficiency and dynamic stability of Ethiopian train locomotives and Light Railway Transit public transport train both regarding aerodynamic drag reduction due to their speeds excluding of head wind effect and cross-wind influence conditions with varying speeds of train on train dynamics.

3.3 PHOENIX and CFD numerical model

PHOENICS VWT (Virtual Wind Tunnel) is a reliable, cost-effective and a general-purpose software package which uses the techniques of CFD a software package aimed at flowing of fluid, heat, mass transfer, chemical reaction and combustion for a wide range applications. It uses mathematical techniques of computational fluid dynamics (CFD) to simulate any process involving fluid flow (in this case air). CFD packages have been available for many years but have, traditionally, been the preserve of big-budget teams due to the computing power required, the cost of the software, and the skills necessary to use it. One of the main aims of the VWT is to simplify the initial set up of a case to provide realistic results.

3D model CFD simulations have been performed reproducing the same conditions of the wind tunnel tests approaching and the geometry of the solid model based on the existing Ethiopian railway locomotive design detail dimensions. By considering more aerodynamic effects on road vehicles body of locomotive cars nose, under body, top part, side part for cross-wind and also using front diffuser this study focused to optimized better train design. The velocity inlet boundary condition is applied on the front and side wall of the control domain plane using 12m/s frequently for a long year recorded side wind speed without considering head wind effect on the running train and the pressure outlet condition is set to atmospheric pressure value. To execute the CFD experiment for the six Model train at varying the running speeds from 40km/h to 160km/h using optimization of the grid test for comparison of the existing model train and new optimized train locomotives.

3.4 Optimization procedure

The optimization was done mainly based on aerodynamic effects such as drag coefficients, lift coefficients and dynamic stability of train in curve railway under the influence of 12 m/s side wind blowing on it. The critical details on optimized trains has a long streamlined nose in both side, has as spoiler or deflector and a smooth round shaped roof. The Regional train has blunt nose, a rectangular body shape, a roof box and roof lines from the nose to the end of the vehicle. These details have a significant impact on the flow field around the vehicle and the under body and bogies are modelled in a way that the blockage is represented. The pantograph aerodynamic effect is neglected in this study. The most critical point is the running vehicle under the influence of cross wind which is therefore, considered in this study.

3.5 Computational Fluid Dynamics (CFD)

Fluid dynamics deals with flow of fluids, which interest scientist and engineers to understand the phenomena and solve the industrial problems. Like other branches of science it needs mathematical and experimental tools to understand aerodynamic effects which deals with excitation of forces, moments and heat transfer on a body due to flow of air. Fluid dynamics study has three different approaches to study fluid flow in the system, i.e. the pure theory, the pure experiment and computational fluid dynamics. Thus, recently advancements of the digital computers are used to predict the fluid flow phenomena based on governing equations of fluid dynamics (conservation laws). CFD computational mainly used to investigate

- How aerodynamic loads on a railway vehicle under real wind conditions.
- The influence of the position of the train on the embankment the wind sheltering effect of walls and fences in different configurations near the track.
- The importance of modelling complex flow situations for the determination of the aerodynamic coefficients easily than experiment.
- To save time and materials than experimental model scale tests.

3.6 Effect of crosswind attack angle on the running train

In this study the crosswind attack angle (α_w) on the train is considered as constant and describes an analysis conducted to assess the combined effects of the vehicle speed and the crosswind speed on the aerodynamic behavior of the train. And also for each models of the train speed V_T was varied from 60 km/h to 160 km/h, the crosswind speed took constant and steady flow the maximum of 12 m/s, and the crosswind attack angle α_w was held constant at 90°. Because, Cross-wind attack angles of 75°–90° correspond to the worst-case scenarios and when (α_w) exceeds 90°, the values of these two aerodynamic effects decrease as the crosswind attack angle increases [39]. But the other parameter values were the same. The crosswind attack angle (α_w) can be expected to have a very important effect on the operating safety of the vehicle in crosswind conditions. For each rail locomotives car, simulations were performed without effect of headwind and 90° cross wind condition. Aerodynamic Forces and moments were computed by CFD model simulation but the restoring moment is taken as the weight of the rail locomotive car acting through the tipping arm and this aerodynamic tipping moment is taken as the weight of the rail locomotive car acting through the tipping arm. So, the restoring moment is equal to aerodynamic tipping moment as shown.

$$W \cdot L_T = \frac{1}{2} \rho \cdot C_{\text{tipping}} A L V^2 \quad (53)$$

Where: W = Weight of Rail locomotive car

L_T = Tipping arm (horizontal distance between Rail locomotive car CG and tipping point)

ρ = Air Density

V = Train Velocity

C_{tipping} = Tipping Moment Coefficient

A = Reference Area

L = rail locomotive car length

C_{tipping} can be defined as a function of yaw angle (θ) using a 7th order polynomial curve fit of the form

$$C_{\text{tip}} = a(\theta) + b(\theta)^3 + c(\theta)^5 + d(\theta)^7 \quad (54)$$

The parameters a , b , c , d are the polynomial curve fit coefficients. Yaw angle and relative wind speed (V) are both functions of train speed, wind speed (V_w), and wind angle (α_w) relative to the rail locomotive car. But in this study wind angle is considered perpendicular to running train side plane surface.

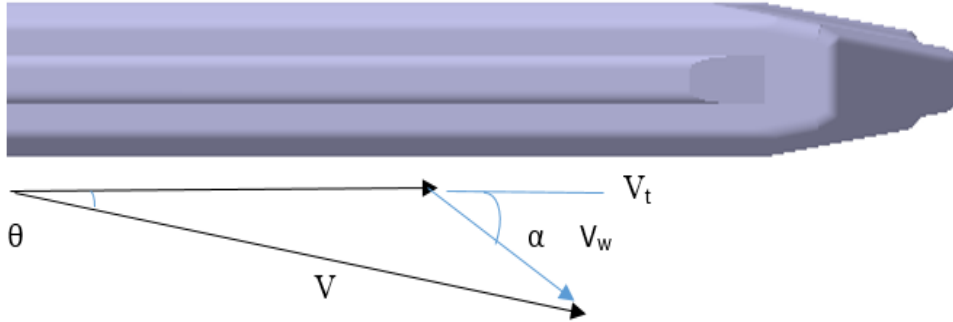


Figure 24: This is the top view of Ethiopian Regional Passenger Train under side-wind

In this case, the relative wind speed (V) and yaw angle can be expressed as follow

$$V^2 = (V_t + V_w \cdot \cos(\alpha))^2 + (V_w \cdot \sin(\alpha))^2 \quad (55)$$

$$\theta = \tan^{-1}[V_w \cdot \sin(\alpha) / (V_t + V_w \cdot \cos(\alpha))] \quad (56)$$

3.7 Ethiopian trains types and shape of body

The existing design and over all geometry of Ethiopian Regional Passenger locomotives, Regional Freight locomotives and Light Railway Transit train model were used a baseline for the comparison of optimized train models locomotives of this study. That of the reference train for optimization of using aerodynamic general concepts which is stated by different scholars under the influence of cross-wind. The Ethiopian train locomotives have not good aerodynamic shape with related to their operational speed design as shown in the classification pictures.

⇒ **Ethiopian Light Railway Transit (LRT):** Light Railway Transit public transportation vehicles have a top speed of 80 km/hour (50 miles/hour). Considering the maximum speed of the vehicles related to aerodynamic shape of the train body under the side wind condition at 2m and 10m height. So, this study has optimized the train shape to be energy efficiency and stability the project sustainability by comparison of the two model vehicles as shown in the Figure 25 up to Figure 36.

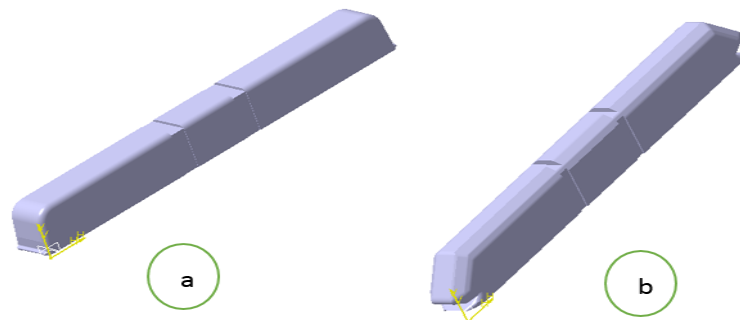


Figure 25: 3D Ethiopian Light Railway Transit Figure **a** is Existing and **b** is Optimized Models.

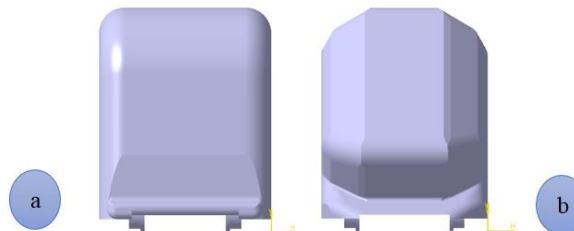


Figure 26: Front view Ethiopian Light Railway Transit Figure **a** is Existing and **b** is Optimized Models.

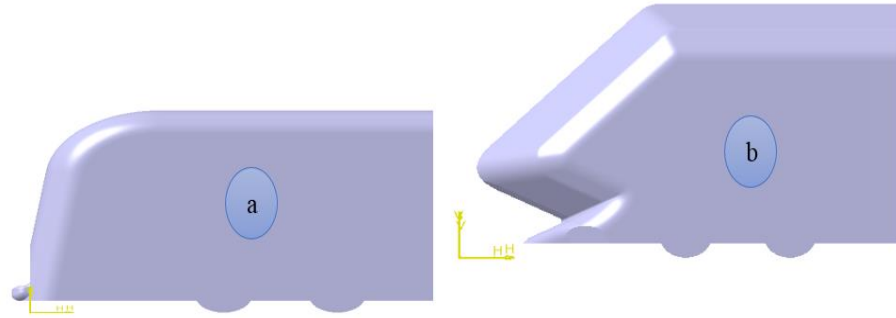


Figure 27: Ethiopian Light Railway Transit Aerodynamic shape of nose Figure **a** is Existing and **b** is Optimized Models.



Figure 28: Ethiopian Light Railway Transit Aerodynamic shape of nose Figure **a** is Existing and **b** is Optimized Models.

⇒ **Ethiopian Regional Passenger Locomotive:** aerodynamic shape of nose Figure **a** is Optimized and **b** Existing is Models Regional Passenger train locomotive vehicles have a top speed of 160 km/hour. Considering the maximum speed of the vehicles related to aerodynamic shape of the train body under the side wind condition at 2m and 10m height according to Ethiopian Meteorology and HYDROCHINA CORPORATION group. So, this study has optimized the train shape to be energy efficiency and stability for the project sustainability by comparison of the two model vehicles as shown in the Figure 29 up to 32

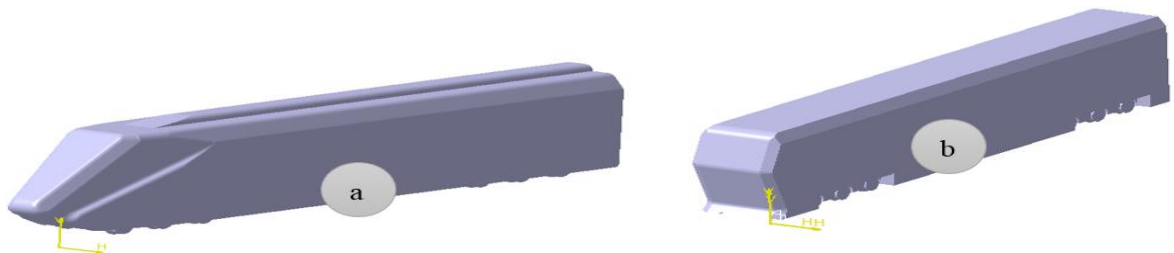


Figure 29: 3D Ethiopian Regional Passenger locomotives Figure **a** is **Optimized** and **b** is **Existing** Models.

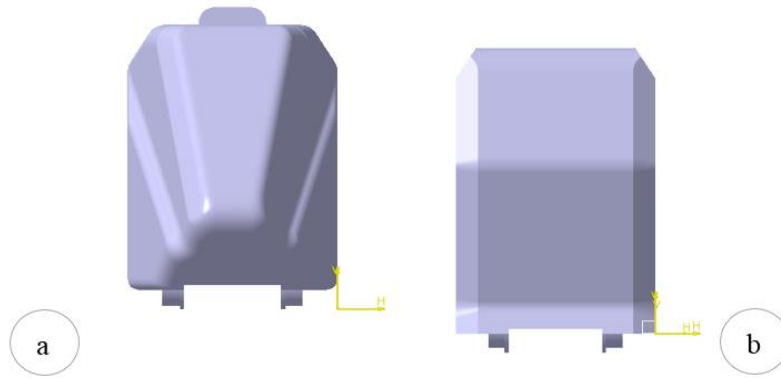


Figure 30: Front view Ethiopian Regional passenger locomotives Figure **a is Optimized** and **b is Existing Models**.

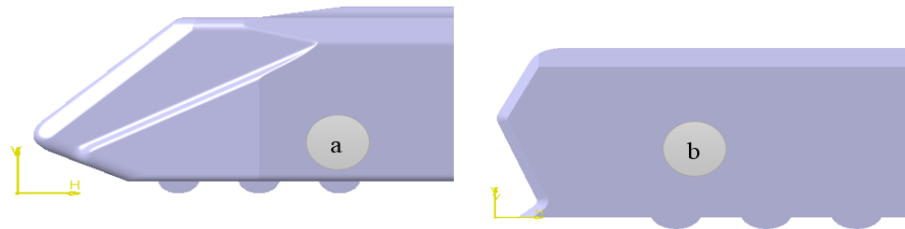


Figure 31: Ethiopian Regional passenger locomotive Aerodynamic shape of nose Figure **a is Optimized** and **b is Existing Models**

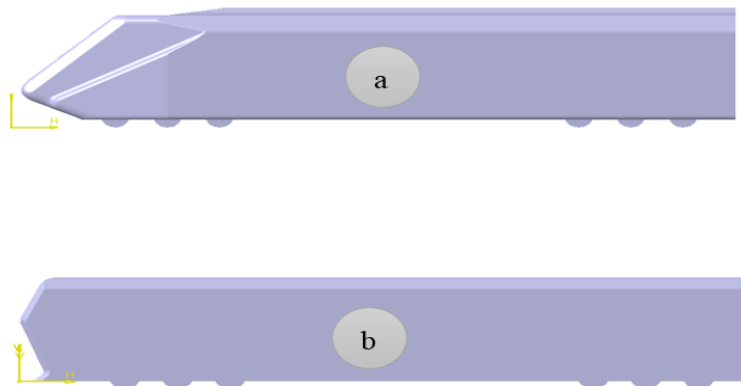


Figure 32: Side view Ethiopian Regional Passenger locomotives Figure **a is Optimized** and **b is Existing Models**.

- ♦ **Ethiopian Regional Freight Locomotive:** regional freight train locomotive vehicles have maximum speed of 120 km/h. Considering the maximum speed of the vehicles related to aerodynamic shape of the train body under the side wind condition at 2m and 10m height according to Ethiopian Meteorology and HYDROCHINA CORPORATION group. So, this study has optimized the train shape to be energy efficiency and stability for the project sustainability by comparison of the two model vehicles as shown in the Figure 33 up to 36.

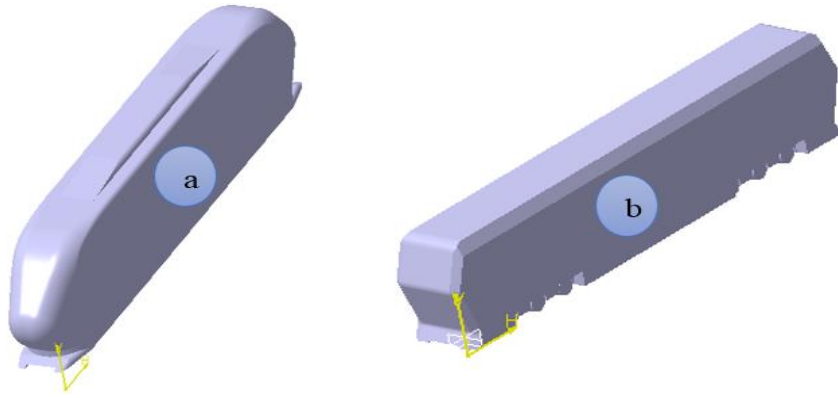


Figure 33: 3D Ethiopian Regional Freight locomotives Figure **a** is **Optimized** and **b** is **Existing Models**.

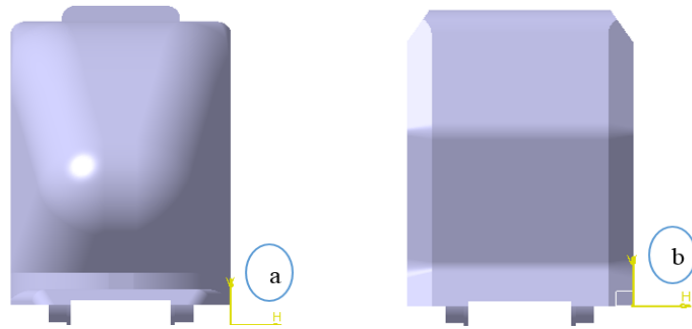


Figure 34: Front view Ethiopian Regional Freight locomotives Figure **a** is **Optimized** and **b** is **Existing Models**.

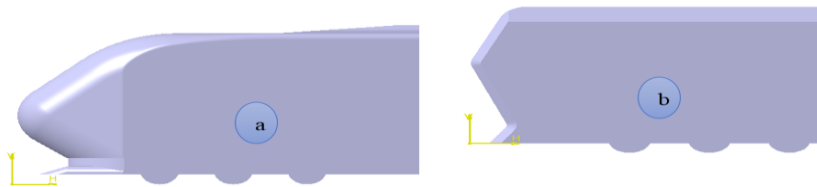


Figure 35: Ethiopian Regional Freight locomotive Aerodynamic shape of nose Figure **a** is **Optimized** and **b** is **Existing Models**.

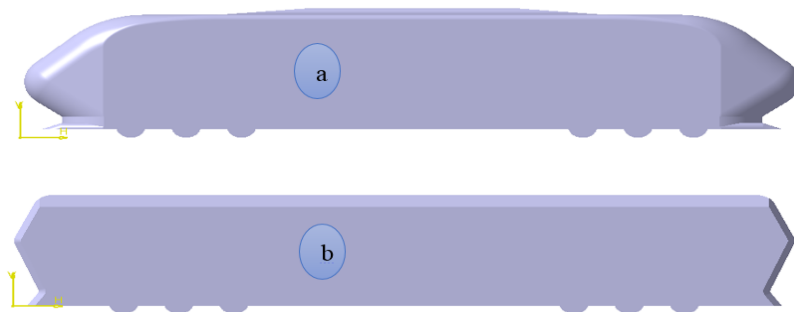


Figure 36: Side view Ethiopian Regional Freight locomotives Figure **a** is **Optimized** and **b** is **Existing Models**.

3.8 Boundary and initial conditions for CFD calculation

The boundary conditions for the CFD- calculations and the model scale tests were given by the full scale. Boundary Conditions were applied on meshed models using CFD and were analyzed in running trains. In this simulation, straight wind condition was considered at Constant velocity inlet condition and zero gauge pressure at the outlet was applied. Operating condition was set to atmospheric pressure. Purple and sky-blue faces indicate velocity inlet and pressure outlet respectively which is indicated as shown in Figure 37 control volume and Table 8.

Table 8: Boundary Conditions setup for CFD numerical simulation.

Boundary	Boundary conditions	Values
Inlet	Velocity inlet	Varying from 11.11 m/s to 45.45m/s depend on model type
Outlet	Pressure outlet	Ambient pressure is $P = 0 \text{ N/m}^2$
Ground	Fixed plate and air moving on it from front and side directions	Varying from 11.11 m/s to 45.45m/s depend on model type
	Side wind velocity at 90° from train side plane	Constant velocity $V = 12\text{m/s}$
Left side wall inlet	Side wind velocity at 90° from train side plane	Constant velocity $V = 12\text{m/s}$
Right side wall outlet	Pressure outlet	Ambient pressure is $P = 0 \text{ N/m}^2$
Train body	Fixed train	Not moving
Domain top	Stationary roof	45m height from ground

3.9 CFD simulation setup procedures

- Size of the controlled region is $X= 120\text{m}$, $Y= 45\text{m}$, $Z= 35\text{m}$ as shown in Figure 37.
- By boundary conditions of the domain using inlet, outlet and ground plate
- Importing model Trains with the dimensions
- Scale size of the models 1.00

- Make boundary plates like inlet, outlet, and ground plate.
- Set initial condition wind velocity
- Set the position of sensor in the domain
- Calculate moments and forces at center of pressure
- Reference density of $\rho = 1.2250\text{kg/m}^3$
- Reference area of models is $W \cdot H$.
- The current domain material treated at air at 20°C , 1atm
- Turbulence model KECHEN standard is selected
- Using question formulation ELLIPTIC STAGGERED
- Total number of iteration is 1000
- Global convergence criterion is 0.01
- Tolerance is 0.001

The flow characteristics were obtained at six different velocities such as 60kM/h, 80kM/h, 100kM/h, 120kM/h, 140kM/h and 160kM/h for regional Passenger and Freight locomotive models and 40kM/h, 50kM/h, 60kM/h, 70kM/h and 80kM/h for Light Railway Transit model.

3.9.1 Coordinate system

The coordinate system is given in the Figure as shown.

- The X-axis represents the direction of trains travel,
- The Y-axis represents the direction perpendicular to the side of the train and the direction of cross-wind blow and
- The Z-axis represents the direction towards the ground.
- The moments M_r (roll moment), M_p (pitch moment) and M_y (yaw moment) are taken as positive anticlockwise to the respective axes.

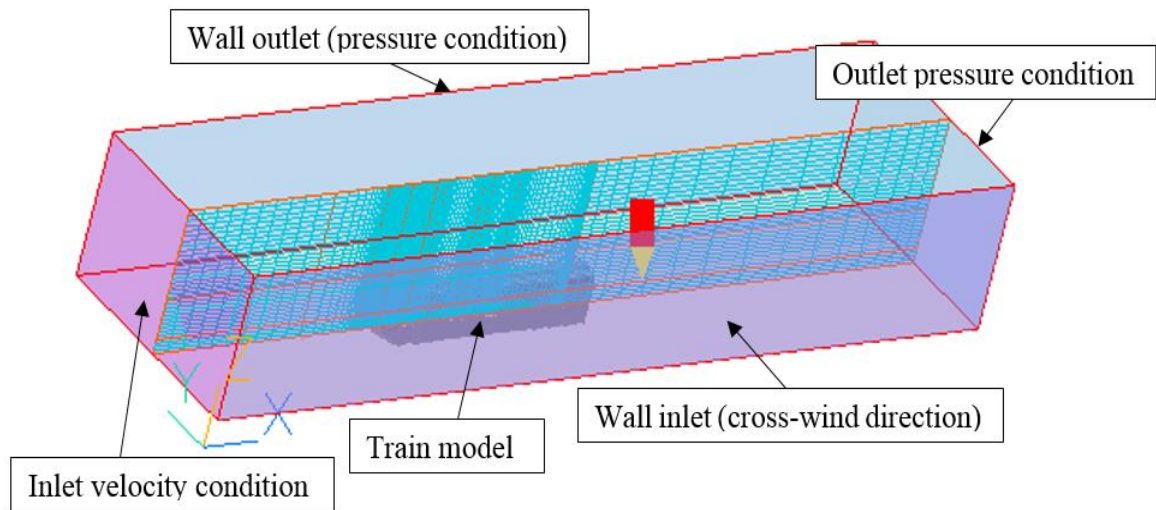


Figure 37: This is the control volume in PHOENICS CFD numerical simulation arrangement.

3.9.2 Computation domain

The generalized rectangular box domain control volume is used for the analysis of CFD software for program run to control the flow of air from inlet both sides and the air speed is given as the speed of train. Thus, the trains moving direction is X-axis and the train models are aligned parallel to the sides of the domain. The front and left side are used as inlets, whereas the right side and rear are outlets. The same domain and mesh setup could be used for both existing and optimized train models. The size of the domain is big enough to satisfy the requirement PHOENICS Software application guides as shown in the Figure 37.

The cell sizes near the train irregular shape should be very fine so that the calculation of the simulation is accurate and near to wind-tunnel test results, flow separations and boundary layer phenomena can be captured. Large vortices in the far wake can be resolved even with a bigger cell size. The cell sizes and regions are defined through the control volumes, as shown in the Figure 37. It is used for both scaled and full scaled models, which are only differing by a scale factor.

3.9.3 Computation and quality of mesh

For more accuracy of the results obtained in the CFD simulation by making group of small cells based on the train body structure edges with using null body for making different regions in complex edges for more reducing errors at different irregular shapes. Thus, the mesh could capable of capturing the phenomenon and regions such as boundary layers, vortices, recirculation cells, stagnation points, wake, and flow accelerations. In this study in order to reduce the computational

grid mesh difference between the two models of the train locomotive analyzed and optimized of grid test has been executed. This is fair enough because a vehicle has symmetry in vertical plane along its longitudinal axis and using more region to be get a good result using grid generation test for optimize the meshing quality to running the simulation at varying velocity of trains.

3.10 Aerodynamic Drag, Lift and Side coefficient reduction calculation formulas

Aerodynamic coefficients are non-dimensional numbers that are used to determine the aerodynamic characteristics of a train energy efficiency and driving stability. Which are characterize the aerodynamic force and moment acting on train moving through gaseous medium. They bring all planes in to the same arena by having a ratio of forces rather than simply using the forces. Each of aerodynamic coefficients reduction can be expressed as following formula.

$$C_D = \frac{C_{D_{Existing Model}} - C_{D_{New Model}}}{C_{D_{Existing Model}}} \times 100\% \quad (57)$$

$$C_L = \frac{C_{L_{Existing Model}} - C_{L_{New Model}}}{C_{L_{Existing Model}}} \times 100\% \quad (58)$$

$$C_S = \frac{C_{S_{Existing Model}} - C_{S_{New Model}}}{C_{S_{Existing Model}}} \times 100\% \quad (59)$$

Where: C_D is the drag coefficient, C_L is the lifting coefficient, and C_S is the side coefficient.

3.10.1 Gird Optimization for each of train type models.

In this study, using grid generation test for each train locomotive model types based on their shape grid mesh has been optimized before simulation the train models at varying each running velocity. For regional passenger, freight locomotive models both using 100 km/h and Light Railway Transit train using 80km/h gird generation test at post process using average values of velocity and pressure at the position of probe (monitor) as shown a, b and c respectively.

- a) Grid convergence test values of average pressure and velocity at the location of monitor for regional passenger locomotive train models at constant speed of 100 km/h. Then after, the calculation has been seated at convergence mesh size.

Table 9 : Grid generation test for regional passenger locomotive train at 100 km/h

No. of Test	No. of grid in X,Y,Z	Velocity in m/s	Pressure in bar
1	124X46X38	45.2644	126.6547
2	154X61X56	30.2104	84.9263
3	184X65X61	38.7613	102.4785
4	186X65X62	39.2371	101.9560
5	192X67X68	39.5963	102.6216

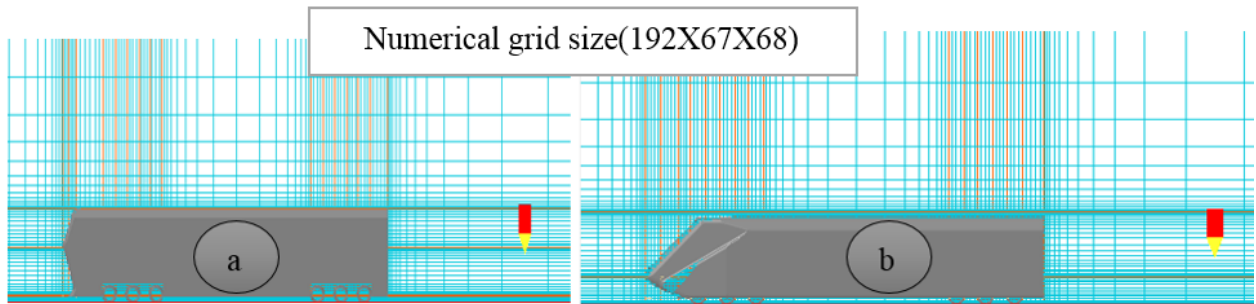


Figure 38: Final grid generation test for using simulation test at varying speeds of existing (a) and optimized (b) Ethiopian regional passenger locomotive train.

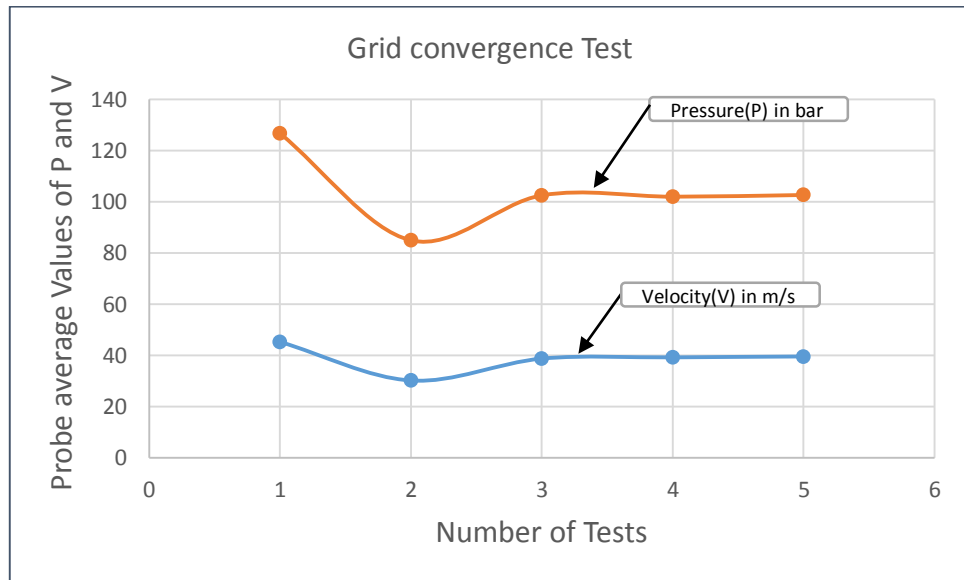


Figure 39: This shows that how grid generation test converge to constant mesh for Regional Passenger train locomotive simulation test.

- b)** Grid convergence test values of average pressure and velocity at the location of monitor for regional Freight locomotive train models at constant speed of 100 km/h.

Table 10: Grid generation test for regional freight locomotive train at 120 km/h

No. of Test	No. of grid in X,Y,Z	Velocity in m/s	Pressure in bar
1	120X36X57	14.6353	143.936
2	152X48X49	19.2104	204.554
3	164X56X56	32.9670	390.0864
4	171X60X58	35.2987	280.9876
5	178X68X62	36.7880	281.5114

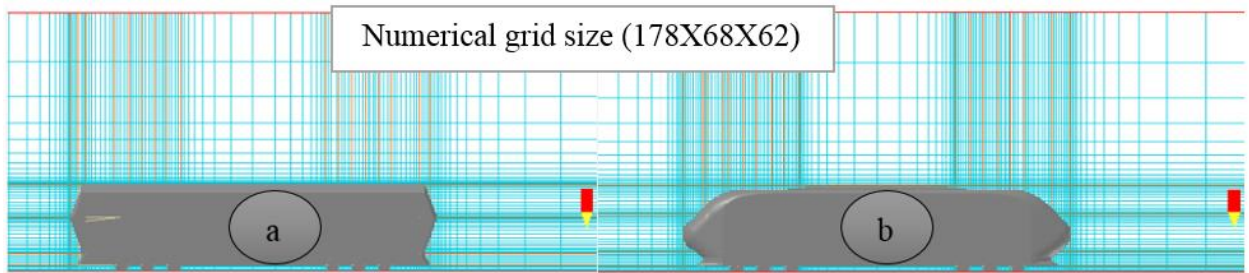


Figure 40: Final grid generation test for using simulation test at varying speeds of existing (a) and optimized (b) Ethiopian regional freight locomotive train.

