

A Numerical Study of Vehicle Mounted Wind Energy Generator for Electric Vehicles' Aerodynamic Properties and Driving Range



Amanuel Abate Bayeh

A Thesis Submitted to

The Department of Mechanical Engineering

School of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master of Science in
Automotive Engineering

Office of Graduate Studies

Adama Science and Technology University

June, 2022

Adama, Ethiopia

A Numerical Study of Vehicle Mounted Wind Energy Generator for Electric Vehicles' Aerodynamic Properties and Driving Range

Amanuel Abate Bayeh

Advisor: Dr. Ramesh Babu Nallamothu

A Thesis Submitted to

The Department of Mechanical Engineering

School of Mechanical, Chemical and Material Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master of Science in
Automotive Engineering

Office of Graduate Studies

Adama Science and Technology University

June, 2022

Adama, Ethiopia

DECLARATION

I hereby declare that this Master Thesis entitled “**A Numerical Study of Vehicle Mounted Wind Energy Generator for Electric Vehicles’ Aerodynamic Properties and Driving Range**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Amanuel Abate Bayeh

Name of student

Signature

Date

RECOMMENDATION

I, the advisor(s) of this thesis, hereby certify that I have read the revised version of the thesis entitled “**A Numerical Study of Vehicle Mounted Wind Energy Generator for Electric Vehicles’ Aerodynamic Properties and Driving Range**” prepared under my guidance by AMANUEL ABATE BAYEH submitted in partial fulfillment of the requirements for the degree of Master’s of Science in Automotive Engineering. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. Ramesh Babu Nallamotheu
Advisor

Signature

Date

APPROVAL

I, the advisor of the thesis entitled “**A Numerical Study of Vehicle Mounted Wind Energy Generator for Electric Vehicles’ Aerodynamic Properties and Driving Range**” and developed by Amanuel Abate Bayeh, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Ramesh Babu Nallamothu

Advisor

Signature

Date

We, the undersigned, members of the Board of Examiners of the thesis by Amanuel Abate have read and evaluated the thesis entitled “**A Numerical Study of Vehicle Mounted Wind Energy Generator for Electric Vehicles’ Aerodynamic Properties and Driving Range**” and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Automotive Engineering.

Chair Person

Signature

Date

Internal Examiner

Signature

Date

External Examiner

Signature

Date

Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

Department Head

Signature

Date

School Dean

Signature

Date

Office of Postgraduate Studies, Dean

Signature

Date

ACKNOWLEDGEMENT

First of all, I would like to give my biggest thank you to the almighty GOD for all that he has done for me. Next, I would like to express my deepest gratitude to my teacher and advisor Dr. Ramesh Babu Nallamotheu whose invaluable advice and guidance helped me in undertaking this thesis work. A special thanks to my special family member Mesfin Megra for his generous support and motivation. Finally, I would remiss in not acknowledging my family for their continuing belief in me and their support that keeps me in my highest spirit and motivation during this endeavor.

TABLE OF CONTENTS

DECLARATION	ii
RECOMMENDATION	iii
APPROVAL	iv
ACKNOWLEDGEMENT	v
TABLE OF CONTENTS	vi
LIST OF TABLES	ix
LIST OF FIGURES	x
LIST OF ACRONYMS AND ABBREVIATIONS	xiv
ABSTRACT	xvii
CHAPTER ONE	1
INTRODUCTION	1
1.1 Background	1
1.1.1 Wind Energy	2
1.1.2 Electric Vehicles and Renewable Energy	2
1.2 Statement of the Problem	4
1.3 Objectives	4
1.3.1 General Objective	4
1.3.2 Specific Objectives	4
1.4 Significance of the Study	5
1.5 Scope and Limitations of the Study	5
1.6 Organization of the Thesis	6
CHAPTER TWO	8
LITERATURE REVIEW	8
2.1 Previous Works	8
2.1.1 Vehicle Aerodynamic Performance	8
2.1.2 System Energy Recovery Potential	10
2.2 Wind Energy	11
2.2.1 Wind Energy Converters	12
2.2.2 Aerodynamics of Wind energy Extraction	13
2.2.3 Wind Turbine Aerodynamics	14
2.3 Vehicle Aerodynamics	21
2.3.1 Flow Phenomenon Related to Vehicles	22

2.4	Computational Fluid Dynamics (CFD)	25
2.5	Numerical Models	26
2.5.1	Governing Equations	26
2.5.2	Turbulence Modelling	27
2.6	Electric Generation	34
2.6.1	DC Generators	34
2.6.2	AC Generators	35
2.7	Rectification	36
2.7.1	Single Phase Full Bridge Rectifiers	36
2.7.2	Three Phase Full Bridge Rectifier	37
2.8	Literature Summary	38
2.9	Research Gaps	38
CHAPTER THREE		39
MATERIALS AND METHODOLOGY		39
3.1	Materials	39
3.2	Methodology	39
3.2.1	Baseline Model	40
3.2.2	Energy Recovery System (ERS) Modelling	43
3.2.3	ERS Integrated Vehicle Modelling	44
3.2.4	CFD Simulation Setup	46
3.2.5	MATLAB Simulink® Modelling	56
3.2.6	Road Test	65
3.2.7	Design Parameters for Model Comparison	67
3.2.8	Driving Schedule (Drive Cycle)	68
3.2.9	Model Efficiency Estimation	69
3.2.10	Extended Vehicle Range Estimation	70
CHAPTER FOUR		71
RESULTS AND DISCUSSIONS		71
4.1	CFD Simulation Results	71
4.1.1	Baseline Model Results	71
4.1.2	Model – 1 Results	75
4.1.3	Model – 2 Results	81
4.1.4	Model Comparisons	86
4.1.5	CFD Result Validation	87

4.2	Simulink® Physical Modelling Results	89
4.2.1	Baseline Model Results.....	89
4.2.2	Model – 1 Results	91
4.2.3	Model – 2 Results	96
4.2.4	Model Comparison.....	100
4.2.5	Actual Model Results.....	101
CHAPTER FIVE.....		103
CONCLUSIONS AND RECOMMENDATIONS		103
5.1	Conclusion.....	103
5.2	Recommendations	104
REFERENCES.....		106
APPENDICES		113
Appendix A: Model Drawings		113
Appendix B: Mesh Detail		119
Appendix C: Simulink® Block Parameters		121
Appendix D: Wind Speed Data.....		126
Appendix E: CFD Simulation Boundary Conditions.....		140
Appendix F: Publications.....		145

LIST OF TABLES

TABLE	PAGE
Table 3.1: HAWT Specifications	43
Table 3.2: Savonius Rotor Specifications	44
Table 3.3: Computational Domain Dimensions	48
Table 3.4: Local Mesh Sizing Setting	50
Table 3.5: Global Mesh Sizing	51
Table 3.6: Solver Setting	55
Table 3.7: Baseline Vehicle Model Specification	58
Table 3.8: ERS Turbine Rotor Dimensions	67
Table 3.9: Gear Ratio Corrected Turbine and PMSM Angular Velocities	67
Table 3.10: Preliminary Control Model Simulation Results	70
Table 4.1: Drag Coefficient Improvement from Baseline Model	87
Table 4.2: Baseline Model Result Summary	91
Table 4.3: Model – 1 Result Summary	95
Table 4.4: Model – 2 Result Summary	99
Table 4.5: Battery State of Charge for Each Model	101
Table 4.6: Actual Battery SOC Gained After Model Efficiency Correction	101
Table 4.7: Extended Driving Range Estimations	102
Table E.1: CFD Simulation Boundary Conditions	140

LIST OF FIGURES

FIGURE	PAGE
Figure 1.1: Feature of an EV(Iqbal, 2021).....	1
Figure 1.2: Wind Powered Prototype Vehicles (Sciencedaily, 2008; Wired, 2012).....	3
Figure 2.1: Cylindrical Approximation of Vortex Tube Expansion (Tony et al., 2001).....	17
Figure 2.2: A Blade Element Sweeps Out an Annular Ring (Tony et al., 2001).....	18
Figure 2.3: Savonius Rotor	19
Figure 2.4: The static torque coefficient as a function of rotor angular position; (a) for two rotor Savonius device and (b) for three rotor Savonius device (Blackwell et al., 1977)	20
Figure 2.5: Power Coefficient Comparisons for Two and Three Rotor Savonius Device (Blackwell et al., 1977)	21
Figure 2.6: Boundary Layer along a flat plate (Hucho, 1990).....	23
Figure 2.7: Separation of Boundary Layer flow at the Wall (Hucho, 1990)	24
Figure 2.8: (a) Attached Flow Over a Streamlined Car, and (b) Locally Separated Flow Behind a More Realistic Automobile Shape (Joseph, 2016).....	24
Figure 2.9: The Different Disciplines Contained Within Computational Fluid Dynamics (Jiyuan et al., 2018).	26
Figure 2.10: Components of a DC Generator	34
Figure 2.11: Construction of AC Generators (Theraja & Theraja, 2005).....	35
Figure 2.12: Field winding of Synchronous Generator (a) Salient, and (b) non-Salient (Theraja & Theraja, 2005)	36
Figure 2.13: Single Phase Full Bridge Rectifier Circuit (Ned et al., 2003)	37
Figure 2.14: Three Phase Full Bridge Rectifier Circuit (Ned et al., 2003).....	37
Figure 3.1: 2012 Tesla Model S (Tesla.Inc., 2012).....	40
Figure 3.2: Baseline Vehicle 3D Model.....	41
Figure 3.3: Baseline Model with Ducting Modification	42
Figure 3.4: Wireframe Diagram of the Internal Ducting	42
Figure 3.5: Flow Treatment Devices.....	43
Figure 3.6: Employed ERSs, (a) Savonius Rotor, and (b) HAWT	44
Figure 3.7: ERS Integrated Models (a) Model – 1, and (b) Model – 2.....	45
Figure 3.8: Wireframe Diagram of (a) Model – 1, and (b) Model – 2.....	46

Figure 3.9: Elements of CFD Analysis Framework (Jiyuan et al., 2018).....	47
Figure 3.10: Computational Domain.....	47
Figure 3.11: Computational Domain Labels (a) Velocity Inlet, (b) Pressure Outlet, (c) Tunnel Walls, and (d) Ground.....	48
Figure 3.12: Bodies of Influence.....	49
Figure 3.13: Surface Mesh Sizing.....	50
Figure 3.14: Volume Mesh Sizing	52
Figure 3.15:Grid Independence Test.....	53
Figure 3.16: Steps in MATLAB Simulink® Physical Modelling.....	56
Figure 3.17: EV Simulink® Model.....	59
Figure 3.18: Reference Speed Tracking.....	59
Figure 3.19: Driver Error for, (a) HWFET, and (b) Custom Cycle	60
Figure 3.20 : Reference and Actual Speed Profile on the New European Drive Cycle (NEDC)(Miri et al., 2021).....	61
Figure 3.21: Baseline EV Battery SOC at Cd Values of (a) 0.24, (b) 0.34, and (c)0.44	61
Figure 3.22: Wind Energy Recovery System Model	62
Figure 3.23: ERS Mechanical Sub-System.....	63
Figure 3.24: ERS Electrical Sub-System	64
Figure 3.25 :Transient Response Comparison of PMSG with a 240-ohm Load from 0-1500rpm in 500ms ramp DC Bus Voltage (Quintal-Palomo et al., 2019)	64
Figure 3.26: Integrated System Model.....	65
Figure 3.27: Road Test Route	66
Figure 3.28: Vehicle Speed Data	66
Figure 3.29: Drive Cycles (a) HWFET, and (b) Custom Cycle.....	68
Figure 3.30: Preliminary Control Simulation SOC Results	69
Figure 4.1: Baseline model convergence history plots of (a) Residuals, and (b) Drag Coefficient	72
Figure 4.2: Static Pressure Contours for Baseline Model	73
Figure 4.3: Velocity Distributions on Baseline Model	74
Figure 4.4: Flow Recirculation Regions on the Baseline Model	75
Figure 4.5: Convergence History of Model – 1 (a) Drag Coefficient, and (b) Residuals.....	76
Figure 4.6: Static Pressure Distribution on Model-1	77

Figure 4.7: Static Pressure Distribution Inside the Ducting on Model-1	77
Figure 4.8: Velocity Distribution Inside Model-1 Ducting (a) Top View, and (b) Side View	78
Figure 4.9: Flow Vector Plot Inside Model-1 Ducting	79
Figure 4.10: Flow Conditions at Ducting Exits	80
Figure 4.11: Exit Flow Interaction with Freestream Flow	80
Figure 4.12: Convergence History of Model – 2 (a) Drag Coefficient, and (b) Residuals.....	81
Figure 4.13: Static Pressure Distribution for Model-2.....	82
Figure 4.14: Static Pressure Distribution Inside the Ducting on Model-2.....	82
Figure 4.15: Velocity Distribution Inside Model-2 Ducting (a) Top View, and (b) Side View...	83
Figure 4.16: Flow Patterns Behind the Savonius Rotor	84
Figure 4.17: Flow Vector plot Inside Model-1 Ducting	85
Figure 4.18: Flow Conditions at Ducting Exit.....	85
Figure 4.19: Exit Flow Interaction with Freestream Flow for Model – 2.....	86
Figure 4.20: Comparison of Model Drag Coefficients	87
Figure 4.21 : Passive Blown Duct, (a) Placement and Design, and (b) Normalized Streamwise Velocity Delt Contour of Ducted Model (Jacuzzi & Granlund, 2019).....	88
Figure 4.22: Baseline Speed tracking efficiency, (a) HWFET, and, (b) Custom Cycle	89
Figure 4.23: Battery SOC of Baseline Model Under, (a) HWFET, and (b) Custom Cycle.....	90
Figure 4.24: Baseline Model Battery Voltage, (a) HWFET, and (b) Custom Cycle	91
Figure 4.25: Model -1 ERS Mechanical Outputs Under, (a) HWFET, and (b) Custom Cycle	92
Figure 4.26: Model -1 Rectifier Terminal Voltage Under, (a) HWFET, and (b) Custom Cycle..	93
Figure 4.27: Battery SOC of Model – 1 Model Under, (a) HWFET, and (b) Custom Cycle	94
Figure 4.28: Model – 1 Battery Voltage Under, (a) HWFET, and (b) Custom Cycle.....	95
Figure 4.29: Model – 2 ERS Mechanical Outputs Under, (a) HWFET, and (b) Custom Cycle...	96
Figure 4.30: Model – 2 Rectifier Terminal Voltage Under, (a) HWFET, and (b) Custom Cycle	97
Figure 4.31: Battery SOC of Model – 2 Model Under, (a) HWFET, and (b) Custom Cycle	98
Figure 4.32: Model – 2 Battery Voltage Under, (a) HWFET, and (b) Custom Cycle.....	99
Figure 4.33: Model SOC Comparison Under, (a) HWFET, and (b) Custom Cycle	100
Figure B.1: Model – 1 Surface Mesh.....	119
Figure B.2: Model – 1 Volume Mesh	119
Figure B.3: Model – 2 Surface Mesh.....	120
Figure B.4: Model – 2 Volume Mesh	120

Figure C.1: Simulink to PS Converter Block.....	121
Figure C.2: PS to Simulink Converter Block.....	121
Figure C.3: Longitudinal Driver Block.....	121
Figure C.4: DC Motor Block	122
Figure C.5: Battery Block	122
Figure C.6: Controlled PWM Voltage Source Block.....	123
Figure C.7: H – Bridge Block	123
Figure C.8: Vehicle Body Block.....	124
Figure C.9: Permanent Magnet Synchronous Machine Block.....	125
Figure F.1: Brochure of the International Conference.....	145
Figure F.2 : Conference Acceptance Notification.....	146
Figure F.3: Accepted Conference Paper	147

LIST OF ACRONYMS AND ABBREVIATIONS

CFD	Computational Fluid Dynamics
ERS	Energy Recovery System
EV	Electric Vehicle
EVs	Electric Vehicles
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
HWFET	Highway Fuel Economy Test
SOC	State of Charge
PWM	Pulse Width Modulated
BoI	Body of Influence
V2G	Vehicle to Grid
RANS	Reynolds Averaged Navier Stokes
RNG	Renormalized Group
BSL	Baseline
SST	Shear Stress Transport
AC	Alternating Current
DC	Direct Current
$\dot{m}$	Wind Flow rate
V_∞	Wind free stream velocity
A	Rotor area
A_r	Control volume area of the rotor
V_r	Air velocity at rotor control

V_o	Air velocity at inlet control
V_2	Air velocity at outlet control
$V_o = V_\infty$	Wind free stream velocity
$A_r = A$	Turbine rotor area
C_p	Power coefficient
p_d^+	Actuator disc upstream pressure
p_d^-	Actuator disc downstream pressure
A_d	Actuator disc area
U_∞	Wind free stream velocity
U_w	Downstream wind velocity
$U_d = U_\infty(1 - a)$	Wind speed at the actuator disc
a	Axial induction factor
C_T	Thrust Coefficient
W	Resultant velocity at the blade element
N	Number of blades
C	Blade aero foil cord centerline length
R	Blade tip radius
r	Blade element radius
$\mu = \frac{r}{R}$	Flow induction
C_l	Blade lift coefficient
C_d	Drag coefficient
ϕ	Flow angle of resultant velocity vector
$\lambda = \frac{\Omega R}{U_\infty}$	Blade tip speed ratio

Q	Turbine torque
Ω	Turbine rotation speed (rpm)
a'_t	Tangential flow induction factor at the blade tip
R	Rotor tip radius
W	Resultant velocity
ξ	Blockage Correction
G_v	Production of turbulent viscosity
Y_v	Destruction of turbulent viscosity
ν	Molecular kinematic viscosity
k	Turbulence kinetic energy.
E	Dissipation rate of Turbulent Kinetic Energy,
μ_t	Turbulent viscosity

ABSTRACT

Electric vehicles (EVs) are the major contributors to the reduction of emissions from road vehicles. From previous studies, this attribute of EVs can further be strengthened by using vehicle-mounted energy recovery systems. This study investigated the implementation of a wind energy recovery system employing a 190mm horizontal axis wind turbine (Model – 1), and a 208mm diameter Savonius rotor vertical axis wind turbine (Model – 2) with an aspect ratio of 1.00 mounted at vehicle front. Computational fluid dynamics (CFD) simulations were performed on a model generated from SOLIDWORKS 2017 in ANSYS 2021 R2. The CFD simulations were performed to study the flow patterns around the designed models, and compute the improvements to the drag coefficients of model – 1 and Model – 2 for comparison with the baseline model which is without an energy recovery system (ERS) onboard. Compared to the baseline drag coefficient value of 0.3463876, model – 1 had a 2.01% improvement while model – 2 had a 3.914% improvement. Physical models were constructed in Simulink® software for the baseline EV and ERS integrated models operating under the Highway Fuel Economy Test (HWFET), and custom driving schedules to estimate the energy recovery potential of the ERS, and the extended driving range of the baseline EV model. The performance of the baseline physical model was assessed from reference speed tracking efficiency, and the model's response to varying drag coefficients. From the conducted physical model simulations battery state of charge (SOC), and battery voltage levels were used to evaluate the energy recovery potential of the system. For simulations under the HWFET the final battery SOC values for the baseline model, model – 1, and model – 2 were 95.37%, 97.8%, and 97.98% respectively; while for simulation under the custom cycle were 87.11%, 93.4%, and 93.65% respectively. To improve the model accuracy preliminary control simulation were performed for model efficiency corrections, and compute the actual battery SOC levels. From subsequent analysis the increased baseline SOC levels for model – 1, and model – 2 simulated under the HWFET cycle were +0.044%, and +0.18% respectively; while for models simulated under custom cycle were 0.1163%, and 0.35% respectively. Extended model driving ranges for model – 1, and model – 2 simulated under the HWFET were 0.157km and 0.643km respectively; while for models simulated under the custom cycle were 0.397km, and 1.216km respectively. The final values obtained showed that energy recoveries were possible for the designed model.

Keywords: *Physical Model, State of Charge, Energy Recovery System (ERS), Electric Vehicles (EV), Computational Fluid Dynamics (CFD), Wind Energy*

CHAPTER ONE

INTRODUCTION

1.1 Background

Automobiles have made great contributions to the growth of modern society by satisfying many of the needs for mobility in everyday life. However, the large number of automobiles in use around the world has caused and continues to cause serious problems for environment and human life (Mehrdad et al., 2010). Hence, the need for electric vehicles with clean and efficient driving ability (which include energy storage, drive train, and energy management).

EVs made their way into public use as early as in the middle of the 19th century, even before the introduction of gasoline-powered vehicles. What is likely the first human-carrying electric vehicle with its own power source was tested along a Paris street in April 1881 by French inventor Gustave Trouvé (Ernest H., 1993). Then after, over the years substantial advancements have been made to the electric vehicle.

An *electric vehicle* is a vehicle having two features: **(i)** The energy source is portable and electrochemical or electromechanical in nature, and **(ii)** traction effort is supplied only by an electric motor. The primary source of energy for electricity generation for these vehicles is varied ranging from fossil fuels to solar energy (Iqbal, 2021).

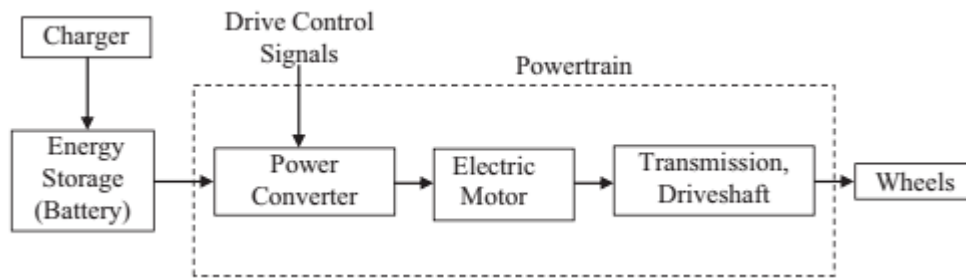


Figure 1.1: Feature of an EV(Iqbal, 2021)

There are several bottlenecks on the take-up by economic operators and the public at large of this technology, mainly: the price of purchasing of an electric vehicle (EV), its limited range (range anxiety) and long charging time (Zoran, 2012).

One of the determining factors of an EV's environmental impact is the nature of the charging electrical energy source utilized. So, one obvious way to ensure the carbon neutrality of an EV is to implement renewable energy infrastructures that are the sources for EV charging.

Renewable technologies are considered to be clean sources of energy. The optimal use of these resources minimizes environmental impacts, produce minimum secondary wastes, and are sustainable based on current and future economic and social needs (Rathore & Panwar, 2022).