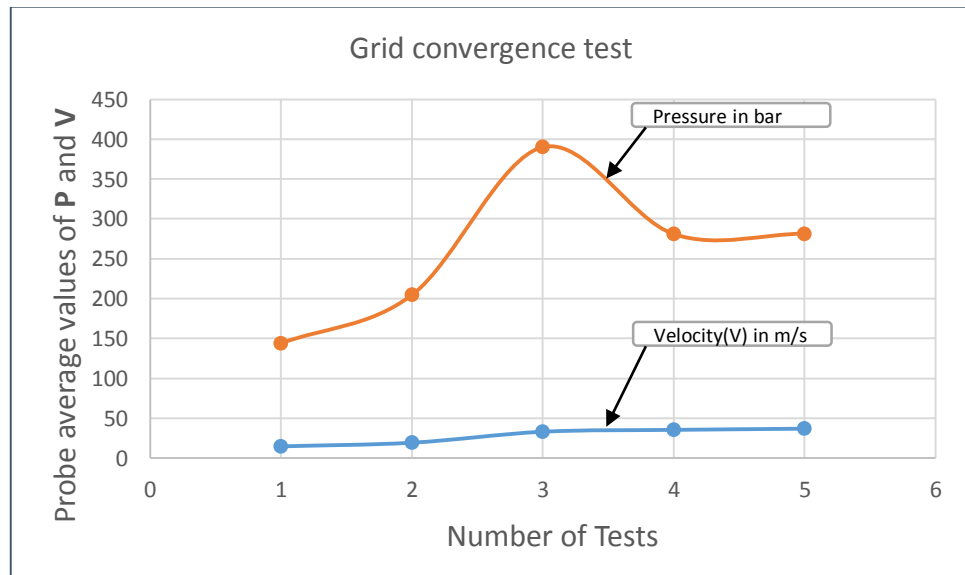


Figure 41: This shows that how grid generation test converge to constant mesh for Regional Freight train locomotive simulation test.

- c) Grid convergence test values of average pressure and velocity at the location of monitor for Light Railway Transit train models at constant speed of 80 km/h.

Figure 42: Grid generation test for Light Railway Transit train at 80 km/h

No. of Test	No. of grid in X,Y,Z	Velocity in m/s	Pressure in bar
1	148X36X46	14.6353	143.936
2	165X48X52	19.2104	204.554
3	170X50X56	18.1991	137.8824
4	284X52X59	18.2053	134.332
5	360X64X51	30.03118	135.7349

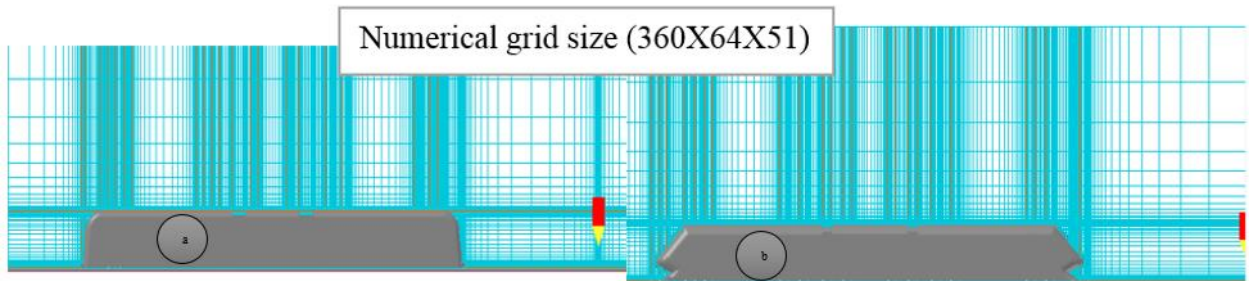


Figure 43: Final grid generation test for using simulation test at varying speeds of existing (a) and optimized (b) Ethiopian Light Railway Transit train.

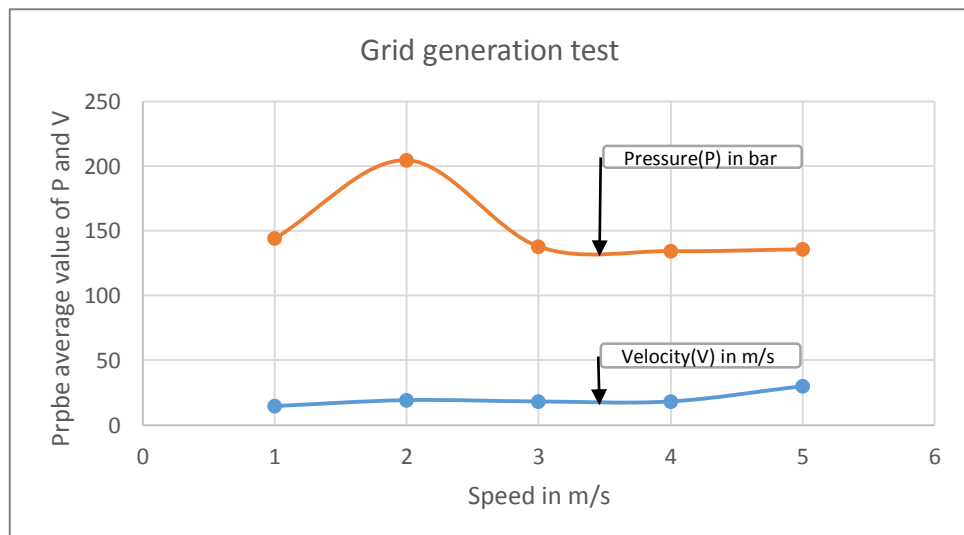


Figure 44: This shows that how grid generation test converge to constant mesh for Light Railway Transit train simulation test.

3.11 Energy consumption

Many engineers think that energy consumption of high-speed trains is very high, because the energy increases with the square of the speed and the power with the cube. Thus, Ecologists said that high-speed train is an energy predator, and the expansion of high-speed trains will be dangerous for the planet. So, this study has saved enough amount of energy within the consideration of Ethiopian train locomotive types depending on their driving velocity. Energy consumption can be calculated in based on driving resistance integrating the instantaneous force over the traveled distance

$$E = \int_1^2 F_t \cdot dx \quad (60)$$

Where F_t is the sum of resistance force

The energy consumption can be calculated as the following formula

$$E = \int_0^t P \cdot dt \quad (61)$$

Where E is energy consumption in J, t is elapsed time in s and P is power in W

$$P = F_t \cdot V \quad (62)$$

Where F_t is total resistance in N and V is speed in m/s.

If power is constant the energy consumption is

$$E = P \cdot t \quad (63)$$

$$P_{\text{saved}} = (F_{D1} - F_{D2}) \cdot V \quad (64)$$

$$P_{\text{Saved}} = \frac{P_{\text{required of Existing Model}} - P_{\text{required for Optimized Model}}}{P_{\text{required of Existing Model}}} \times 100\% \quad (65)$$

Where: P_{saved} is the drag power saved in kW or %, F_{D1} and F_{D2} are drag resistance forces in N, V is velocity of train locomotive in m/s, P is power in kW, E is energy in J and t is elapsed time in s.

3.12 Aerodynamic Stability of train locomotive models at straight track

When the train locomotives travels on the track there is aerodynamic pressure loads are applied on the train locomotive body which are acting at the center of pressure (CP). The net effect of the aerodynamic force includes drag (F_D), lift (F_L), side force component (F_S) which due to lateral wind components imposed on a train locomotive that is attempting to change the direction of train travel but the exact effects depend on the train body and the nature of cross-wind conditions, and moments yawing (M_y), rolling (M_r), pitching (M_p) are acting on a principal axis of a train. But the gravitational force is acting from the center of gravity (CG) which is the resistance force to compensate the aerodynamic forces with the side wind effects. In this study, the train locomotive speed becomes varying up to the maximum speed of rang design and traveling under the influence of cross-wind condition at the constant speed of 12m/s which is studied for long years in Ethiopia at the height of 2m and 10m, the train locomotive gravity component in the track plane may not be enough to support the centripetal force any more. In this study, the rotational direction has considered clockwise is positive and counter clockwise is negative.

3.12.1 Rotational moments at each axis

1. **Yawing moment (M_y):** when the aerodynamic forces and the crosswinds effect loads do not act at the middle of the wheelbase at the center of gravity as shown in the Figure 45 a yawing moment is develop. The yawing moment can be calculated as

$$M_y = F_x \cdot dy - F_y \cdot dx \quad (66)$$

Where: dx and dy are distance between CP and CG, F_x and F_y are negative forces

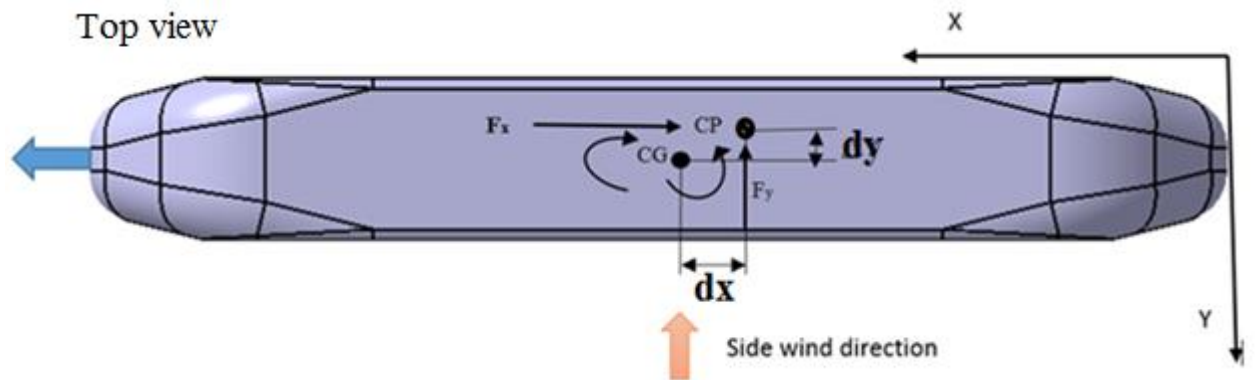


Figure 45: Yawing moment on the moving train locomotive due of aerodynamic forces acting at the center of pressure.

2. **Rolling moment (M_r):** when the crosswind effect and aerodynamic lift develop a side force acting on the train body at the center of pressure as shown in Figure 46. The rolling moment can be calculated as

$$M_r = F_y \cdot dz - F_z \cdot dy \quad (67)$$

Where: dy and dz are distance between CP and CG, F_z and F_y are negative forces

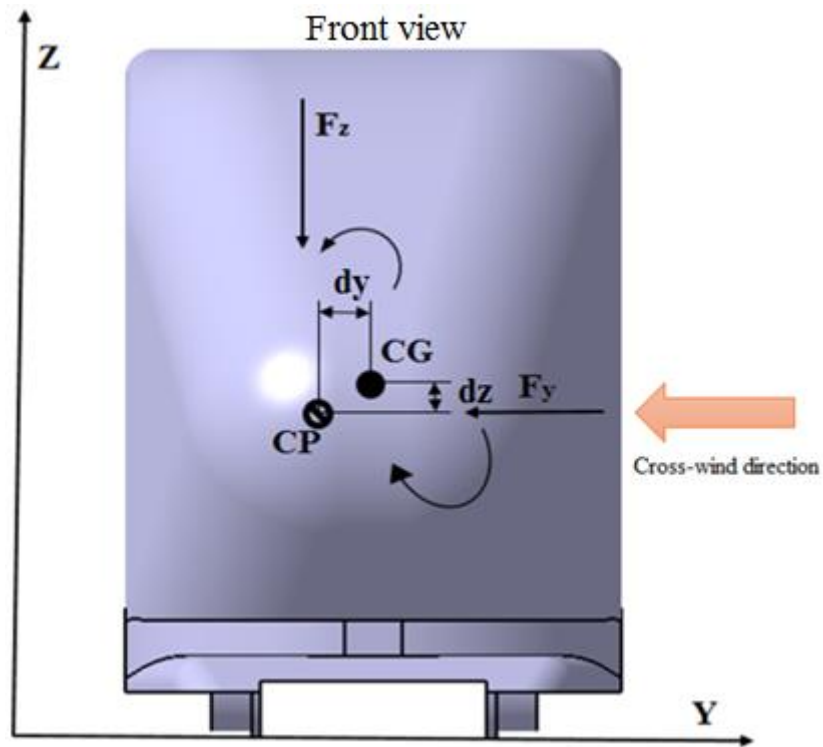


Figure 46: Rolling moment on the moving train locomotive due of aerodynamic forces acting at the center of pressure.

3. **Pitching moment (M_p):** Is affects when the weight distribution between the front and the rear of running train varying due to aerodynamics forces which are acting at the center of pressure as shown in Figure 47. Which can be calculated as

$$M_p = -F_x \cdot dz + F_z \cdot dx \quad (68)$$

Where: dx and dz are distance between CP and CG, F_z and F_x are negative forces

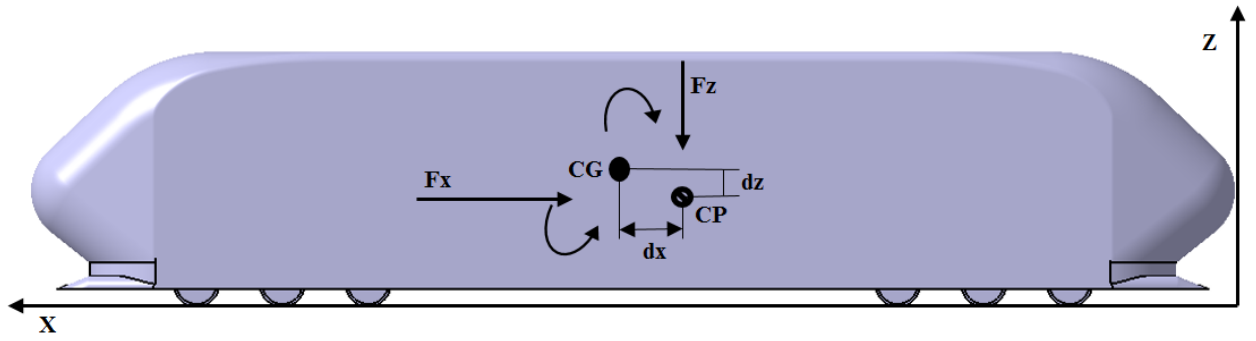


Figure 47: Pitching moment on the moving train locomotive due of aerodynamic forces acting at the center of pressure.

3.12.2 Numerical calculation of Resistance moments

Which are the moment compensate the rotational moments acting on the running train vehicles.

1. **Yawing resistance moment (M_{yr}):** which is the resistance moment of resisting the rotational moment due to weight of train reaction force of rail surface on the wheels of train as friction force. As shown in the Figure 48 the calculation of yawing resistance is

$$M_{yr} = [F_1 \cdot L_1 + F_2 \cdot L_2 + F_3 \cdot L_3 + F_4 \cdot L_1 + F_5 \cdot L_2 + F_6 \cdot L_3 + F_7 \cdot L_1 + F_8 \cdot L_2 + F_9 \cdot L_3 + F_{10} \cdot L_1 + F_{11} \cdot L_2 + F_{12} \cdot L_3] \cdot \mu \quad (69)$$

Where: L_1 , L_2 and L_3 are distance of center of wheels from CG point, F_1 , F_2 , ..., F_{12} are reaction forces on the wheel of train. And μ values is for steel on steel, the coefficient of friction can be as high as 0.78, but typically on railways it is between 0.35 and 0.5.

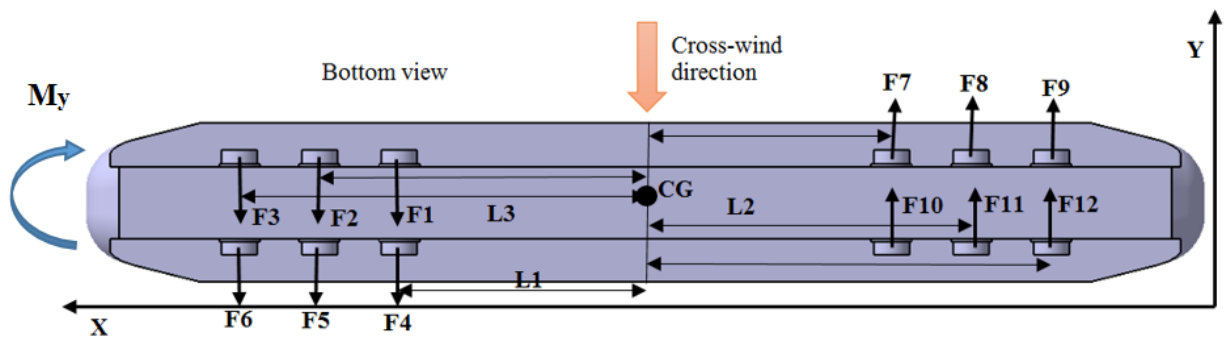


Figure 48: Yawing resistance of dynamic stability of moving train.

2. Rolling resistance moment (M_{rr}): which is the resistance moment to resist the rolling moment that acts on the train body. Rolling resistance moment is develop due to the weight of train. As shown in the Figure 49 rolling resistance can be calculated as

$$M_{rr} = -W \cdot L_w \quad (70)$$

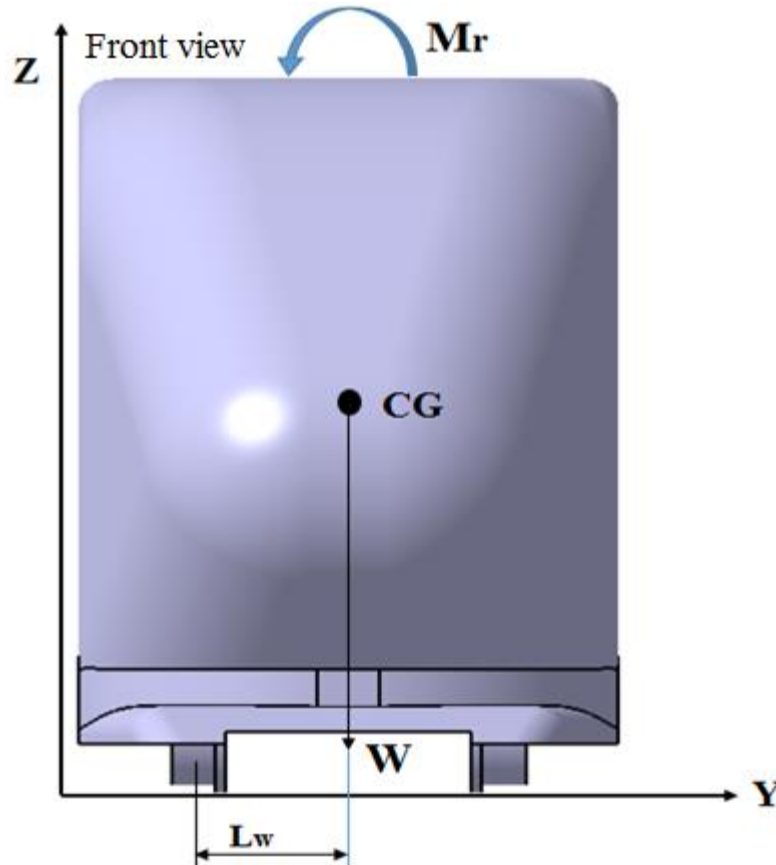


Figure 49: Rolling resistance of dynamic stability of moving train.

3. **Pitching resistance moment (M_{pr}):** which is the resistance moment to resist the pitching moment that acts on the train body. Pitching resistance moment is develop due to the weight of train. As shown in the Figure 50 pitching resistance can be calculated as

$$M_{pr} = W \cdot L_w \quad (71)$$

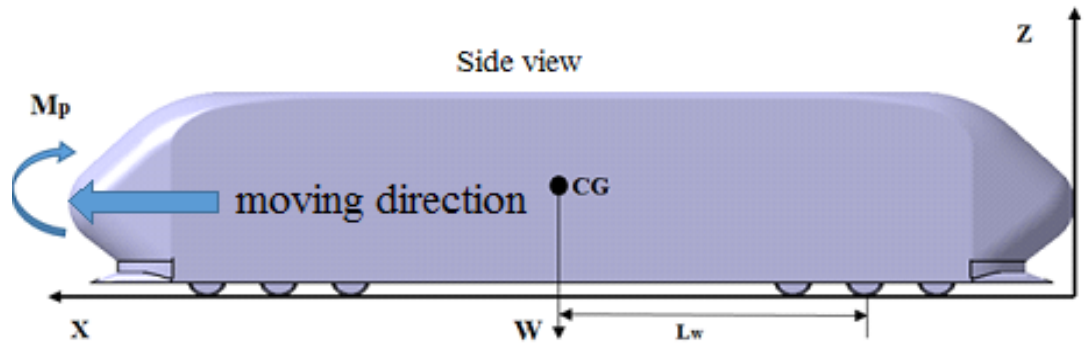


Figure 50: Pitching resistance of dynamic stability of moving train.

Therefore, in this study, to judge aerodynamic stability condition of Ethiopian train locomotive both existing and Optimized models using the comparison between the rotational moment such as yawing (M_y), rolling (M_r) and pitching (M_p) and resistance moment which are yawing resistance (M_{yr}), rolling resistance (M_{rr}) and pitching resistance (M_{pr}) of the moving train locomotives at maximum operation speed under the influence of at 12 m/s cross-wind speed. When the value of $M_y < M_{yr}$, $M_r < M_{rr}$, and $M_p < M_{pr}$ the train locomotive models driving stability is safe at the all conditions of moving train locomotives at maximum operation speed of 160 km/h for Regional Passenger train, 120 km/h Regional Freight train and 80 km/h Light Railway Transit train in under the influence of cross-wind at the speed of 12 m/s otherwise even one of rotational moment is greater than the resistance moment is the train locomotive does not have guarantee to driving stability in this case train locomotive is instable or unsafe.

3.13 Dynamic Stability of railway locomotive models moving on the curved rail track.

In this study, when train locomotive travels over with a constant curvature, there is the lateral force or the centrifugal force tends to push the train locomotive out of the curve with in different factors such as, side wind condition, high-speed of train and the rail curvature height that is called super-elevation or the height difference between the inner and outer rail track height. Therefore, if the curve has a certain curvature and has constant super-elevation, there is a balance speed at which the component of the centrifugal force is equal to the lateral component of the gravity force, as shown in Figure 51.

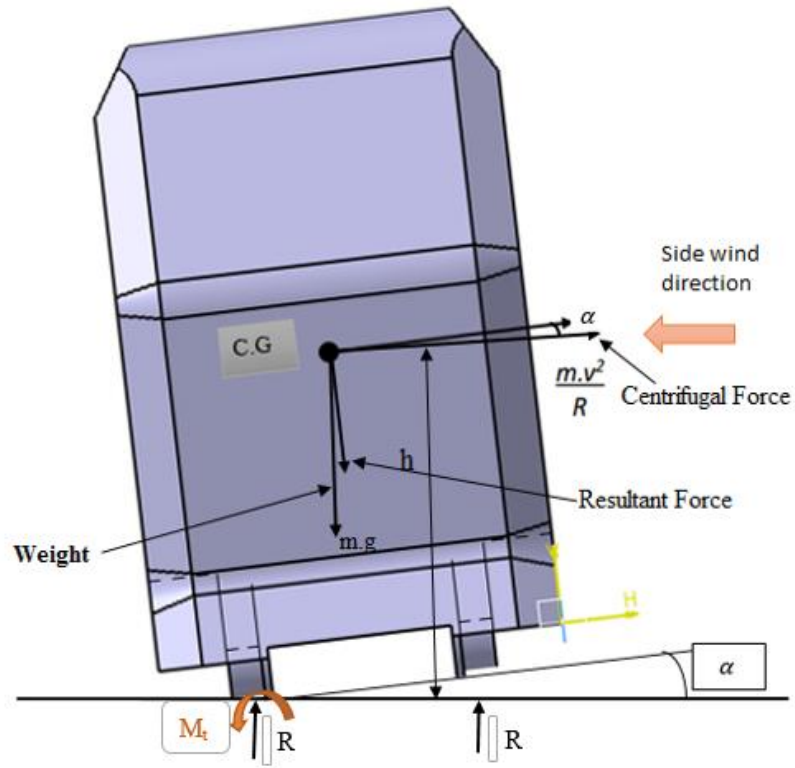


Figure 51: Front view sketch for Passenger train locomotive under side wind excitations.

Thus, the vehicle is traveling with a speed equal to V over a track that has a radius of curvature R , then at the balance speed, has the following relationship.

$$\frac{MV^2}{R} \cos \alpha = Mg \sin \alpha \quad (72)$$

$$F_c = \frac{M V^2}{R} \quad (73)$$

$$W = M \cdot g \quad (74)$$

Where V is the speed of train locomotive, R is radius of curvature, g is the gravity constant, W is weight and M is the mass of train locomotive. When considering α is very small for this study, used the following small angle approximation in mathematics.

$$(\alpha \approx 0). \cos \alpha = 1 \text{ and } \sin \alpha = \alpha \quad (75)$$

This study has considered the track curvature height is zero which means the height of inner and outer have same rail height and has considered the cross-wind direction from inner and outer side of rail track curvature independently. When the train locomotives moving on the curved track there are aerodynamic (F_x , F_y , F_z) and dynamic forces weight of train on each wheel, centrifugal force always acting on outward of the center of curvature and due to precession and other rotating parts on train gyroscopic effects acting on the train outward of curvature as shown in the Figure 52.

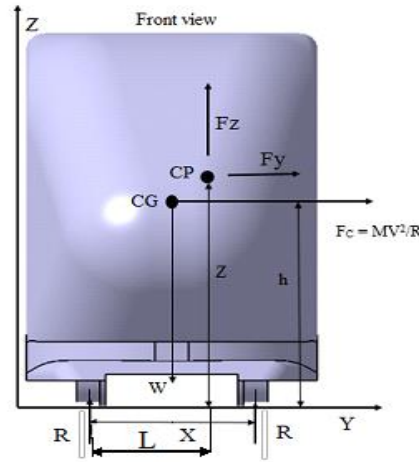


Figure 52: Train locomotive moving on curved track road at radius of minimum curvature.

For calculation of stability of moving train takes a turn toward either left or right direction dynamic and aerodynamic loads acting on the moving train locomotive of rail reaction on each wheels due to weight is upward, gyroscopic couple effect towards outer wheels, centrifugal force acting outward of the curvature, aerodynamic forces (F_y and F_z) acting vertical and horizontal direction as shown in the Figure 52. The stability of moving trains at curving track is calculated analytically for each type of train models as shown below.

3.13.1 Calculation of reaction forces on train locomotive model wheels

As shown in the Figure 52 front view the train move at turning toward the right (negative y-axis) and considered the cross-wind direction is from inner rail track to outward (toward positive y-axis). The reaction forces are considered as

- **Reaction (R_F)** due to weight of train of rail track on each wheel upward direction (positive z-axis) is

$$R_F = \frac{W}{12} \quad (76)$$

- **Centrifugal force**(F_c) act outward of the curve (in this case positive y-axis) is

$$F_c = \frac{M V^2}{R} \quad (77)$$

Due to centrifugal force the centrifugal couple (C_c) will act overturning the train at the center of gravity as shown in the Figure 52.

$$C_c = \frac{M V^2}{R} \cdot h \quad (78)$$

This overturning couple is balanced by vertical reactions on the wheels which are vertically upward the outer side of wheels and vertically downward the inner side wheels. Let the magnitude of this reaction for inner or outer wheels is Q . Then,

$$C_c = Q \cdot X \quad (79)$$

So, vertical reaction at each of outer or inner wheels

$$\frac{Q}{6} = \frac{M V^2}{6XR} \cdot h \quad (80)$$

- **Gyroscopic couple** (C) effect due to 12 wheels on moving train turn toward outer side of rail track curvature is

$$C = C_w = 12I_w \omega_w \omega_p \quad (81)$$

$$\omega_p = \frac{V}{R} \quad (82)$$

$$\omega_w = \frac{V}{r_w} \quad (83)$$

$$I_w = \frac{1}{2} M_w \cdot r_w^2 \quad (84)$$

But in this study, the rotating part of the train engine not considered. Due to gyroscopic couple, vertical reaction (P) the rail track on inner or outer wheels will develop. P is the magnitude of the reaction vertically upward on the outer wheels or vertically downward on inner wheels is

$$C = P \cdot X \quad (85)$$

Hence, vertical reaction at each of the outer or inner wheels,

$$\frac{P}{6} = \frac{C}{6X} \quad (86)$$

- **Aerodynamic forces** are acting on vertical in upward and horizontal to positive y-axis for this case and if the cross-wind direction is from outer rail track toward inner rail track the horizontal force will act toward the negative y-axis direction. Due to aerodynamic side force which is acting on the center of pressure in this case toward positive y-axis as shown in the Figure 52 make overturning the train outside of the rail track. The moment due to **Side force** on the center of gravitational point from center of pressure is

$$M_y = F_y \cdot \Delta z \quad (87)$$

This over turning moment balanced by vertical reaction in this case, which are vertically upward on the outer wheels and vertically downward on the inner wheels. Let the magnitude of this reaction for the 6 outer or inner wheels is U. Then,

$$U \cdot X = M_y \text{ or } U = \frac{M_y}{X} \quad (88)$$

Vertical reaction at each of the outer wheels upward direction

$$\frac{U_o}{6} = \frac{F_y \cdot \Delta z}{6X} \quad (89)$$

Vertical reaction at each of the inner wheels downward direction

$$\frac{U_i}{6} = \frac{F_y \cdot \Delta z}{6X} \quad (90)$$

Similarly the moment due to **lift force** on the center of gravitational point from center of pressure is

$$M_z = F_z \cdot \Delta y \quad (91)$$

This over turning moment balanced by vertical reaction which are vertically upward on the inner wheels and vertically downward on the outer wheels. Let the magnitude of this reaction for the 6 outer or inner wheels is V.

Then,

$$V \cdot X = M_Z \text{ or } V = \frac{M_Z}{X} \quad (92)$$

Vertical reaction at each of the inner wheels upward direction

$$\frac{V_i}{6} = \frac{F_Z \cdot \Delta y}{6\Delta x} \quad (93)$$

Vertical reaction at each of the outer wheels downward direction

$$\frac{V_o}{6} = \frac{F_Z \cdot \Delta y}{6X} \quad (94)$$

Where: R is radius of curvature in m, C_c centrifugal couple in Nm, W is the total weight of train in N, M is mass of train locomotive in kg, M_w is mass of wheel in kg, V is the speed of train locomotive in m/s, C is gyroscopic couple in Nm, C_w is gyroscopic couple due to wheels in Nm, I_w is mass of moment of inertia of one of the wheel in kg-m^2 , Δy is the horizontal distance from CP to CG, Δz is the vertical distance from CP to CG, ω_w is angular velocity of wheels in rad/s, ω_p is velocity of precession in rad/s, r_w is the radius of wheel in m, C_c is centrifugal couple in Nm, Z is the height of center of pressure, L is the length of center of pressure to wheels and h is height of center of gravity in m. Therefore,

i) The total force acting of the train locomotive when the train move a turn toward the right direction with respect to the driver as shown in the Figure 52 and the side wind direction is toward the left (from inner to outer curvature).

- The total reaction (R_o) at each of the outer wheels is

$$R_o = \frac{W}{12} + \frac{Q}{6} + \frac{P}{6} + \frac{F_y \cdot \Delta z}{6X} - \frac{F_Z \cdot \Delta y}{6X} \quad (95)$$

- The total reaction (R_i) at each of the inner wheels is

$$R_i = \frac{W}{12} - \frac{Q}{6} - \frac{P}{6} - \frac{F_y \cdot \Delta z}{6X} + \frac{F_Z \cdot \Delta y}{6X} \quad (96)$$

When the cross-wind direction is toward right (from outer to inner rail track curvature) only the horizontal force direction is changed.

- The total reaction (R_o) at each of the outer wheels is

$$R_o = \frac{W}{12} + \frac{Q}{6} + \frac{P}{6} - \frac{F_y \cdot \Delta z}{6X} + \frac{F_Z \cdot \Delta y}{6X} \quad (97)$$

- The total reaction (R_i) at each of the inner wheels is

$$R_i = \frac{W}{12} - \frac{Q}{6} - \frac{P}{6} + \frac{F_y \cdot \Delta z}{6X} - \frac{F_z \cdot \Delta y}{6X} \quad (98)$$

ii) The total force acting of the train locomotive when the train move a turn toward the left direction with respect to the driver as shown in the Figure 52 and the side wind direction is toward the right.

- The total reaction (R_o) at each of the outer wheels is

$$R_o = \frac{W}{12} + \frac{Q}{6} + \frac{P}{6} + \frac{F_y \cdot \Delta z}{6X} + \frac{F_z \cdot \Delta y}{6X} \quad (99)$$

- The total reaction (R_i) at each of the inner wheels is

$$R_i = \frac{W}{12} - \frac{Q}{6} - \frac{P}{6} - \frac{F_y \cdot \Delta z}{6X} - \frac{F_z \cdot \Delta y}{6X} \quad (100)$$

When the cross-wind direction is toward the left (from outer to inner rail track curvature) only the horizontal force direction is changed.

- The total reaction (R_o) at each of the outer wheels is

$$R_o = \frac{W}{12} + \frac{Q}{6} + \frac{P}{6} - \frac{F_y \cdot \Delta z}{6X} - \frac{F_z \cdot \Delta y}{6X} \quad (101)$$

- The total reaction (R_i) at each of the inner wheels is

$$R_i = \frac{W}{12} - \frac{Q}{6} - \frac{P}{6} + \frac{F_y \cdot \Delta z}{6X} + \frac{F_z \cdot \Delta y}{6X} \quad (102)$$

Table 11: Ethiopian Existing train locomotive models Specification for dynamic stability calculation.

Type of train locomotive	Regional Passenger train locomotive	Regional Freight train locomotive	Light Railway Transit train
Aerodynamic forces acting on the train	$F_y = 21.8\text{N}$ $F_z = 2.4\text{N}$	$F_y = 22\text{N}$ $F_z = 2.4\text{N}$	$F_y = 21.6\text{N}$ $F_z = 1.5\text{N}$
Weight	1,069,290N	1,471,500	618,030N
Maximum speed	45.45m/s	33.33m/s	22.22m/s
Minimum radius of curvature of track	300m	300m	100m
Wheel mass	351kg	351kg	302kg
Wheel nominal radius	0.42m	0.42m	0.32m
CP position from CG point.	$\Delta y = 0.28\text{m}$ $\Delta z = 0.84\text{m}$	$\Delta y = 0.44\text{m}$ $\Delta z = 0.79\text{m}$	$\Delta y = 0.27\text{m}$ $\Delta z = 0.01\text{m}$
From Figure 52 the dimension of CG, CP height and length	$L = (0.7175 \pm \Delta y)\text{ m}$ $h = 1.6\text{m}$ $X = 1.695\text{m}$ $Z = (h \pm \Delta z)$	$L = (0.7175 \pm \Delta y)\text{ m}$ $h = 1.6\text{m}$ $X = 1.695\text{m}$ $Z = (h \pm \Delta z)$	$L = (0.7175 \pm \Delta y)\text{ m}$ $h = 1.5\text{m}$ $X = 1.695\text{m}$ $Z = (h \pm \Delta z)$

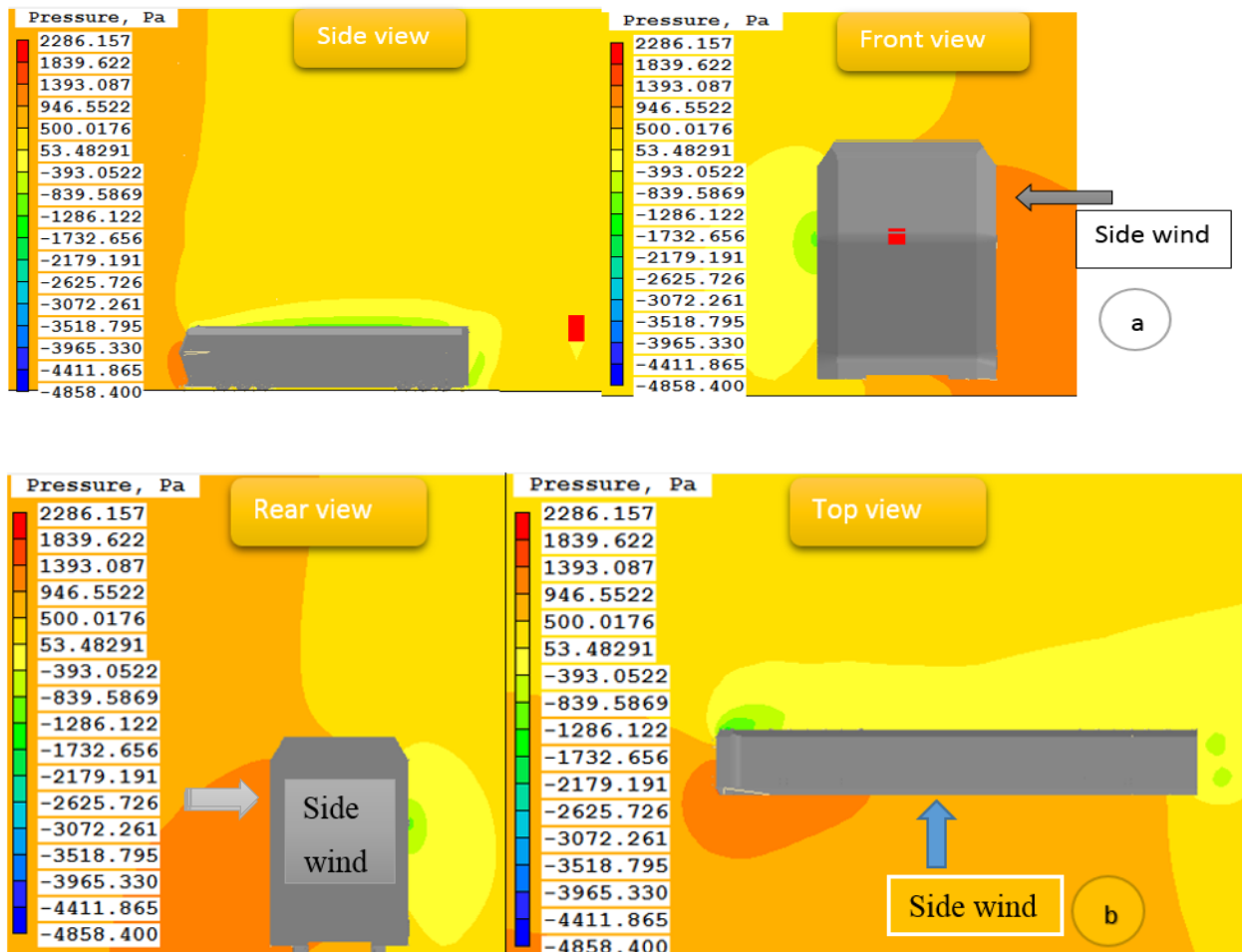
Therefore, in this study, for the two types of Ethiopian train locomotive and Light Railway Transit train dynamic safety judgments when the train moving on the minimum rail track curvature under the influence of cross-wind at the 12 m/s speed on inner as well as outer curvature direction independently. On this work Considered the wind is blowing horizontal and at angle of 90° from the train locomotive side. When the cross-wind direction is change the center of pressure (CP) position is shift from right to left and vice versa as shown in the Figure 52. Thus, for train locomotive is safe when it moves on the curvature of rail track at certain speed under cross-wind condition in either side of train locomotive the inner wheels not loss contact to rail track. Hence, on all cases which is the train locomotive moving either toward right or left direction and the side wind is blowing from either inner or outer side of curvature the reaction of each inner wheels (R_i) should be greater than zero ($R_i > 0$) at critical speed of the train locomotive otherwise unstable.

4. RESULT AND DISCUSSION

4.1 Results

Results was taken from CFD simulation test and dynamic stability analysis for six types of Ethiopian regional passenger and freight train locomotives and Light Railway Transit public transport train at varying traveling speed under the cross-wind condition for detail analysis of energy efficiency and stability of baseline and Optimized models as shown in the Figure 53 up to 64 results was achieved. Indicating the pressure and velocity distribution on moving train locomotives and Light Railway Transit train Models to judge how and where the pressure load resist and affect the running models. And also the structure of air flow on the moving looks like for qualitatively analysis and also quantitatively comparison the base models and Optimized models.

4.1.1 Aerodynamic Pressure and Velocity Distribution on Train locomotive Models at Various Speeds.



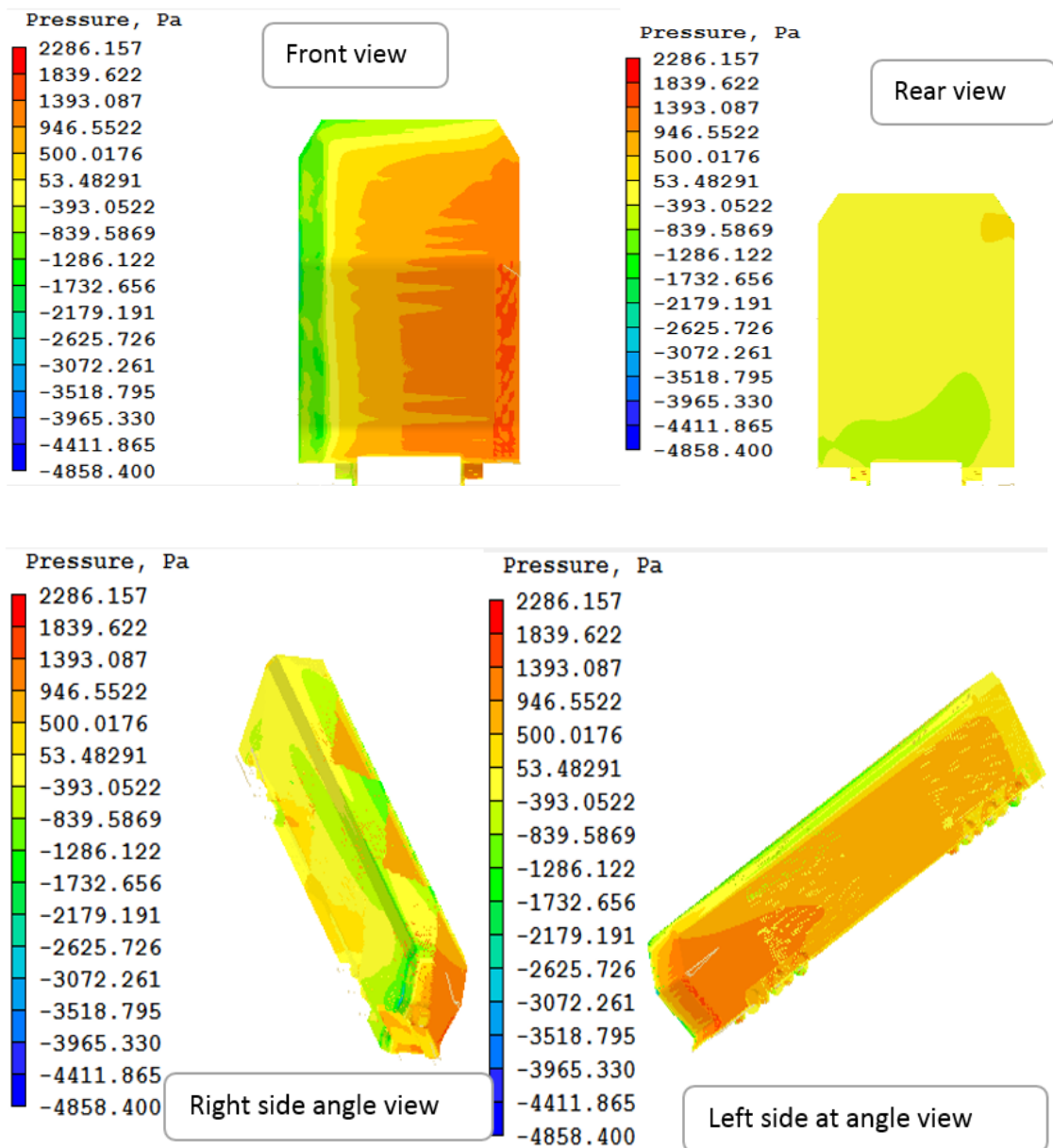
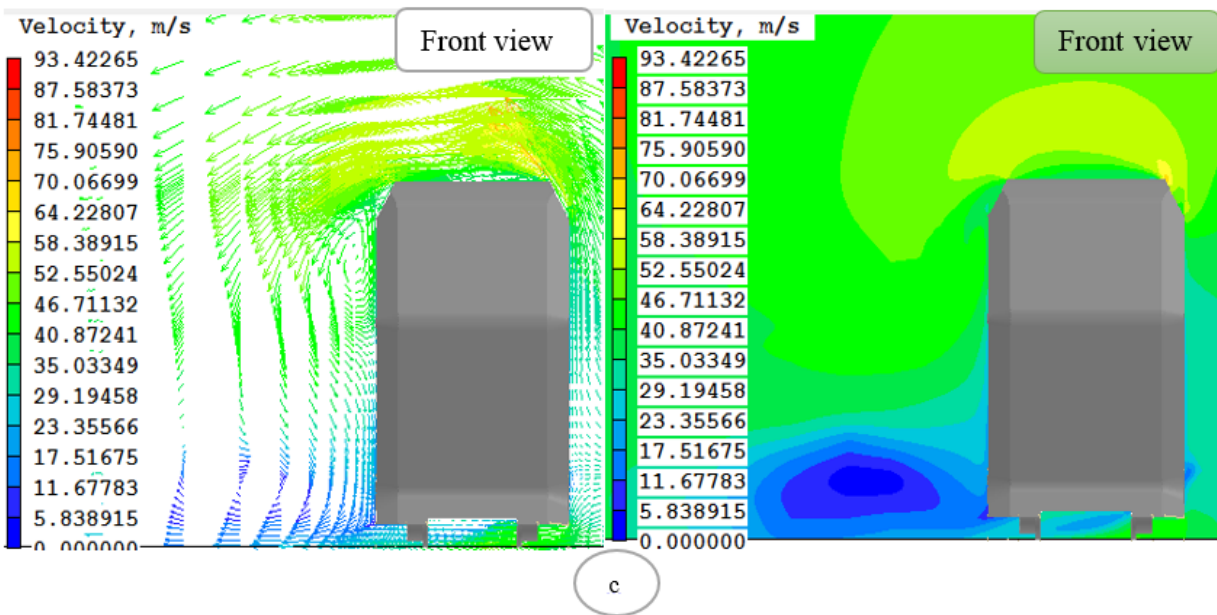
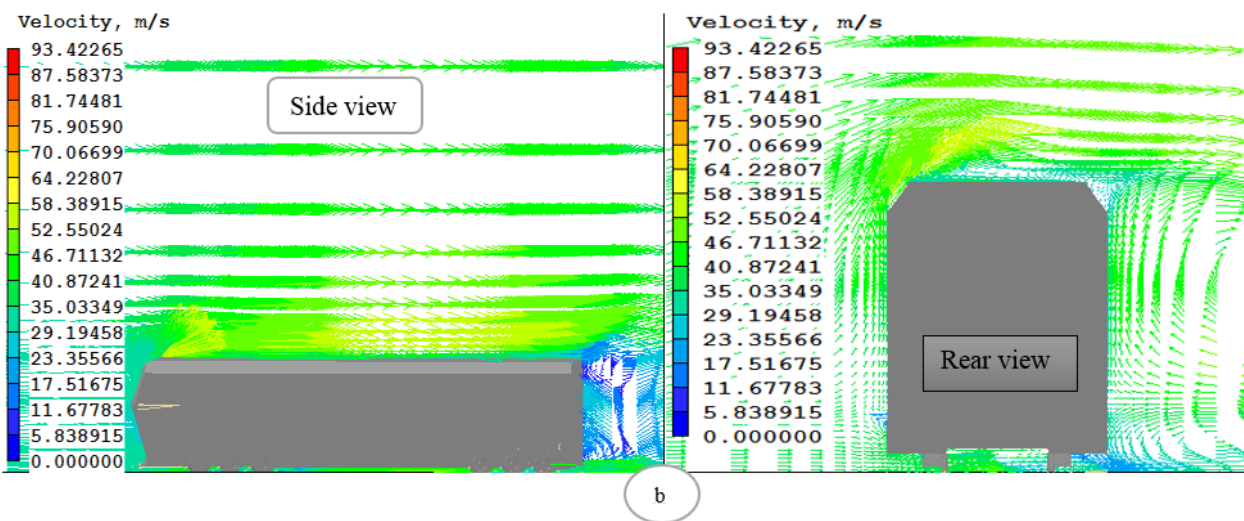
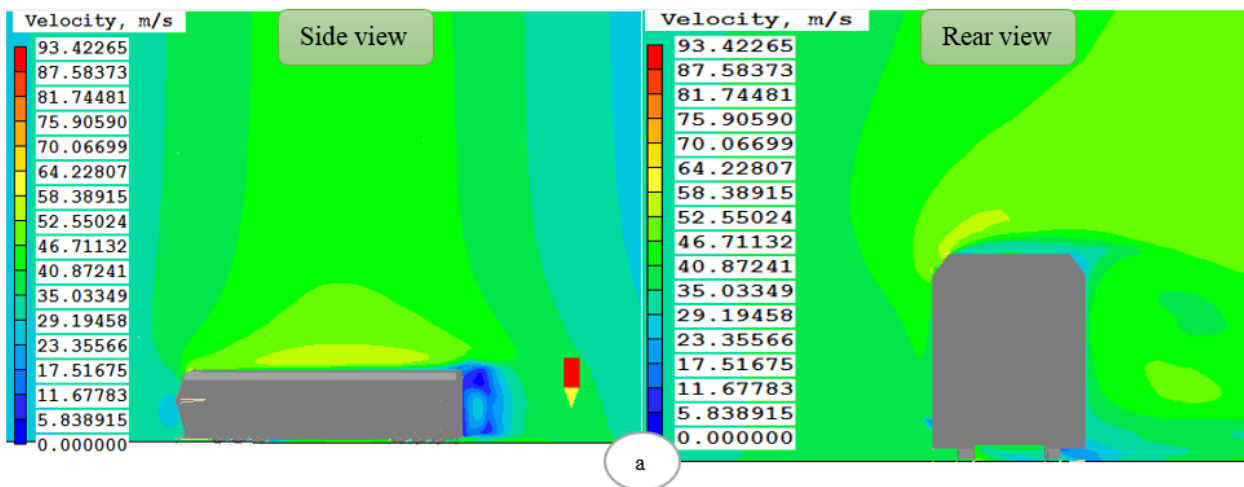


Figure 53: Pressure distribution on Regional Passenger train locomotives Existing Model at 100km/h Running Speed under the influence of side wind.



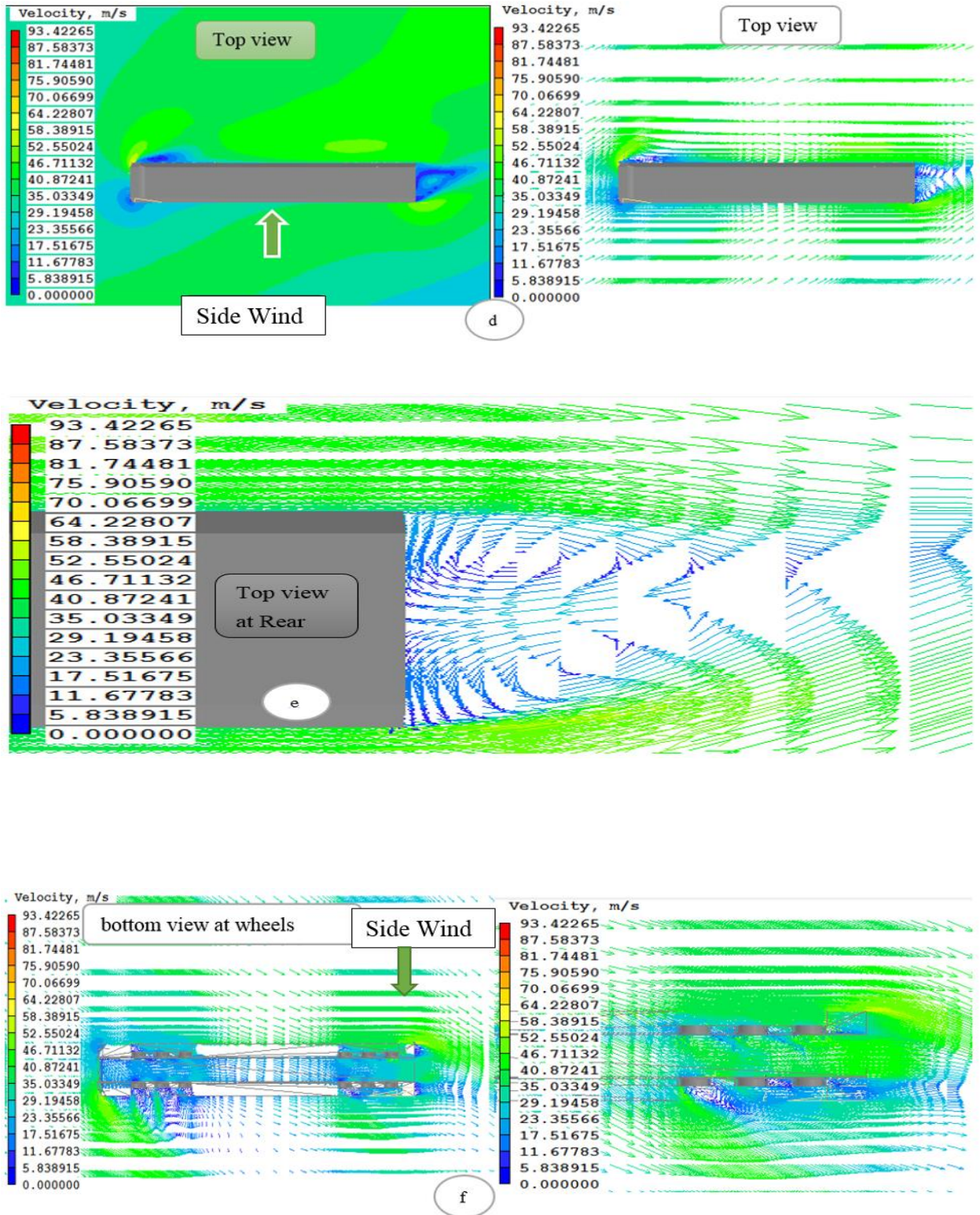
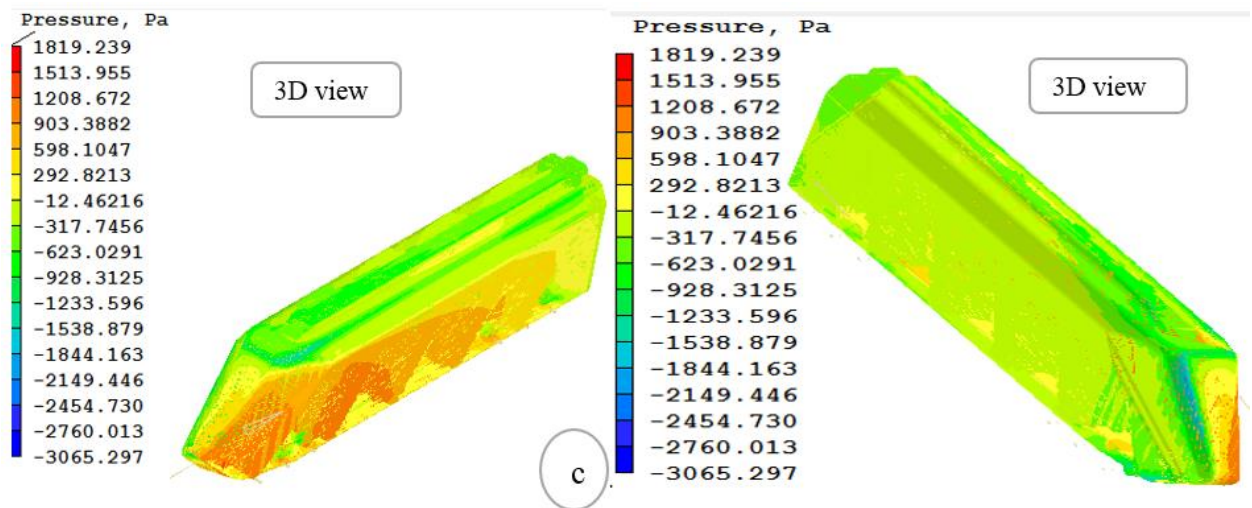
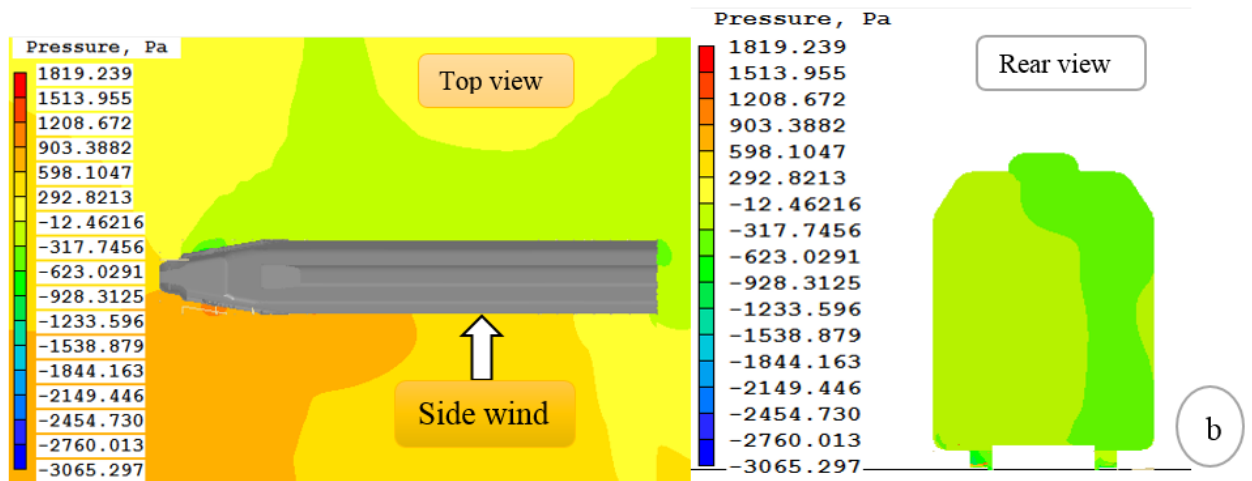
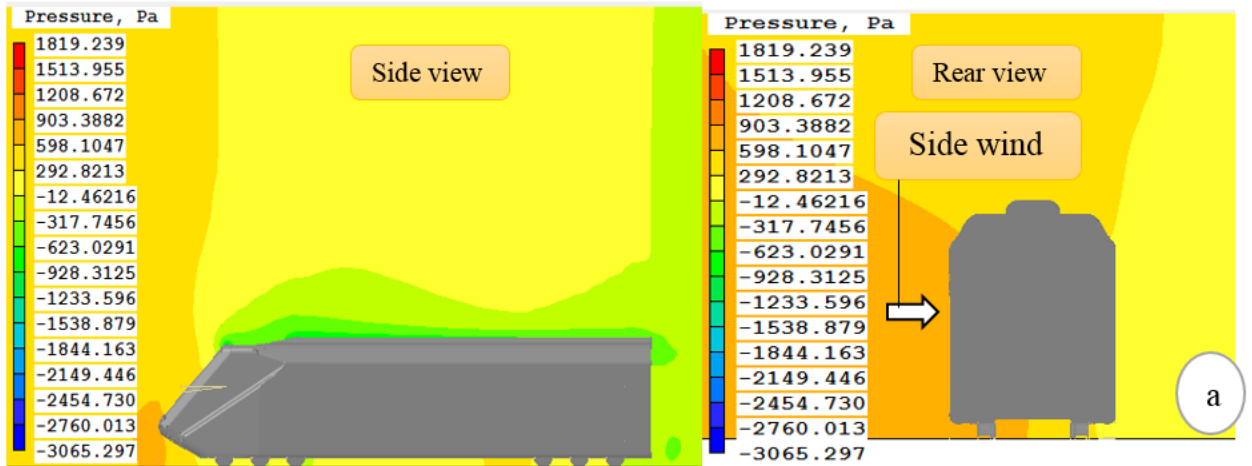


Figure 54: Velocity distribution on Regional Passenger train locomotives Existing Model at 100km/h Running Speed under the influence of side wind.