Solar energy is referred to as renewable or sustainable energy because it will be available as long as the sun continues to shine. The other main renewable energies are wind, bioenergy, geothermal, hydro, tides, and waves (Vaughn, 2011).

1.1.1 Wind Energy

Before the Industrial Revolution, wind was a major source of power for pumping water, grinding grain, and long-distance transportation (sailing ships) (Vaughn, 2011). Windmills have been used for at least 3000 years, mainly for grinding grain or pumping water, while in sailing ships the wind has been an essential source of power for even longer. The use of windmills (or wind turbines) to generate electricity can be traced back to the late nineteenth century with the 12 kW DC windmill generator constructed by Brush in the USA and the research undertaken by LaCour in Denmark (Tony et al., 2001). At the beginning of 2017, worldwide more than 340,000 windmills of about 487 GW installed power generation capacity are in operation. Wind energy offers many advantages, which explains why it is the fastest-growing energy source in the world. Research efforts are aimed at addressing the challenges (Wagner & Mathur, 2018).

1.1.2 Electric Vehicles and Renewable Energy

It is suggested that both private and public sectors invest in clean technology by transitioning from conventional homes to smart homes and from conventional vehicles to electric vehicles (Longo et al., 2018). Among the different sectors, the transport sector is responsible for more than 20% of global greenhouse gas emissions, mostly emitted in cities. Therefore, initiatives and analysis focused on electric vehicles integration powered by renewables is currently a desirable solution to mitigate climate change and promote energy transition (Gil-García et al., 2021).

The penetration of EVs is reshaping the transportation system. Many positive impacts can be expected from the growing number of EVs, including lower fossil oil dependency and fewer carbon emissions (Liansheng et al., 2015).

Wind turbines were not incorporated into motor vehicles as driving power generators until the 21st century. (Rubio & Llopis-Albert, 2021) discussed three main schools or trends have developed in the use of wind power as a source of energy to move vehicles in general and the theoretical studies that have been carried out on its viability. The energy that is available in a moving wind is being harnessed to be used as a means for vehicle propulsion. A number of rotor-based design prototypes that adjust their orientation up or down wind to the apparent wind direction in order for the propellers to act as drives have theoretically been studied by (Gaunaa et al., 2009; Khan et al., 2013). Prototypes based on the theoretical works that are constructed by university students for the Racing Aeolus Competition and by independent projects are shown below:

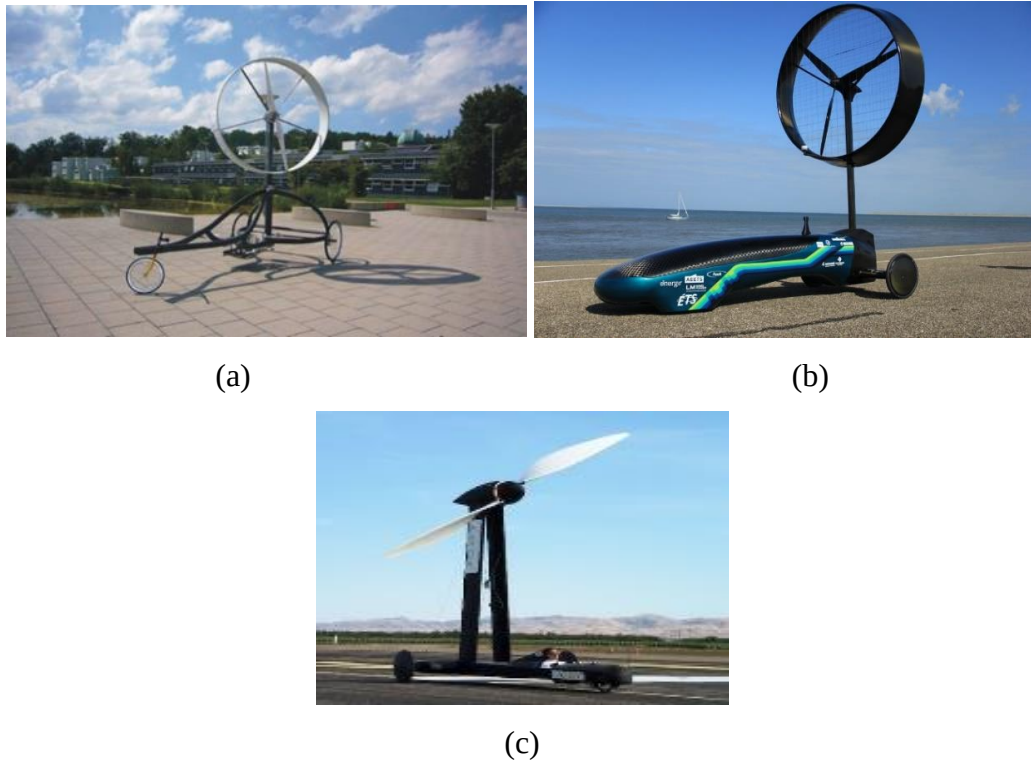


Figure 1.2: Wind Powered Prototype Vehicles (Sciencedaily, 2008; Wired, 2012)

The wind energy around the vehicle can also be harnessed by vehicle mounted systems. Multiple researchers have studied this implementation for aerodynamic property alterations, (Bangi et al., 2017; M. C. Feudjio Nguenfack et al., 2022; M. Carlos Feudjio Nguenfack et al., 2019; Sofian et al.,

2014) observing increase vehicle drag coefficient for roof mounted system and negligible to no changes to the vehicle drag coefficient for vehicle front mounted system.

Vehicle front mounted low output wind energy harvesting systems form (Bangi et al., 2017; Fathabadi, 2019; Zahir Hussain et al., 2020) have shown scalable potential for further study.

1.2 Statement of the Problem

Electric vehicles (EVs) are becoming preferred modes of transportation. Even though electric vehicles bring about multiple benefits, driver range anxiety is a major problem facing them. Additionally, when the electric vehicle (EV) is driving on the road the renewable energies that are available around the car are not being utilized and their potential has not been fully explored. The renewable energy utilization selected for study involves harnessing the kinetic energy of the wind moving around the EV. Implementation studies of vehicle front mounted wind energy harnessing device have shown promise with small scale applications. But, when considering full scale systems with larger devices, their implementation gives rise to unique problems in the form of altered vehicle aerodynamic properties and mounting challenges, which may result in subsequent performance deviation from stock EV.

1.3 Objectives

1.3.1 General Objective

The general objective of this thesis work is to implementation vehicle mounted wind energy generators and study their effects on an electric vehicle's aerodynamic properties and driving range.

1.3.2 Specific Objectives

The specific objectives of this study are:

- Design/Adoption of a suitable wind turbine.
- Modeling the base vehicle and the wind turbines designs using SOLIDWORKS 2017 Software.
- Performing CFD analysis.

- Determining the vehicle driving range by using MATLAB Simulink® physical modeling
- Comparison of the modified models with the baseline model in:
 - Drag Coefficient
 - Battery State of Charge
 - Battery Voltage and
 - Extended Range

1.4 Significance of the Study

The study intends to substantiate that an electric vehicle with a wind turbine mounted onboard to charge the batteries can travel increased or reduced distance when compared to stock electric vehicle. As more and more electric vehicles are appearing on the road; new and innovative ways to recover and conserve the energy used by electric vehicles may appear. One way to achieve this is to use the renewable energy available around the car. Thus, the result of this study can serve as a launching pad for researchers whose aim is to work on harnessing the wind energy with a vehicle mounted device/wind turbine.

The results obtained and conclusions reached in this thesis work can also have a domino effect for the development of wind energy recovery with a vehicle mounted wind turbine specifically and other electric vehicle energy recovery and conservation means in general. Meaning, a number of favorable subsequent merits are predicated on the conformation of the proposed hypothesis which include:

- Real world prototype testing can be investigated without prior extensive aerodynamic study.
- Load on the electric power grid due to electric vehicle charging can be reduced. This in-turn may improve the EV's market penetration and vehicle operating cost.
- Vehicle to grid (V2G) technology may benefit from the excess energy produced by the system.

1.5 Scope and Limitations of the Study

As stated in the title, this study is numerical investigation simulated on a computing machine virtually. So, prototype construction and vehicle road testing for result conformation is simulated

by using different softwares. The input parameters for the simulations will be obtained from road tests, standards and analysis results.

This study focuses on the implementation of the proposed system only on electric vehicles. This is due to,

- Efficient recovered energy utilization because of the large amount of energy storage available.
- Available increased space on electric vehicles compared to conventional IC engine and Hybrid Electric Vehicles (HEVs) because of the absence of internal combustion engine.

The design and simulation for this thesis work will be for a sedan vehicle. This is because majority of current commercial electric vehicle adoptions is on sedan vehicles. The results obtained in this study can be extrapolated for future electric vehicle adoptions of pickups, trucks and public transport vehicles.

The installation location of the system on the vehicle is limited to a single location. The reason behind location selection being:

- **Front of the vehicle:** it is of interest because there will not be any increase to the vehicle surface area and it is the area with the highest drag force on the vehicle.

Electrical modeling and simulation do not encompass complex and part specific control and actuation schemes, the primary reason being my knowledge and expertise gap on the subject matter. Additionally, these vehicle specific control and actuation schemes are not open-source information since they are a closely guarded manufacturer's trade secret.

The quality of simulation results obtained are dependent on the software capability and computing ability of the machine used.

1.6 Organization of the Thesis

There are five chapters in this thesis. **Chapter One** provides an overview of the research. It comprises the background of the study, problem statement, objectives, scopes, significance of study, and document structure. **Chapter Two** focuses on the survey of prior literatures and the development of theoretical frameworks in the study's topics. **Chapter Three** discusses the materials and methodology implemented in the study. **Chapter Four**, titled Results and

Discussions, provides a detailed analysis of the results acquired from the simulations with the use of figures and tables, a detailed discussion of CFD and physical model simulation results was presented. Conclusion and recommendations make up **Chapter Five** which is the final portion of this thesis.

CHAPTER TWO

LITERATURE REVIEW

Previous related works to energy recovery from wind energy for Electric vehicles and other vehicle implementations will be reviewed and discussed in this chapter along with relevant basic theoretical concepts employed thorough out the study.

2.1 Previous Works

This section contains reviewed literatures which were considered based on their focus on two main performance characteristics of the system to be implemented. These characteristics are discussed below:

2.1.1 Vehicle Aerodynamic Performance

The wind energy recovery systems can be mounted at multiple locations on the EV; Quartey & Adzimah, 2014, studied the implementation of a horizontal axis wind turbine that is mounted on the roof of the vehicle to harness the wind energy. The position of the turbine was determined for the reason that the wind speed at the roof top is the highest. The turbine also has diffuser augmented lay out for improved performance. Another roof mounted system was studied by M. Carlos Feudjio Nguetack et al., 2019, who studied the aerodynamic effects of a two-rotor horizontal axis savonius wind turbine with straight and/or side mounted generators fixed on the roof of an electric vehicle. The researchers observed that the vehicle drag coefficients increased from 0.3148705 to 0.46134410 for straight mounted generator and 0.4779705 for the side mounted generators. Their simulation was performed with 27.77m/s wind speed and K- ϵ turbulence model used in SOLIDWORKS 2014 software. The study conducted by Quartey & Adzimah, 2014, does not consider the altered aerodynamic characteristics of the vehicle under study, but a study by M. Carlos Feudjio Nguetack et al., 2019; Sofian et al., 2014, observed that roof mounted systems will result in increased vehicle aerodynamic drag coefficient. Furthermore, Bangi et al., 2017, used a set of two micro wind turbines with micro generators mounted at the rear of the vehicle to study the power harnessing abilities of the wind turbines without affecting the vehicle aerodynamics.

The work done investigated the performance parameters through experimental approach and CFD analysis using Autodesk flow simulation. From the methods realized the drag coefficient and mileage of the vehicle is negligibly affected.

A sole aerodynamic performance study conducted by Sofian et al., 2014, involved the evaluation of the drag coefficient of a vehicle with a mockup rectangular block sections constructed on the vehicle body to represent wind turbine mounting locations. The researchers considered mounting the turbine at three locations on the vehicle; (i) In front of the front bumper, (ii) On top of the hood, and (iii) On top of the roof; from which they found that hood and roof mounted turbines resulted in increased vehicle drag coefficient, while the vehicle's drag coefficient remained unaffected by the front mounted turbine. A Study conducted by Nasser, 2014, proposed a roof mounted system with modified placement alternative aimed at improving vehicle aerodynamics and stability. Honeycomb structures at the inlet and outlet of the turbine were placed to obtain laminar flow and minimize the system's effect on the vehicle's aerodynamic properties. A more comprehensive aerodynamic study by M. C. Feudjio Nguefack et al., 2022 conducted aerodynamic analysis of two horizontally arranged Savonius turbine configurations mounted at vehicle front, roof top and tailgate with two generator arrangements. The study employed the realizable K- ϵ turbulence model using the Menter-Lechner wall functions. In order to understand the external forces of the rotor, the study considered three turbine rotor angles of attack 0° (parallel to the flow), 90° (perpendicular to the flow) and 135° (intermediate position). By imposing the above stated design modifications, the drag and lift forces and coefficients were numerically computed for which front end turbine placement on the vehicle showed virtually identical air flow characteristics to that of the base vehicle when compared with the other turbine placements.

Unique turbine placement and augmentation studies; for instance an investigation conducted by Hegde et al., 2016 performed CFD analysis on chassis mounted single stage impulse turbine with nozzle augmented inlet design for power generation while the vehicle is cruising. The CFD analysis results showed increased vehicle drag coefficient as a result of the introduced nozzle augmented impulse turbine generator. Another unique design proposed by Ferdous et al., 2011, places the wind turbines parallel to the wind flow. From comparisons made with base model design, the proposed design arrangement showed increased outlet pressure meaning reduced vehicle drag coefficient.

Kassem, 2018, conducted a unique study which focused on the aerodynamic drag study of a racing car. The research involved the design and analysis of a race car model with three vertical axis wind turbine variations that are used for propulsion (the three turbine variations include NACA aero foil with 2^0 angles of attack, C-section and big single C-section). Then, while the race car is stationary the aerodynamic effects as drag coefficient and drag force are determined using Autodesk CFD simulation under K- ϵ turbulence model at varying wind speeds of 4,6 and 8m/s. furthermore, stream flow properties of the model such as velocity and pressure distributions were studied for more detailed investigation. The investigator determined that the single Big C – section blade vertical axis turbine propelled race car had the highest performance at 8m/s.

2.1.2 System Energy Recovery Potential

The energy recovery systems proposed by multiple researchers in their respective works involved theoretical estimation and small-scale experimental validations to corroborate their studies. Considering the work by Quartey & Adzimah, 2014, from the theoretical design calculations considering a system with three blade turbine and direct transmission (no gearbox) operating at 120 km/hr wind speed (=vehicle speed), the researcher was able to obtain a restored power of 3.26kW to the batteries without considering vehicle performance deviations and energy losses. A more detailed investigation into the energy recovery potential of a vehicle mounted wind energy system was conducted by Rubio & Llopis-Albert, 2019, 2021, who computed the %theoretical and %real energy that can be recovered by regenerative braking only and regenerative braking + Horizontal axis micro wind turbine with 50cm swept diameter installed at the front of the vehicle. To validate their work the researchers employed World harmonized Light-duty vehicle Test Procedures (WLTP) cycle as scenario -1, urban driving covering 20.25 minutes cycle time as scenario – 2, and high-way driving covering 1.7Hr cycle time as scenario – 3. From the analysis they carried out energy recovery with scenario – 3 was found to have the largest potential. A unique design proposed by Ferdous et al., 2011, implemented dual turbine arrangements in which the researchers estimated total extracted wind power of 360W. This extracted power was able to improve the vehicle milage by 24%. The study on nozzle augmented impulse turbine generator from (Hegde et al., 2016), computed the power production potential of the system based on the nozzle inlet and outlet mass flow rates. Form theoretical and ANSYS simulated power calculation at various inlet velocities, a maximum of 5.686kW and 5.447kW of power were computed for theoretical and ANSYS simulated power calculations respectively.

The electrical performance of the design proposed by Bangi et al., 2017, which connects two micro turbine generators in parallel with two arrangements, the first with voltage controller (cutoff limit at 3.5V) was able to reach 3.5V and 0.8A generated when connected to four parallel LED bulb loads and the second arrangement, with no voltage controller and six flash bulb loads in series was able to reach 18.91V and 0.65A max values. From the conducted experimental study, the researchers stated, the system will have some degree of flexibility for varying loads and further work need to be done to use the system for high current demand applications. Another experimental study courtesy of Fathabadi, 2019, proposed a research work to evaluate the feasibility of inserting small wind turbine at the back of the vehicle condenser to harness energy from the wind. The work uses a 100W turbine with a PMSG and a novel constructed hybrid power generation system. The applied scheme was assessed by measuring the systems power flow hour by hour over two sequential days and moreover two road tests, with and without wind turbine were performed to record the maximum velocity, travelling range and acceleration of the vehicle. From the measurements the researcher found that the wind turbine enhanced the travelling range of the electric vehicle by 6.4km and the power efficiency of the EV's power supply by 0.2%. The system proposed by Nasser, 2014, employed energy recovery scheduling with system engagement while the vehicle is braking, parked or travelling down a gradient. But no confirmed recovered energy figures are given.

Zahir Hussain et al., 2020, tested a system with a Vertical axis wind turbine mounted at the front of the vehicle to harness the wind energy when the vehicle is moving to charge the batteries. The investigators carried out experiment on a system with a 32Ah and 12V battery, power boost converter (DC), 12V DC generator and voltage regulator. Their system was designed to operate between 40-60kmph vehicle speed range and the investigators have observed that the system can provide constant power to a 12V battery at varying speeds.

2.2 Wind Energy

Tony et al., 2001 and Vaughn, 2011, state that energy from the wind is mentioned as one of the oldest sources of energy employed by mankind, dating back several thousand years. Their application (energy conversion usage) ranges from early implementations for grinding and pumping to current implementations for electrical power production.

Wind energy converters used for electric power generation appeared towards the end of the 19th century, employing small wind mill rotors. By the first half of the 20th century turbine construction concepts generated brought about substantial influence of the current turbine technologies (Manwell et al., 2009).

2.2.1 Wind Energy Converters

Wind turbine classifications take many different forms (Vaughn, 2011). These classifications are based on:

- **Interaction of blade with the wind:**

This classification includes drag, lift or a combination of the two. For a drag device; the wind pushes against the blade, turning the rotor on its axis. Lift devices on the other hand use mostly airfoil blades (Wagner & Mathur, 2018). The orientation of this blades is varied, which is referred as angle of attack, according to the wind speed and direction for optimum lift forces generation used to turn the rotor.

Drag devices are inherently limited in efficiency, about 15% theoretical max efficiency due to the large blade area resulting in increased material, which causes problem with wind forces on the rotor at high speeds. Another reason for the low efficiency of drag type turbines is the device cannot reach speeds greater than the wind speed.

On the other hand, when using lift devices, the blades possess the performance ability to move faster than the wind and are more efficient in terms of aerodynamics and use of material, a ratio of around 100 to 1 compared to a drag device (Vaughn, 2011).

- **Orientation of rotor axis with respect to the ground and tower:**

The turbine rotor axis will have two major orientations with respect to the ground. (i) horizontal axis wind turbines, which have parallel orientation to the ground (Vaughn, 2011). The horizontal axis wind turbines range from single to multiblade designs and their rotors are usually classified according to the rotor orientation (Up/Down wind), hub design, rotor control and alignment with the wind (Manwell et al., 2009). (ii) vertical axis wind turbines, which have perpendicular

orientation with respect to the ground (Vaughn, 2011). The most common types include Darrieus and Savonius turbines.

2.2.2 Aerodynamics of Wind energy Extraction

Wind turbine is a device for extracting kinetic energy from the wind; By removing some of its kinetic energy the wind must slow down but only that mass of air which passes through the rotor disc representing the overall swept area of the turbine rotor during one rotation, where the rotor disc radius equals the distance from the hub center to the turbine tip (Tony et al., 2001). The decelerating air molecules exert force on the turbine blades which is then converted into torque. According to (Wagner & Mathur, 2018) the amount of energy transfer from the wind to the rotor depends on:

a. Density of air

The kinetic energy of a mass body is proportional to its mass. Thus, the kinetic energy in the wind depends on the mass of air per unit of volume.

b. Rotor Area

The rotor area determines how much energy a wind turbine is able to harvest from the wind. Rotor dimensioning must be optimized based on the wind conditions (Wagner & Mathur, 2018). Hence, it is a sound reasoning to have larger turbines at high wind area and smaller turbines at low wind areas to maximize the turbine efficiency and output.

c. Wind Velocity

As stated in section (2.2.2) the energy in the wind is a kinetic energy. Thus, one defining characteristics is the free stream velocity (V_∞) of the wind on the rotor area (A). considering an area (A) and applying a wind velocity V_∞ , the change in volume ΔV with respect to the length (l) and time (t) is:

$$\Delta V = AV_\infty \Delta t \quad \dots (2.1)$$

2.2.3 Wind Turbine Aerodynamics

Throughout the development of wind turbines aerodynamic studies developed for the aviation industry were the earliest adoptions (Mathew, 2006). However, now theories are specifically formulated for wind turbines which are further refined and reinforced with the help of experimentation techniques.