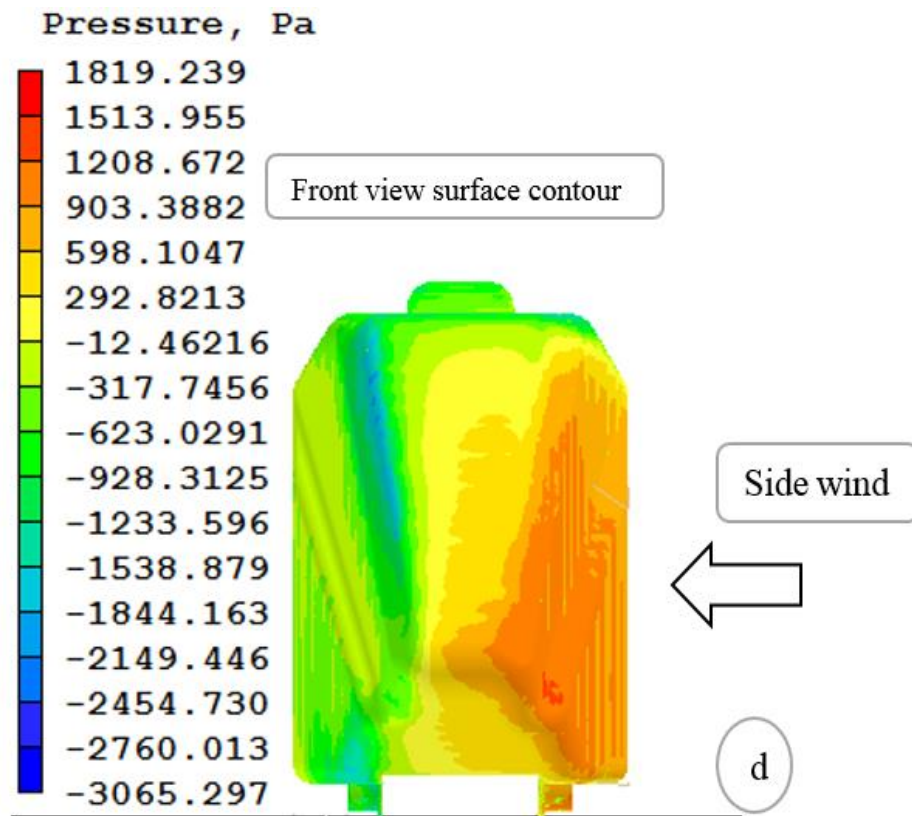
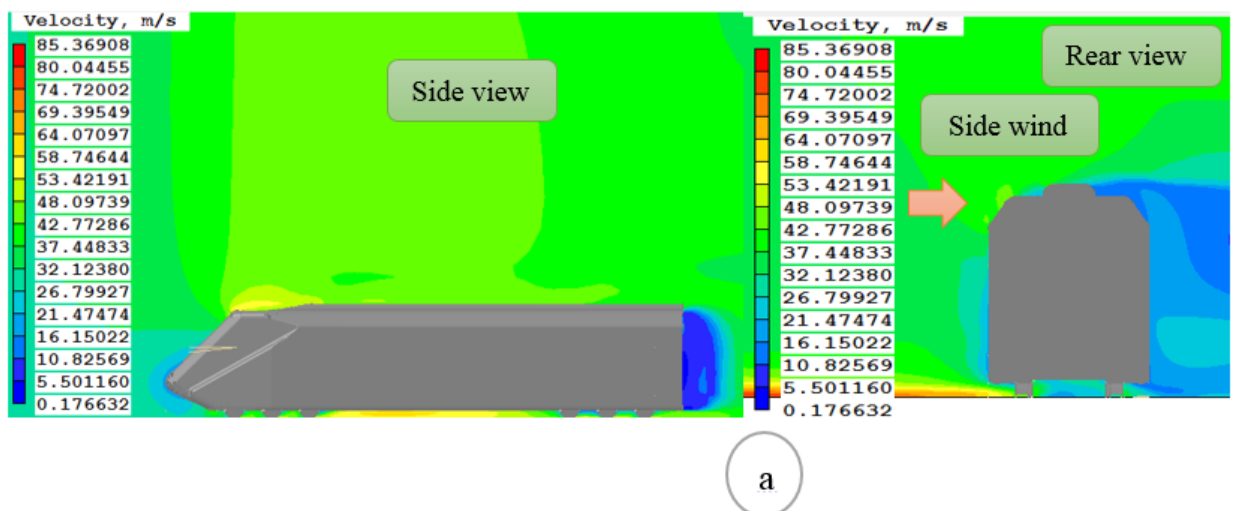
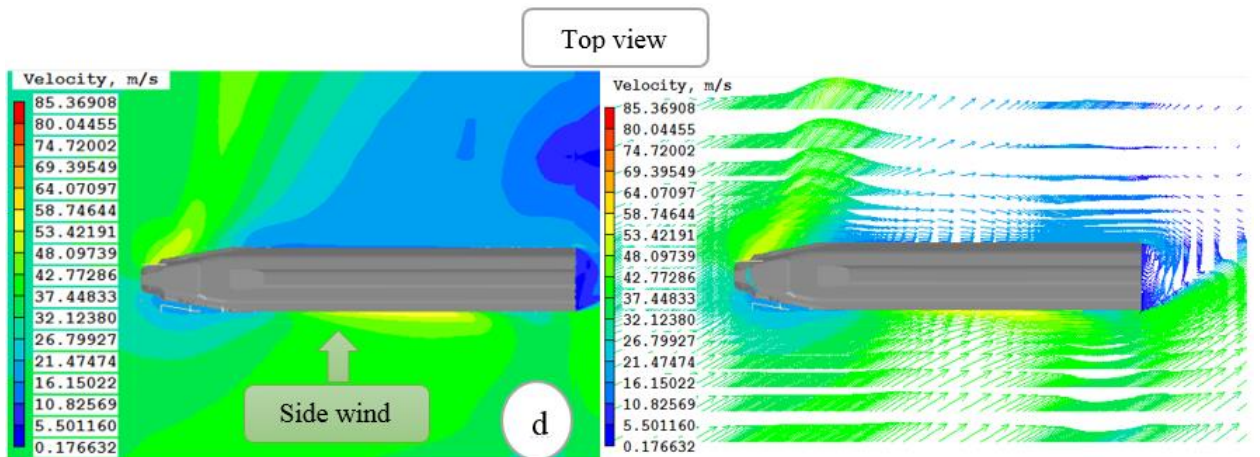
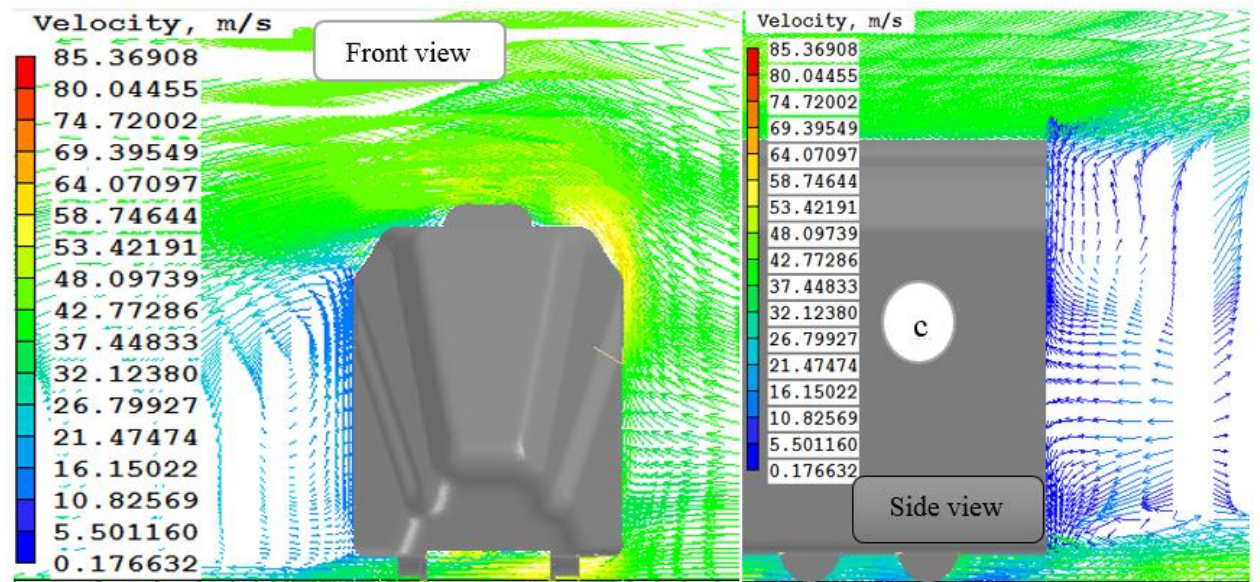
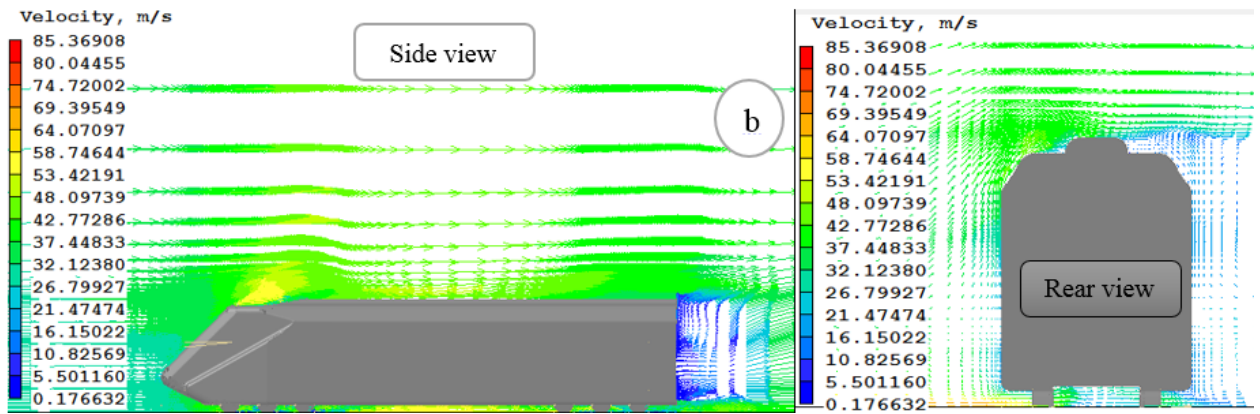


Figure 55: Pressure distribution on Regional Passenger train locomotives Optimized Model at 100km/h Running Speed under the influence of side wind.





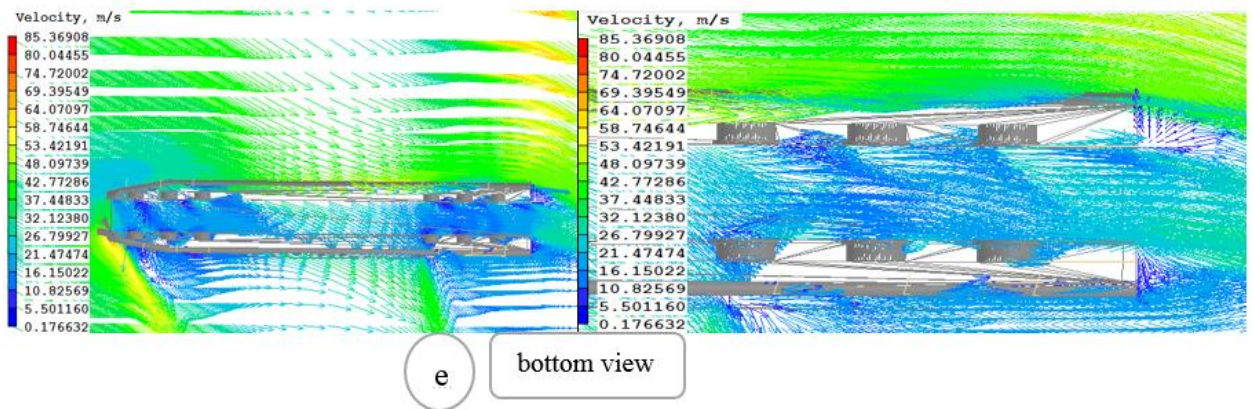
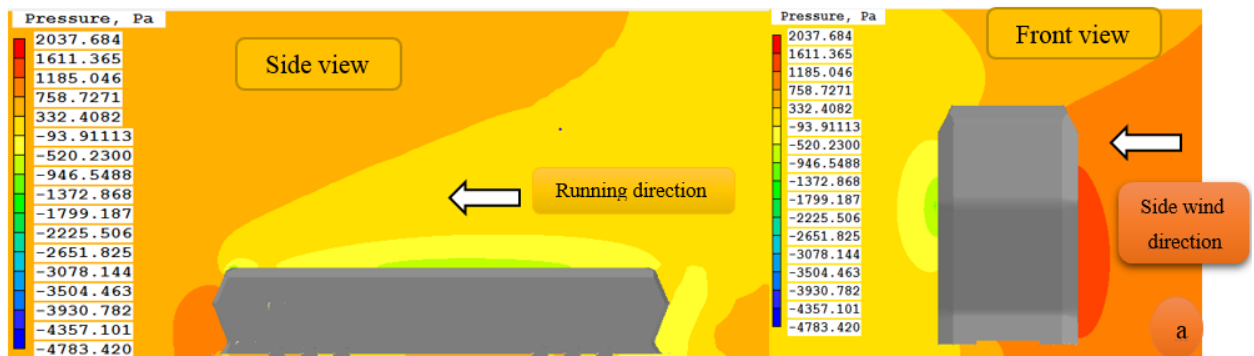
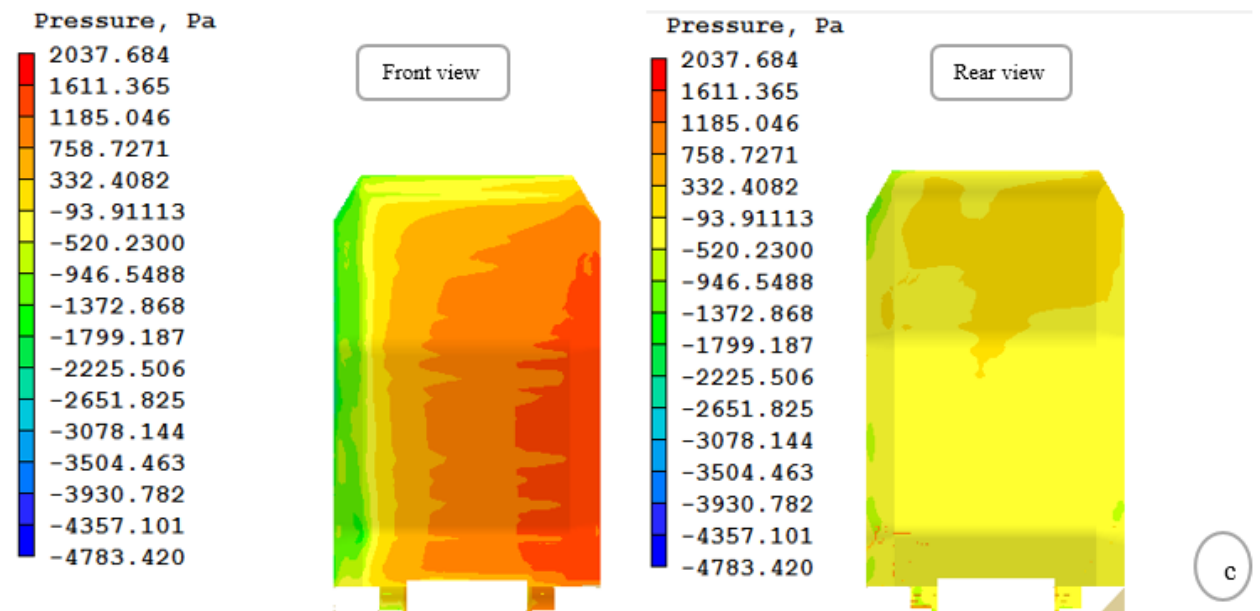
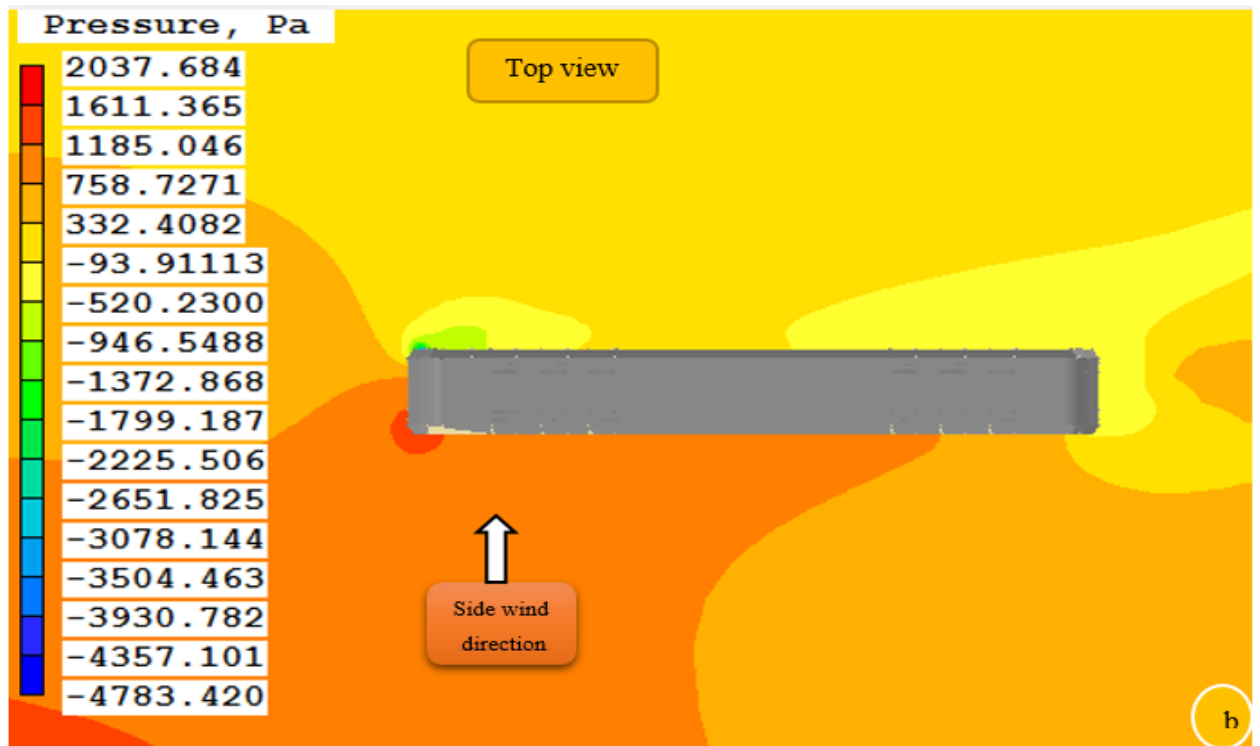


Figure 56: Velocity distribution on Regional Passenger train locomotives Optimized Model at 100km/h Running Speed under the influence of side wind.





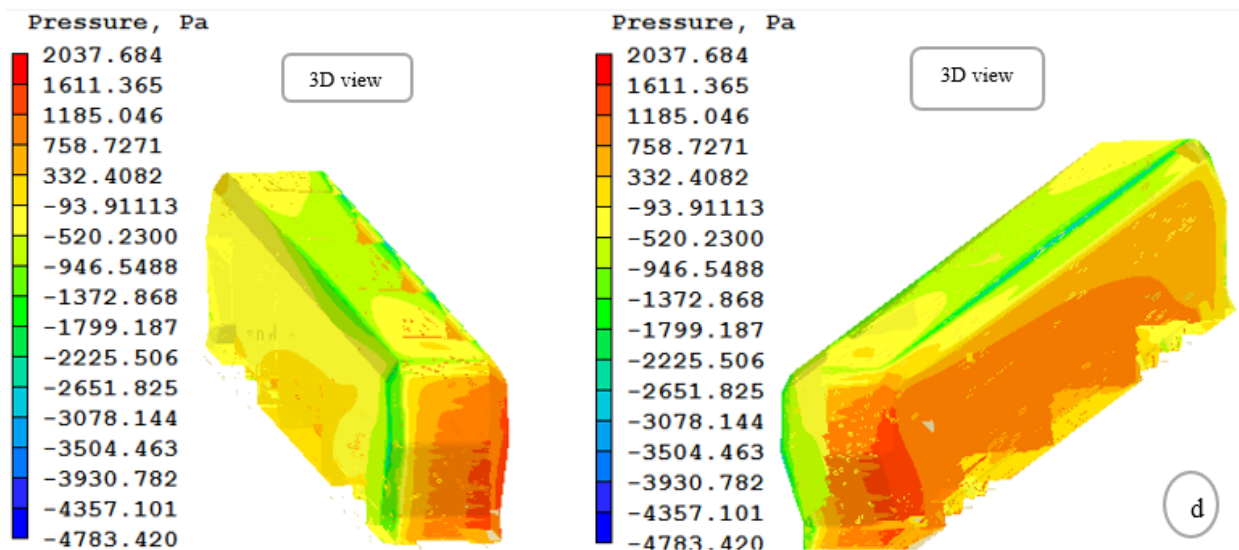
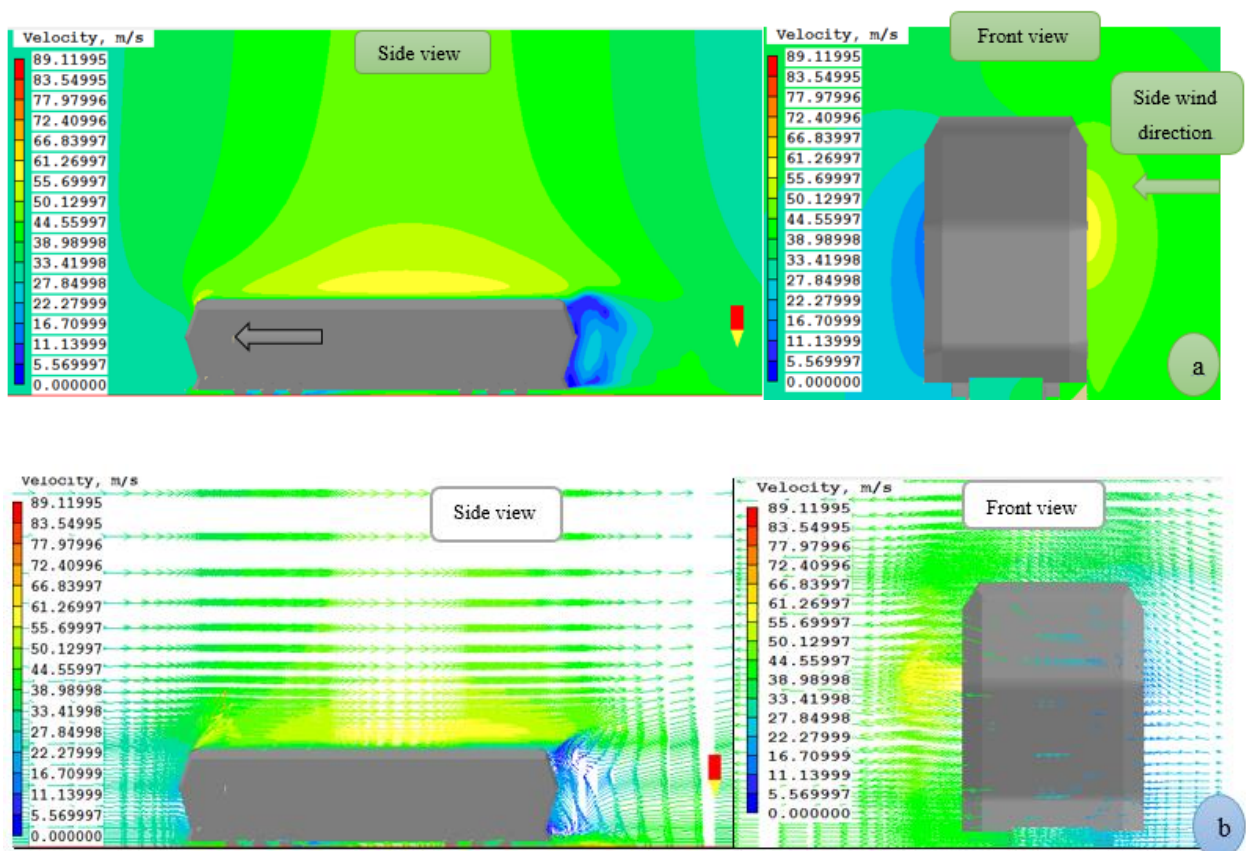
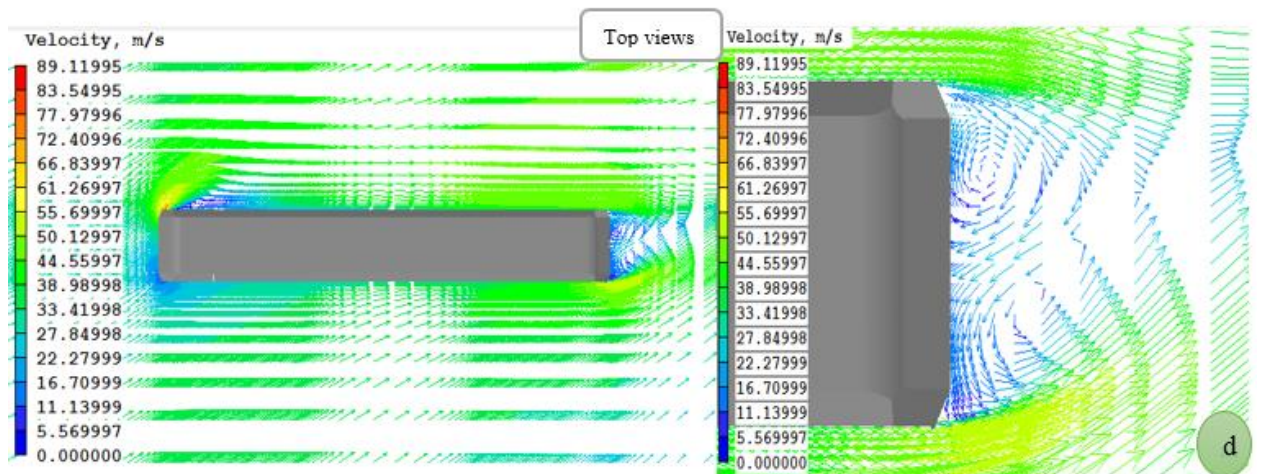
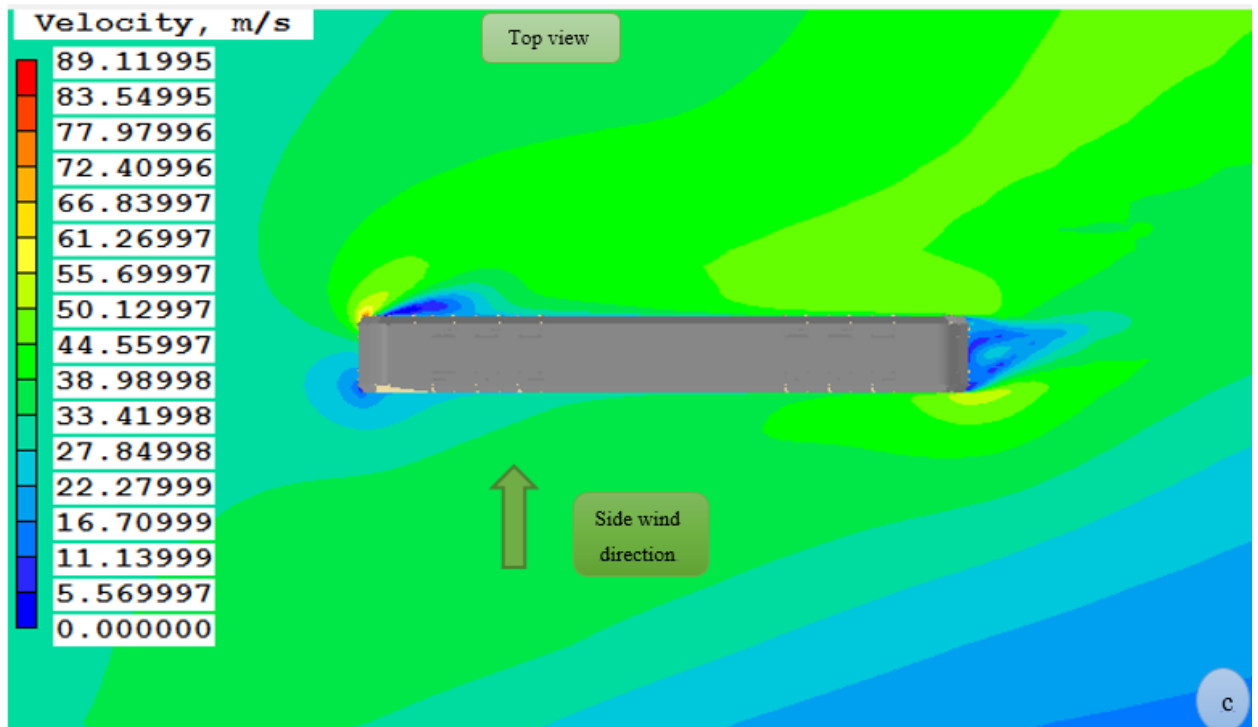


Figure 57: Pressure distribution on Regional Freight train locomotives Existing Model at 100km/h Running Speed under the influence of side wind.





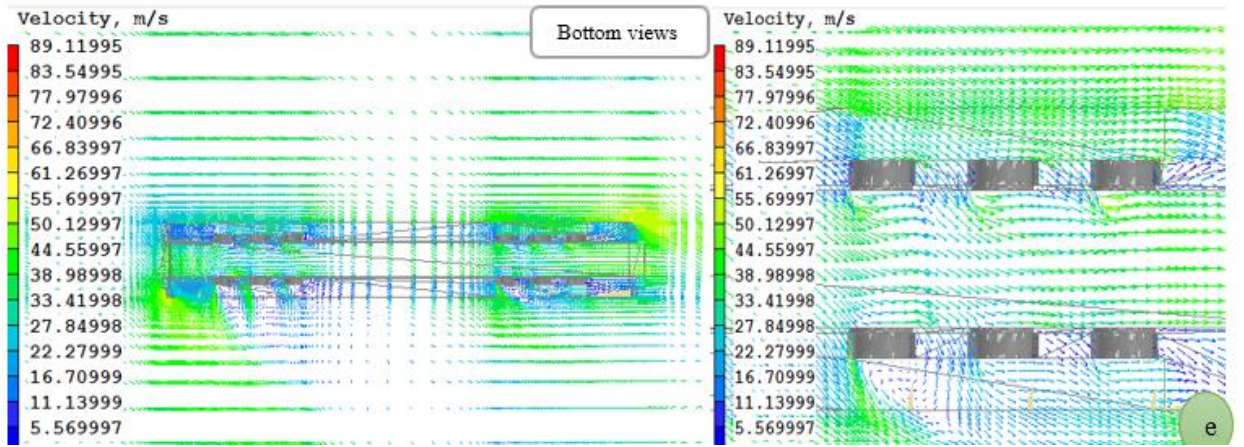
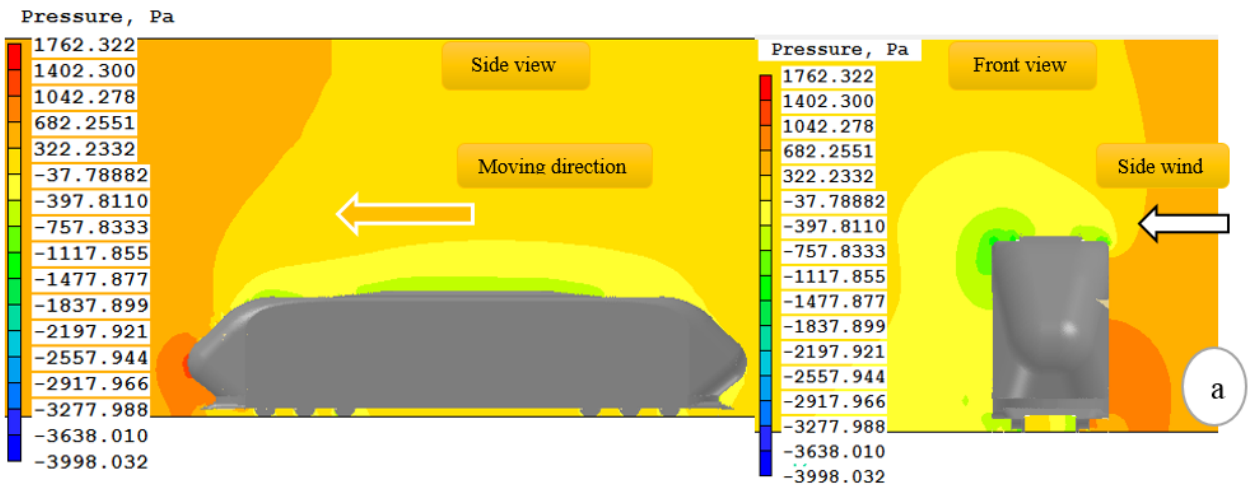
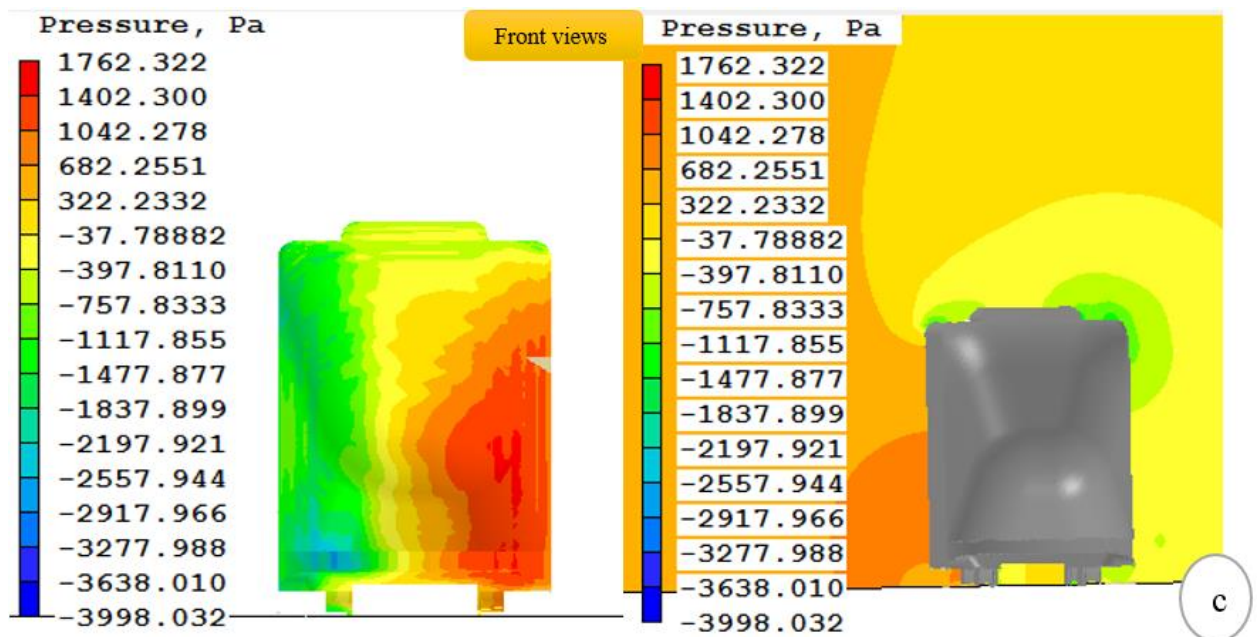
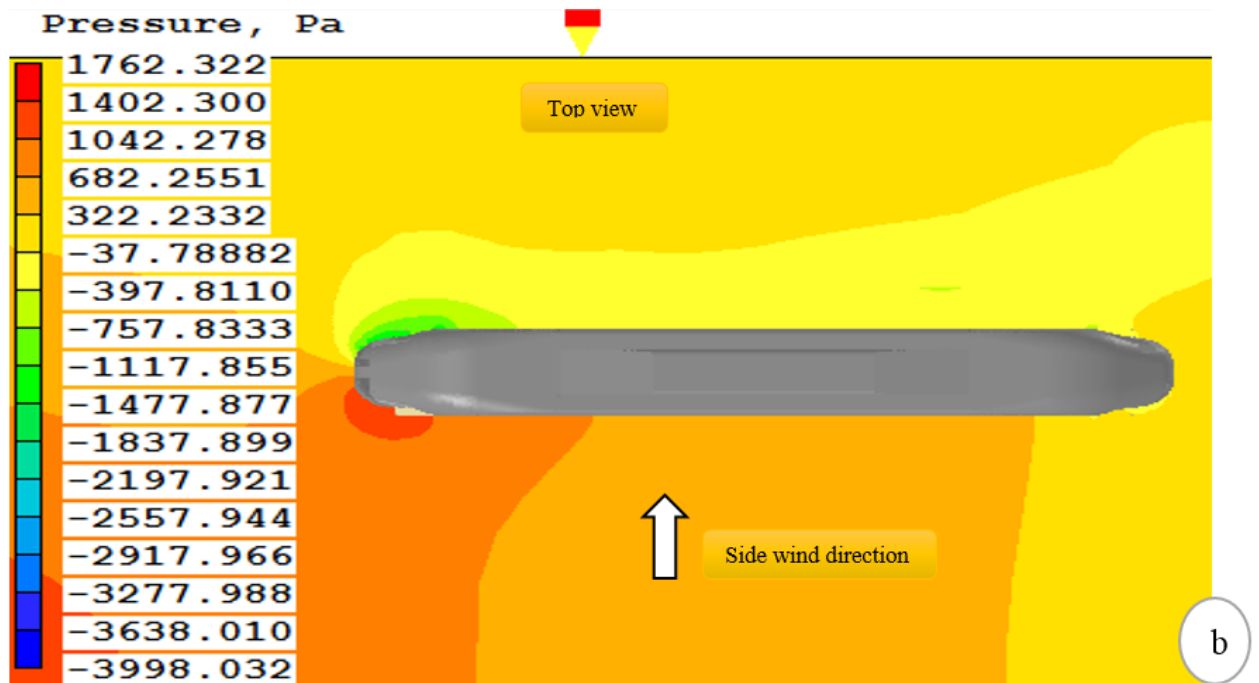


Figure 58: Velocity distribution on Regional Freight train locomotives Existing Model at 100km/h Running Speed under the influence of side wind.





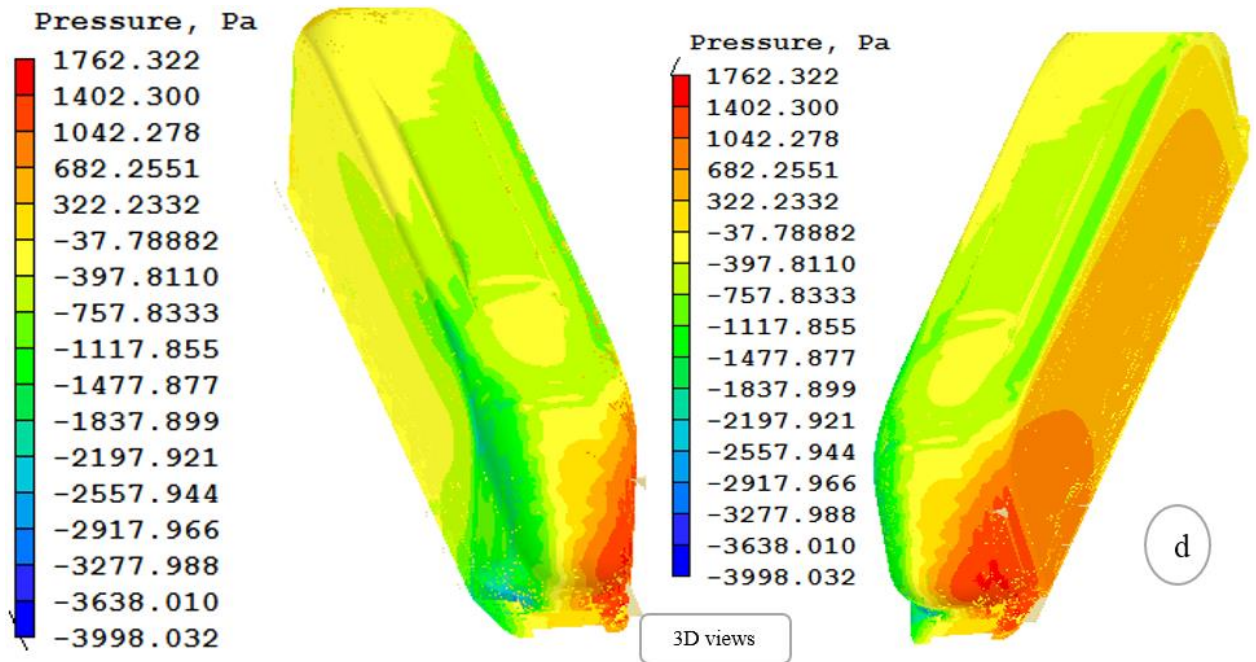
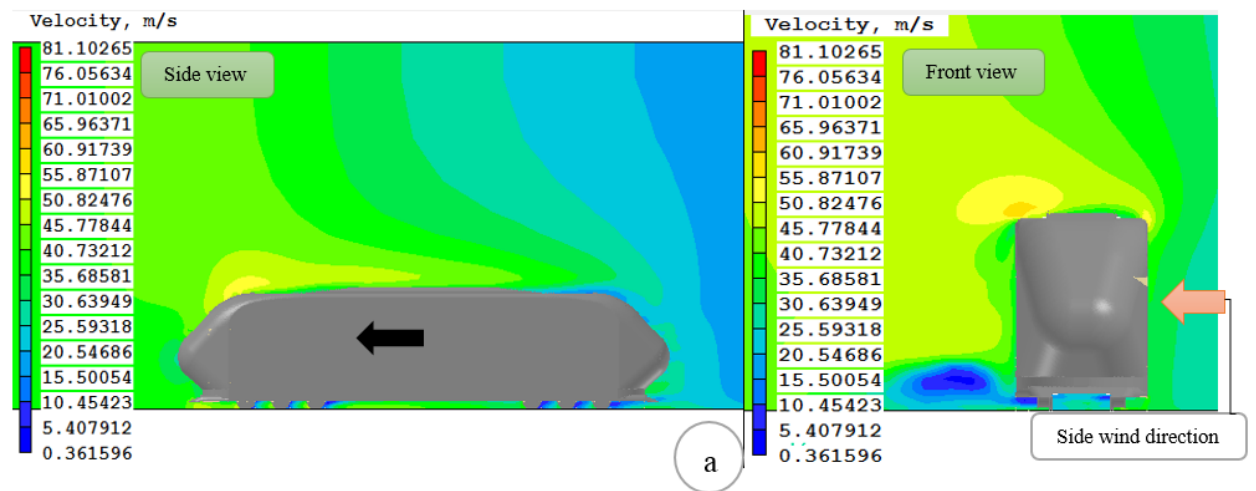


Figure 59: Pressure distribution on Regional Freight train locomotives Optimized Model at 100km/h Running Speed under the influence of side wind.



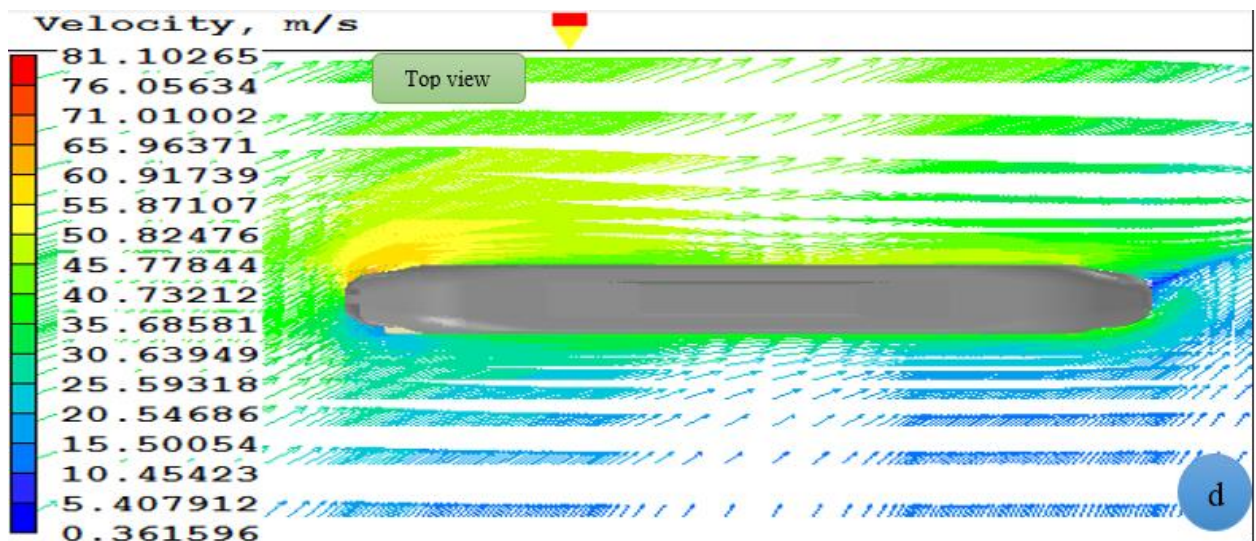
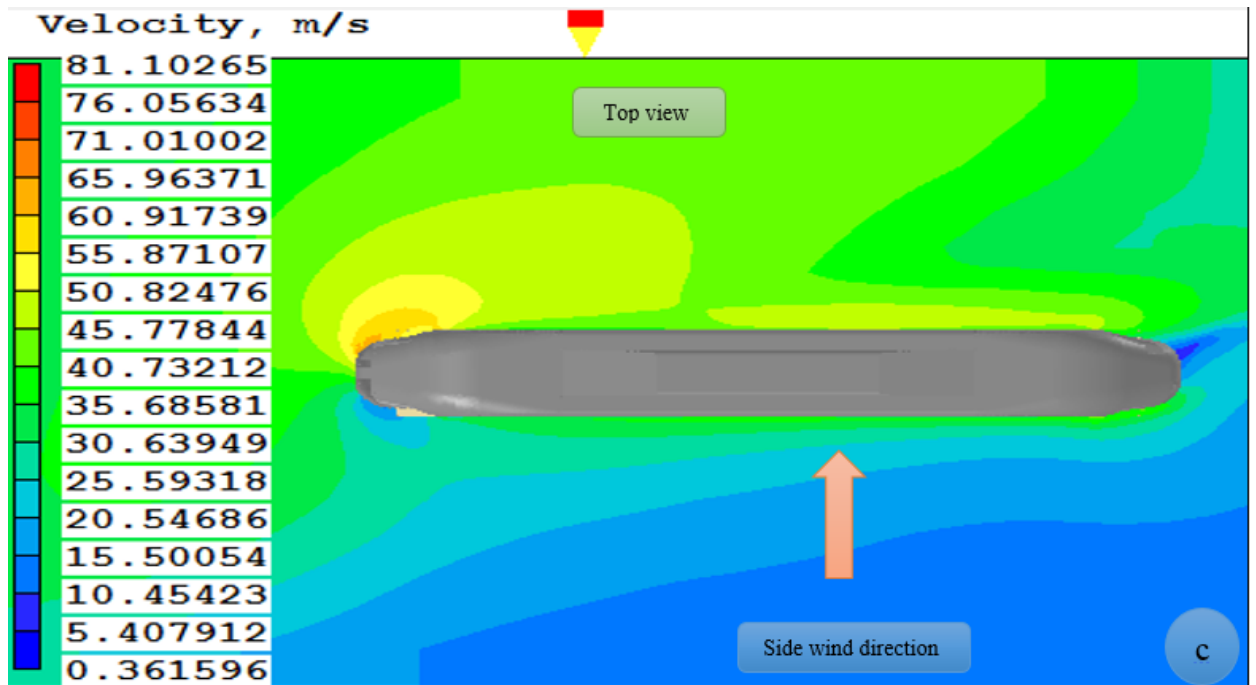
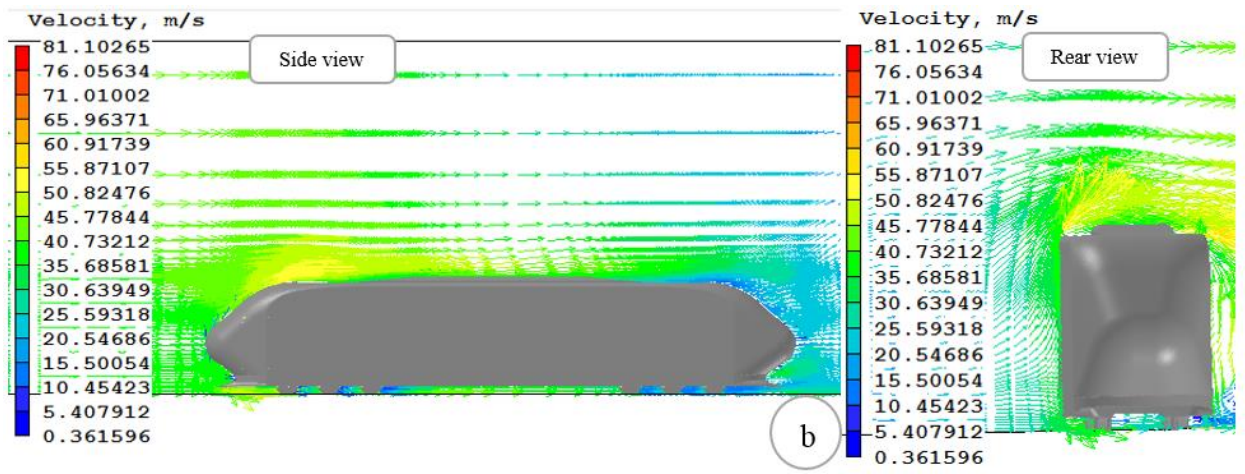
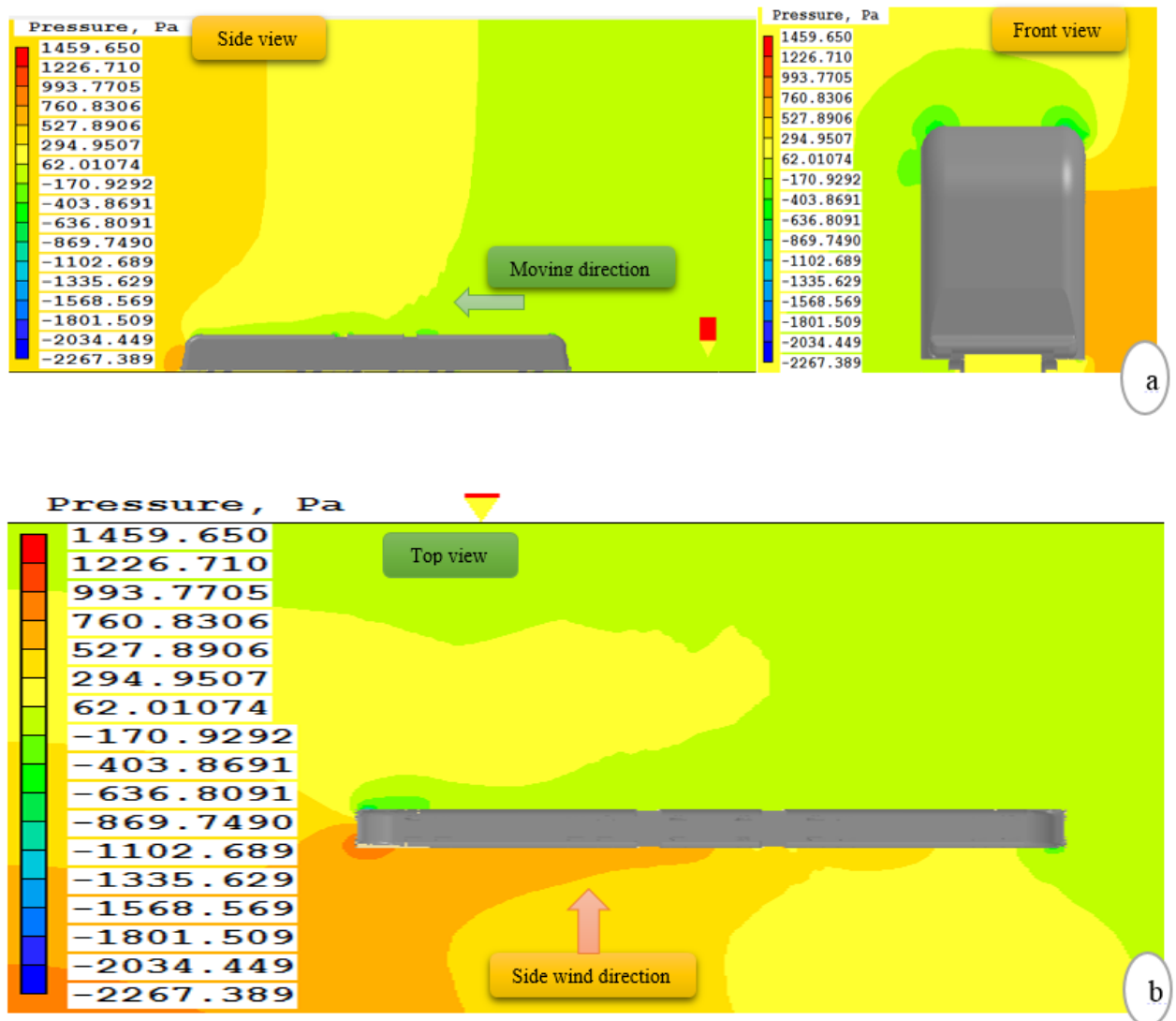


Figure 60: Velocity distribution on Regional Freight train locomotives Optimized Model at 100km/h Running Speed under the influence of side wind.



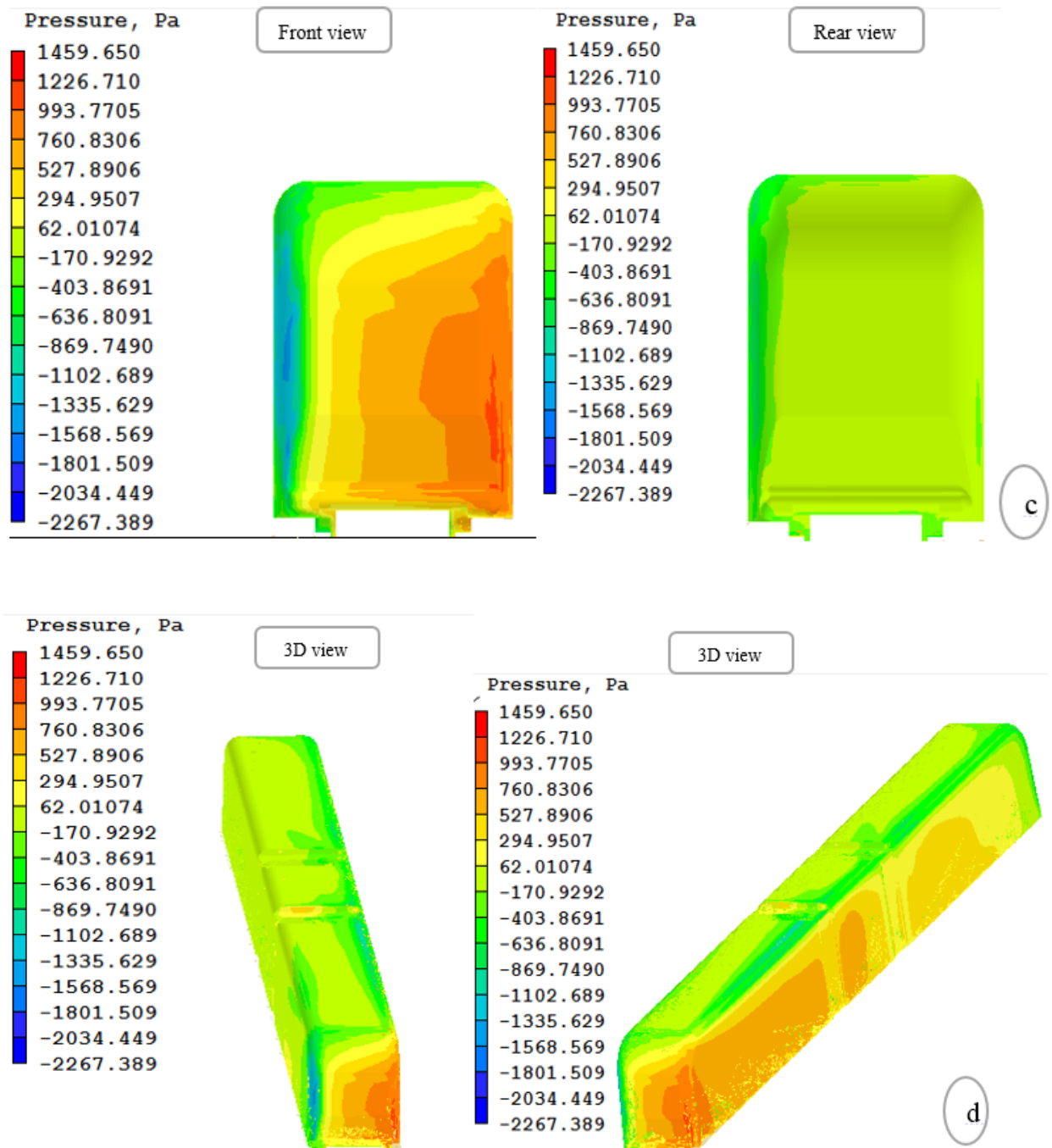
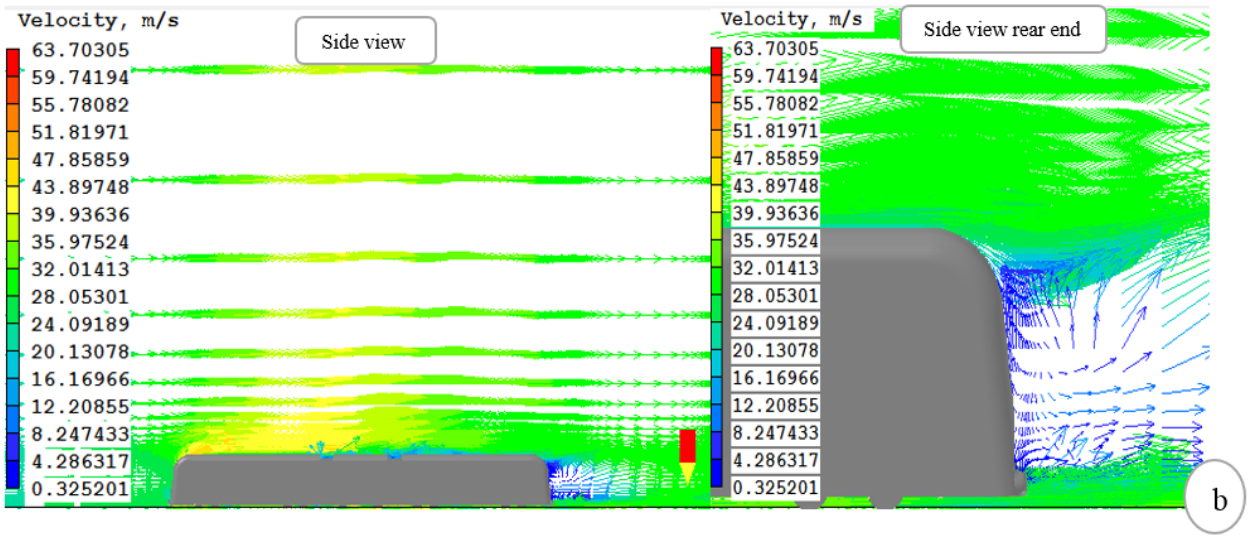
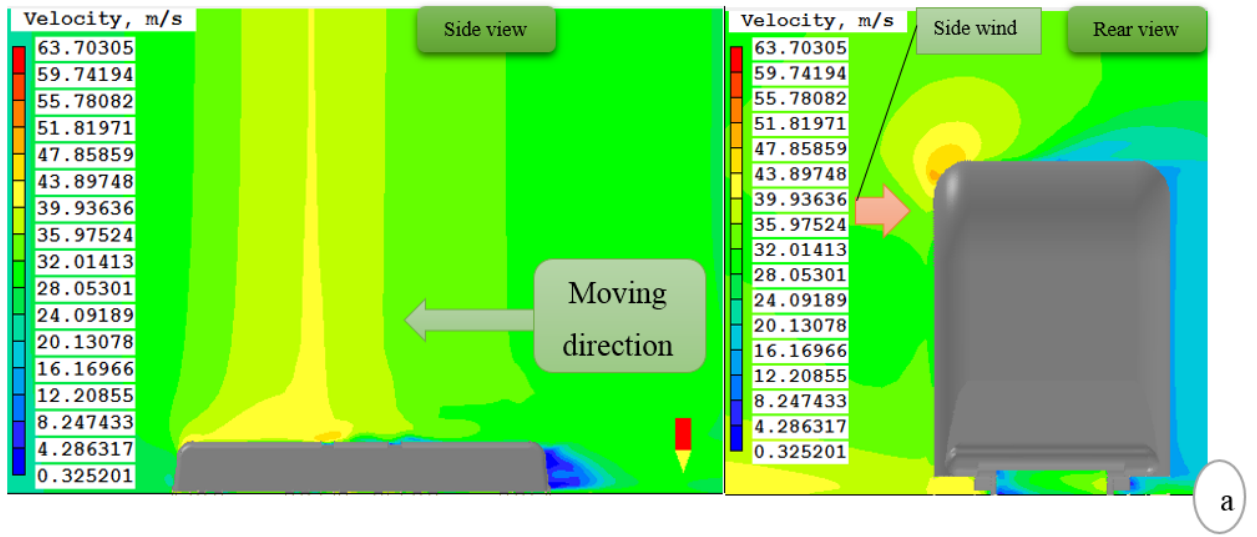
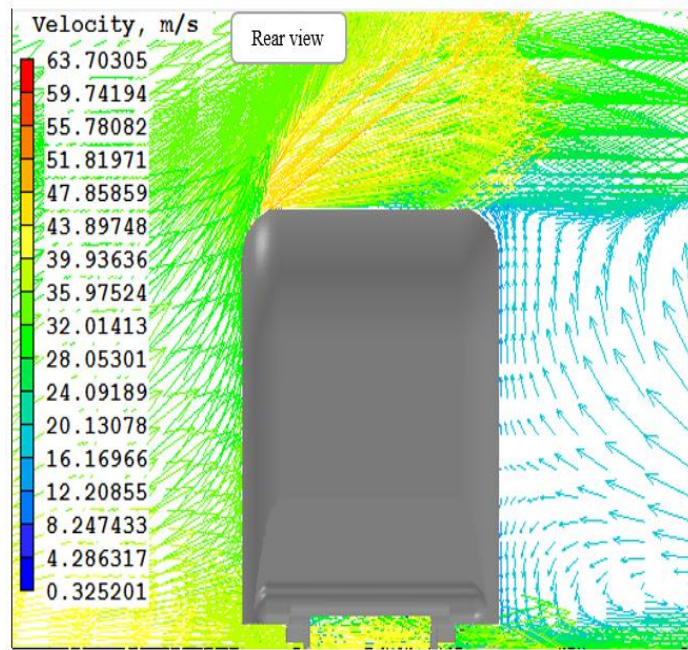
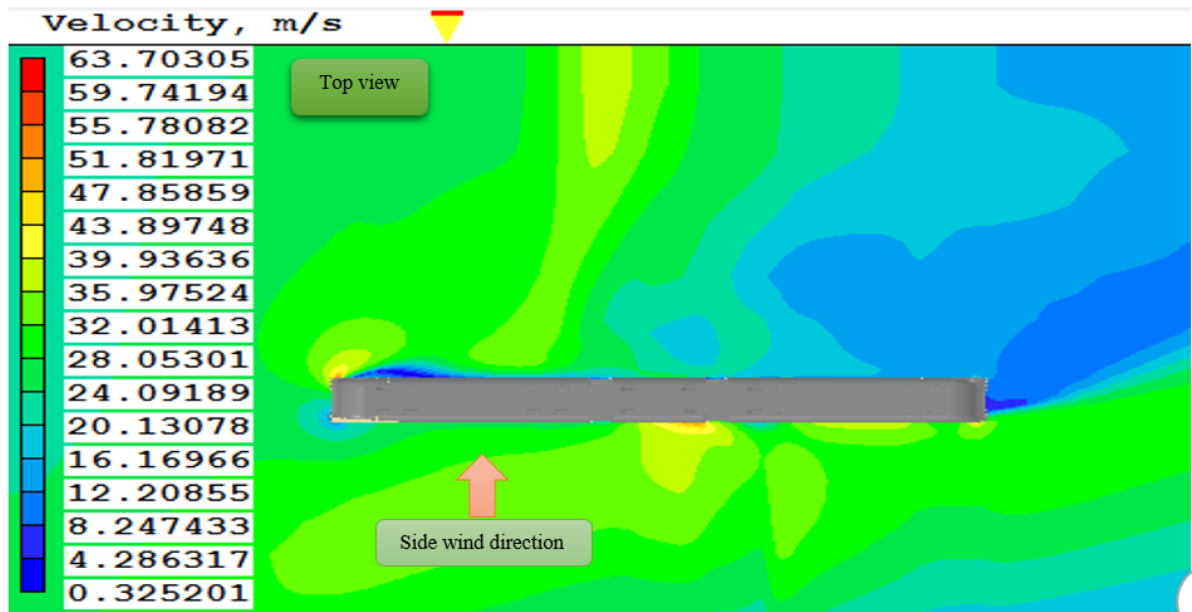