2.2.3.1 Wind Power Fundamental Equation

The fundamental equation of wind power answers the most basic quantitative question, how much energy is in the wind? The wind energy depends of three main parameters (Letcher, 2017):

- Volume of air
- Speed of wind
- Mass of air

Considering a cylinder of air flowing through the rotor the mass (m) in the cylinder of air with volume (V) is the source of the energy extraction. The cylinder of air is moving with velocity V_∞ , and mass m will pass through the rotor per second. Therefore, the mass flow rate $\dot{m}$ can be used to compute the wind power (Pramod, 2011). Thus,

$$\dot{m} = \rho_{air} A V_\infty \quad \dots (2.2)$$

The kinetic energy (E) in the wind is [Ref]:

$$E = \frac{1}{2} m V_\infty^2 \quad \dots (2.3)$$

Wind power (P) is the rate of kinetic energy:

$$P = \frac{1}{2} \rho_{air} A V_\infty^3 \quad \dots (2.4)$$

2.2.3.2 Betz's Limit and Wind Turbine Power Coefficient

The performance of a theoretical wind turbine operating in a control volume space can be described with principal equation of (i) conservation of mass, (ii) conservation of energy and (iii)

conservation of momentum. The assumption needed for the formulation stated in, Pramod, 2011; Tony et al., 2001, are taken into consideration the power from the rotors due to the pressure difference across the blade surfaces. The maximum theoretical power extracted will be

$$P = \rho_{air} A_r V_o^3 \frac{8}{27} \quad \dots (2.5)$$

The maximum theoretical wind turbine power coefficient (C_p), which is also referred as the Betz's limit is the ratio between the maximum power extracted by the rotor to power available in the wind, which is:

$$C_p = \frac{\text{Max power extracted}}{\text{Power available in the wind}} = \frac{\rho_{air} A_r V_o^3 \frac{8}{27}}{\frac{1}{2} \rho_{air} A V_{\infty}^3} \quad \dots (2.6)$$

From further simplification the maximum theoretical power coefficient attainable by a wind turbine is:

$$C_p = \frac{8}{27} = 0.593$$

2.2.3.3 Aerodynamics of Horizontal Axis Wind Turbines

Horizontal axis wind turbines (HAWTs) are devices used to extract kinetic energy from the wind. The aerodynamic study of HAWTs goes back more than a century (Letcher, 2017). According to Letcher, 2017, the original studies were developed by Froude and Rankine, which the theory initially was developed for marine propulsion. The aerodynamic studies of HAWT designs involve computing the power and torque produced, turbine power coefficient, turbine thrust coefficient and etc. some of the HAWT aerodynamic study theories include:

2.2.3.3.1 The Actuator Disc Concept (1-D Momentum Theory) (Tony et al., 2001)

The analysis of the wind energy device in this concept is performed without any specific turbine design, and only considers the energy extraction process. The turbine considered for wind energy extraction is called an actuator disc.

The air that passes through the disc under goes an overall change in velocity from free stream velocity (U_{∞}) to wind down stream velocity (U_w) resulting in air momentum change. The force

causing the change of momentum comes entirely from the pressure difference across the actuator disc.

$$Force = (p_d^+ - p_d^-)A_d = (U_\infty - U_w)\rho A_d U_\infty (1 - a) = (U_\infty - U_w)\rho A_d U_d \dots (2.7)$$

The power extracted from the wind is given by:

$$Power = FU_d = 2\rho A_d U_\infty^3 a(1 - a)^2 \dots (2.8)$$

The power coefficient (C_p) is given by;

$$C_p = 4a(1 - a)^2 \dots (2.9)$$

2.2.3.3.2 Rotor Disc Theory

This theory allows the variation of tangential induced velocity and axial induced velocity radially. To allow this variation, the theory considered an annulus ring of rotor disc.

The increment of rotor torque acting on the annulus ring will be responsible for imparting the tangential velocity component to the air, whereas the axial force acting on the ring will be responsible for the reduction in axial velocity. The whole disc comprise a multiplicity of annular rings and each ring is assumed to act independently in imparting momentum only to the air which actually passes through the ring (Tony et al., 2001).

The mathematical derivation from Tony et al., 2001, expressed the power coefficient (C_p) as

$$C_p = 4a(1 - a)^2 \dots (2.10)$$

Which is precisely identical to the non-rotating wake (actuator disc theory) case.

2.2.3.3.3 Vortex Cylinder Model of The Actuator Disc (Tony et al., 2001)

In the rotor disc theory, the actuator disc is described as being swept out by a multiplicity of aero foil blades each with radially uniform bound circulation $\Delta\Gamma$. From the tip of each blade a helical vortex of strength $\Delta\Gamma$ converts down-stream with the local flow velocity. As the number of airfoil approach infinity, the helical tip vortices will form a tubular surface that becomes a continuous tubular vortex sheet. The vortex tube will expand in radius as the flow of the wake inside the tube

slows down. To determine the nature of the tube's expansion, the tube is assumed to remain cylindrical, shown in Figure 2.1. The cylindrical vortex model allows the whole flow field to be determined on is accurate within the limitation of the non-expanding cylindrical wake.

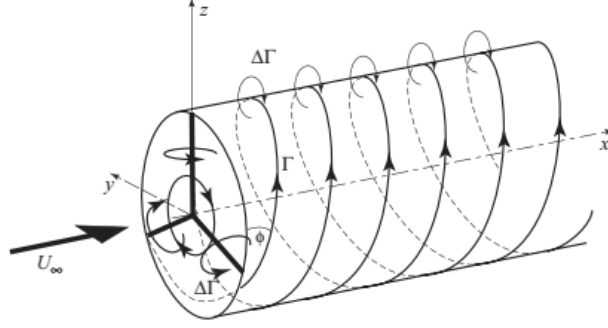


Figure 2.1: Cylindrical Approximation of Vortex Tube Expansion (Tony et al., 2001)

The torque on the annulus of radius r and radial width δr is:

$$\frac{dQ}{dr} = \frac{\frac{1}{2}\rho U_\infty^3 2\pi r 4a(1-a)^2}{\Omega(1+a_t')} \quad \dots (2.11)$$

The turbine power is given by:

$$\frac{dP}{dr} = \Omega \frac{dQ}{dr} \quad \dots (2.12)$$

$$P = \frac{\frac{1}{2}\rho U_\infty^3 \pi R^2 4a(1-a)^2}{(1+a_t')} \quad \dots (2.13)$$

The power coefficient is:

$$C_P = \frac{4a(1-a)^2}{1+a_t'} = 4a_t'(1-a)^2$$

The reduced efficiency compared with the simple actuator disc result, $C_P = 4a_t'(1-a)^2$, is caused by the energy required to spin the wake, as a rigid body, with an angular velocity $4a_t'\Omega$.

2.2.3.3.4 Blade Element Momentum Theory (BEM)

The blade element theory is that the flow past a given section is considered 2D and that the effective inflow velocity can be constructed as the vector sum of the incoming (axial) velocity and rotational speed which gives the Resultant velocity (W) at the blade (Letcher, 2017).

The aerodynamic lift (and drag) forces on the span-wise elements of radius r and length δr of the several blades of a wind turbine rotor are responsible for the rate of change of axial and angular momentum of all of the air which passes through the annulus swept by the blade elements (Tony et al., 2001). In addition, the force on the blade face as a result of pressure difference across the blade face associated with turbine blade wake will cause the axial moment variations and will have no effect on the angular momentum, as the wake is rotating far downstream.

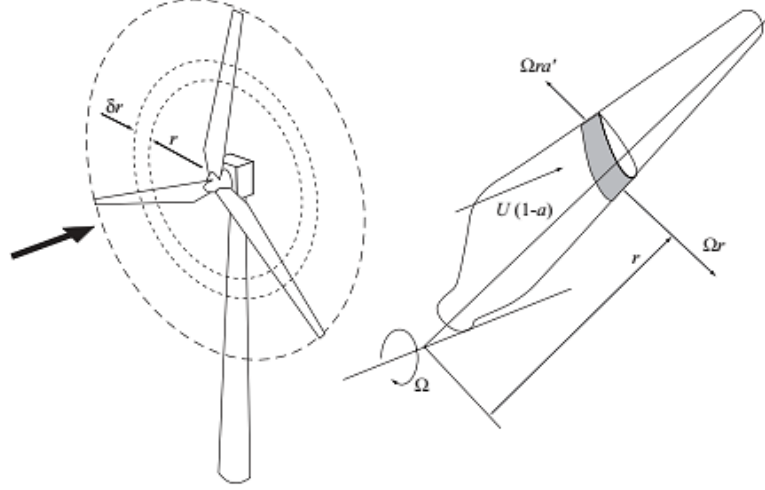


Figure 2.2: A Blade Element Sweeps Out an Annular Ring (Tony et al., 2001)

The components of axial aerodynamic forces and angular aerodynamic forces on the blade element are independently resolved to obtain two principal equations (Tony et al., 2001).

Resolved axial aerodynamic forces

$$\frac{W^2}{U_\infty^2} N \frac{c}{R} (C_l \cos \phi + C_d \sin \phi) = 8\pi(a(1-a) + (a'\lambda\mu)^2)\mu \quad \dots (2.14)$$

Resolved angular aerodynamic forces

$$\frac{W^2}{U_\infty^2} N \frac{c}{R} (C_l \sin \phi - C_d \cos \phi) = 8\pi\lambda\mu^2 a'(1-a) \quad \dots (2.15)$$

The torque developed by blade element δQ is

$$\delta Q = 4\pi\rho U_\infty(\Omega r)a'(1-a)r^2\delta r - \frac{1}{2}\rho W^2 N c C_d \cos \phi r dr \quad \dots (2.16)$$

The complete rotor develops a total torque (Q) which is the sum of all the blade element torque developed. It is calculated as:

$$Q = \frac{1}{2} \rho U_{\infty} \pi R^3 \lambda \left[\int_0^R \mu^2 [8a'(1-a)\mu - \frac{W}{U_{\infty}} \frac{Nr}{c} C_d(1+a')] du \right] \quad \dots (2.17)$$

The power developed by the rotor (P):

$$P = \Omega Q \quad \dots (2.18)$$

The power coefficient (C_P) is

$$C_P = \frac{P}{\frac{1}{2} \rho U_{\infty}^3 \pi R^2} \quad \dots (2.19)$$

2.2.3.4 Aerodynamics of Vertical Axis Wind Turbines

The earliest practical vertical axis wind machine use dates back to 1200-1300 AD. Extensive studies for vertical axis wind turbine (VAWT) implementation in power generation involving wind tunnels began in the early 1900s (Paraschivoiu, 2002). When considering VAWTs they incorporate both drag and lift driven devices. Savonius, Darrieus and Magnus effect devices are well known design variation. In this study the savonius rotor design will be implemented. VAWT aerodynamics mathematical modelling as proposed by Chauvin & Benghrib, 1989, commences by evaluating the pressure drop across/on each side of the blade.

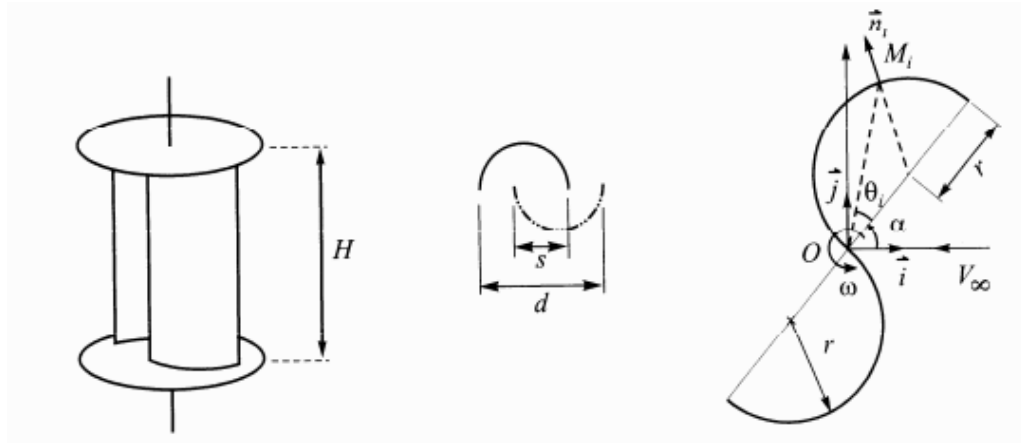


Figure 2.3: Savonius Rotor

Considering a two rotor savonius device with a gap spacing $\frac{s}{d} = 0$, first the total torque available (Q), which is the sum of retreating(driven) blade component (Q_m) and the advancing (resistant) blade component (Q_D), is computed. Supposing the two torque components have pressure difference ΔP_m and ΔP_D on their respective blades, then the total torque will be:

$$Q = 2r^2 \int_0^{\pi} (\Delta P_m - \Delta P_d) \sin 2\theta d\theta \quad \dots (2.20)$$

Then, the average power will be:

$$P = WQ = \frac{W}{\pi} \int_0^{\pi} Q dx \quad \dots (2.21)$$

The normalized power coefficient (C_P^*)

$$C_P^* = \frac{p}{\frac{1}{2} \rho V_{\infty}^3 (A_s)} \quad \dots (2.22)$$

Experimental study conducted by Sandia National Laboratories, at the Vought Systems Division Low Speed Wind Tunnel, examined two and three bucket Savonius wind turbine configurations with varying gap spacing and two rotor heights. The study was a wind tunnel experiment for which the researchers took into account the tunnel blockage correction (ζ) to correct the free measured free stream velocity and dynamic pressure. The data measurements of the Savonius device were used to compute the turbine torque and power coefficients (C_Q and C_P respectively).

Blackwell et al., 1977 expressed the static C_Q and C_P as a function of turbine tip speed ratio and plotted the static torque as a function of angular position of the turbine rotor(θ) see figure 2.4. The normalized power coefficient was also plotted as a function of rotor tip speed ratio for different gap spacing (s/d) see figure 2.5.

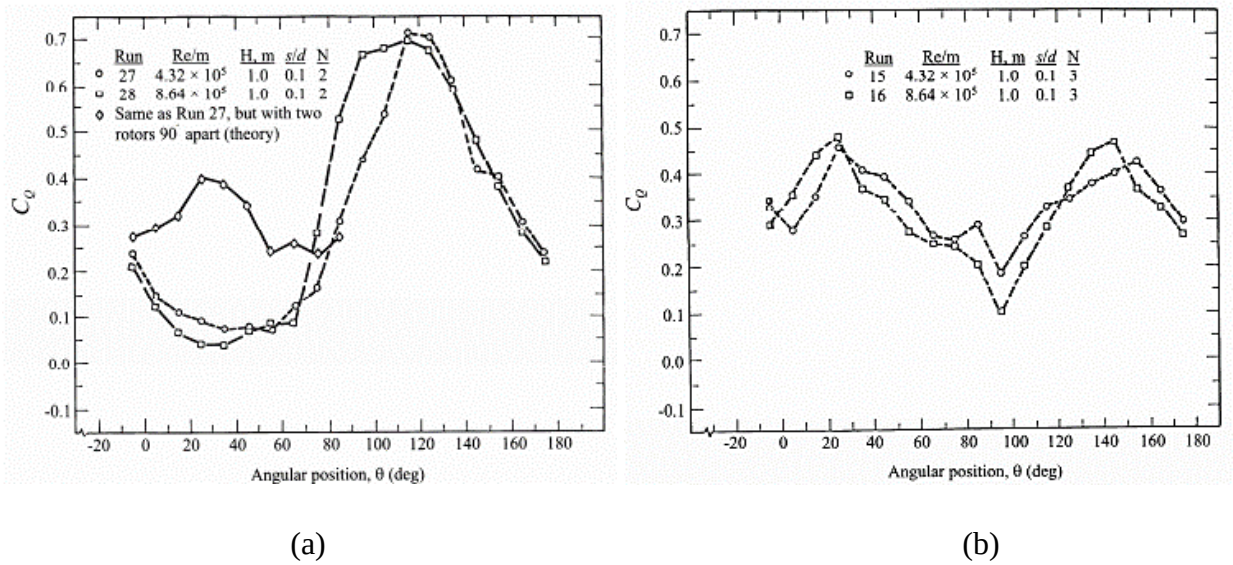


Figure 2.4: The static torque coefficient as a function of rotor angular position; (a) for two rotor Savonius device and (b) for three rotor Savonius device (Blackwell et al., 1977)

In the case of two-bucket Savonius rotor a large variation of the static torque with the angular position is observed. However, the three-bucket Savonius rotor exhibits a smaller variation in static torque coefficient than the two-bucket configuration.

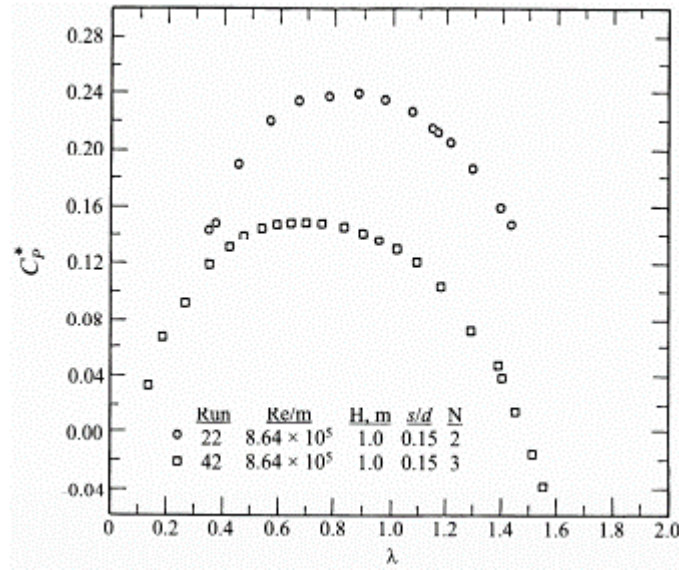


Figure 2.5: Power Coefficient Comparisons for Two and Three Rotor Savonius Device (Blackwell et al., 1977)

For rotors with $\frac{s}{d} = 0.15$ (blade overlap) it was observed that the maximum power coefficient of the two bucket Savonius rotor was found to be approximately 1.5 times that of the three-bucket configuration. These power coefficient values were observed at tip-speed ratios of 0.8 – 0.9.

2.3 Vehicle Aerodynamics

Aerodynamics affects the essential properties of an automobile. These range from vehicle performance in terms of fuel (Energy) consumption, top speed, stability, and etc. to esthetics and functionality. The flow characteristic to which a moving vehicle is subjected falls into three categories according to Thomas, 2016:

- i. Flow of air around the vehicle
- ii. Flow of air through the vehicle's body
- iii. Flow processes within the vehicle machinery

2.3.1 Flow Phenomenon Related to Vehicles

In vehicle aerodynamics, with regards to vehicle shape and kinematic flows around the vehicle are fully three dimensional and turbulent (Thomas, 2016).

2.3.1.1 Fluid Properties

- **Density:** is a fluid property defined as its mass per unit volume. In fluids this property depends on pressure and temperature. For road vehicles operated at 1/3 of the speed of sound the variation of density due to pressure and temperature changes is negligible. Thus, the fluid is regarded as incompressible (Hucho, 1990).
- **Viscosity:** is caused by the molecular friction between the fluid particles (Hucho, 1990). In a very generic sense, it is a measure of fluid resistance to motion (Joseph, 1995). The viscosity of a real fluid is the physical reason for the occurrence of friction drag.
- **Reynold's Number (Re):** is a dimensionless parameter and describes the physical relation between inertia to friction terms in the Navier Stokes equation (Thomas, 2016). The magnitude of Reynold's number indicates in a flow is either laminar or turbulent (with increasing magnitude becoming more turbulent) (Joseph, 1995). This dimensionless number is a function of vehicle's speed (V), fluid kinematic viscosity (ν) and characteristics length of the vehicle (L) (Hucho, 1990).

$$Re = \frac{V_{\infty} L}{\nu} \quad \dots (2.23)$$

When considering the characterization of a viscous flow it depends on the body shape and the dimensionless Reynold's number. In low sub-sonic flows, the Reynold's number relation of mechanically similar bodies can be achieved by increasing the free stream velocity for scaled down baseline models.

2.3.1.2 The Boundary Layer

Considering flow past a body submerged in a uniform stream; due to the fluid viscosity, the velocity on the surface of the stationary plate becomes zero while the thin layer exists where the velocity parallel to the plate gradually reaches the freestream velocity V_{∞} . This layer of rapid change of in tangential velocity is called boundary layer. The thickness of the boundary layer is

several millimeters at the front and can be several centimeters at the back of a streamlined car (Joseph, 1995).

2.3.1.3 Laminar and Turbulent Boundary Layer Development

The flow in a boundary layer along a thin flat plate, the corresponding external flow has parallel streamlines and constant velocity V_∞ , and pressure P_∞ . The viscous flow within the boundary layer fulfills the no slip conditions along the wall. At the front part of the plate the boundary layer flow is steady and almost parallel to the wall. This flow is called laminar flow (Hucho, 1990).

The thickness of the boundary layer increases down-stream with increasing distance and kinetic viscosity, with the decreasing freestream velocity the boundary layer thickness increase (Joseph, 1995).

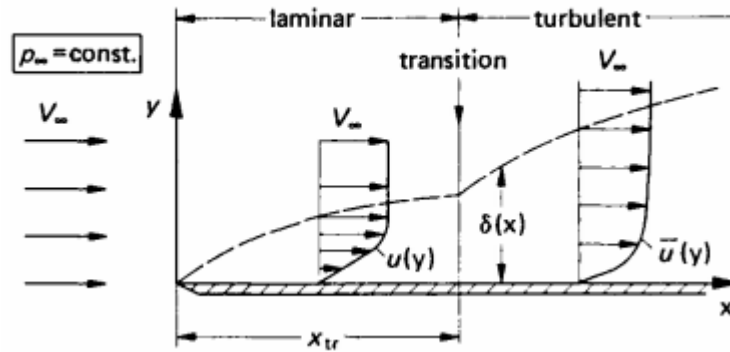


Figure 2.6: Boundary Layer along a flat plate (Hucho, 1990)

The laminar state of the boundary layer flow is stable against disturbances for certain conditions only. At distance $x=x_{tr}$ from the leading edge of the plate a transition to the so-called turbulent state of the boundary takes place. The transition between the two states of boundary layer flows is largely governed by the value of the Reynold's number (Hucho, 1990).

2.3.1.4 Flow Separation

Laminar and turbulent boundary layer flows depend strongly on the pressure distribution which is imparted by the external flow. For a pressure increase in flow direction the boundary layer flow is retarded, especially near wall and even reversed flow may occur (Hucho, 1990).

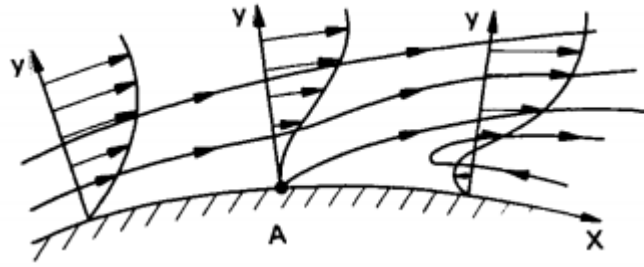


Figure 2.7: Separation of Boundary Layer flow at the Wall (Hucho, 1990)

In the figure above it is observed that between the forward and reversed flow a dividing streamline leaves the wall. This phenomenon is what is called flow separation (Hucho, 1990). This flow separation usually occurs at the rear of the vehicle (Cakir, 2012). Such separated flows around the vehicle result in unsteady wake flows, which are likely to generate higher resistance (Drag) (Joseph, 2016).