Figure 61: Pressure distribution on Light Railway train Existing Model at 80 km/h Running Speed under the influence of side wind.





c



d

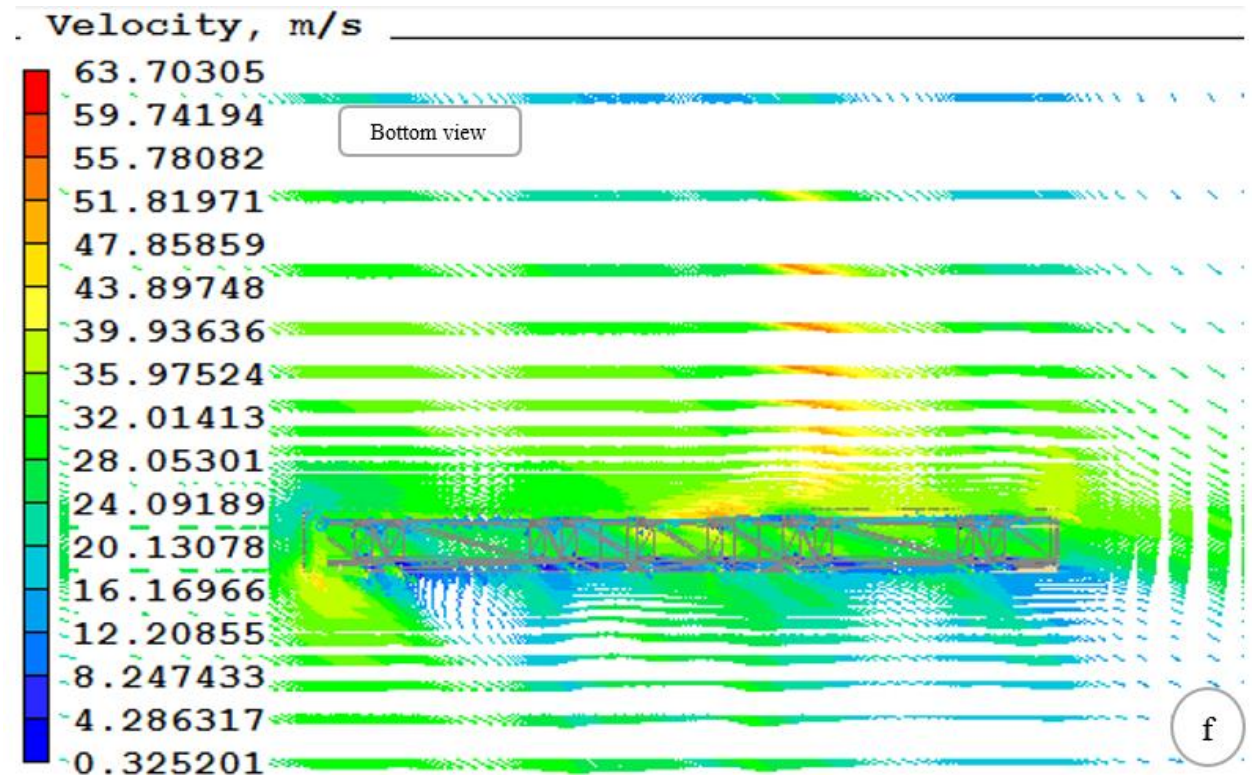
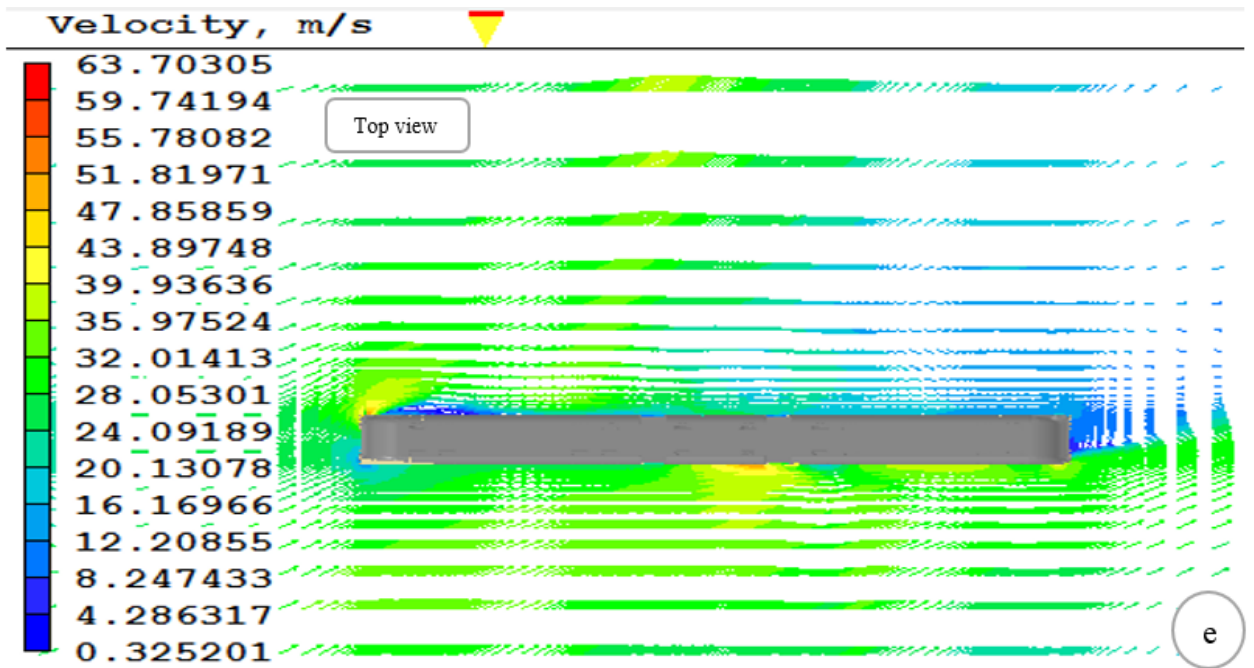
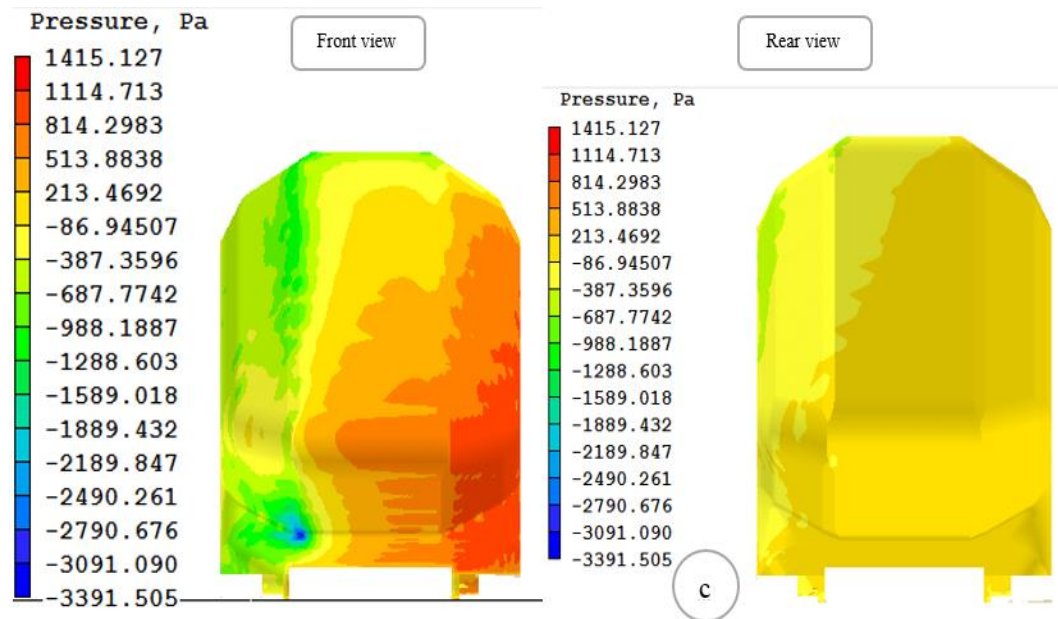
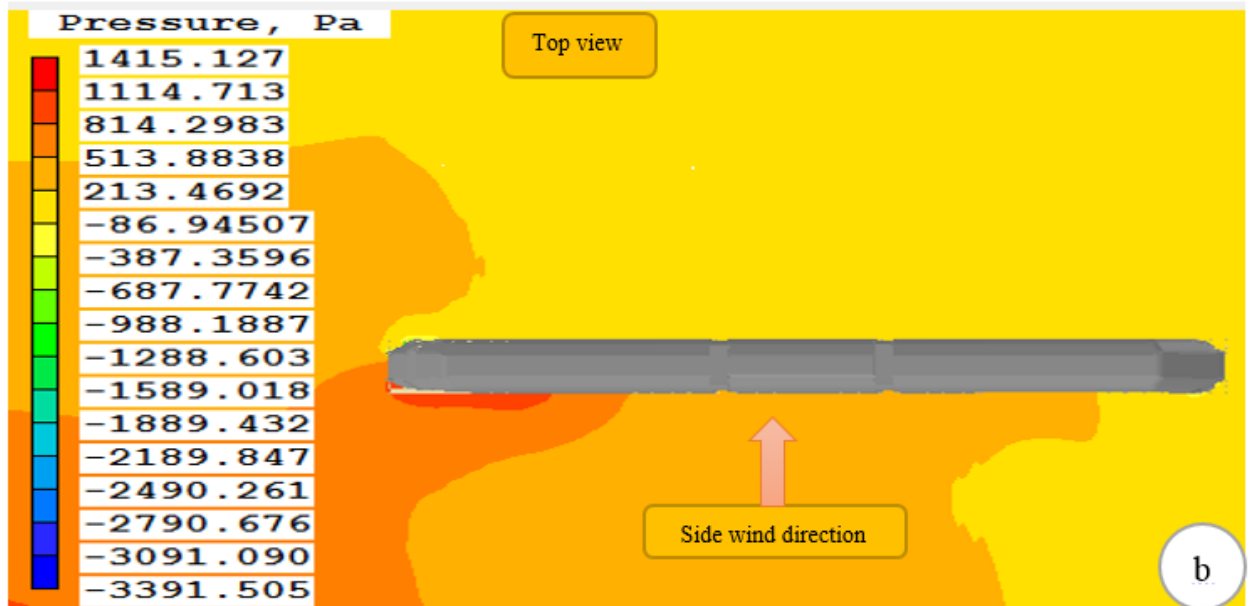
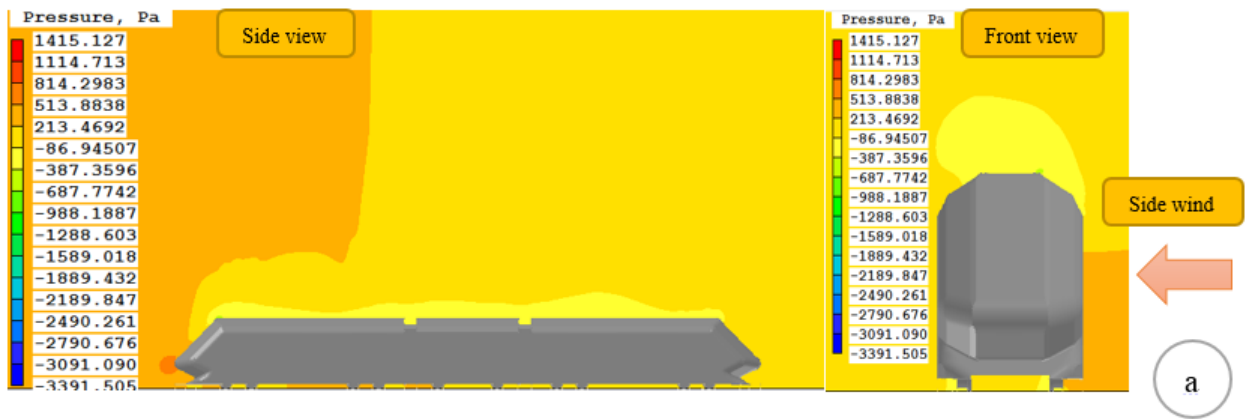


Figure 62: Velocity distribution on Light Railway Transit train Existing Model at 80 km/h Running Speed under the influence of side wind.



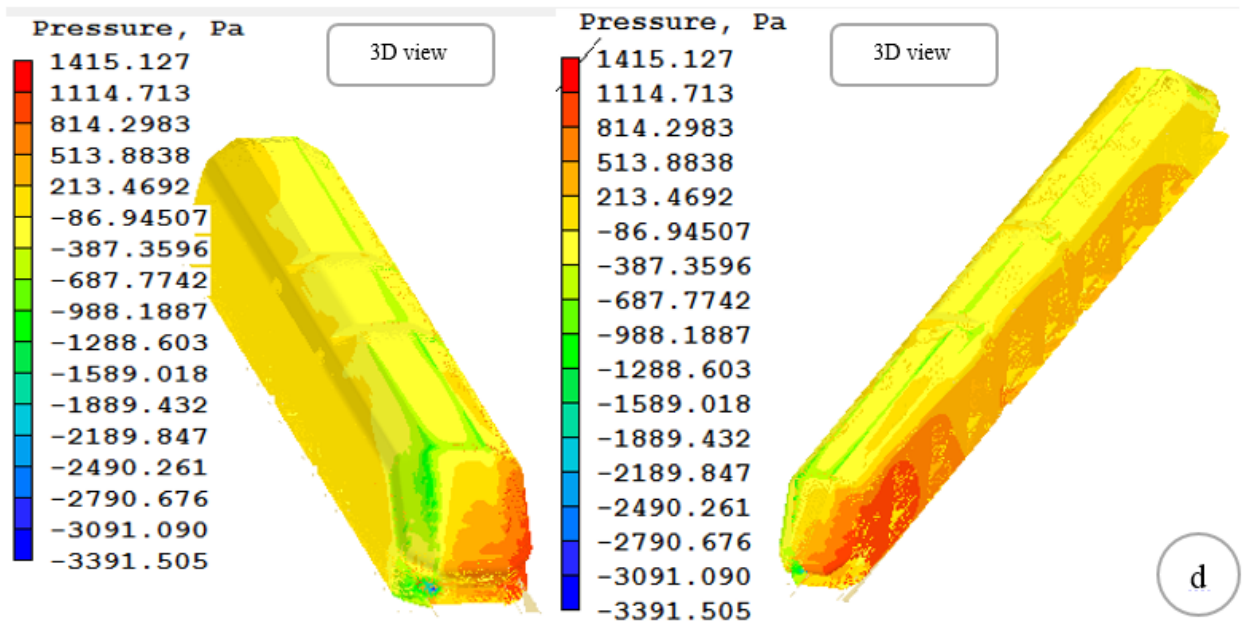
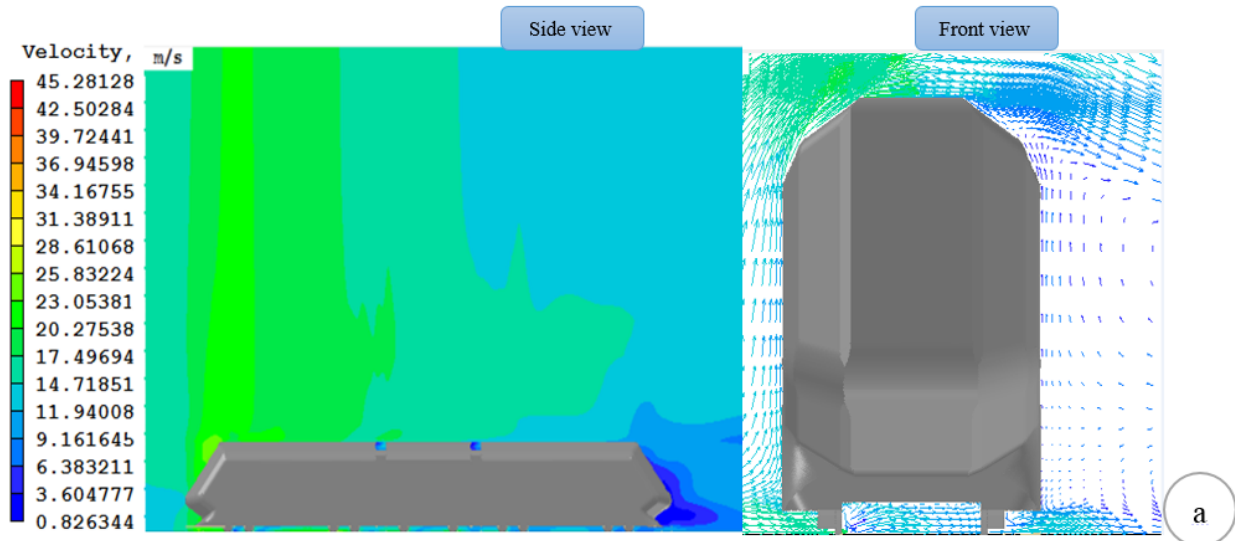
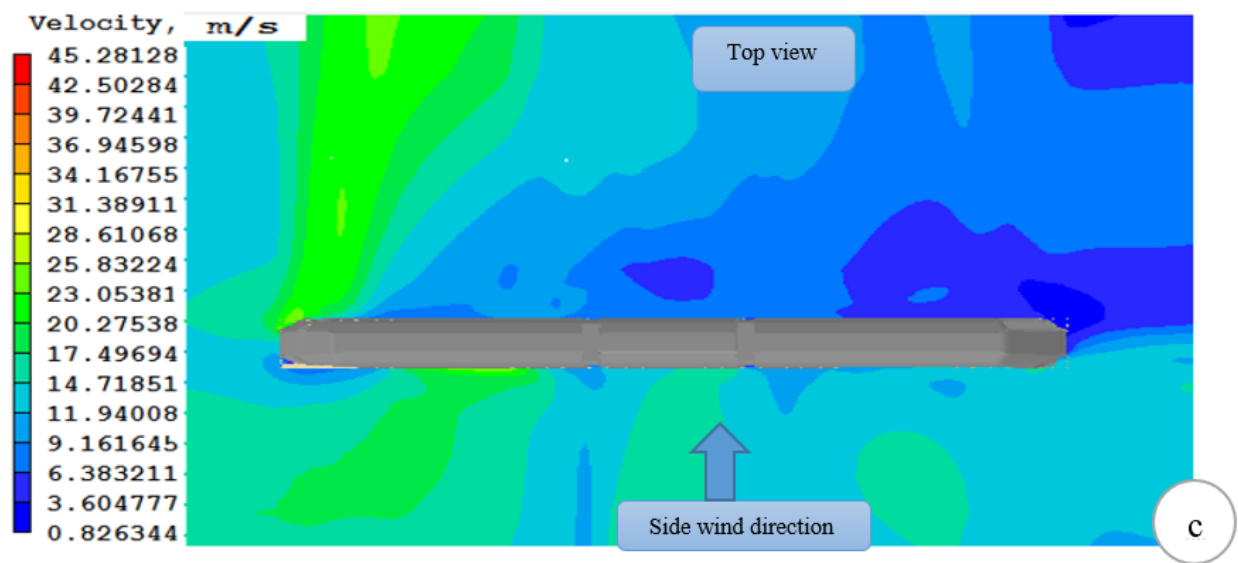
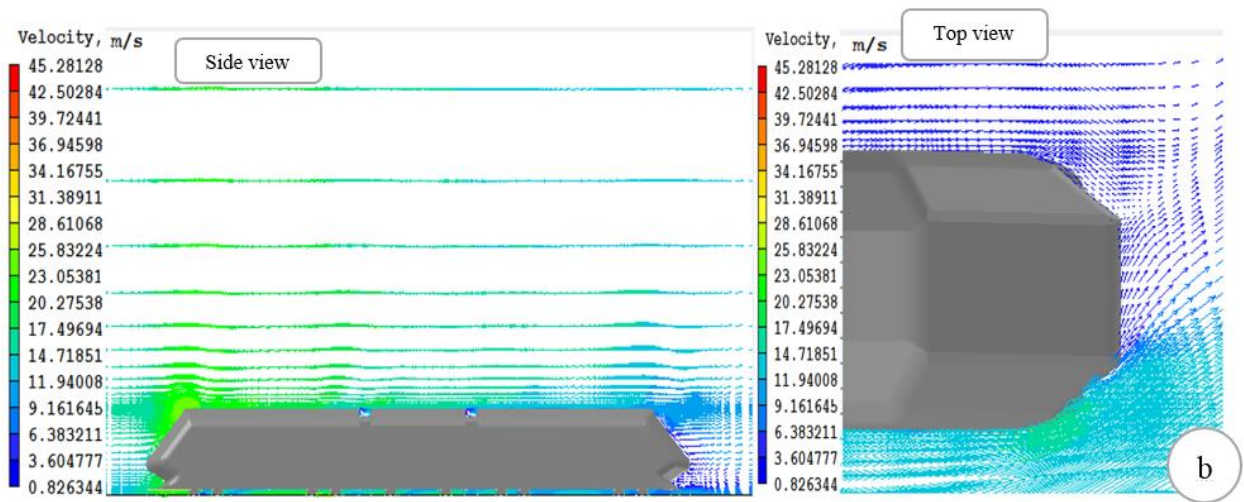


Figure 63: Pressure distribution on Light Railway train Optimized Model at 80 km/h Running Speed under the influence of side wind.





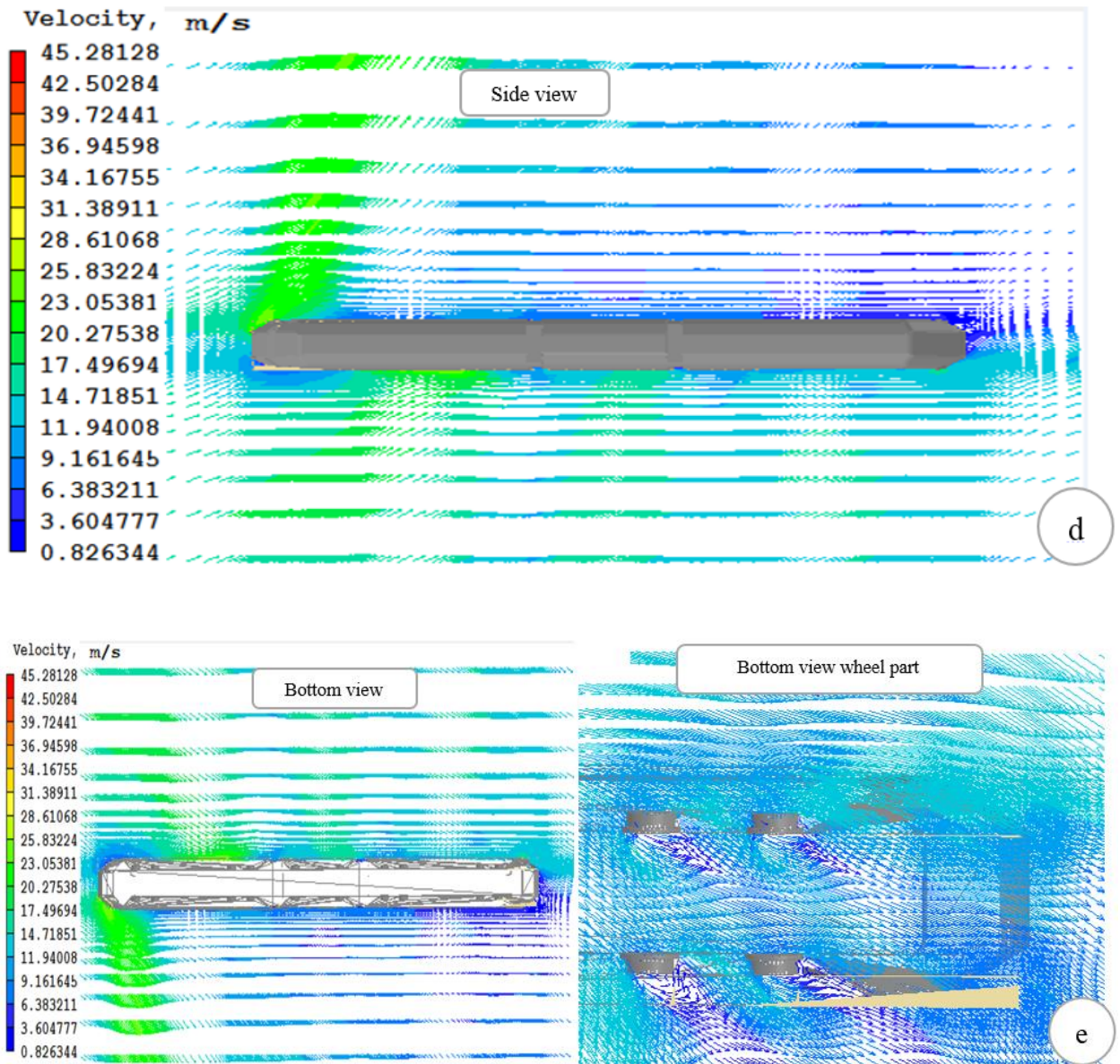


Figure 64: Velocity distribution on Light Railway Transit train Optimized Model at 80 km/h Running Speed under the influence of side wind.

4.2 Discussions

Firstly, the pressure distribution results as shown in Figures 53 and 55 the existing and optimized regional passenger train locomotives respectively indicated that the pressure effecting load distribution has significant difference due to body optimized particularly the front part of train locomotives. As the Figures 53 shows 2286.157 Pa maximum pressure load on baseline locomotive nose part reduced to 1819.239 Pa optimized locomotive shown in Figures 55 results

due to lowering the nose point of height to penetrate atmospheric head wind and cross-wind easily that helps the optimized train locomotive has drag reduced. In the other hand, the velocity distribution as shown in Figures 54 and 56 the existing and optimized models respectively indicated the flow of air on optimized train locomotive has relatively smooth at front and side part the body. As the Figures 54 shows 93.42265m/s maximum velocity profile on baseline locomotive top part reduced to 85.36908m/s on optimized locomotive shown in Figures 56 results due to smooth flow of air on front and side part of locomotive body reduction of vortex is shown on leeward side of optimized locomotive from Figure 56(a) than 54(c). Which indicate great power reduction at this speed.

Secondly, from regional freight train locomotive simulation result as shown in the Figure 57 and 59 the baseline and modified models have the pressure distribution on front and side part of train locomotives slightly different so that, the center of pressure position is shift. As the Figures 57 shows 2037.684 Pa maximum pressure load on baseline locomotive front area reduced to 1762.322 Pa optimized locomotive shown in Figures 59 results due to lowering the nose center height point with round surface to penetrate atmospheric head wind and cross-wind easily that helps the optimized train locomotive has drag reduced more. The velocity distribution also slightly decreasing as shown in the Figure 58 and 60 particularly rear part and leeward side of existing and optimized train locomotive models respectively. As the Figures 58 shows 89.11995m/s maximum velocity profile on baseline locomotive top part reduced to 81.10265m/s on optimized locomotive shown in Figures 60 results due to smooth flow of air on front and side part of locomotive body reduction of vortex is shown on leeward side and rear end part of optimized locomotive from Figure 58 (a and b) than 60 (a and c). Which shown great power reduction at this speed.

Thirdly, the pressure distribution between the existing and optimized model Light Railway Transit from Figure 61 and 63 respectively has slightly difference on the front and wind ward part of the train body. As the Figures 61 shows 1459.650 Pa maximum pressure load on baseline train front wind ward area reduced to 1415.1270 Pa optimized train shown in Figures 62 results due to lowering the nose center height point angle with side tapering modification with round surface to penetrate atmospheric head wind and cross-wind easily that helps the optimized train has drag reduced slightly relative to high-speed regional train locomotives. The velocity vector distribution difference is visible especially at front part, top corner of windward side, vortex formation on rear part and side of middle part of the vehicle on the direction of windward. As the Figures 62 shows 63.70305m/s maximum velocity profile on baseline model top part reduced to 45.28128m/s on

optimized model shown in Figures 64 results due to smooth flow of air on front and side part of body reduction of vortex is shown on leeward side and rear end part of optimized model surface from Figure 64 (a and b) than 62 (b and c). Which brought slightly power reduction at this speed.

From the result of pressure drag and velocity profile flowing effects on the train models as previous indicated in qualitatively proved by numerical simulation result quantitatively as shown on Table 12, 13 and 14 aerodynamic drag reduction at their maximum operation speed of model types. For regional passenger train locomotive baseline and modified models the calculation of aerodynamic force coefficients CFD numerical simulation based on optimization grid size as show in the Figure 38 and with six different speed under cross-wind condition. The result values is below at Table 12 and the aerodynamic drag, lift and side force coefficient values drawn with respect of train models speed as show in the Figure 65, 66 and 67. Which aerodynamic coefficients decreased with respect of their velocity at maximum of 23.01% drag reduction compare to baseline model.

Table 12 : Regional passenger locomotive train models drag, side and lift coefficient values at varying velocity.