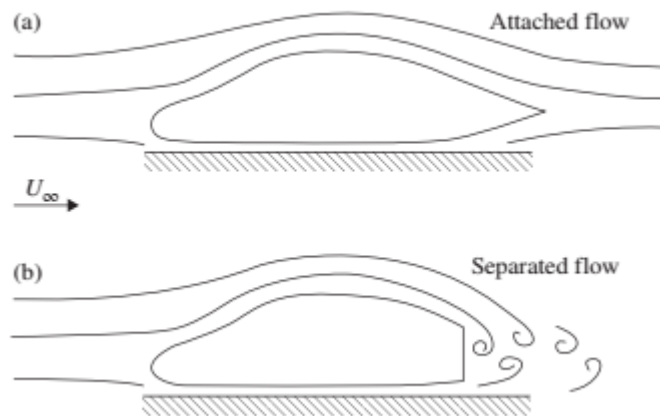


Figure 2.8: (a) Attached Flow Over a Streamlined Car, and (b) Locally Separated Flow Behind a More Realistic Automobile Shape (Joseph, 2016)

Flow separation controls to mitigate its adverse effects have been studied and applied (Collis et al., 2004; Mathieu et al., 2008; Mohamed et al., 1998). Another novel solution is to slightly smoothen sharp flow edges (Thomas, 2016).

2.3.1.5 Friction Drag

As a result of velocity gradient present in a viscous fluid at the wall due to molecular friction a shear stress acts everywhere on the surface of the body. The integration of the corresponding force

components in the freestream direction leads to friction drag $[D]$ (Hucho, 1990). The non-dimensional drag coefficient is represented as:

$$C_D = \frac{D}{\frac{\rho}{2} V_\infty^2 b l} \quad \dots (2.24)$$

2.3.1.6 Pressure Drag

At the rear of blunt bodies (for example, automobiles) in inviscid external flow, extremely steep pressure gradient occur which lead to flow separation (Hucho, 1990). The flow at the front of the bluff body experience suction due to the flow separation, hence, low pressure exists at the rear (Cakir, 2012). Integrating the force components in the freestream direction, resulting from the pressure distribution gives pressure drag (Hucho, 1990). The non-dimensional drag coefficient is represented as:

$$C_D = \frac{D}{\frac{\rho}{2} V_\infty^2 A} \quad \dots (2.25)$$

2.4 Computational Fluid Dynamics (CFD)

According to (Oleg, 2010) CFD can be defined as:

“CFD (Computational fluid dynamics) is a set of numerical methods applied to obtain approximate solution of problems of fluid dynamics and heat transfer.”

According to the definition by (Oleg, 2010), CFD is not a science in and of itself, but rather a method of applying methods from one discipline (numerical analysis) to another (heat and mass transfer). In retrospect, it integrates not only the disciplines of fluid mechanics with mathematics but also with computer science (Jiyuan et al., 2018). CFD is a cost-effective alternative to experimental and analytical approaches for simulating real-world fluid flows. CFD, in particular, significantly reduces design and production lead times and costs when compared to an experimental-based approach, and allows for the solution of a variety of complex flow problems where the analytical approach fails (Jiyuan et al., 2018).

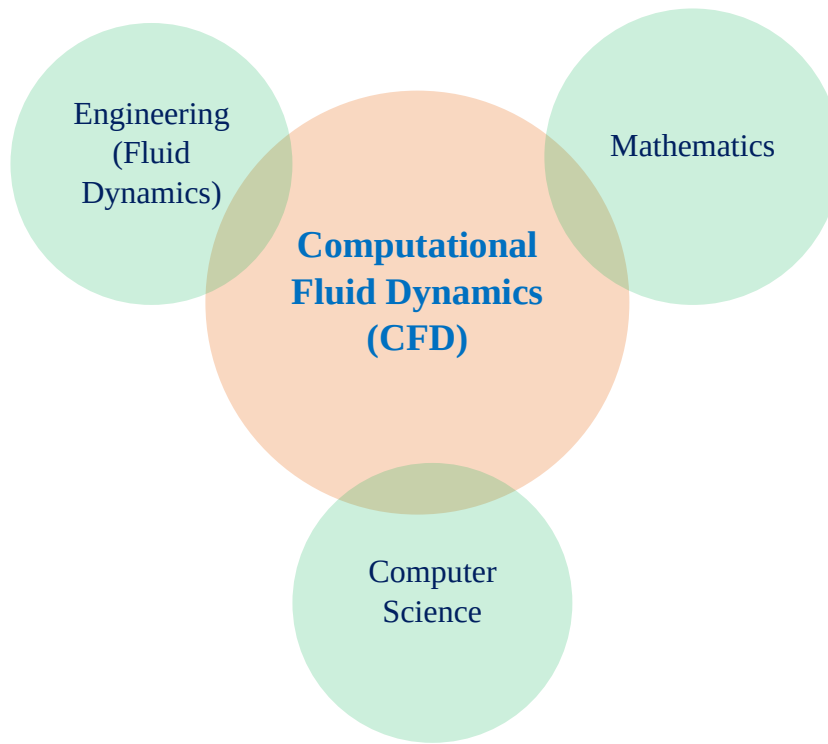


Figure 2.9: The Different Disciplines Contained Within Computational Fluid Dynamics (Jiyuan et al., 2018).

2.5 Numerical Models

Assumptions

The numerical model is based on the following initial assumptions:

- The flow is steady, turbulent and three-dimensional
- The fluid flow is characterized by single phase and non – chemically reacting gas.
- The velocity over the vehicle body is uniform
- Constant fluid (air) properties are considered, and treated using the Boussinesq Approximation.

2.5.1 Governing Equations

The cornerstone of computational fluid dynamics is the fundamental governing equations of fluid dynamics; the continuity, momentum and energy equations. These equations speak physics. They are the mathematical statements of three fundamental physical principles upon which all of fluid dynamics is based (Wendt, 2009). The air flow can be considered incompressible as the velocities are low (air flows can usually be considered incompressible if the Mach number is less than

roughly 0.3 or about 100m/s). Also, air being a Newtonian fluid displays a linear relationship between shear and strain rate. The laws of conservation of mass (continuity) and conservation of momentum are used to describe the flow based on the assumptions discussed. Expressions (2.26), (2.27), (2.28), and (2.29) below are Navier Stokes equations in the x, y and z directions and the continuity equation which describes the flow (Cable, 2009).

Conservation of Momentum equations:

$$\text{x-component:} \quad \frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u \vec{V}) = -\frac{\partial P}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \quad \dots (2.26)$$

$$\text{y-component:} \quad \frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v \vec{V}) = -\frac{\partial P}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \quad \dots (2.27)$$

$$\text{z-component:} \quad \frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w \vec{V}) = -\frac{\partial P}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \quad \dots (2.28)$$

Conservation of mass (continuity) equation:

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0 \quad \dots (2.29)$$

2.5.2 Turbulence Modelling

Turbulent flows are characterized by fluctuating velocity fields. These fluctuations mix transported quantities such as momentum, energy, and species concentration, and cause the transported quantities to fluctuate as well. Since these fluctuations can be of small scale and high frequency, they are too computationally expensive to simulate directly in practical engineering calculations. Instead, the instantaneous (exact) governing equations can be time-averaged, ensemble-averaged, or otherwise manipulated to remove the resolution of small scales, resulting in a modified set of equations that are computationally less expensive to solve. However, the modified equations contain additional unknown variables, and turbulence models are needed to determine these variables in terms of known quantities (ANSYS®, 2009).

Admittedly, no single turbulence model is universally acknowledged as being preferable for all kinds of situations. The physics included in the flow, the known practice for a certain type of problem, the level of precision desired, the available computational resources, and the amount of time available for the simulation will all influence the turbulence model used.

Two time-dependent solutions turbulence modeling alternatives that render the Navier-Stokes equations so that small scale turbulent fluctuations do not have to be directly simulated, can be employed; namely Reynolds Averaging (RANS) and Reynolds Spatial Filtering (LES). Both in RANS and LES, are eddy viscosity models that are used to substitute either the Reynolds- or the sub grid stress tensor. After the introduction of an eddy viscosity (turbulent viscosity), both the RANS and LES momentum equations are formally identical. The difference lies exclusively in the size of the eddy viscosity provided by the underlying turbulence model (ANSYS®, 2009, 2016). The Reynolds-averaged Navier-Stokes (RANS) equations govern the transport of the averaged flow quantities, with the whole range of the scales of turbulence being modeled. The RANS-based modeling approach therefore greatly reduces the required computational effort and resources, and is widely adopted for practical engineering applications. A brief description of the RANS models will be discussed in this section. The Entire hierarchy of the RANS models include Spalart-Allmaras, k- ϵ and its variants, k- ω and its variants, and the Reynolds stress equation model (RSM) (ANSYS®, 2009).

2.5.2.1 Spalart-Allmaras Model

The Spalart-Allmaras model (Spalart & Allmaras, 1994), is a one-equation model that solves a modeled transport equation for the kinematic eddy (turbulent) viscosity. The Spalart-Allmaras model was designed specifically for aerospace applications involving wall-bounded flows. The transport equation for the modified turbulent viscosity is:

$$\frac{\partial}{\partial t}(\rho \tilde{\nu}) + \frac{\partial}{\partial x_i}(\rho \tilde{\nu} u_i) = G_v + \frac{1}{\sigma_{\tilde{\nu}}} \left[\frac{\partial}{\partial x_j} \left\{ (\mu + \rho \tilde{\nu}) \frac{\partial}{\partial x_j}(\tilde{\nu}) \right\} + C_{b2} \rho \left(\frac{\partial}{\partial x_j}(\tilde{\nu}) \right)^2 \right] - Y_v + S_{\tilde{\nu}} \dots (2.30)$$

Turbulent viscosity, production and destruction terms are computed from (modelled us) using the expressions on (2.31), (2.32), and (2.33) respectively:

$$\mu_t = \rho \tilde{\nu} f_{v1} \dots (2.31)$$

$$G_v = C_{b1} \rho \tilde{S} \tilde{\nu} \dots (2.32)$$

$$Y_v = C_{w1} \rho f_w \left(\frac{\tilde{\nu}}{d} \right)^2 \dots (2.33)$$

2.5.2.2 K-Epsilon Turbulence Model

The K-Epsilon model has become one of the most widely used turbulence models as it provides robustness, economy and reasonable accuracy for a wide range of turbulent flows. The model uses two-equation turbulence models that allow the determination of both, a turbulent length and time scale by solving two separate transport equations. This model includes the standard, RNG, and realizable k- ϵ models. All three models have similar forms, with transport equations for k and ϵ . The major differences in the models are stated in (ANSYS®, 2016):

2.5.2.2.1 Standard k- ϵ Model

The standard **k- ϵ** model proposed by Launder and Spalding (Launder & Spalding, 1972) is a model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ϵ). The model transport equation for k is derived from the exact equation, while the model transport equation for ϵ was obtained using physical reasoning and bears little resemblance to its mathematically exact counterpart. The turbulence kinetic energy, k, and its rate of dissipation, ϵ , are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial}{\partial x_j} (k) \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \dots (2.34)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial}{\partial x_j} (\epsilon) \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} + S_\epsilon \dots (2.35)$$

The turbulent (or eddy) viscosity at each point is related to the local values of turbulent kinetic energy and its dissipation rate by:

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \dots (2.36)$$

2.5.2.2.2 RNG k- ϵ Model

According to (Yakhot & Orszag, 1986) The RNG-based k- ϵ turbulence model is derived from the instantaneous Navier-Stokes equations, using a mathematical technique called “renormalization group” (RNG) methods. The analytical derivation results in a model with constants different from those in the standard k- ϵ model, and additional terms and functions in the transport equations for k and ϵ . The RNG k- ϵ model was derived using a statistical technique called renormalization group theory. It is similar in form to the Standard k- ϵ model, but includes multiple refinements (ANSYS®, 2016). Due to the refinements stated in (ANSYS®, 2016) the RNG k- ϵ model is

considered more accurate than the standard k- ε model for a wide range of flow conditions. The transport equations are expressed as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left[\alpha_k \mu_{eff} \frac{\partial}{\partial x_j}(k) \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad \dots (2.37)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_i} \left[\alpha_\varepsilon \mu_{eff} \frac{\partial}{\partial x_j}(\varepsilon) \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon \dots (2.38)$$

The RNG model uses a scale elimination technique that defines the effective viscosity given in the equation below.

$$d \left(\frac{\rho^2 k}{\sqrt{\varepsilon \mu}} \right) = 1.72 \frac{\hat{v}}{\sqrt{\hat{v}^3 - 1 + C_v}} d\hat{v} \quad \dots (2.39)$$

Where $C_v \cong 100$. This equation incorporates the ability to accurately define how the effective turbulent transport varies with effective Reynolds number to obtain more accurate results for low-Re flows and near-wall flows. For high Reynolds numbers, the effective viscosity is defined by:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad \dots (2.40)$$

Even though the equation is identical to the standard k- ε model the computed value for the constant C_μ is 0.0845, while the standard model value is 0.09.

The model constants $C_{1\varepsilon}$ and $C_{2\varepsilon}$ have values derived analytically by the RNG theory

$$C_{1\varepsilon} = 1.24 \quad C_{2\varepsilon} = 1.68 \quad \dots (2.41)$$

2.5.2.2.3 Realizable k- ε Model

The Realizable model by (Shih et al., 1995) is the most recently developed of the three K-Epsilon variations and features two main differences from the standard K-Epsilon model. It uses a new equation for the turbulent viscosity and the dissipation rate transport equation has been derived from the equation for the transport of the mean-square vorticity fluctuation. The form of the eddy viscosity (turbulent) equations is based on the realizability constraints; the positivity of normal Reynolds stresses and Schwarz' inequality for turbulent shear stresses (i.e., certain mathematical constraints on the normal stresses are satisfied). This is not satisfied by either the standard or the RNG K-Epsilon models which makes the realizable model more precise than both models at

predicting flows such as separated flows and flows with complex secondary flow features (Cable, 2009). The modeled transport equations for k and ε in the realizable k - ε model are:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial}{\partial x_j} (k) \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad \dots (2.42)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial}{\partial x_j} (\varepsilon) \right] + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \dots (2.43)$$

Where, C_2 is a constant and $C_1 = \max(0.43, \frac{\eta+5}{\eta})$.

As in other models, the eddy viscosity is computed from (ANSYS®, 2009):

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad \dots (2.44)$$

The difference between the realizable k - ε model and the standard and RNG k - ε models is that C_μ is no longer constant. It is computed from:

$$C_\mu = \frac{1}{A_0 + A_S \frac{k U^*}{\varepsilon}} \quad \dots (2.45)$$

The model constants A_0 and A_S are given by:

$$A_0 = 4.04, A_S = \sqrt{6 \cos \phi} \quad \dots (2.46)$$

The values of model constants are computed as; $C_{1\varepsilon} = 1.44$, $C_2 = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$ & $\sigma_\varepsilon = 1.2$

2.5.2.3 K-Omega Turbulence Model

Another form of RANS modeling is the two-equation K-Omega turbulence model. Standard, baseline (BSL), and shear-stress transport (SST) k - ω models are the three formulations. The transport equations for k and ω are identical in all three models. The significant differences between the BSL and SST models, and the standard model are given on (ANSYS®, 2016).

2.5.2.3.1 Standard K-Omega Turbulence Model

The standard k - ω model in ANSYS Fluent® is based on the Wilcox k - ω model (Wilcox, 1993), which incorporates modifications for low-Reynolds number effects, compressibility, and shear flow spreading. One of the weak points of the Wilcox model is the sensitivity of the solutions to

values for k and ω outside the shear layer (freestream sensitivity). The turbulence kinetic energy, k , and the specific dissipation rate, ω , are obtained from the following transport equations (ANSYS®, 2016):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left[\Gamma_k \frac{\partial}{\partial x_j} (k) \right] + G_k - Y_k + S_k \quad \dots (2.47)$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_i} \left[\Gamma_\omega \frac{\partial}{\partial x_j} (\omega) \right] + G_\omega - Y_\omega + S_\omega \quad \dots (2.48)$$

The effective diffusivities for the standard k - ω model are given by:

$$\Gamma_k = \mu + \frac{\mu_t}{\sigma_k} \quad \dots (2.49)$$

$$\Gamma_\omega = \mu + \frac{\mu_t}{\sigma_\omega} \quad \dots (2.50)$$

where σ_k and σ_ω are the turbulent Prandtl numbers for k and ω , respectively. The turbulent viscosity, μ_t , is defined using a damping coefficient α^* and computed by combining k and ω as follows:

$$\mu_t = \alpha^* \frac{\rho k}{\omega} \quad \dots (2.51)$$

The coefficient α^* damps the turbulent viscosity causing a low-Reynolds-number correction. It is given by:

$$\alpha^* = \alpha_\infty^* \left(\frac{\alpha_0^* + \frac{Ret}{R_k}}{1 + \frac{Ret}{R_k}} \right) \quad \dots (2.52)$$

Note that, in the high-Reynolds-number form of the k - ω model, $\alpha^* = \alpha_\infty^* = 1$.

Additional mathematical relations for turbulence production and dissipation are discussed in (ANSYS®, 2016; Wilcox, 1993).

2.5.2.3.2 Baseline (BSL) K-Omega Turbulence Model

The baseline k - ω model was developed by (Menter, 1993), to effectively blend the robust and accurate formulation of the k - ω model in the near-wall region with the freestream independence of the k - ε model in the far field. To achieve this, the k - ε model is converted into a k - ω formulation.

The BSL k- ω model is similar to the standard k- ω model, but includes the additional refinements (ANSYS®, 2016).

The BSL k- ω model has a similar form to the standard k- ω model:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left[\Gamma_k \frac{\partial}{\partial x_j} (k) \right] + G_k - Y_k + S_k \quad \dots (2.53)$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_i} \left[\Gamma_\omega \frac{\partial}{\partial x_j} (\omega) \right] + G_\omega - Y_\omega + D_\omega + S_\omega \quad \dots (2.54)$$

The effective diffusivities for the BSL k- ω and standard k- ω model are expressed by identical mathematical expressions (2.44), and (2.50). Where σ_k and σ_ω are the turbulent Prandtl numbers for k and ω , respectively. The turbulent viscosity, μ_t , is computed as defined by (2.51), where:

$$\sigma_k = \frac{1}{\frac{F_1}{\sigma_{k,1}} + \frac{(1-F_1)}{\sigma_{k,2}}} \quad \dots (2.55)$$

$$\sigma_\omega = \frac{1}{\frac{F_1}{\sigma_{\omega,1}} + \frac{(1-F_1)}{\sigma_{\omega,2}}} \quad \dots (2.56)$$

Additional mathematical relations for turbulence production and dissipation, and cross-diffusion are discussed in (ANSYS®, 2016; Wilcox, 1993) along with the modeling constants.

2.5.2.3.3 *Shear Stress Transport (SST) K-Omega Turbulence Model*

The SST k- ω model includes all the refinements of the BSL k- ω model, and in addition accounts for the transport of the turbulence shear stress in the definition of the turbulent viscosity. These features make the SST k- ω model by (Menter, 1993), more accurate and reliable for a wider class of flows than the standard and the BSL k- ω models.

The BSL model described previously combines the advantages of the Wilcox and the k- ϵ model, but still fails to properly predict the onset and amount of flow separation from smooth surfaces. The main reason is that both models do not account for the transport of the turbulent shear stress. This results in an overprediction of the eddy-viscosity. The proper transport behavior can be obtained by a limiter to the formulation of the eddy-viscosity (ANSYS®, 2016):

$$\mu_t = \frac{\rho k}{\omega} \frac{1}{\max \left[\frac{1}{\sigma^*}, \frac{SF_2}{a_1 \omega} \right]} \quad \dots (2.57)$$

The model constants are discussed in (ANSYS®, 2016; Wilcox, 1993).

2.6 Electric Generation

An electric generator is a machine that converts mechanical energy into electrical energy (Theraja & Theraja, 2005). There are two types of generators – Direct Current (DC) generator and Alternating Current (AC) Generators.

2.6.1 DC Generators

DC generators convert mechanical energy into an electrical energy characterized by direct current. The generator construction consists of a central looped conductor rotating on its axis in a magnetic field provided by either a permanent magnets or electro magnets. The ends of the conductors are joined to a commutator with insulated partitions. The current induced in the rotating conductors by the magnetic field is collected at the commutator and is conveyed to external load through collecting brushes pressed against the commutator. Essential components of a DC generator are show in figure 2.10.

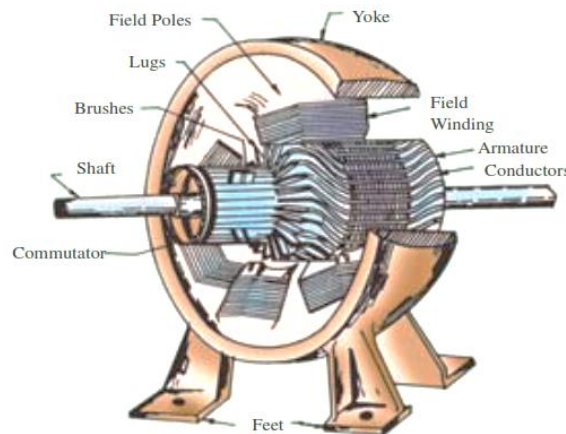


Figure 2.10: Components of a DC Generator

Even though, the DC generator produce unidirectional current, the voltage induced in the armature is still AC.

Total Losses in a DC Generator

- i. Copper losses
- ii. Iron losses
- iii. Mechanical losses
- iv. Stray/rotational losses

2.6.2 AC Generators

AC generators are machines that convert mechanical energy into electrical energy which is characterized by alternating current (Stephen, 2005). AC generators operate on the same fundamental principle of electromagnetic induction as DC generators. But the one important difference between the two is in AC generators the armature winding is mounted on the stator while the field windings/Permanent magnets are mounted on the rotating element or rotor. The reverse arrangement is true for DC generators (Theraja & Theraja, 2005). Detailed construction of AC generators is shown on figure 2.11.

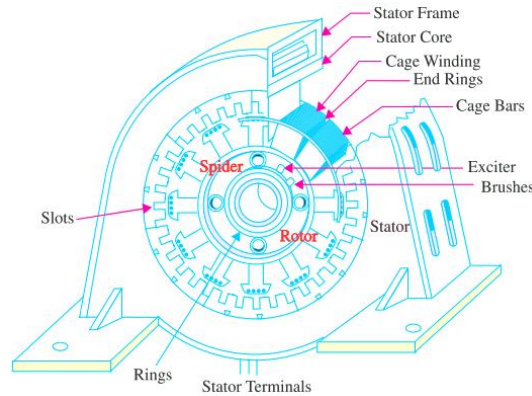


Figure 2.11: Construction of AC Generators (Theraja & Theraja, 2005)

There are two major classes of ac machines - synchronous machines and induction machines.

- i. **Induction (Asynchronous) Generator:** is a generator that operates with an independent source for its rotor field current, in which the rotor field current is supplied by electromagnetic induction from the magnetic field of the armature coil. The rotor in induction generators always lags behind the armature magnetic field frequency, this difference is called slip speed [3]. Even though an induction generator operates with independent power source it cannot be started up without being connected to a live AC source initially.
- ii. **Synchronous Generator:** is a generator whose fields windings are supplied by a separate DC power source to generate magnetic field (Stephen, 2005)[2]. The rotor of a synchronous generator is essentially a large elector magnet. The magnetic poles on the rotor can either be of Salient or Non-Salient (Smooth) construction as shown in figure 2.12. As the name synchronous generator implies, the rotor rotation per second is identical/synchronous with the frequency of induced magnetic field in the armature coil (Alexandera, 2006).

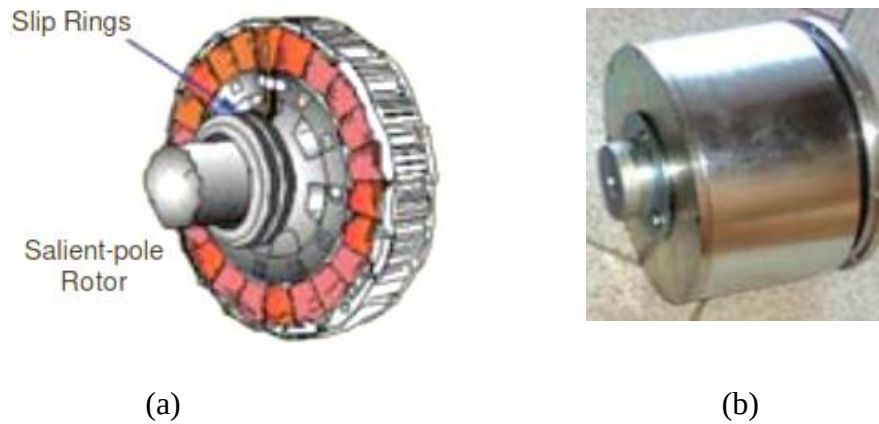


Figure 2.12: Field winding of Synchronous Generator (a) Salient, and (b) non-Salient (Theraja & Theraja, 2005)

Another design iteration of synchronous generators replaces the field winding and its excitation source with a permanent magnet. This design iteration is called permanent magnet synchronous generator (PMSG).

2.7 Rectification

The purpose of a rectifier circuit is to produce a DC voltage (VDC) and current from an AC source. There are two types of rectification processes – Controlled rectification and Uncontrolled rectification. Controlled rectification is accomplished by silicon-controlled rectifiers (SCR), also known as Thyristors; Uncontrolled rectification is performed by diodes (Randall, 2007). Uncontrolled rectification in comparison provides a less expensive alternative with performance limitations (Laughton & Warne, 2003; Ned et al., 2003). The current from AC generators range from single to multiple phases. The AC phase can be rectified using half or full wave rectifiers. As far as this thesis work is concerned un controlled single and three phase full wave rectifiers discussed for comparison.

2.7.1 Single Phase Full Bridge Rectifiers

Theis single phase rectifiers use two pairs of diodes that are use alternating pairs to rectify the positive and negative cycles of the single-phase AC source. The single-phase full bridge rectifier shown in figure 2.13 uses D_1 and D_2 for the positive cycle and D_3 and D_4 for the negative cycle (Ned et al., 2003).

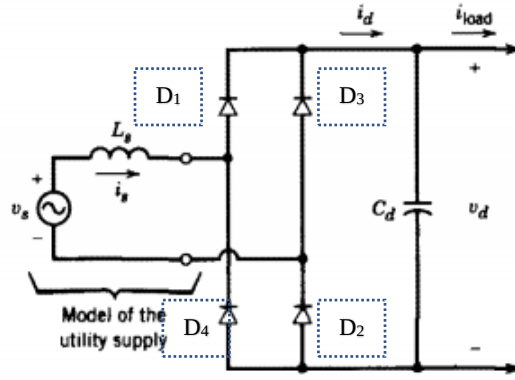


Figure 2.13: Single Phase Full Bridge Rectifier Circuit (Ned et al., 2003)

A capacitor is used to filter the rectified output from the diode pairs. The filtered voltage is constant and has low ripples, which is desirable for DC application (Fitzgerald et al., 2003).

2.7.2 Three Phase Full Bridge Rectifier

The rectifier shown in figure 2.14 is a three phase six pulse full bridge diode rectifier, which is the most commonly used circuit arrangement (Ned et al., 2003). The rectification action employs 3 pairs of diodes and a filter capacitor connected on the DC side.

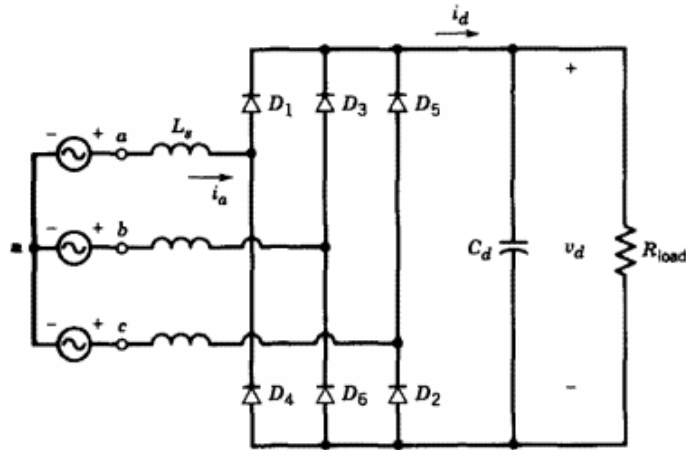


Figure 2.14: Three Phase Full Bridge Rectifier Circuit (Ned et al., 2003)

In industrial applications where three-phase AC voltages are available, it is preferable to use three-phase rectifier circuits, compared to single-phase rectifiers, because of their lower ripple content in the waveforms and a higher power-handling capability.

2.8 Literature Summary

From the literatures surveyed, different methods with various analytical approaches were implemented to validate and realize the energy recovery potential of a vehicle mounted wind turbine systems. The works reviewed so far have indicated that:

- i. A small-scale micro wind turbine assembly mounted at the front of the vehicle can have a potential for supplying power to the battery with negligible effect on the vehicle aerodynamics.
- ii. Carrying out drive cycle-based analysis and tests has shown varying recovery potential which can determine the system utilization scheduling/forecast.
- iii. For a wind turbine generator assembly mounted on the vehicle roof top the vehicle's drag coefficient greatly increases.
- iv. The majority of the reviewed works suggest for further detailed and thorough investigation.

2.9 Research Gaps

The reviewed literatures are works to corroborate a valid and potentially viable means of energy recovery approach. But the work done in some of the literatures is too small to be applicable for a real-world application involving electric vehicle drive range extension.

Also, works which employ CFD analysis computed the results for a single type of turbine design to identify the aerodynamic property effects only. This kind of analysis do not give a comparative perspective for varying effects arising from turbine designs. This study aims to provide a broader range of CFD simulations result datas by expanding the design alterations.

Recovered energy and vehicle driving range estimations are in some cases based on a system with no loss. One work has estimated the recovered energy by considering performance coefficients of three components (turbine, multipliers and generator). In none of the works reviewed in section 2.1 that a credible range estimation has been made whether it be an increased or reduced driving range. So, one of the emphases of this work is true estimation for the vehicle driving range by implementing physical modeling.

CHAPTER THREE

MATERIALS AND METHODOLOGY

The materials used to conduct the research and the methodologies used are discussed in this chapter. The activities carried out in the study include road tests for data collection and multiple software simulations with inter-dependent variables.

3.1 Materials

Materials utilized for the study are for the purposes of acquiring simulation input parameters, i.e., Digital Anemometer (BT-866A) to measure wind speed and a GPS to record vehicle speed, and to conduct simulations which involved utilization of a number of hardware (Personal Computers) and softwares (SOLIDWORKS 2017, ANSYS 2021 R2, and MATLAB 2019b). The purpose of each software is stated below:

- SOLIDWORKS 2017: used of generating 3D models.
- ANSYS 2021 R2: used for performing CFD simulations, and
- MATLAB 2019b: used to construct Physical Models and simulate the required electric vehicle performance parameters.

3.2 Methodology

First the baseline vehicle model for study is selected on which implementation of the ERS is realized. Using Solidworks 2017 software the 3D geometries of the baseline model, and the ERS with its components are generated. Then the simulations to be performed were identified which are categorized as:

a. CFD analysis of vehicle aerodynamic properties

This involves using ANSYS Fluent® software to determine the relevant aerodynamic properties of the vehicle being investigated. These properties include:

- ✓ Vehicle drag coefficient
- ✓ Pressure and Velocity distributions on aerodynamic surfaces.

b. Physical Modeling and Simulation

This involves using MATLAB Simulink® software, where real world equivalent electric vehicle and wind turbine generator components are simulated using blocks from Simscape™ libraries. From the physical model simulation, the obtained results include:

- ✓ Battery State of Charge (SOC)
- ✓ Vehicle travel distance
- ✓ Battery voltage and current

The above results are obtained for varying simulation input parameters of:

- ✓ Vehicle drag coefficient
- ✓ Driving Schedules

The results obtained from the simulation were compared and contrasted using tabulated and graphical formats to make the result analysis easy to understand. Once the simulation results are aggregated and represented in tabulated and graphical formats; the comparative differences in the obtained results are briefly explained with scientific reasoning.

3.2.1 Baseline Model

A 2012 Tesla Model S electric vehicle shown in figure 3.1 was selected as a baseline model. Body contour of the vehicle that outline the body shape of the base model were drafted. The three-dimensional (3D) model was generated for full scale corresponding vehicle dimensions. The model is designed with no side mirrors and smooth under-body. The three-dimensional model of the baseline model was generated using the SOLIDWORKS 2017 Software. The generated 3D model was transported to ANSYS Fluent® to carry out CFD simulations.



Figure 3.1: 2012 Tesla Model S (Tesla.Inc., 2012)

3.2.1.1 Geometry Generation

The baseline vehicle model's geometry was generated from the dimension given on table 3.8 using the SOLIDWORKS 2017 Software. The model design shown in figure 3.2 was considered as the baseline vehicle model throughout the simulations performed in the study.

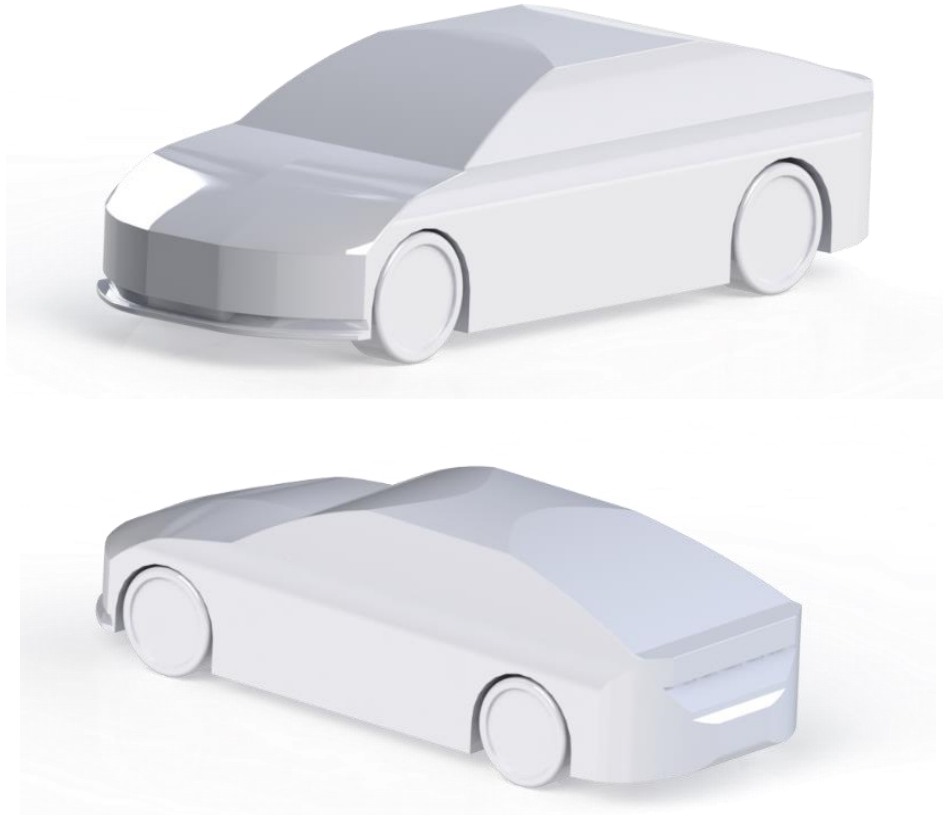


Figure 3.2: Baseline Vehicle 3D Model

3.2.1.2 Modifications Made to the Baseline Model

In order to accommodate the onboard installation of the energy recovery system, geometric alterations were made to the baseline model. A Y – shaped square ducting was cut through the baseline vehicle model's front end under the bonnet as shown in figure 3.3. The size of the ducting was dictated by the size of the energy recovery system installed. The ERS uses either a horizontal axis wind turbine (HAWT) or a vertical axis Savonius rotor wind turbine. Ducting size for the ERS with a HAWT is $200mm \times 200mm$ and for ERS with vertical axis savonius rotor wind turbine is $212mm \times 212mm$.

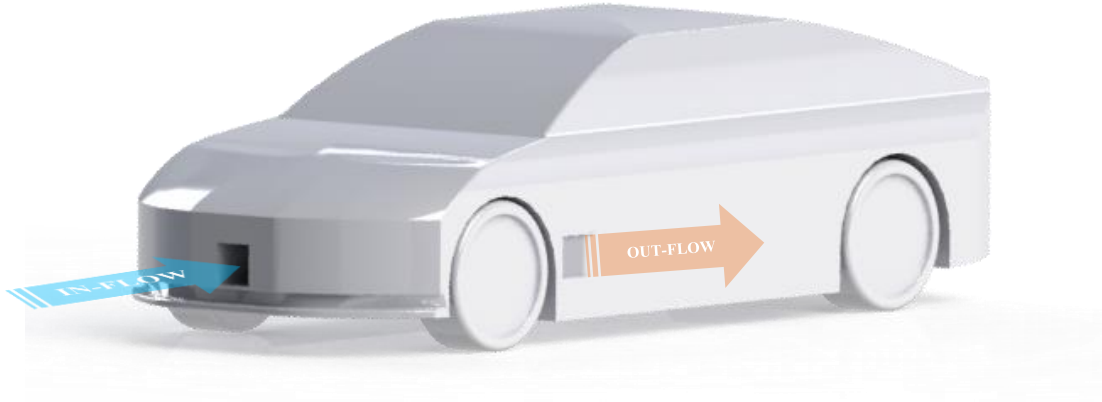


Figure 3.3: Baseline Model with Ducting Modification

The single ducting that starts at the front of the vehicle will split into two diverging paths that ideally divide the inflow in half and guide it to the outlets in two identical paths. At the ends of the two diverging flow paths is a flow outlet located right after the front wheel well arches. A more detailed inner ducting is shown using wireframe diagram in figure 3.4.

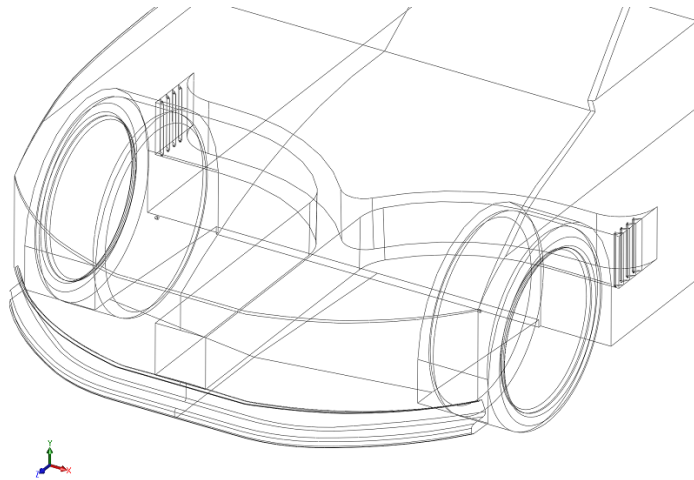


Figure 3.4: Wireframe Diagram of the Internal Ducting

At the outlets flow treatment devices (guide vanes) are placed to correct the out flow from the outlets, which is normal to the external flow. The flow treatment devices, which are symmetric airfoils, were placed at $45\text{-}60^\circ$ angle to the outlet flow to induce a more attached flow and reduce flow disturbance.



Figure 3.5: Flow Treatment Devices

3.2.2 Energy Recovery System (ERS) Modelling

The energy recovery system turbine designs considered in this thesis work are adopted from previous works done on turbine rotor design. The HAWT implementing ERS uses a HAWT adopted from (Kosasih & Tondelli, 2012), and the Vertical axis savonius rotor wind turbine implementing ERS uses a two-bucket single stage Savonius rotor adopted from (Kamoji et al., 2008). The specifications of both models are given on tables 3.1 & 3.2. The 3D models were then generated based on the stated specifications, shown in figure 3.6.

Table 3.1: HAWT Specifications (Kosasih & Tondelli, 2012)

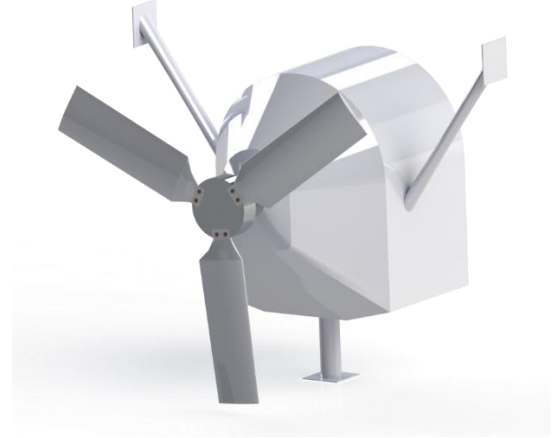
HAWT Specifications	
Airfoil Profile	NACA 63-210
Turbine Tip Diameter	190mm
Turbine Tip Speed Ratio (λ)	3.5
Area	0.028353m ²
Power Coefficient (C_p) at λ	0.45
Pitch angle (β)	5°
Chord Length	25mm (Constant)

Table 3.2: Savonius Rotor Specifications (Kamoji et al., 2008)

Savonius Rotor Specifications	
Rotor Diameter (D)	208mm
Rotor Height (H)	208mm
Aspect Ratio	1.00
Turbine Area	0.043264mm ²
Rotor Radius (R)	94.345
Overlap Ratio ($G = \frac{2}{2R}$)	0.15
Overlap Distance (a)	27.13
Turbine Tip Speed Ratio (λ)	0.78
Power Coefficient ($C_{p \max}$) at λ	0.161 (16.1%)
End Plate Diameter (D_o)	1.1(D)
End Plate Thickness (t)	1mm
Rotor Thickness (t_r)	1mm



(a)



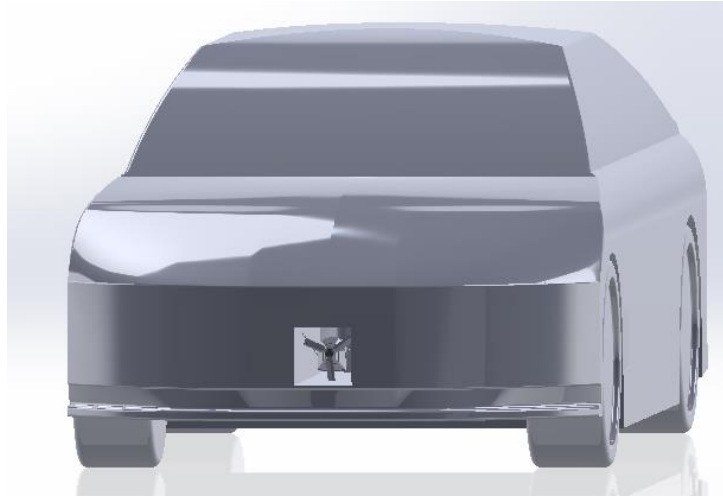
(b)

Figure 3.6: Employed ERSs, (a) Savonius Rotor, and (b) HAWT

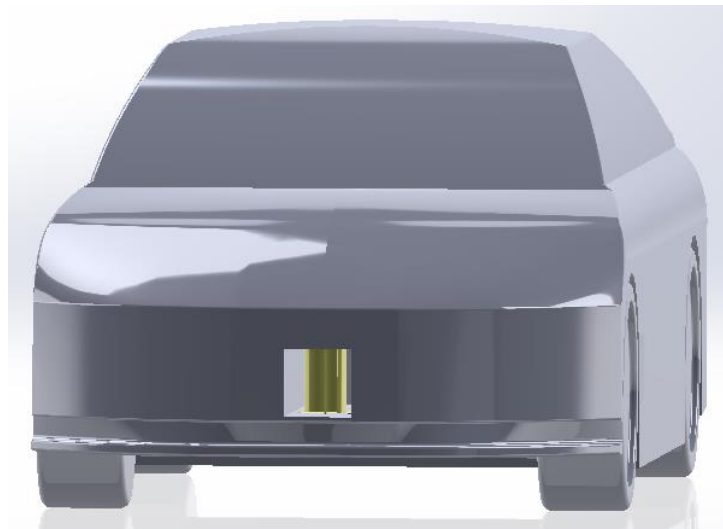
3.2.3 ERS Integrated Vehicle Modelling

The designed ERS models must now be integrated into the modified baseline vehicle model. Due to the existence of overhanging edges at the very front of the vehicle turbine accommodation at the very edge of the vehicle might be structurally compromising. Therefore, the ERS models were

installed at a distance of two time the dimension of the largest ERS model. Both ERS models were installed 400mm from the edge of vehicle's frontend. For ease of understanding from here on the integrated vehicle model with HAWT will be referred as Model – 1 and the integrated vehicle model with vertical axis savonius rotor wind turbine will be referred as Model – 2, as shown in figure 3.7.



(a)



(b)

Figure 3.7: ERS Integrated Models (a) Model – 1, and (b) Model – 2

The electric generation unit of model – 1, and model – 2 have varied orientations. The electric generating unit for model – 1 is located in a housing behind the rotor and for model – 2 the electric generating unit is located below the Savonius rotor. These arrangements can be seen on figure 3.8.