Drag coefficient (C_D) at various speed at 12 m/s cross-wind speed					Lift coefficient (C_L)		Side coefficient (C_s)	
Speed in km/h	Speed in m/s	Existing Model	New Model	reduction of C_D in %	Existing Model	New Model	Existing Model	New Model
60	16.67	0.864	0.810	6.25%	1.762	1.426	5.1308	4.725
80	22.22	0.962	0.871	9.46%	2.289	1.932	6.146	5.647
100	27.78	1.087	0.938	13.71%	3.161	2.507	7.523	6.321
120	33.33	1.255	1.037	17.37%	4.212	3.384	9.484	8.109
140	38.89	1.348	1.079	19.96%	5.221	4.317	11.707	10.230
160	45.45	1.560	1.201	23.01%	6.166	5.068	14.089	12.190

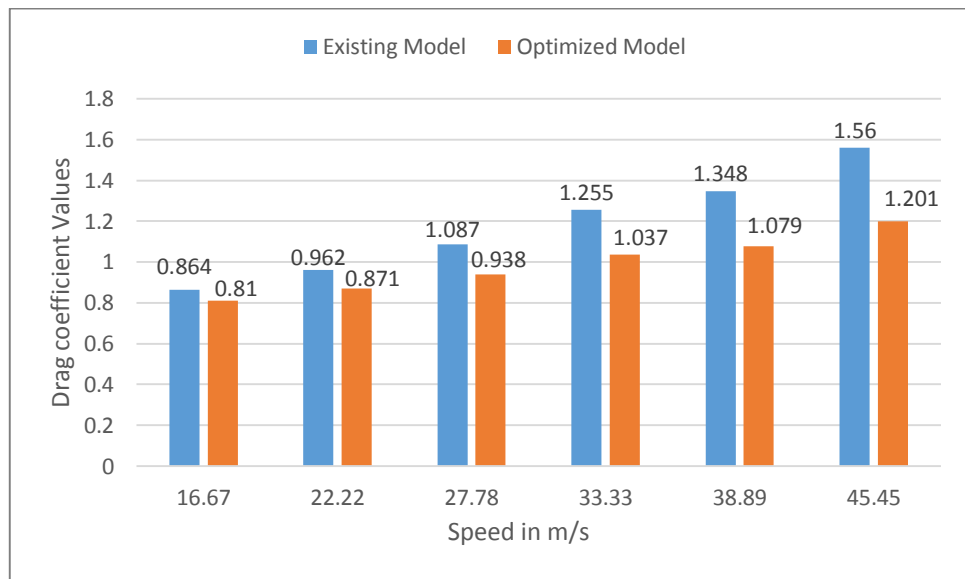
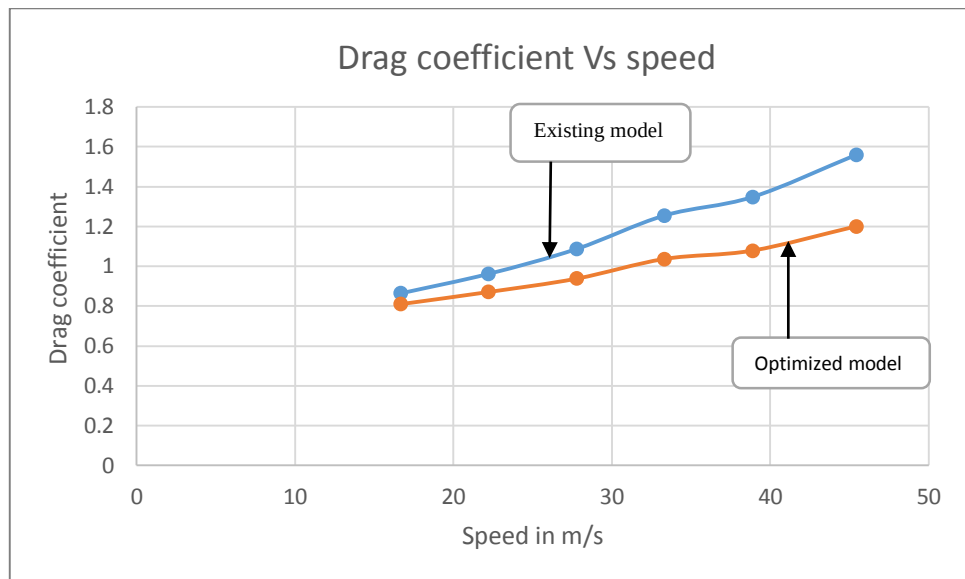


Figure 65: Aerodynamic drag coefficient with the speed of regional passenger train locomotive graphs.

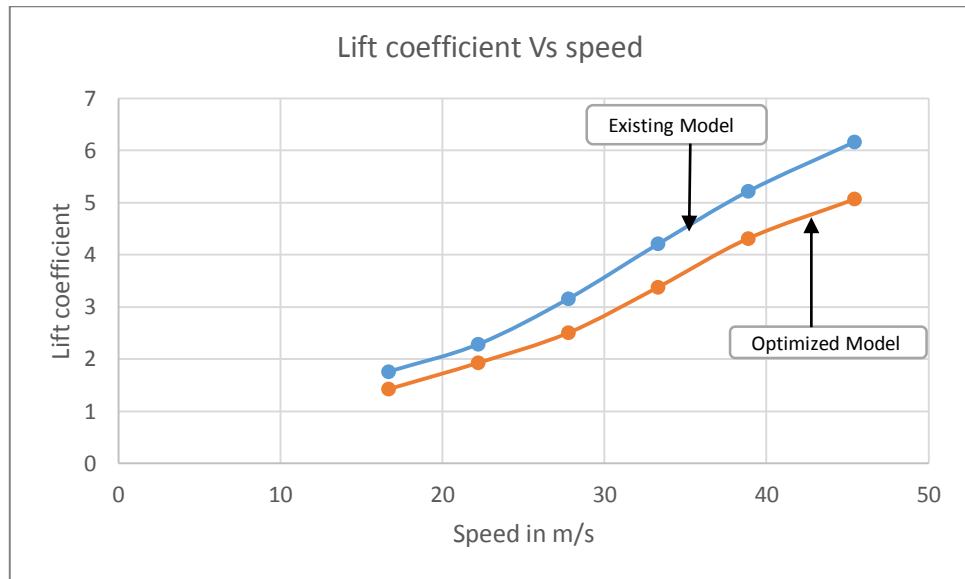


Figure 66: Aerodynamic Lift coefficient with the speed of regional passenger train locomotive graph.

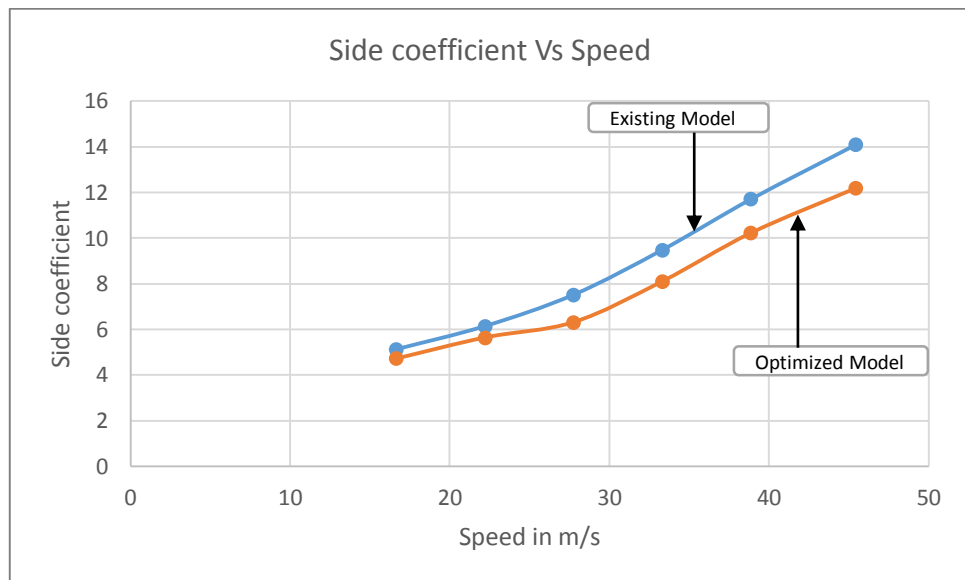


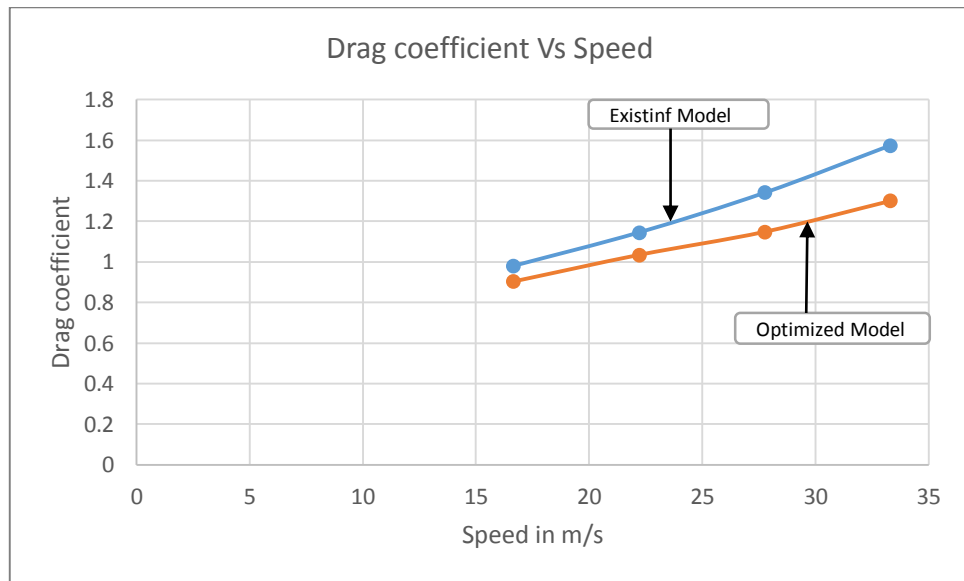
Figure 67: Aerodynamic Side coefficient with the speed of regional passenger train locomotive graph.

For regional freight train locomotive baseline and modified models the calculation of aerodynamic force coefficients in CFD numerical simulation based on optimization grid size as show in the Figure 40 and with four different speed under cross-wind condition. The result values is below at Table 13 and the aerodynamic drag, lift and side force coefficient values drawn with respect of

train models speed as show in the Figure 68, 69 and 70 has more significant drag reduction with related increasing of their speed value of 21.84% drag reduction at maximum speed 120kM/h under cross-wind condition.

Table 13: Regional Freight train locomotive models drag, side and lift coefficients both models using at varying velocity.

Drag coefficient (C_D) at various speed at 12 m/s cross-wind speed					Lift coefficient (C_L)		Side coefficient (C_S)	
Speed in km/h	Speed in m/s	Existing Model	New Model	reduction of C_D in %	Existing Model	New Model	Existing Model	New Model
60	16.67	0.981	0.904	4.79%	1.972	1.424	5.625	5.201
80	22.22	1.146	1.035	9.68%	3.014	2.308	6.237	5.628
100	27.78	1.342	1.149	16.62%	4.432	3.102	7.025	6.134
120	33.33	1.575	1.301	21.84%	5.893	4.371	9.257	7.209



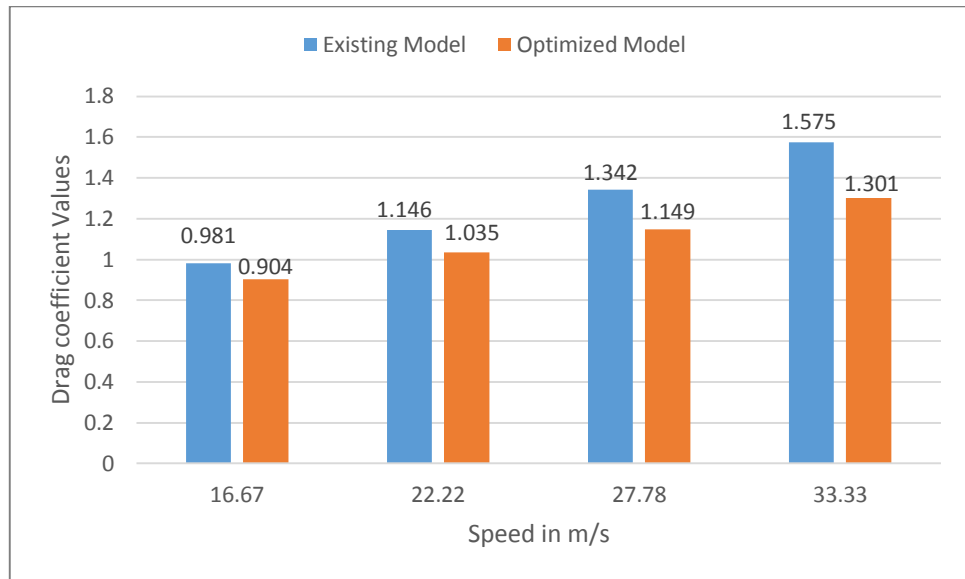


Figure 68: Aerodynamic Drag coefficient with the speed of regional Freight train locomotive graphs.

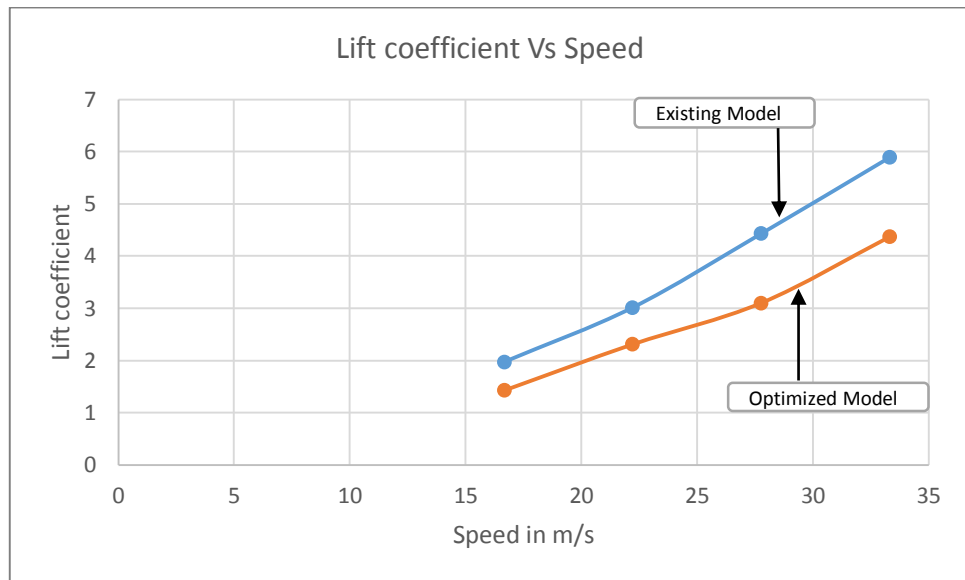


Figure 69: Aerodynamic Lift coefficient with the speed of regional Freight train locomotive graph.

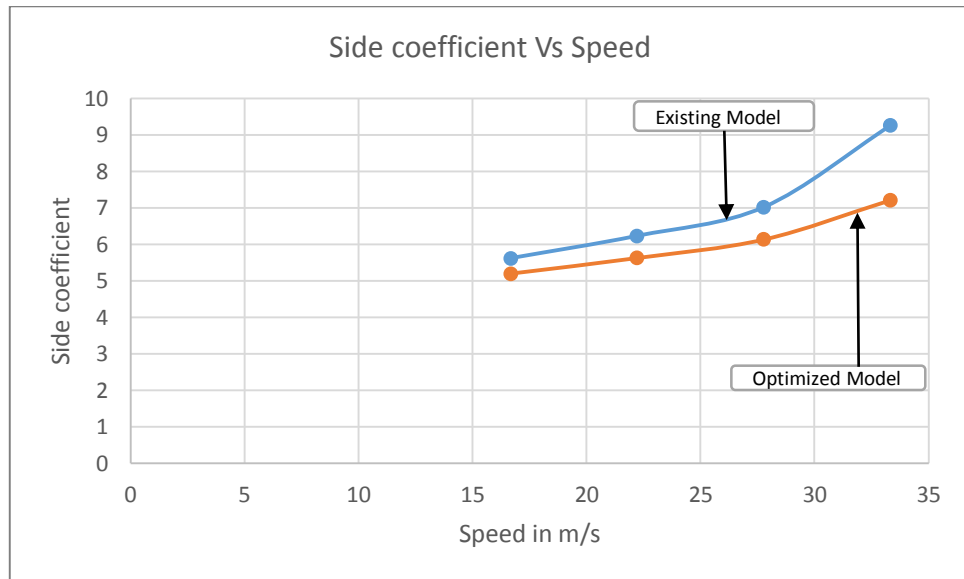


Figure 70: Aerodynamic Side coefficient with the speed of regional Freight train locomotive graph.

For Light Railway Transit train baseline and modified models the calculation of aerodynamic force coefficients in CFD numerical simulation based on optimization grid size as show in the Figure 43 and with five different speed under cross-wind condition. The result values is below at Table 14 and the aerodynamic drag, lift and side force coefficient values drawn with respect of train models speed as show in the Figure 71, 72 and 73 with in 80km/h speed in under 12m/s cross-wind has shown slightly reduction of aerodynamic drag resistance.

Table 14: Light Railway Transit both models drag, side and lift coefficient using at varying velocity

Drag coefficient (C_D) at various speed at 12 m/s cross-wind speed					Lift coefficient C_L		Side coefficient C_s	
Speed in km/h	Speed in m/s	Existing Model	New Model	reduction of C_D in %	Existing Model	New Model	Existing Model	New Model
40	11.11	0.872	0.861	1.26%	2.062	1.762	6.501	6.344
50	13.89	0.897	0.880	1.34%	2.270	1.954	6.541	6.221
60	16.67	0.932	0.902	3.22%	2.814	2.301	7.011	4.928
70	19.44	0.991	0.924	6.70%	3.206	2.530	7.134	6.309
80	22.22	1.032	0.956	7.36%	4.108	3.181	8.271	7.036

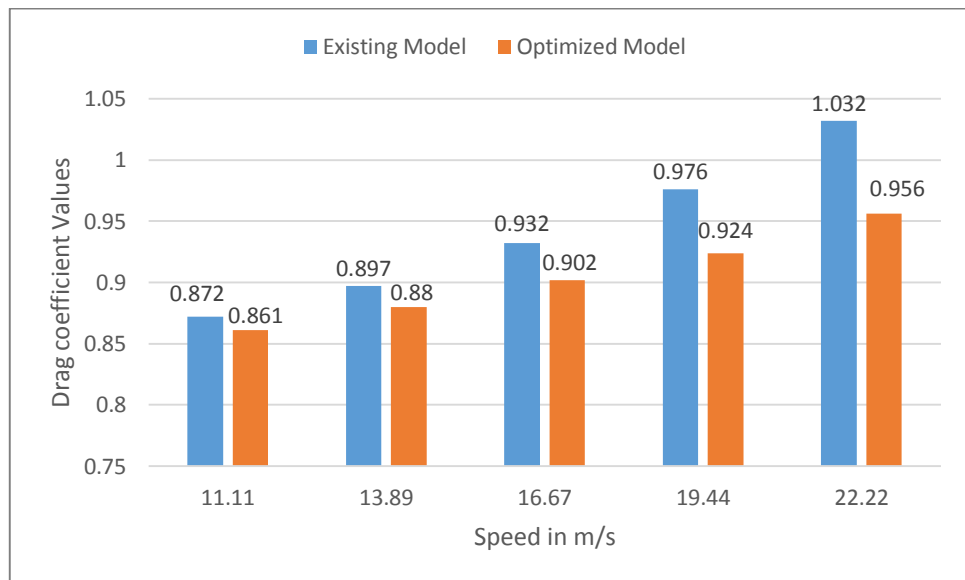
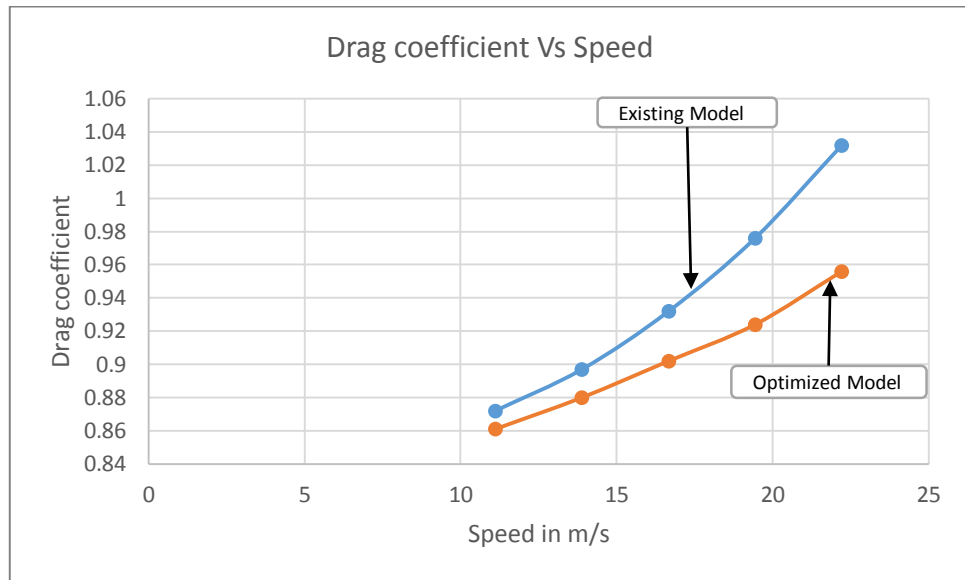


Figure 71: Aerodynamic Drag coefficient with the speed of Light Railway train graphs.

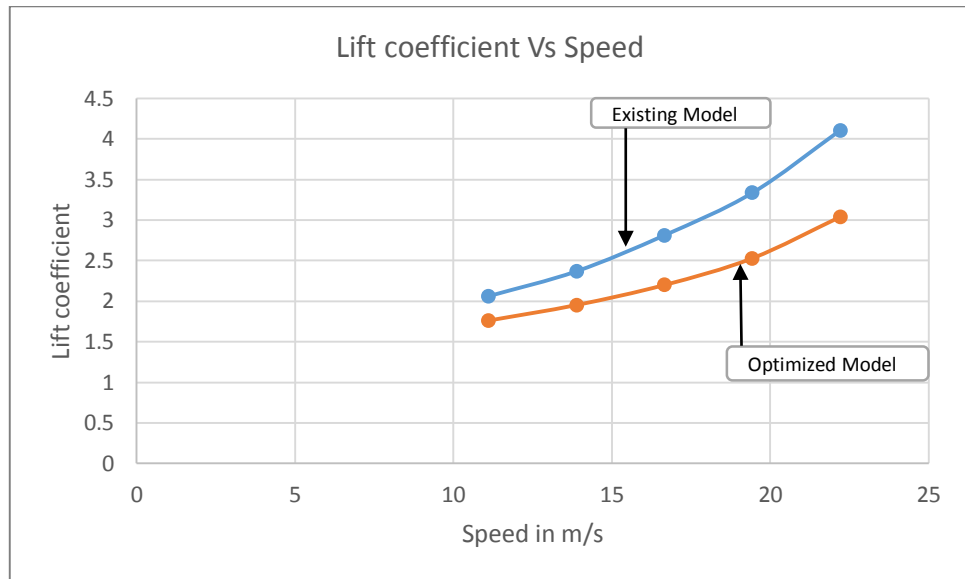


Figure 72: Aerodynamic Lift coefficient with the speed of Light Railway train graph.

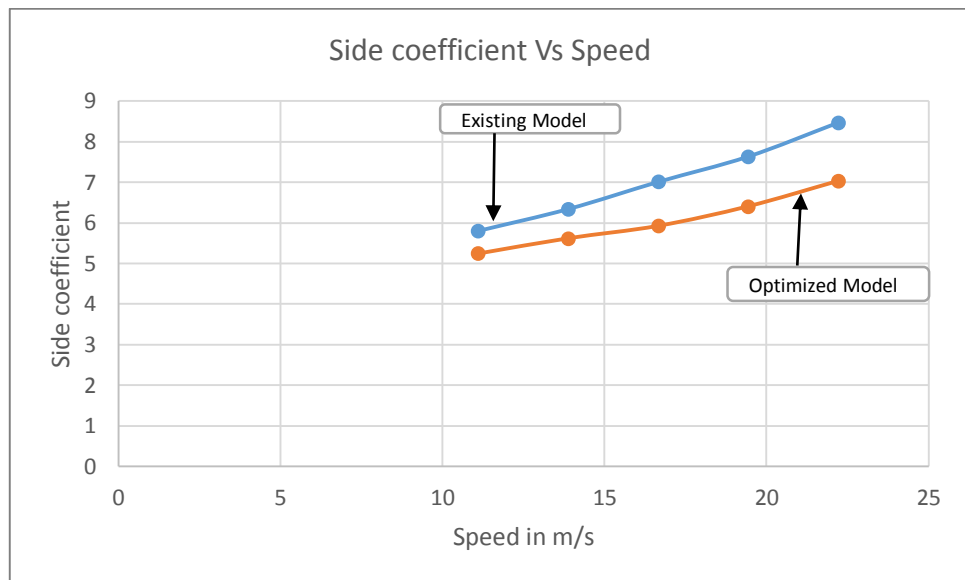


Figure 73: Aerodynamic Side coefficient with the speed of Light Railway train graph.

Therefore, as the result indicated by the pressure surface contour distribution and velocity vector distribution on the six models the value of aerodynamic drag, lift and side coefficients are listed for both models as shown in the Table 12, 13 and 14 for regional passenger, freight and Light Railway Transit train models respectively. The relation between aerodynamic coefficients and speed of train locomotive has indicated as shown in the graph of 65 up to 73 respectively.

From the CFD simulation results the calculation of driving resistance between baseline and modified models on varying train locomotive models speed has slightly different values. In this study has only considered calculations of aerodynamic drag resistance of locomotives and Light Railway Transit Ethiopian train for comparison of the existing and optimized models as shown in Table 12, 13, 14 and Figure 65, 68, 71.

Table 15: Aerodynamic pressure drag resistance load on the regional passenger train locomotive for both existing and optimized models.

Drag Resistance in N at Various Speeds for Regional Passenger locomotive Models		
Speed in km/h	Existing Model	Optimized Model
60	2,103.57	1,972.10
80	4,161.37	3,767.72
100	7,349.65	6,342.20
120	12,214.82	10,093.04
140	17,862.35	14,297.83
160	28,233.52	21,736.19

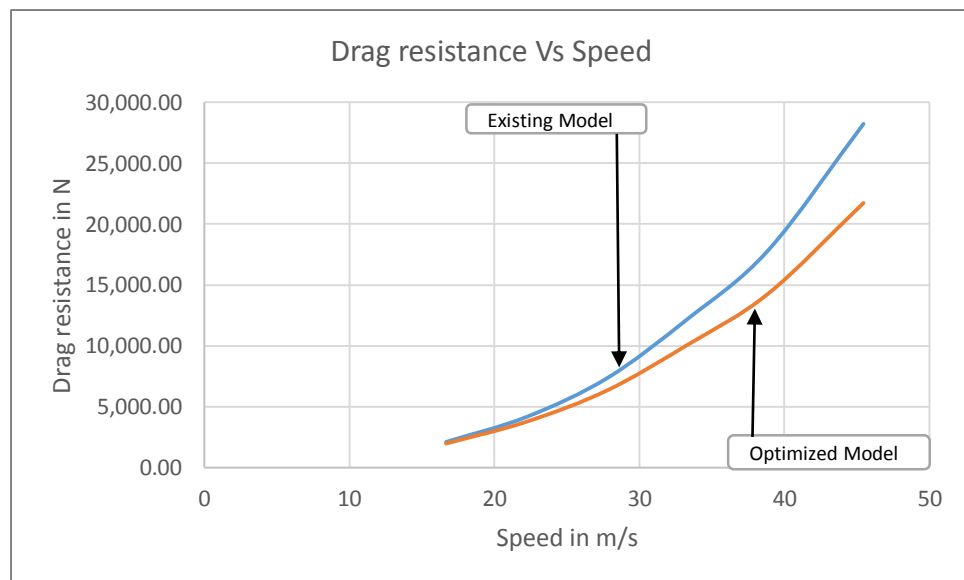


Figure 74: Drag resistance force with relation of regional passenger train locomotive both models at driving speed.

Table 16: Aerodynamic pressure drag resistance load on the regional Freight train locomotive for both existing and optimized models.

Drag Resistance in N at Various Speeds for Regional Freight locomotive Models		
Speed in km/h	Existing Model	Optimized Model
60	2,432.61	2,241.67
80	5,048.99	4,559.96
100	9,241.65	7,912.56
120	15,612.91	12,896.76

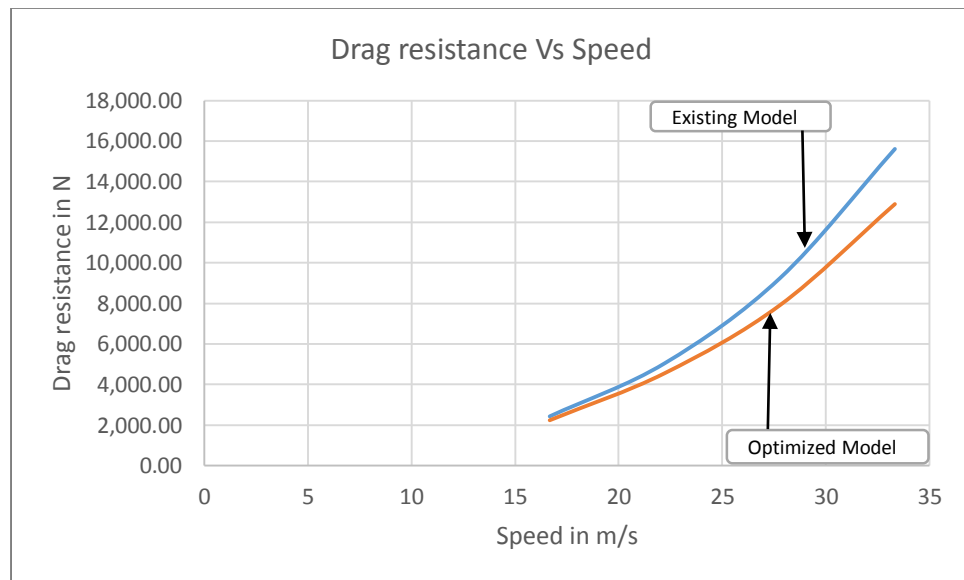


Figure 75: Drag resistance force with relation of regional Freight train locomotive both models at driving speed.

Table 17: Aerodynamic pressure drag resistance load on the Light Railway Transit train for both existing and optimized models.

Drag Resistance in N at Various Speeds for Light Railway Transit Models		
Speed in km/h	Existing Model	Optimized Model
40	593.49	585.99
50	954.25	936.17
60	1,428.08	1,382.11
70	2,067.14	1,925.44
80	2,809.53	2,602.63

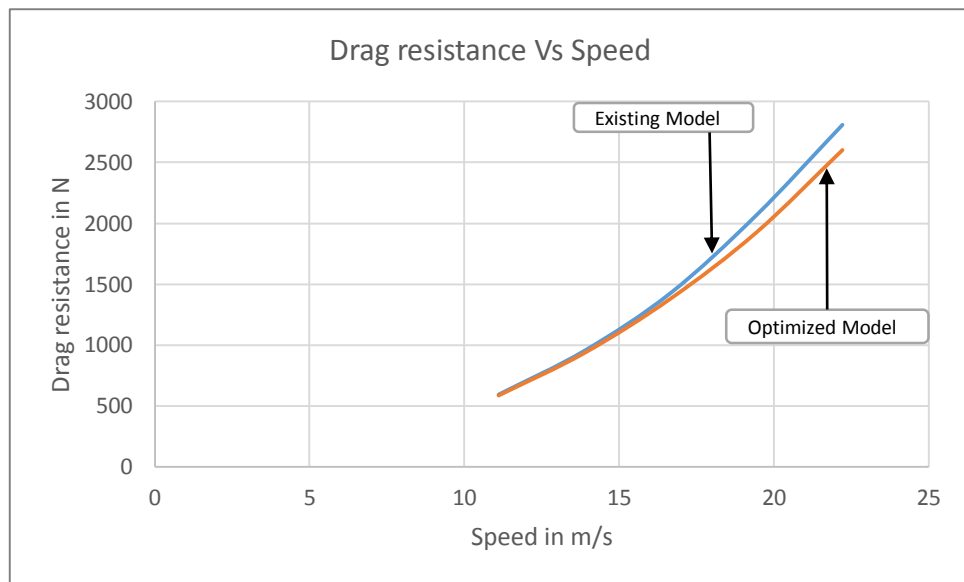


Figure 76: Drag resistance force with relation of Light Railway train both models at driving speed.

The required power to consume for driving resistance of train locomotives with the relation of train models type and varying speed has calculated. In this study has only considered calculations of power required for aerodynamic drag resistance of locomotives and Light Railway Transit Ethiopian train for comparison of the existing and optimized as shown in Table 12, 13, 14 and Figure 65, 68, 71.

Table 18: Power required for drag resistance at varying velocity of Regional passenger train locomotive Models.

Power requirement for both Models of Regional Passenger train locomotive and Power saving at each speed in percent			
Speed in km/h	Existing Model (kw)	Optimized Model (kw)	Power Saving In %

60	35.067	32.875	6.251
80	92.466	83.719	9.460
100	204.173	176.186	13.707
120	407.120	336.401	17.371
140	694.667	556.043	19.955
160	1,283.213	987.910	23.013

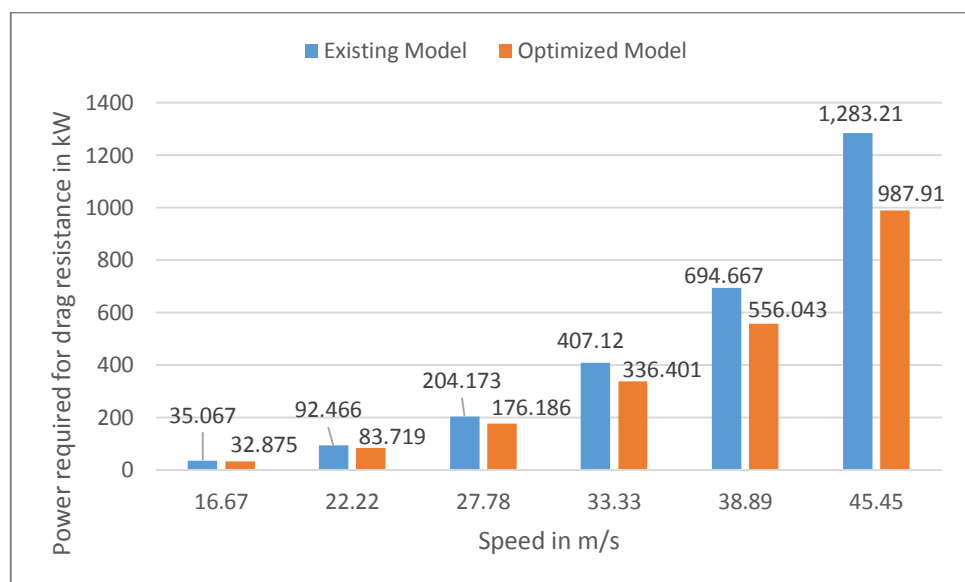
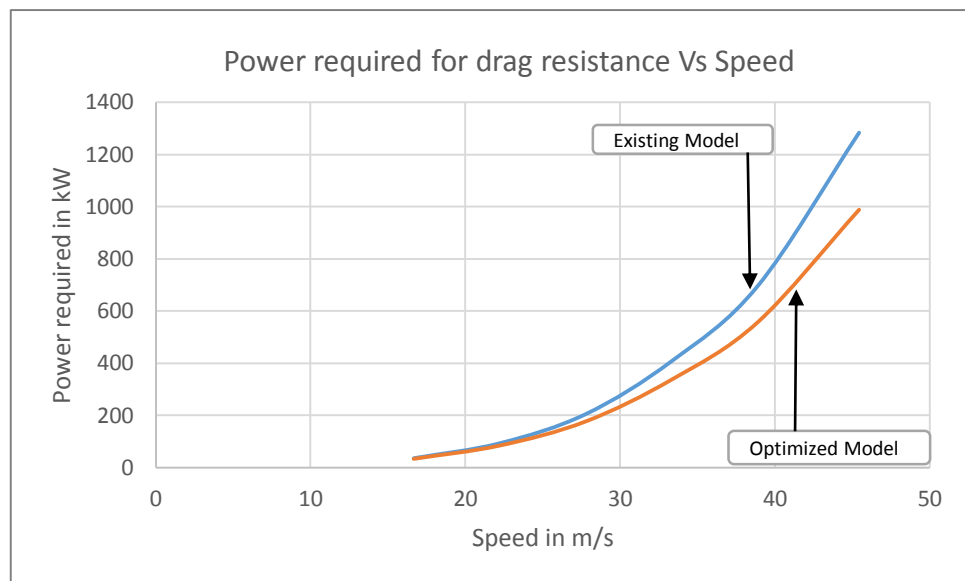
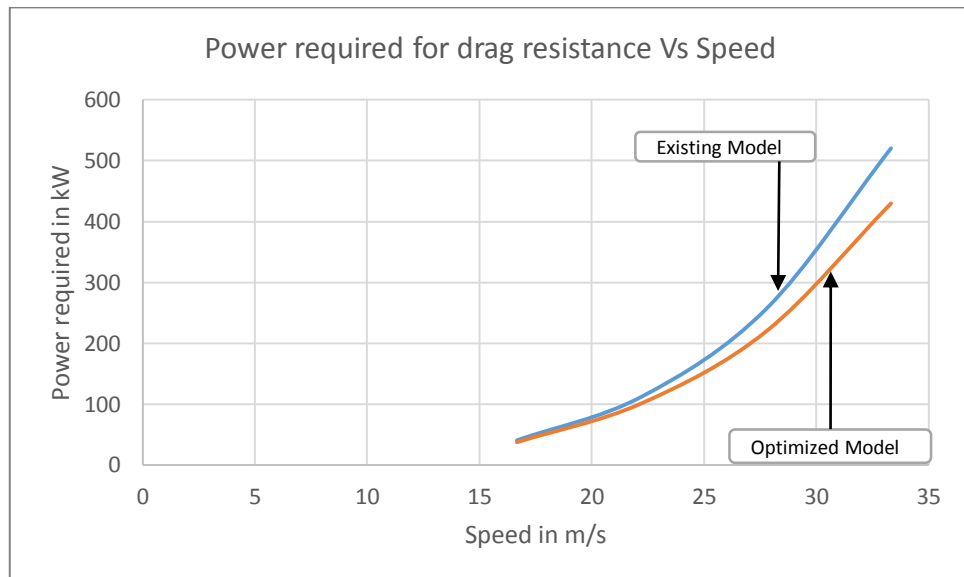


Figure 77: Power required for drag resistance versus at varying velocity for Regional passenger train locomotive Models.

Table 19: Power required for drag resistance at varying velocity of Regional Freight train locomotive Models.

Power requirement for both Models of Regional Freight train locomotive and Power saving at each speed in percent			
Speed in km/h	Existing Model (kw)	Optimized Model (kw)	Power Saving In %
60	40.552	37.367	7.854
80	112.189	101.322	9.686
100	256.733	219.811	14.109
120	520.378	429.849	17.397



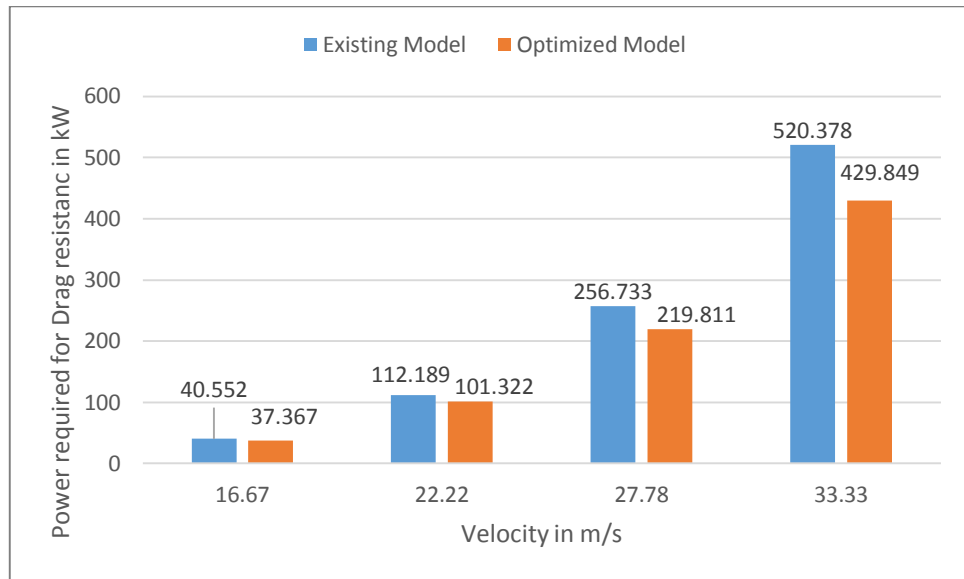


Figure 78: Power required for drag resistance versus at varying velocity for Regional Freight train locomotive Models.

Table 20: Power required for drag resistance at varying velocity of Light Railway Transit train Models.

Power requirement for both Models of Light Railway Transit train and Power saving at each speed in percent			
Speed in km/h	Existing Model (kw)	Optimized Model (kw)	Power Saving In %
40	6.594	6.510	1.274
50	13.255	13.003	1.901
60	23.806	23.039	3.222
70	40.185	37.431	6.853
80	62.428	57.830	7.365

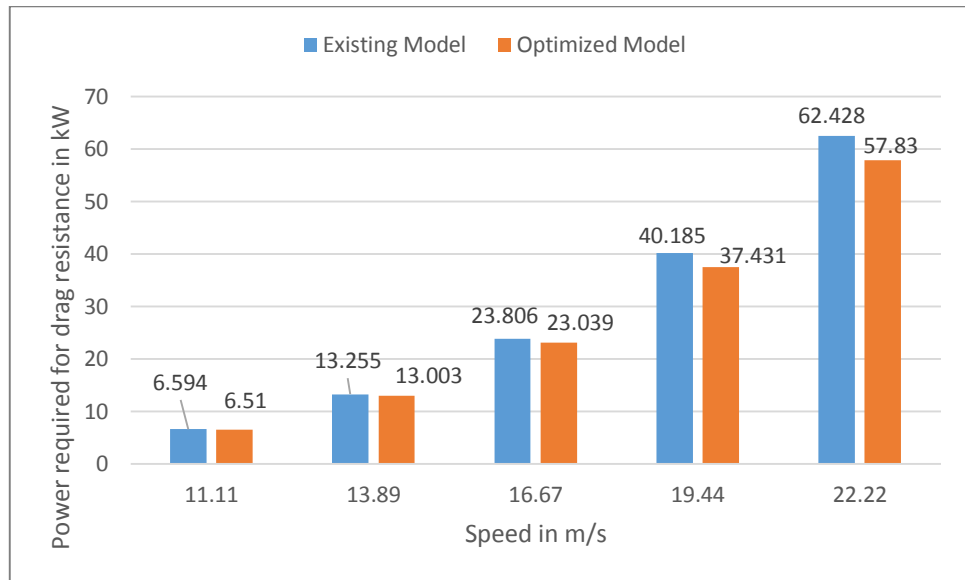
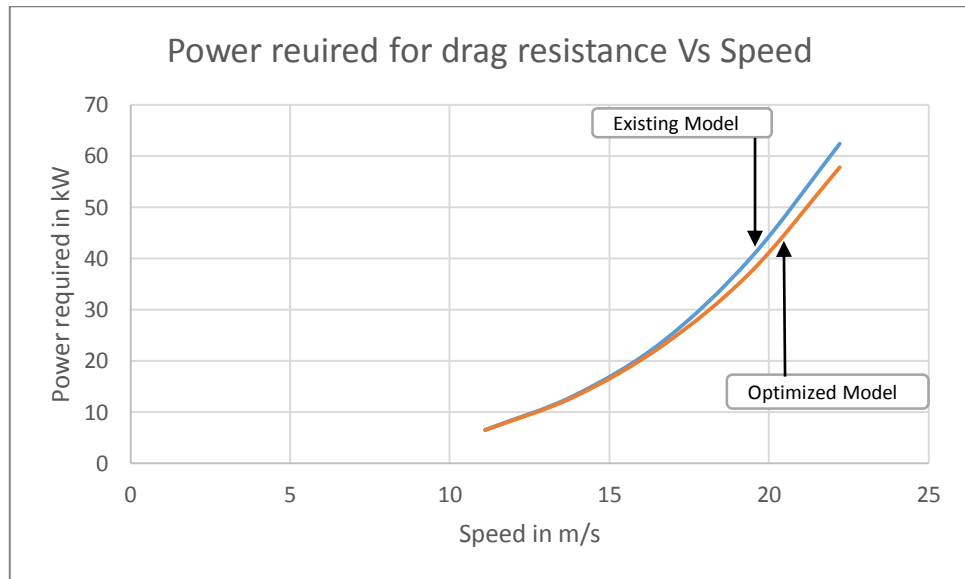


Figure 79: Power required for drag resistance versus at varying velocity for Light Railway train Models.

The stability from CFD numerical simulation result of train models at maximum operation speed with under the influence of side wind conditions the rotational moments and resistance moments listed in the Table 21, 22 and 23 regional passenger, freight and Light Railway Transit train locomotive models respectively, for comparison to judge the train locomotives safety analysis. Which indicated that CP to CG position difference is reduced on three case of Optimized models as the table shown below. When the CP position is more close to CG aerodynamic rotational moment is lowered which leads to the train model more stable.

Table 21: Aerodynamic forces acting on the running regional passenger train locomotives at maximum speed of 160km/h.

Type of train locomotive	Aerodynamic forces acting on center of pressure	Rotational moments about user coordinate in Nm	CG position in m	CP position in m	Distance between CG and CP in m
Existing RPT Model	$F_x = 95.20248\text{N}$	$M_y = 182,707.3$	93.90405	95.20248	$\Delta x = 1.29843$
	$F_y = 21.83429\text{N}$	$M_r = 139,494.4$	21.55	21.83429	$\Delta y = 0.28429$
	$F_z = 2.440600\text{N}$	$M_p = 96,929.7$	1.6	2.440511	$\Delta z = 0.84050$
Optimized RPT Model	$F_x = 94.95733$	$M_y = 100,120.2$	93.90405	94.811726	$\Delta x = 0.907676$
	$F_y = 21.67893\text{N}$	$M_r = 68,458.9$	21.55	21.67893	$\Delta y = 0.12893$
	$F_z = 2.157847\text{N}$	$M_p = 48,761.2$	1.6	2.15784	$\Delta z = 0.55784$

Table 22: Aerodynamic forces acting on the running regional Freight train locomotives at maximum speed of 120km/h.

Type of train locomotive	Aerodynamic forces acting on center of pressure in N	Rotational moments about user coordinate in Nm	CG position in m	CP position in m	Distance between CG and CP in m
Existing RFT Model	$F_x = 95.66745$	$M_y = 229,389.7$	93.69135	95.66745	$\Delta x = 1.976097$
	$F_y = 22.01694$	$M_r = -114532.9$	21.58	21.01694	$\Delta y = 0.436935$
	$F_z = 2.391133$	$M_p = 102,646.9$	1.6	2.391133	$\Delta z = 0.791133$
Optimized RFT Model	$F_x = 95.9838$	$M_y = 288,628$	93.69135	95.89042	2.19907
	$F_y = 21.10389$	$M_r = -86,690.3$	21.58	22.10388	0.52388
	$F_z = 2.167272$	$M_p = 105,356.6$	1.6	2.167272	0.56727

Table 23: Aerodynamic forces acting on the running Light Railway Transit train at maximum speed of 80 km/h.

Type of train locomotive	Aerodynamic forces acting on center of pressure in N	Rotational moments about user coordinate in Nm	CG position in m	CP position in m	Distance between CG and CP in m
Existing LRT Model	$F_x = 93.83247$	$M_y = 176,910.8$	90.8	93.83247	$\Delta x = 3.03247$
	$F_y = 21.59185$	$M_r = -8,147.2$	21.325	21.59184	$\Delta y = 0.26684$
	$F_z = 1.51323$	$M_p = 83,814.2$	1.5	1.513229	$\Delta z = 0.013229$
Optimized LRT Model	$F_x = 94.3007$	$M_y = 135,536.1$	90.8	94.000	$\Delta x = 3.2000$
	$F_y = 21.4659$	$M_r = -3,947.05$	21.325	21.46594	$\Delta y = 0.14094$
	$F_z = 1.28149$	$M_p = 120,339.7$	1.5	1.281149	$\Delta z = -0.21851$

Table 24: The critical speed of Ethiopian train locomotive and Light Railway Transit models moving on the minimum curved rail track.

Type of train locomotive Models	Critical speed at condition A	Critical speed at condition B	Critical speed at condition C	Critical speed at condition D
Regional Passenger train locomotives	$V < 20.608\text{m/s}$	$V < 20.609\text{m/s}$	$V < 20.609\text{m/s}$	$V < 20.608\text{m/s}$
Regional Freight train locomotives	$V < 20.610\text{m/s}$	$V < 20.611\text{m/s}$	$V < 20.611\text{m/s}$	$V < 20.610\text{m/s}$
Light Railway locomotive at	$V < 12.0022\text{m/s}$	$V < 12.0024\text{m/s}$	$V < 12.0024\text{m/s}$	$V < 12.0022\text{m/s}$

Note:

Explanation for condition **A**, **B**, **C** and **D** according to Figure 51 and 52 front view of train model and the direction is with respect of driver.

- Condition **A**: when the train locomotive moving a turn to right on curved path and the wind blowing direction is from inner to outer rail track curvature.
- Condition **B**: when the train locomotive moving a turn to right on curved path and the wind blowing direction is from outer to inner rail track curvature.
- Condition **C**: when the train locomotive moving a turn to left on curved path and the wind blowing direction is from outer to inner rail track curvature.

- Condition **D**: when the train locomotive moving a turn to left on the curved path and the wind blowing direction is from inner to outer rail track curvature.

Finally the resistance moments calculated using the above yawing resistance moment (M_{yr}), rolling resistance moment (M_{rr}) and pitching resistance moment (M_{pr}) formulas as below. Thus,

For regional passenger train locomotive existing and optimized models the total yawing resistance moment $M_{yr} = 2.660176 \times 10^6$ Nm, rolling resistance moment $M_{rr} = 9.70380 \times 10^5$ Nm and pitching resistance moment $M_{pr} = 7.600513 \times 10^6$ Nm. As shown from Table 21 for both models

$$M_y < M_{yr}, M_r < M_{rr} \text{ and } M_p < M_{pr}$$

Therefore, the train locomotives are Safe at these conditions

For regional freight train locomotive existing and optimized models the total yawing resistance moment $M_{yr} = 3.660798 \times 10^6$ Nm, rolling resistance moment $M_{rr} = 1.335386 \times 10^6$ Nm and pitching resistance moment $M_{pr} = 1.0459422 \times 10^7$ Nm. As shown from Table 22 for both models

$$M_y < M_{yr}, M_r < M_{rr} \text{ and } M_p < M_{pr}$$

Therefore, the train locomotives are Safe at these conditions

For Light Railway Transit train existing and optimized models the total yawing resistance moment $M_{yr} = 7.09498 \times 10^5$ Nm, rolling resistance moment $M_{rr} = 5.60862 \times 10^5$ Nm and pitching resistance moment $M_{pr} = 2.027138 \times 10^6$ Nm. As shown from Table 23 for both models of LRT

$$M_y < M_{yr}, M_r < M_{rr} \text{ and } M_p < M_{pr}$$

Therefore, the train locomotives are Safe at these conditions

From dynamic stability study on this paper Ethiopian train locomotives and Light Railway Transit models moving on minimum curvature of rail track which is 300m for regional passenger and freight train locomotive and 100m for Light Railway Transit models under the influence 12 m/s side wind condition the maximum or critical speed of a train locomotive traveling is calculated as shown in the Table 24.

In all cases the value of $M_y < M_{yr}$, $M_r < M_{rr}$, and $M_p < M_{pr}$ the train locomotive models driving stability is safe at the condition of moving train locomotives at maximum operation speed 160 km/h for Regional Passenger train, 120 km/h Regional Freight train and 80 km/h Light Railway Transit train in under the influence of cross-wind at the speed of 12 m/s. judgments of stability for each train type indicated on Table 21, 22 and 23.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As many researchers indicated that currently railway transportation system is widely used and improved its technology. Because, this technology attracts the researchers due to its huge and long distance transportation system has catastrophic accident and environmental problem. Now a day many countries has forced to use this transport system due to their population increment. Ethiopia is one of African country has more population growth due to this transport of passengers and freight cannot balance. In our country, the government has planned to construct more than 5000km national railway network in all regions and African connection as shown in Figure 4. But as shown in Figure 5 and 6 the Ethiopian Light Railway Transit and regional passengers and freight train locomotives have poor aerodynamic body shape with relation to their operation speed respectively. This poor aerodynamic external body shape of train cause for more driving power consumption depends on speed varying and which makes driving instability under the cross-wind condition. Hence, in this study has focused on the aerodynamic energy efficiency and stability of Light Railway Transit public transport train in Addis Ababa city, regional passenger and freight Ethiopian train under the influence of 12m/s cross-wind speed condition for sustainability of the system.

This paper has focused on development of aerodynamic body shape optimization of Ethiopian train locomotives under the cross-wind condition for energy saving and driving stability on straight and curved rail track. Particularly, redesigned the front and side part of train locomotives based on aerodynamic specification from Table 7, train locomotive nose height, angle and length indicated from Figure 23 and used the theoretical aerodynamic technical concepts of body shape modify has significant effects on the energy saving and stability of dynamic and aerodynamic of running train locomotive on straight and curvature railroad. But the design has considered the other train locomotives of functions and body size as shown in Figure 25 up to 36 for Light Railway Transit public transport train model, regional passengers and freight train locomotive models.

The analysis has done by PHOENICS Software a tool of Computation Fluid Dynamics (CFD) method considering boundary condition as shown on the Table 8 and Figure 37 for both existing and optimized models of each type of train locomotives with CFD numerical simulation setups.

As shown the result of this work, the Computational Fluid dynamics analysis shows that there is possibility of improving the aerodynamic drag reduction performance and both driving aerodynamic and dynamic stability judgments of Ethiopian Light Railway Transit public transport train, regional passengers and freight train locomotives respectively for passengers safety, comfort, saving operation power and reducing noise on this transport system by simple modification of only the front, top and side part of the vehicles exterior body. These modifications are helpful in reducing of drag, lift and side coefficients for the train locomotives have good energy efficiency at high speed and have good driving stability at 12 m/s side wind speed condition.

In this study found that the maximum aerodynamic drag reduction of Light Railway Transit Public transport, regional passengers and freight train locomotives are 7.36% at 80 km/h speed, 23.01% at 160 km/h speed and 21.84% at 120 km/h speed respectively and in this study the drag resistance effect of front wind is not included. Which are described as shown the graphs on Figure 65, 68 and 71 respectively in the comparison drag coefficients of the existing and modified models with related of their varying speeds have significant reduction by optimized of some part of train locomotives such as front, side, rear end and top part. Due to these drag reduction of each train locomotive has power saved at their maximum speed 23.013%, 17.397% and 7.365% from regional passengers, regional freight and Light Railway public transport train locomotive models respectively with more explained as shown in graph on Figure 77, 78, 79.

The judgment of both dynamic and aerodynamic stability of driving train locomotives on straight and curved rail track of minimum radius of curvature 300m for regional train locomotives and 100m for Light Railway Transit public transport train as shown in the Table 21, 22, 23. From CFD numerical simulation result of train models at maximum operation speed with under the influence of side wind conditions the rotational moments for regional passenger, freight and Light Railway Transit train locomotive models both existing less than the resistance moments $M_y < M_{yr}$, $M_r < M_{rr}$ and $M_p < M_{pr}$. Therefore the train locomotives driving stability have guaranteed when driving 160 km/h for passengers train locomotive, 120km/h for freight train locomotive and 80 km/h for Light railway Transit train on straight rail track and also on curved rail track regional train locomotives can move less than 20m/s speed and Light Railway Transit train can travel less than 12m/s speed. Therefore, from these aerodynamic drag improvement in energy efficiency has a high impact on the reduction of annual energy consumption and the stability of both models of each type of train locomotive are safe. So, the aim of this study has achieved.

5.2 Recommendation and Future work

This study is used only some part of locomotive body shape optimization , which has expected good drag reduction with under the influence of cross-wind condition required to improve the aerodynamic performance (drag coefficient, lift coefficient, side coefficient), to reduce the annual energy consumption of Ethiopian regional locomotives and Light Railway Transit public transport train. But for better energy saving of such vehicle and more improve driving stability in under cross-wind and head wind condition the following points should be study.

- Using the finding ERC has should be check each train type energy consumption and safety with respect to trains speed, driving stability and the vehicle weight as well.
- ERC should have train vehicle body manufacturing unit to develop Ethiopian new design train locomotive and train car for improving of such finding to be real.
- This project needs farther research activity on
 - Tunnel passage at high-speed side wind effect on dynamic stability of train
 - Farther front nose Optimization with different parameter
 - Underbody and farther side part of train redesign
 - For regional trains driving stability passing each other at high-speed
 - Regional passenger and freight cars need aerodynamic and dynamic study

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APPENDIX

Appendix-A

Table 25: Railway System Power consumption by Types of Services [56]

Railway Systems	Power consumption
Light Rail	<1MW
Commuter trains	≈3-4 MW
High Speed Inter-city rails	≈4-6 MW
Very Fast Commuter Trains (TGV)	≈8-10 MW
Freight Trains(in Europe)	≈6-10 MW
Freight Trains(in USA)	> 18-24MW

Table 26: Ethiopian Light Rail Transit (LRT) Cab Design specifications data [58].

Specification	Value
Track Gauge(standard)	1,435mm
Vehicle weight(Empty, average)	41,000kg
Vehicle weight(Full, average)	63,000kg
Single vehicle Height(with pantograph)	3,900mm
Single vehicle length(average)	28,000mm
Number of cars per unit	2 to 6 basic version 3-car per unit
Single Vehicle width	2,650mm
Horizontal vehicle clearance(total)	1,000mm
Vertical vehicle clearance(minimum)	410mm
Ballast/Track bed depth (average)	740mm
Passengers (seated/standing, total)	60/130, 190
Maximum Operation speed	80km/hr.

Minimum negotiable curve	For Single car 100m
	For Coupling 145m
Ride index	$W \leq 2.5$
Axle Load	$\leq 17t$
Axle arrangement	Bo-Bo

Table 27: Ethiopian high-speed Passenger train locomotive specification data [58].

Specification	Value
Track gauge	1,435mm
Minimum curve radius	300m
Maximum gradient	Ruling gradient 9‰, Pusher grade 18.5‰
Traction type	Electric
Locomotive type	HXD series
Max. operational speed	160km/h
Block type	Semi-automatic block
Length of arrival & departure track	850m(Dual loco. 880m)
Traction mass	Preliminary stage:3500t Long-term:4000t
Full length	22,216mm
Width	3,100mm
height	4,754mm
Equivalent length	2,400mm
Gross vehicle mass	109,000kg
Axle load	25,000kg
Transmission	AC-DC-AC
Electric brake	Regenerative brake (max. 354kN)
Catenary voltage	25kv/50Hz

Axle arrangement	Co-Co
Length of coupler centerline	
Wheel axle traction power	5400kw
Startup traction effort	286kN
Seating capacity	118 per vehicle
Speed range at constant power	169kN
Target weight	49,5000kg
Emergency brake distance on straight line (with 30% over load and initial speed 120km/hr.)	≤800m
Noise Level (120km/hr.)	≤68dB(A)

Table 28: Ethiopian high-speed Freight train locomotive design specification data [58].

Specification	Value
Track gauge	1,435mm
Minimum curve radius	300m
Maximum gradient	Ruling gradient 9‰, Pusher grade 18.5‰
Traction type	Electric
Locomotive type	HXD series
Max. operational speed	120km/h
Block type	Semi-automatic block
Length of arrival & departure track	850m (Dual loco. 880m)
Traction mass	Preliminary stage:3500t Long-term:4000t
Distance between lines	4,000mm
Full length	22,670mm
Width	3160mm
height	4,750mm
Gross vehicle mass	150,000kg
Axle load	25,000kg

Transmission	AC-DC-AC
Catenary voltage	25kv/50Hz
Axle arrangement	Co-co
Length of coupler centerline	
Wheel axle traction power	6,400kw
Startup traction effort	570kN
Electric brake	Regenerative brake (max. 480kN)
Speed range at constant power	506kN
Emergency brake distance on straight line (with 30% over load and initial speed 120km/hr.)	≤800m
Noise Level (120km/hr.)	≤68dB(A)

Table 29: Ethiopian High-speed Railway Power Supply System Technical Description [58] [59] [60].

Traction Power Supply System	
Feeding System-the standard	25kV, 50Hz Direct power feeding with return wire mode
Nominal Voltage	25kV
Short-term	29kV (maximum)
Operating voltage	20kV (minimum)
Abnormal operating voltage	19kV
Number and location of substations (with average distance of 35.81km)	21+1 ; at :Sebeta, Indode, Bishoftu, Mojo, Merebe, Senga Beret, Metehara, Awash, Sirba-Kunkur, Mieso, AK313 (long term), Afdem, Gota, Hurso, Lonnis, Mile, Adigala, Lasarat, Suburban 8, Alisabieh, Holhol, and Nagad
Overhead Contact System (OCS)	
Operation Mode	Unilateral for single track
	Bilateral for double track
Suspension type	Full compensation simplified catenary
Tensioning mechanism	Auto-tensioned catenary

Contact wire height	6,000mm (at contact point)
Minimum clearance	5,750mm
System height	1,400mm
Shortest dropper length	500mm
Vehicle loading height	5,300mm (no longer than)
Span (at straight line)	60m
Maximum span	65m (not longer than)
Overlapping section length	Not greater than 2x800m for bilateral power supply operation
	50% of bilateral for unilateral power supply operation
Return line	Insulated installation
Traction Substation	
Primary side voltage	Two separate and reliable 132kV from utility side
	Adopts phase sequence rotation mode
	System short circuit capacity 400MVA
Utility grid side substations	1x400kV, 2x230kV and 6x132kV
Traction Transformer	Single-phase (at Sebeta and Nagad Substations)
	Three-phase, Vv -connection (at the rest stations)
	Fixed reservation system (as hot spare)
	Oil-immersed self-cooled and reserved wind-cooled condition
	Outdoor layout
	27.5kV secondary side voltage
	20MVA with overload multiplier 2.0
	132kV traction transformer impedance voltage percentage 8.4%
Power compensation	Compensator is installed at substations

Table 30: Ethiopian Freight car specification data

Specifications	Values
Loading capacity	70 tonne
Dead weight	≤ 25 tonne

Volume	145m ³
Design Speed	100km/h
Vehicle Length at coupler connection point	≤ 1,7400mm
Minimum curve radius	145m
Height from center of coupler to top of rail	880mm
Body type	Wagon body

Table 31: The Ethiopian Freight car bogie technical specification data

Specifications	Values
Fixed wheel base	1,830mm
Side bearing center distance	1,520mm
Height from cored disk to rail surface	680mm
Wheel diameter	840mm
Railway gauge	1,435mm
Axle load	25 tonne
Design speed	100km/h

Table 32: The Ethiopian passenger car technical specification data

Specifications	Values
Body model type	YZ25G hard seat
Service life	30 years
Maintenance back to factory	2.4(±0.6)Mkm Or 10 year
Maintenance in depot	0.6(±20)Mkm Or 2.5 years
Railway gauge	1435mm
Maximum configuration	20 car per transite
Platform height	300,500,1250mm
Design speed	120km/h
Distance between platform edge to railway center	1750mm
Maximum line gradient	≤ 30%

Minimum negotiable curve	100m (for single) 145m (for couple)
Overall dimension (LxWxH)	25,500x3,105x4,433mm
Height from rail top to coupler center	880mm
Height from rail top to inter car crossing pedal	1,333
Height from rail top to floor surface	1,283
Car body center plate to rail top	780mm

Table 33: The Ethiopian Passenger car bogie technical specification data

Specifications	Values
Bogie axle load	≤ 17 tonne
Bogie axle base	2,400mm
Bogie wheel diameter	915mm
Design speed	140km/h
Bogie Derail parameter	≤ 1.0
Bogie wheel load reduction rate	≤ 0.6
Bogie overturning coefficient	≤ 0.8
Power supply (center power source)	DC600v
Rated seat	118 person

Appendix-B

Detail 2D drawing of Optimized model vehicles

1. Regional Passenger train locomotive (drawing No.1/3)
2. Regional Freight train locomotive (drawing No.2/3)
3. Light Railway Transit Public transport train (drawing No.3/3)