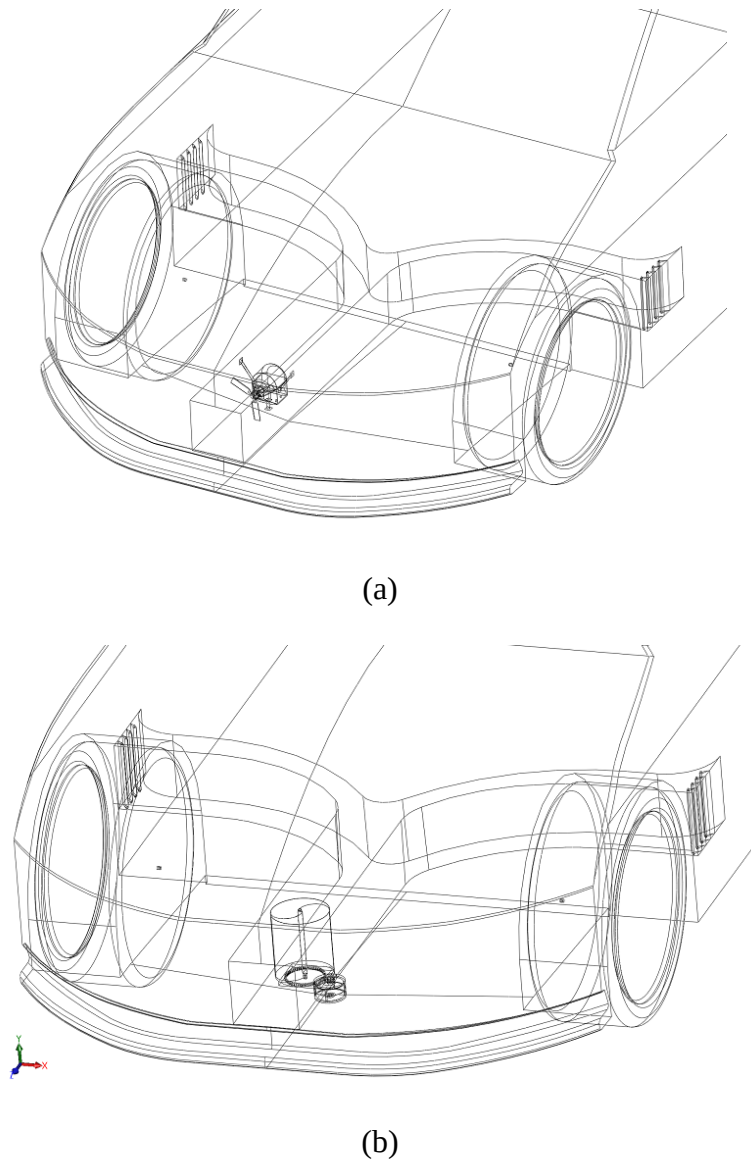


Figure 3.8: Wireframe Diagram of (a) Model – 1, and (b) Model – 2

3.2.4 CFD Simulation Setup

According to (Oleg, 2010) computational fluid dynamics (CFD) is a set of numerical methods applied to obtain approximate solution of problems of fluid dynamics and heat transfer. A number of commercially available softwares with prominent and widely used CFD solution codes are being used in many fields of academia, industrial sectors and research stations. For this thesis study ANSYS Fluent® 2021 R2 was used for CFD simulation on a geometry generated from SOLIDWORKS 2017. Procedures for CFD simulation were referred from (Jiyuan et al., 2018), which is shown in figure 3.9.

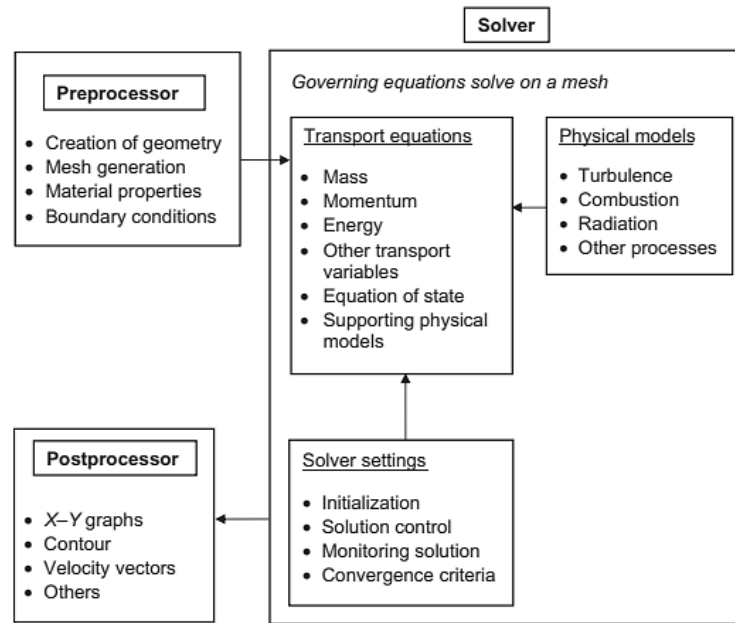


Figure 3.9: Elements of CFD Analysis Framework (Jiyuan et al., 2018)

3.2.4.1 Preprocessing

3.2.4.1.1 Creation of Geometry

Creation of geometry was the initial step in the CFD analysis. It involved the defining and generation of the flow computational domain for the CFD simulation by creating an enclosure around the models. In determining the dimensions of the domain, suggestion by Lanfrit, 2005 was considered. Lanfrit, 2005 Suggests computational domain dimensions to be at least three times the length of the vehicle upstream of the model and five times the length of the model downstream. Domain dimension to the top, and left & right of the model are three-fold of the height, and width respectively.

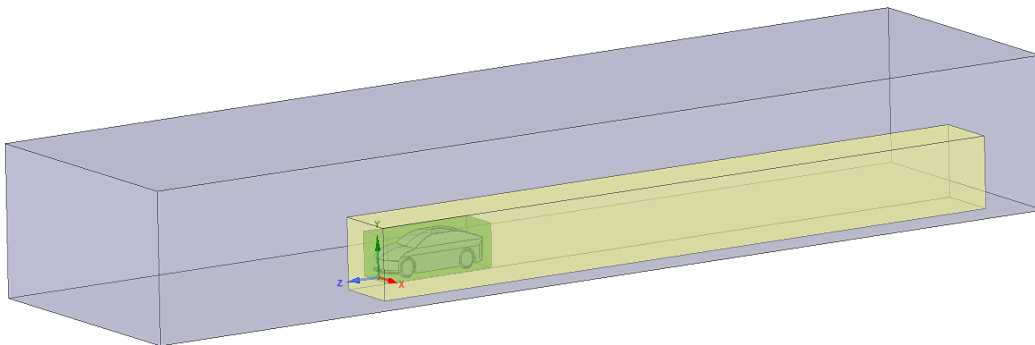


Figure 3.10: Computational Domain

The CFD computation was performed on full-scale models of baseline and ERS models. So, the computational domain is constructed on the bases of the full-scale vehicle model. The dimensions of the domain are given in table 3.4. The CFD simulation was performed over the entire domain due to the position of ERS on the vehicle.

Table 3.3: Computational Domain Dimensions

Computational Domain Boundary Dimensions				
Upstream Domain Boundary (mm)	Downstream Domain Boundary (mm)	Right Domain Boundary (mm)	Left Domain Boundary (mm)	Top Domain Boundary (mm)
14700	24500	5400	5400	4200

Computational domain wall labels shown on figure 3.11, were given to all six wall surfaces so that the numerical solver in ANSYS Fluent® identifies them and automatically applies the appropriated boundary conditions.

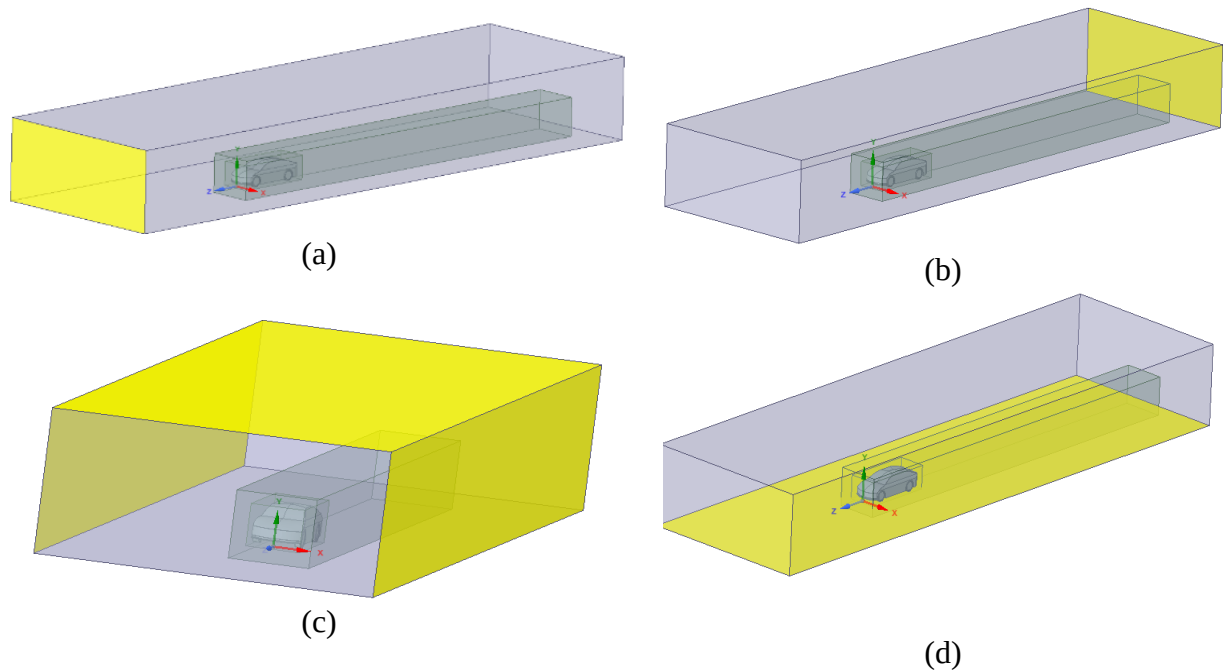
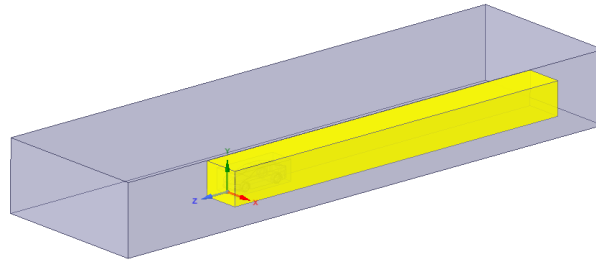
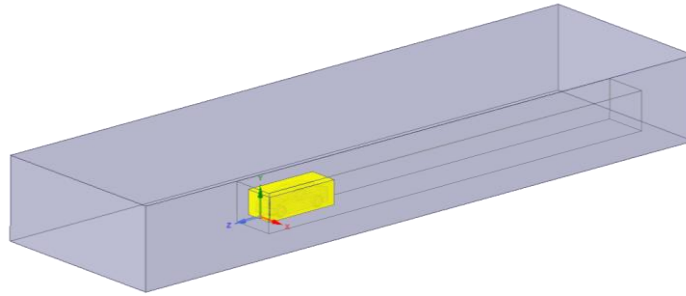


Figure 3.11: Computational Domain Labels (a) Velocity Inlet, (b) Pressure Outlet, (c) Tunnel Walls, and (d) Ground

Additionally, two bodies of influence (BoIs) were used to control the volume mesh on the models. (i) BoI near field, and (ii) BoI Far Field, shown in figure 3.12 will have gradually increasing mesh refinements from the model walls surfaces to the freestream conditions.



(a)

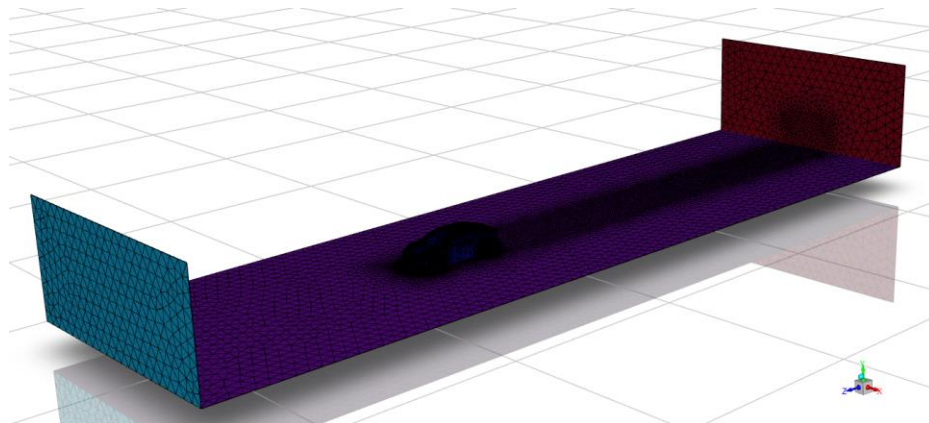


(b)

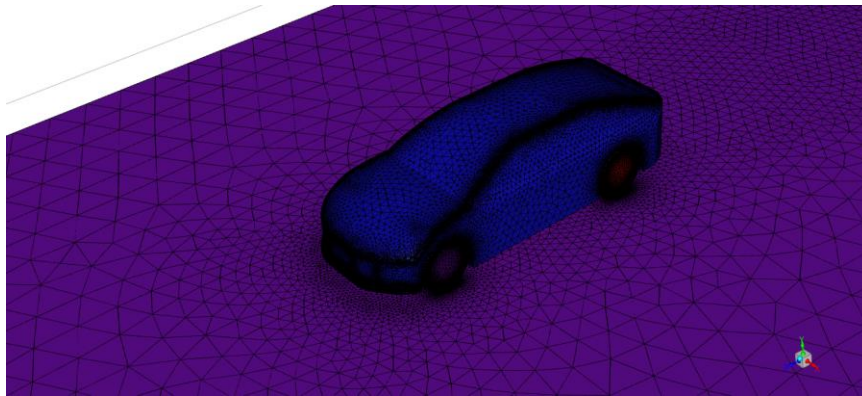
Figure 3.12: Bodies of Influence

3.2.4.1.2 Mesh Sizing

Meshing is an important step that comes after creating the geometry for simulation. It involves setting up mesh types and their sizing. In this study triangular meshes were developed to generate the surface mesh with local and global sizing. The local sizing was applied to the bodies of influence and model components with size control types of body of influence, face size and curvature. The local and global mesh sizing are listed on table 3.4 and table 3.5.



(a)



(b)

Figure 3.13: Surface Mesh Sizing

Table 3.4: Local Mesh Sizing Setting

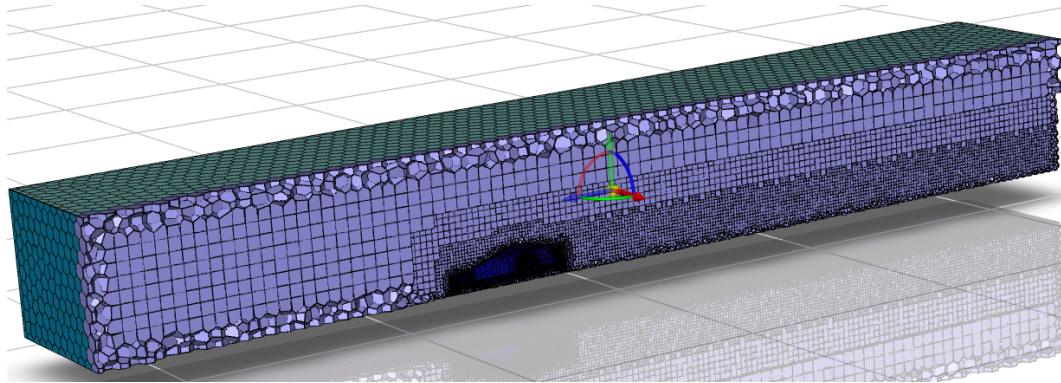
	Baseline Model	Model - 1	Model - 2
Body of Influence Near-Wall			
Size Control	Body of Influence		
Growth Rate	1.2 (20%)		
Target Mesh Size	125 mm		
Body of Influence Far Field			
Size Control	Body of Influence		
Growth Rate	1.2 (20%)		
Target Mesh Size	200 mm		
Vehicle Body			
Size Control	Face size		
Growth Rate	1.2 (20%)		
Target Mesh Size	125 mm		
Turbine Nacelle for Model - 1			
Size Control	Face Size		
Growth Rate	-	1.2 (20%)	-
Target Mesh Size	-	100 mm	-
Guide Vanes			
Size Control	Curvature		
Growth Rate	1.2 (20%)		
Local Min Size	1 mm		
Local Max Size	20 mm		
Curvature Normal Angle	18 ⁰		
Wheel Radii			
Size Control	Curvature		

Growth Rate	1.2 (20%)		
Local Min Size	1 mm		
Local Max Size	10 mm		
Curvature Normal Angle	18 ⁰		
Wheels			
Size Control	Curvature		
Growth Rate	1.2 (20%)		
Local Min Size	50 mm		
Local Max Size	125 mm		
Curvature Normal Angle	18 ⁰		
Turbine Nacelle Support for Model - 1			
Size Control	Curvature		
Growth Rate	-	1.2 (20%)	-
Local Min Size	-	5 mm	-
Local Max Size	-	20 mm	-
Curvature Normal Angle	-	18 ⁰	-
Savonius Rotor (Model – 2)			
Size Control	-	-	Curvature
Growth Rate	-	-	1.2 (20%)
Local Min Size	-	-	2 mm
Local Max Size	-	-	40mm
Curvature Normal Angle	-	-	18 ⁰
Turbine Rotor for Model – 1			
Size Control	Curvature		
Growth Rate	-	1.2 (20%)	-
Local Min Size	-	1 mm	-
Local Max Size	-	8 mm	-
Curvature Normal Angle	-	18 ⁰	-

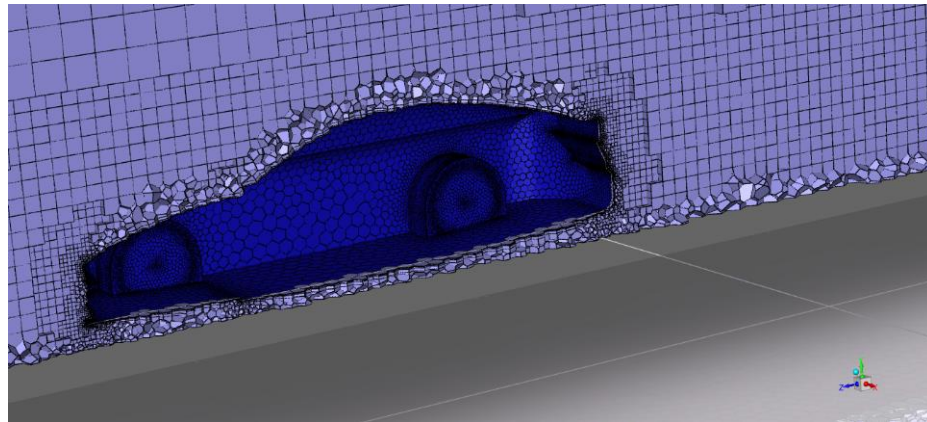
Table 3.5: Global Mesh Sizing

Global Mesh Sizing			
	Baseline Model	Model - 1	Model - 2
Minimum Size	10 mm		
Maximum Size	600 mm		
Growth Rate	1.2 (20%)		
Size Function	Curvature and Proximity		
Curvature Normal Angle	18 ⁰		
Cells Per Gap	1		

Once the surface mesh was generated a poly-hexacore volume mesh with manually assigned prismatic inflation layers was generated. Three inflation layers were used with 0.5mm first height and 0.2 transition ratios having last aspect ratio offset method for each layer. The volume mesh shown in figure 3.14 was generated with poly-hexacore fill having 1mm minimum cell length and 512mm maximum cell length. The final volume meshes were checked for orthogonal mesh quality of less than 0.1mm ($< 0.1\text{mm}$), which all the model meshes satisfied.



(a)



(b)

Figure 3.14: Volume Mesh Sizing

3.2.4.1.3 Grid independence Test

For the grid independence study, the volume mesh cell counts were refined to observe changes in the results of the study. The test was conducted by reducing values of the global surface mesh sizing, hence increasing the mesh cell count. As shown on Table 3.6 seven test runs were performed for gradually reducing and increasing mesh sizing.

Table 3.6: Mesh Refinements for Grid Independence Test

Test Runs	Global Mesh Sizes		Volume Mesh Cell Counts
	Minimum	Maximum	
1	17	800	183,539
2	15	800	335,471
3	11	600	627,489
4	9	600	738,940
5	8	600	853,552
6	5	500	1,156,919
7	3	500	1,588,735

The grid independence testing was performed to validate the accuracy of mesh refinements performed in the study, and determine the best grid size for the numerical investigation. The baseline model drag coefficient values were used for validation. From the further mesh refinements, it was observed that the percent variation of drag coefficient result after run 4 with volume mesh cell count of 738940 was less than 1.5%, from which it was concluded that the mesh independence can be achieved for volume mesh counts above seven hundred thousand cells. Therefore, the volume mesh with 853,552 cell count was selected for use in order to conserve both computing resources and time while retaining the result accuracies benefits of finer mesh. Figure shows the drag coefficient values for employed mesh refinements.

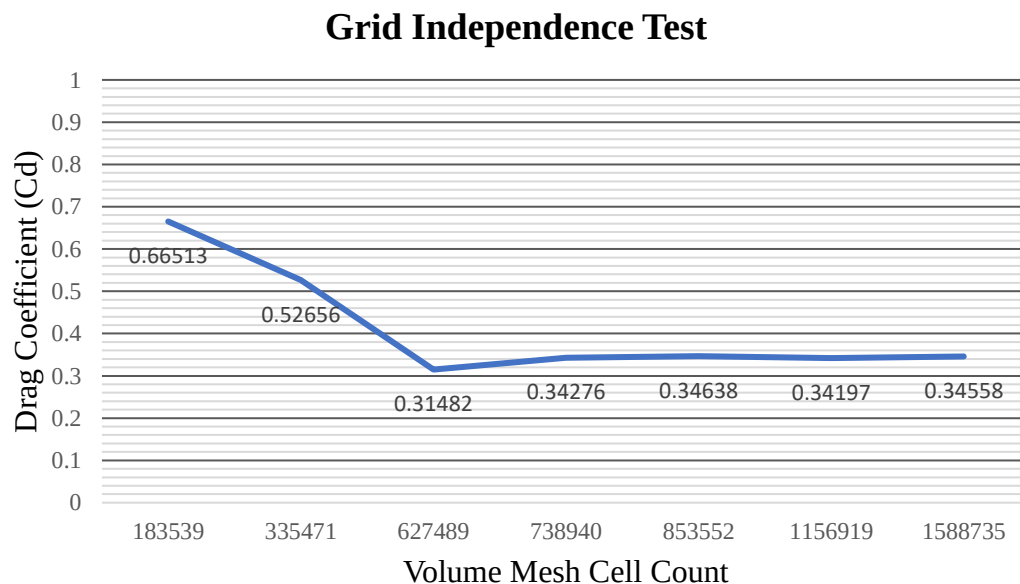


Figure 3.15: Grid Independence Test

3.2.4.2 Solver Settings

The solver setting includes identifying the type of solver, turbulence model, boundary condition and solution controls. The air in the simulation has flow path from velocity inlet which is upstream to the models to the pressure outlet downstream from the models. the flow velocity of air at the velocity inlet was set to 100 *km/hr* (27.78 **m/s**). The 100 *km/hr* speed limit for the simulation is set because of the recommended maximum cursing speed on the Addis Ababa – Adama high way is 100 *km/hr*.

The velocity inlet and outlet's turbulent intensity and turbulence rations were set with identical values of 0.5% and 2%respectively. These values were assigned to set the flow properties at both extremities to a relatively laminal flow with few fluctuations. Other solver settings related variables are listed in Table 3.7.

The study employed the Shear Stress Transport (SST) K-omega turbulence model for the simulation of all models. **WHY THE SST K-Omega MODEL?** The SST k- ω model which was developed by Menter, 1993, effectively blended the standard k- ω model's robust and accurate near wall region formulation to the freestream independent k- ϵ model formulation in the far field. The blended formulation ensures that the model equation behaves appropriately for both the near wall and far field zones. Section 2.7.2.3.3 discussed further refinements to the model that made it more accurate and reliable for a wider class of flows.

There are a number of research works which employ the k- ϵ models for external flow simulation around automobiles. The realizable k- ϵ model which is the most recent formulation with superior refinements when compared with the other k- ϵ models is accurate for flows with singular flow domains. When the computational domain contains both rotating and stationary fluid zones the model produces non-physical turbulent viscosities, and this is not desirable. The simulation carried out in this study contains both rotating (i.e., turbine rotors and wheel) and stationary flow regions (i.e., rest of model components), hence the reason for not choosing the k- ϵ models. After setting the turbulence model to be implemented boundary conditions listed on appendix – E were assigned to each component of the models. One final step following setup of all needed variables before running calculation was to set simulation/calculation monitor for drag and scaled residuals. The setup of only two monitors was dictated by the scope of the study which is identifying the model drag coefficients. The residual convergence absolute values were set to 0.001 (1e-3).

Table 3.7: Solver Setting

Equations	
Flow	True
Turbulence	True
Numeric	
Absolute Velocity Formulation	True
Pseudo Transient Explicit Relaxation Factors	
Density	1
Body Forces	1
Turbulent Kinetic Energy	0.75
Specific Dissipation Rate	0.75
Turbulent Viscosity	1
Explicit Momentum	0.5
Explicit Pressure	0.5
Pressure-Velocity Coupling	
Type	Coupled
Pseudo Transient	True
Discretization Scheme	
Pressure	Second Order
Momentum	Second Order Upwind
Turbulent Kinetic Energy	Second Order Upwind
Specific Dissipation Rate	Second Order Upwind
Solution Limits	
Minimum Absolute Pressure [Pa]	1
Maximum Absolute Pressure [Pa]	5e+10
Minimum Temperature [K]	1
Maximum Temperature [K]	5000
Minimum Turb. Kinetic Energy [m ² /s ²]	1e-14
Minimum Spec. Dissipation Rate [s ⁻¹]	1e-20
Maximum Turb. Viscosity Ratio	100000

The total iteration number of the simulation for convergence to be reached was set to 600 iterations. Finally, hybrid and fmg solution initialization provided by ANSYS Fluent® were run prior to the simulation run to reduce computational time and resources.

3.2.5 MATLAB Simulink® Modelling

The MathWorks™ Simulink® software enabled the creation of physical system models in the Simulink® environment. For this study physical system modelling for electrical and mechanical components were obtained from the libraries provided in Simscape™. Model components obtained include electric motor, electrical machines/generator, power electronics components, drivetrain components, tires, transmission (simple gearbox) and vehicle body. These model components are used to model the subsystem and complete system models of the electric vehicle and ERS.

3.2.5.1 Simulink® Modelling and Simulation Procedures

The Simulink® system modelling and simulation performed in the current study involve the steps stated in figure 3.16 below.

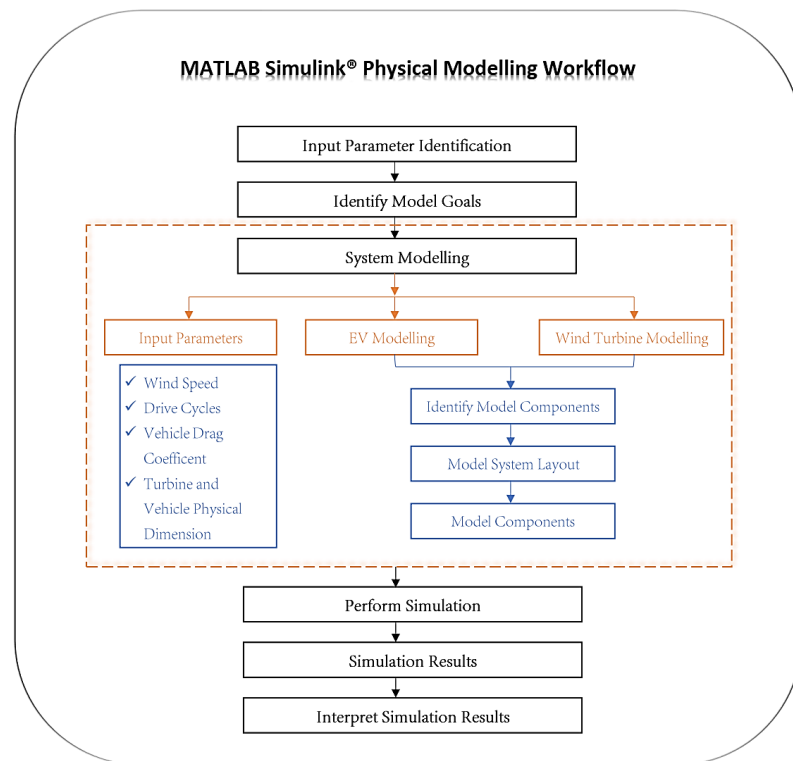


Figure 3.16: Steps in MATLAB Simulink® Physical Modelling

3.2.5.2 Input parameter Identification

The most basic and preliminary step in the system modeling is to identify the input parameters used for simulation. These inputs include:

- **Datas Obtained from Road Tests:** wind and vehicle speed datas which are obtained from road tests are used to relate the wind speed to vehicle speed, and also drive the custom drive cycle.
- **Geometric and Physical Dimensions of Model Components:** these parameters include baseline model and energy recovery system dimensions.
- **Material Property Constant:** air density ($\rho_{air} = 1.225 \frac{kg}{m^3}$)
- **Results Obtained from Preceding Simulation:** the input parameter is the drag coefficient of baseline model, Model – 1 and Model – 2, which are obtained from preceding CFD simulation.
- **Adopted Component Properties:** these parameters are ERS performance specification such as wind turbine rotor tip speed ratio (λ) and power coefficient C_p . These input parameters are used to calculate the ERS's performance characteristics.
- **Driving Schedules:** EPA's HWFET drive cycle and custom diving schedule are used as operating conditions in which the vehicle is to travel under. The drives cycles are characterized by varying vehicle velocity with time over a fixed runtime.

3.2.5.3 Model Goals

Once the input parameters were identified, the model goals were set. The goals of this model are to model the physical systems of the EV and ERSs, and assessing their performance under the specified operating conditions.

3.2.5.4 System Modelling

The electric vehicle and ERSs are modelled using equivalent real world physical system component block from Simscape™ libraries with physical and Simulink® input and output signals.

Vehicle Model selected for the study is the 2012 Tesla Model S 75. Table 3.8, will give the specification for the vehicle.

The electric vehicle model constructed in the MATLAB Simulink® software implements real world component equivalent blocks with physical and Simulink® signal input and outputs. The EV model shown in figure 3.17 consists of driving reference signal (Drive Cycle), driver model (Longitudinal Driver), motor drive control (PWM, Controlled Voltage sources and H-Bridge), DC Motor, Vehicle Drivetrain (Vehicle Body, Tires, Differential and Simple Gear Box), and EV battery.

Table 3.8: Baseline Vehicle Model Specification (Tesla.Inc., 2012)

Baseline Vehicle Model Specification	
Vehicle Model	Tesla Model S 75
Year Made	2012
Length	4980 mm
Width	1964 mm
Height	1445mm
Wheelbase (b)	2960 mm
Centre of Gravity Height	460 mm
Vehicle Curb Weight	2027 kg
Weight Distribution (F/R)	48/52 %
Type of drive	RWD
Tire size	235/35R21
Wheel radius	350 mm
Drag coefficient (C_d)	0.34
Battery type	Lithium ion
Battery capacity	85kWh

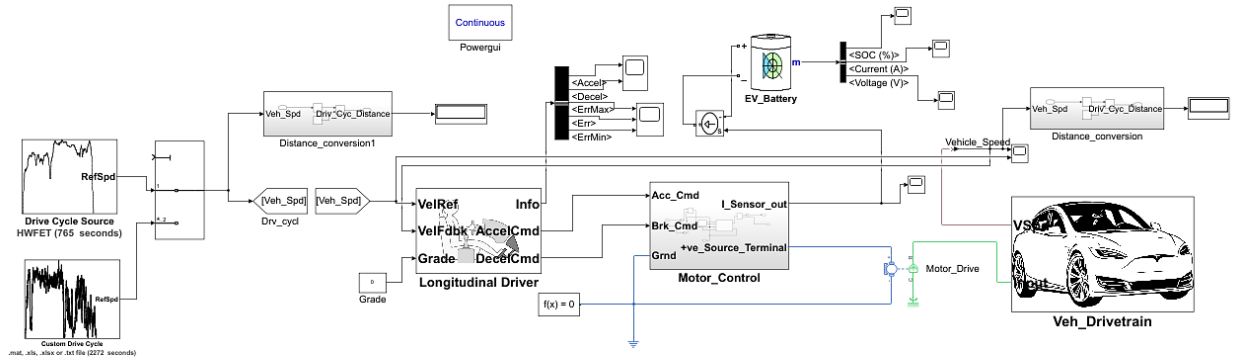


Figure 3.17: EV Simulink® Model

The longitudinal driver is a PI controller used to generate acceleration and braking commands computing the error of vehicle reference speed to the actual vehicle speed. The motor control unit receives a pulse width modulated (PWM) acceleration command and raw deceleration command to send required electrical current to the motor drive. The current being sent to the motor drive is measured to separately discharge the EV's battery model with the identical current magnitudes. The EV Simulink® model performance was assessed by examining the reference speed tracking efficiency shown in figure 3.18 and the model's response to change in vehicle C_d value shown in figure 3.18.

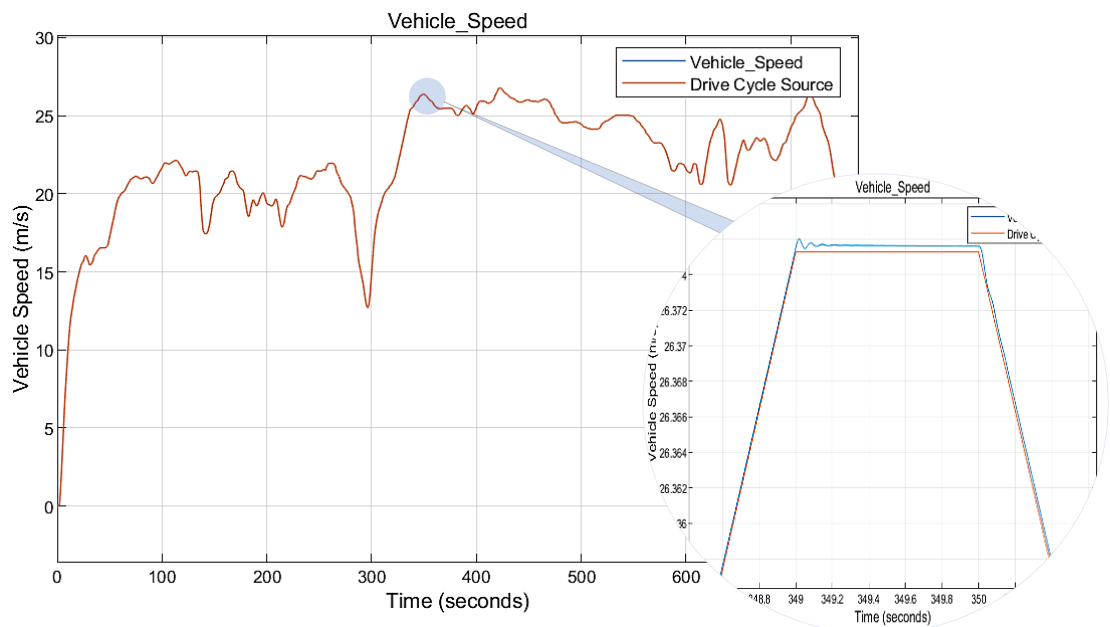


Figure 3.18: Reference Speed Tracking

The HWFET drive cycle source covers distance of 16.51 *km* while the Simulink® model covers distance of 16.53 *km*. For the custom drive cycle source computed from the road test discussed in section 3.2.8; the road test covers 42.2 *km* while the computed drive cycle and Simulink® model cover 44.89 *km* and 44.8 *km* respectively.

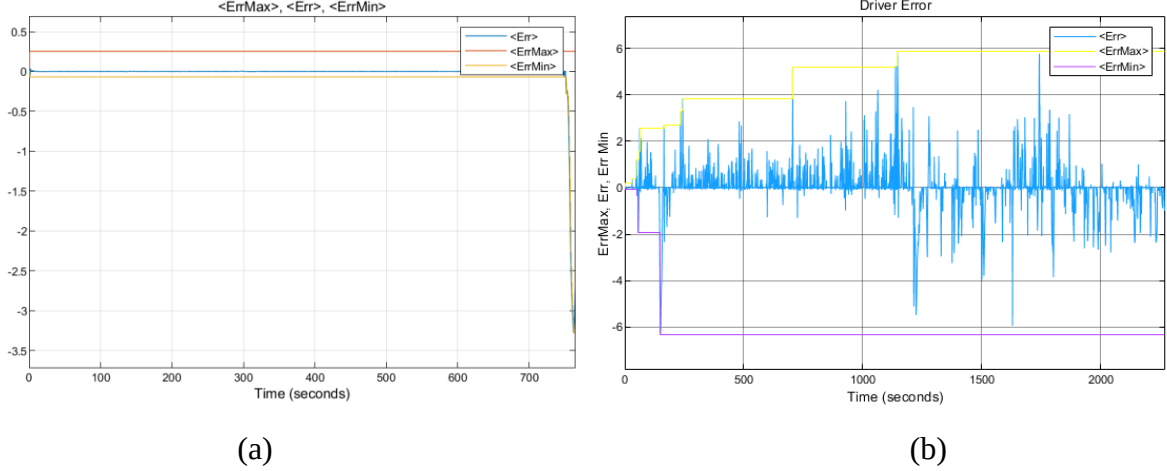


Figure 3.19: Driver Error for, (a) HWFET, and (b) Custom Cycle

The model's high degree of HWFET cycle tracking accuracy shown on figure 3.18 gave maximum tracking error (+) of less than 0.5% under semi-uniform driving instances and maximum error (-) above -3.5% shown in figure 3.19 (a). For the custom cycles shown on figure 3.19 (b) the maximum error (+) and maximum error (-) driving errors were below 6% and above -6.5% respectively.

The Electric vehicle baseline model was validated against an electric vehicle model developed by Miri et al., 2021. As validation criterion the maximum driver errors were considered. The model by Miri et al., 2021, operated in driver error range between ± 2 km/hr shown on figure 3.20. The model in the present study had maximum driver errors between ± 3.5 km/hr and ± 6.5 km/hr for the HWFET, and custom drive cycles respectively. The difference in the errors is mainly due to the lack of braking strategy. The current model lacks accuracy during steep braking scenarios and exhibited good accuracy during acceleration and soft braking instances. The current model has shown good accuracy in tracking reference speed.

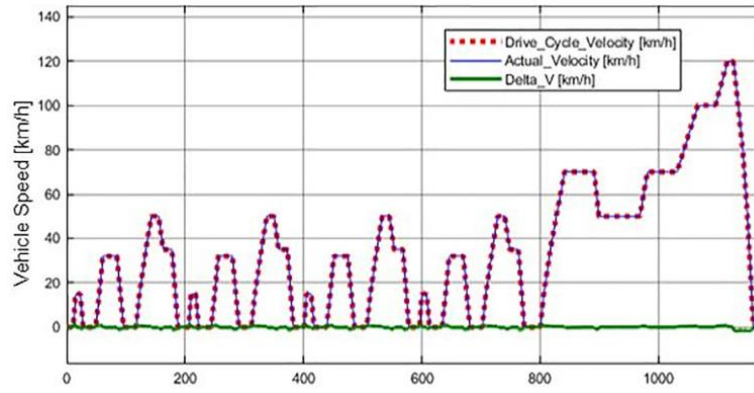


Figure 3.20 : Reference and Actual Speed Profile on the New European Drive Cycle (NEDC)(Miri et al., 2021)

The baseline vehicle model response to varied C_d values of $C_{d \text{ Baseline}}$ and $C_{d \text{ Baseline}} \pm 0.1$ are shown on figure 3.21. The responses are verified by assessing the battery state of charge (SOC), after conducting simulation under the HWFET drive cycle.

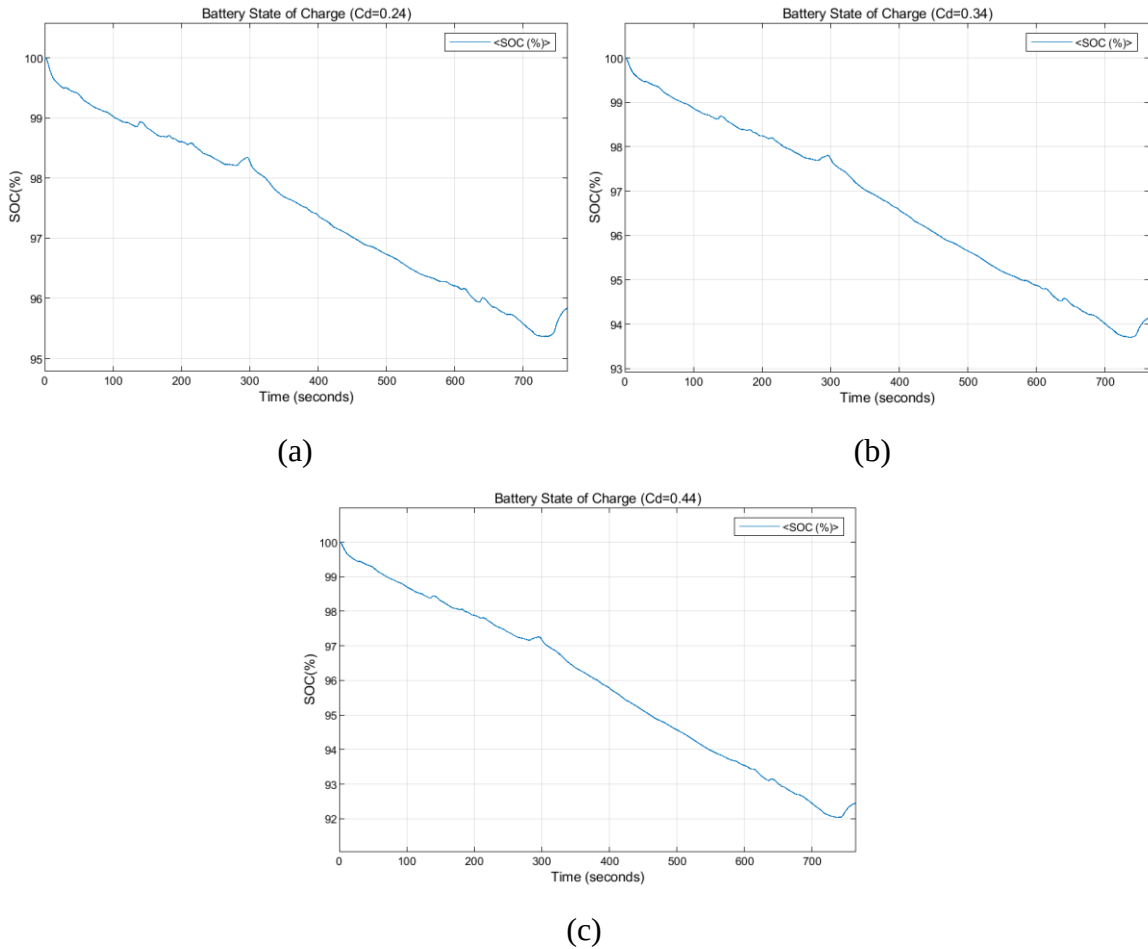


Figure 3.21: Baseline EV Battery SOC at C_d Values of (a) 0.24, (b) 0.34, and (c) 0.44

SOC of the baseline model with C_d Value of 0.34 was 94.15%. When the baseline model's C_d value was increased by 0.1 ($C_d = 0.44$) and reduced by 0.1 ($C_d = 0.24$), the battery SOC values were 92.456% and 95.85% respectively. The baseline physical model showed lower SOC levels for increased drag coefficients, and higher SOC levels for reduced drag coefficients.

3.2.5.4.1 Wind Energy Recovery System Modeling

The wind energy conversion goes through two major stages. First, the wind turbine blades capture and convert the kinetic energy in the wind to rotational mechanical energy. Second, the rotational mechanical energy is sent to the PMSG to be converted into electrical energy. The energy recovery system adopts a HAWT from (Kosasih & Tondelli, 2012) and Savonius rotor form (Kamoji et al., 2008). The turbine specifications are given on table 3.2, and table 3.3. The system has two main components shown on figure 3.22:

- i. Wind Turbine Mechanical Sub-System
- ii. Wind Turbine Electrical Sub-System

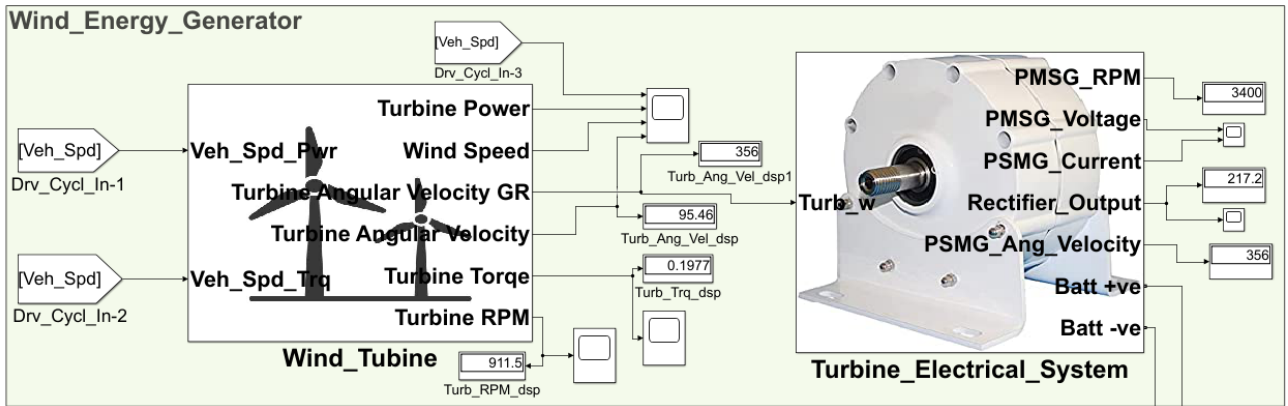


Figure 3.22: Wind Energy Recovery System Model

Considering a wind turbine operating under real condition and considering an ideal scenario in which induced losses due to of the wind turbine are neglected. Within the scope of these assumptions the power produced by the wind turbine intensely depends on the power coeffect (C_p), whose characteristics can be expressed by a curve as a function of the blade tip speed ratio (λ) (Naama et al., 2019; Zou & He, 2016). These relations developed for the selected turbine designs by (Kosasih & Tondelli, 2012), and (Kamoji et al., 2008) are used for Physical modeling. The wind turbine mechanical sub-system, shown in figure 3.23, computes turbine yield by using the wind energy fundamental equation, tip speed ratio relation, and turbine design parameters adopted from (Kosasih & Tondelli, 2012), and (Kamoji et al., 2008). The block output includes

turbine power, angular velocity, torque and rotational speed (rpm). The vehicle to wind speed relation of 0.75 was in the turbine mechanical sub-system computations.

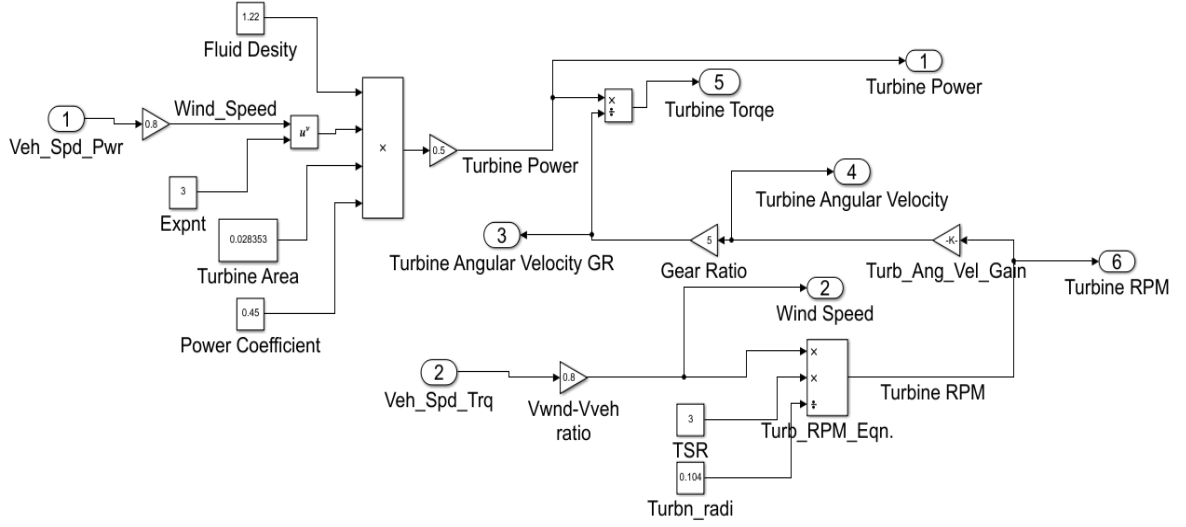


Figure 3.23: ERS Mechanical Sub-System

The electrical system seen on figure 3.24, employs a permanent magnet synchronous machine (PMSM) with a trapezoidal Back EMF. Even Though when compared to a model with co-simulation performed across multiple software platforms, the Simpower (MATLAB) model simulation exhibits noticeable discrepancies (Quintal-Palomo et al., 2019). But this is not to say the model is completely unusable for simulation. If a simulation requiring reasonably accurate simulation and reduced computational resources, then the PMSM block in MATLAB Simulink® is plenty sufficient. The PMSM with trapezoidal Back-EMF is used the study. The turbine angular velocity signal obtained from the ERS mechanical sub-system was used to run the permanent magnet synchronous machine/generator (PMSM/G). The PSMG is a three-phase, 4 pole-pair AC machine. The generated AC is rectified by using the generic/basic full wave bridge rectifier with 10^{-6} F C-filter and 10-ohm resistor load.

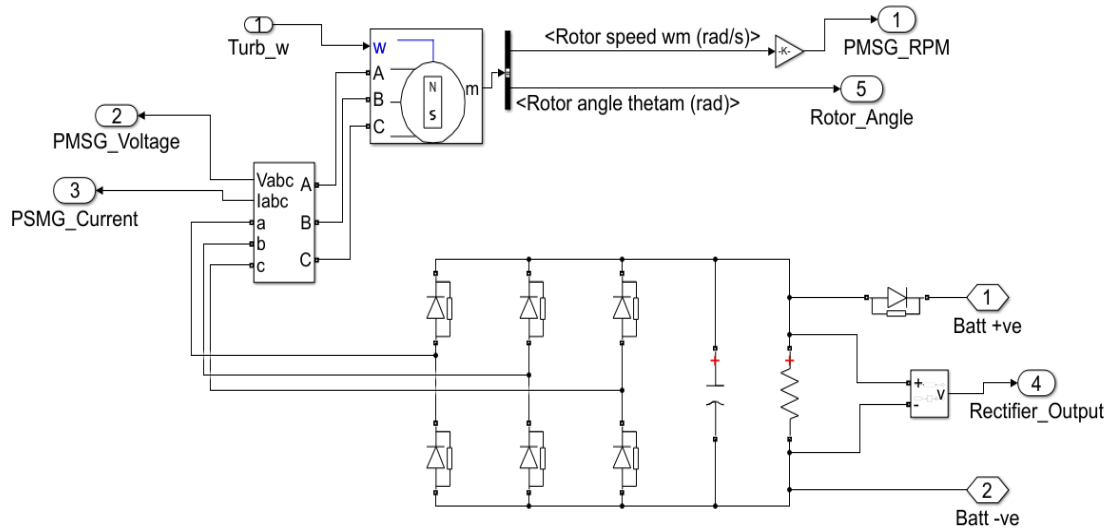


Figure 3.24: ERS Electrical Sub-System

The justification for Simulink® simulation of the permanent magnet synchronous machine is based on the simulation work by Quintal-Palomo et al., 2019, on the model's transient response at different loads, which were conducted for comparison using the PMSM block from Simscape™, co-simulation, and actual measurements. From figure 3.25, it can be seen that even though the PMSM block form Simscape™ library lacks in performance, for the computational resources that can be allocated for current work its performance was satisfactory.

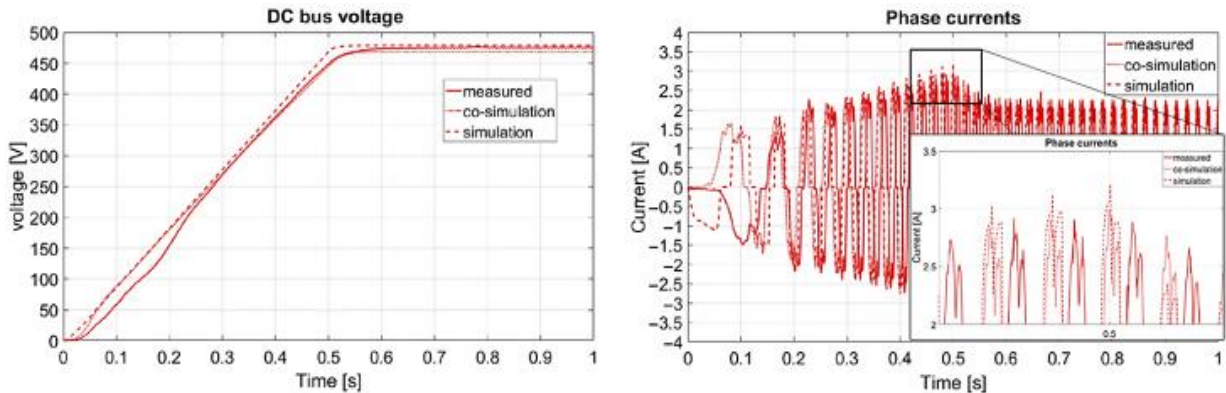


Figure 3.25 :Transient Response Comparison of PMSG with a 240-ohm Load from 0-1500rpm in 500ms ramp DC Bus Voltage (Quintal-Palomo et al., 2019)

The output from the rectifier was then used to charge the EV's battery while in motion.

3.2.5.4.2 Integrated System Model

The complete system model shown in Figure 3.26 integrates the EV and ERS models. The simulation was solved by using the powergui block with continuous simulation type employing variable time step for computing.

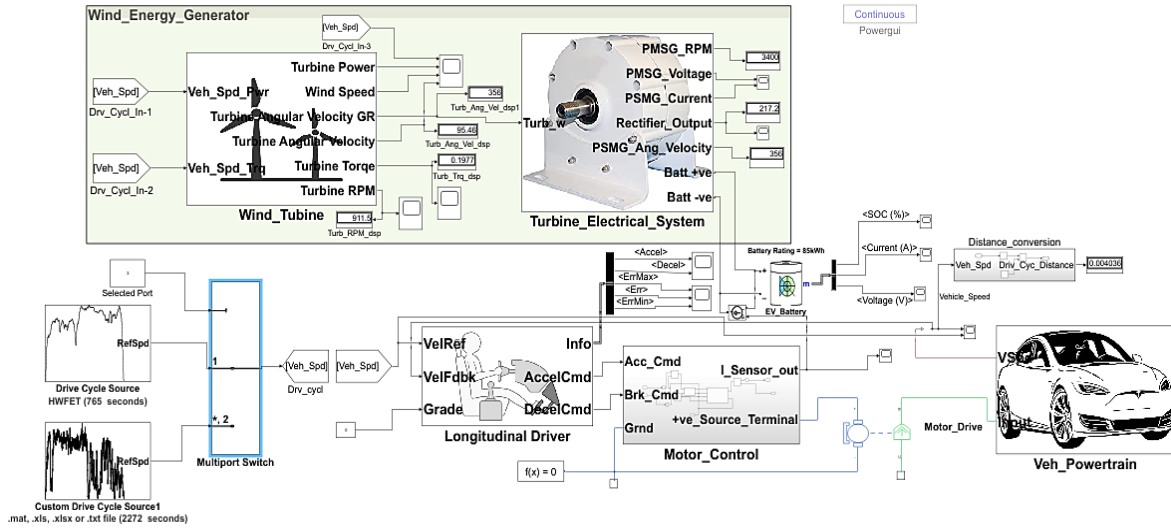


Figure 3.26: Integrated System Model

3.2.6 Road Test

When a vehicle is travelling at a certain speed the relative wind speed across the vehicle may vary depending on apparent direction of wind. So, to mitigate the issue vehicle and wind speed relations were obtained from vehicle road tests. The road test involved vehicle speed measurements with GPS, which was conducted from Bishoftu, Ethiopia to Adama, Ethiopia routing through the Addis Ababa – Adama Expressway. As can be seen from figure 3.27 the road test begun from the outskirts of Bishoftu city to the Adama’s city center (locally known, Franco). This route was selected due to its ability to provide varied driving scenarios ranging from low speed to sustained high speed conditions. Additionally, its closeness to ASTU made it the most viable choice, considering research budget constraints.

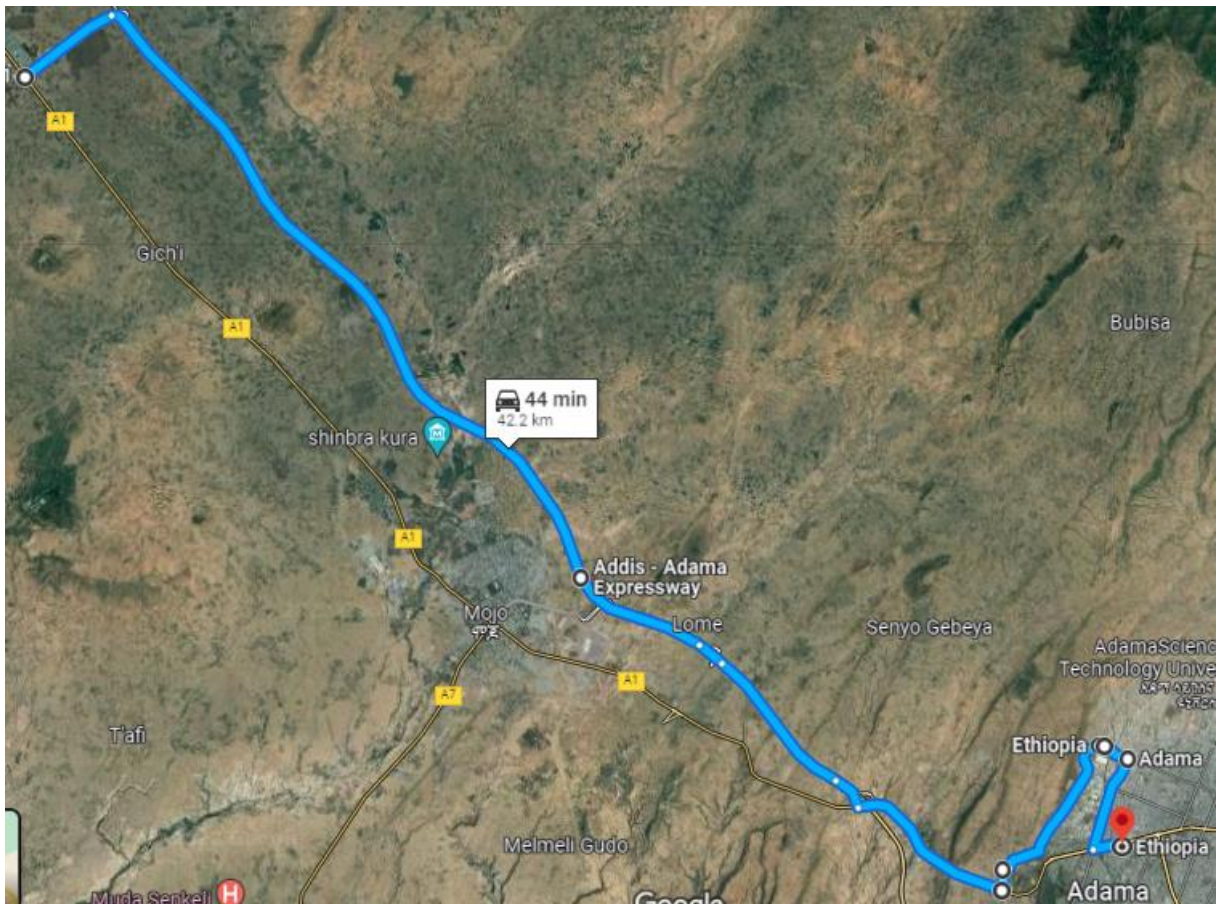


Figure 3.27: Road Test Route

The actual road test took around 38 minutes (2272 seconds) to conduct. Measured vehicle speed data is shown in figure 3.28.

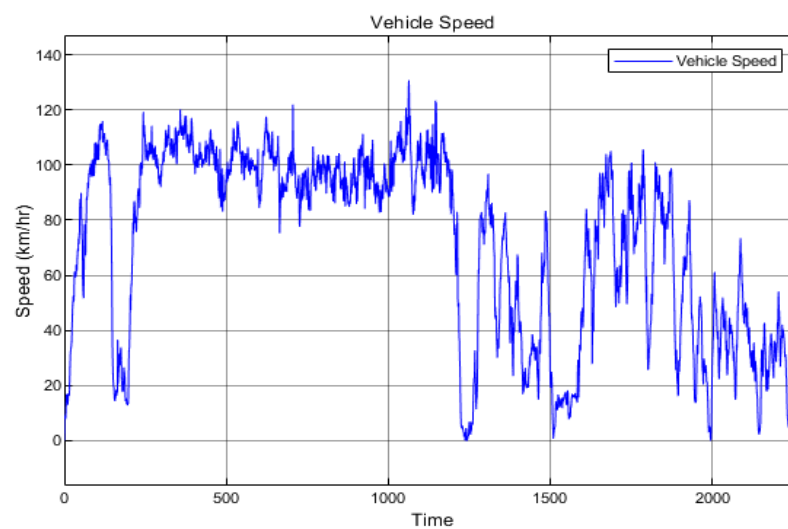


Figure 3.28: Vehicle Speed Data

3.2.7 Design Parameters for Model Comparison

The ERSs implemented will have their own specific features that make them unique. But in order to have comparable results some common and restricting design parameters need to be stated to achieve the modeling scope. These parameters consist of:

- a. **Comparable Turbine Rotor Areas:** Since the turbine rotors of the ERSs implemented are adopted from different literatures, completely identical rotor areas might not be achieved, but turbine rotor areas must be reasonably comparable.

Table 3.9: ERS Turbine Rotor Dimensions

ERS	Turbine Diameter (m)	Turbine Area (m^2)
Model – 1	0.190	0.028353
Model – 2	0.208	0.043264

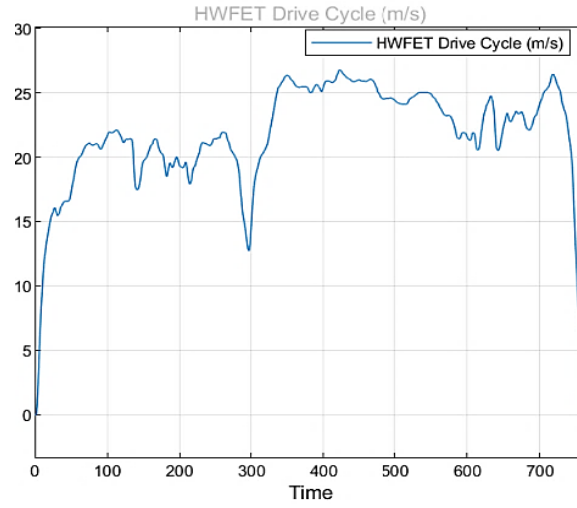
- b. **Identical Electric Generator Machines:** the electric power generating capacities of electrical generators used for both models must be identical. For the Simulink® Simulation a permanent magnet synchronous machine (PMSM) block from Simscape™ library is used with identical block parameters. Block parameters are given in Appendix - C.
- c. **Uniform Operating Conditions:** any variables/constants that are not directly related to ERS properties, such as driving signals, Baseline EV model parameters, and air density, must be kept uniform.
- d. **Identical Turbine Angular Velocity after Applying Gear Ratio:** the focus of the study is on aerodynamic effect of the ERS on the baseline EV's aerodynamics. So, keeping the turbine angular velocities identical by assessing the ERS specific gear ratios (GR) eliminates differences that arise due to varied turbine efficiencies. ERSs on both models were calibrated in the Simulink® model at 100 km/hr (27.78 m/s) to operate at identical turbine angular velocity (ω). Relevant characteristics are given on the table below.

Table 3.10: Gear Ratio Corrected Turbine and PMSM Angular Velocities

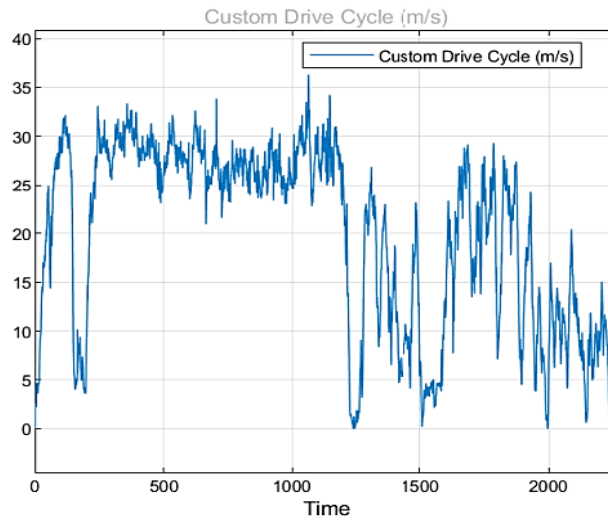
	Base Turbine ω (rad/s)	GR Applied Turbine ω (rad/s)	Gear Ratio (GR)	PMSG Angular Velocity (rad/s)
Model – 1	95.46	356	3.73	356
Model - 2	18.04	356	19.735	356

3.2.8 Driving Schedule (Drive Cycle)

The physical model was tested under the EPA's driving schedule of Highway Fuel Economy Test (HWFET) which had duration of 765 seconds and covered 16.51km, and a custom driving schedule constructed from the conducted road test which had a duration of 2272 Seconds and covered 44.9km. The vehicle speed data recorded during the road test, was conducted with an accurate speed reading. Thus, the custom drive cycle was realized using the recorded vehicle speed. Figure 3.29 shows the drive cycles used in the study. The battery SOC and battery voltage simulation results from the models were considered for analysis.



(a)



(b)

Figure 3.29: Drive Cycles (a) HWFET, and (b) Custom Cycle

3.2.9 Model Efficiency Estimation

Energy recovery potential of wind energy recovery systems was studied. Even though it was a novel idea, its implementation must not violate any laws of physics. The installed system will have its own effect on the vehicle aerodynamic properties resulting in increased, reduced or unaltered vehicle drag. For the system implemented to be feasible the baseline model's aerodynamic drag must be improved. If the baseline model drag was to increased or unaltered; according to the first law of thermodynamics when the model drag increased the driving distance will reduce and when the drag remains unchanged there will not be any net gain in recovered energy. In order to estimate the designed system model efficiency control models with no changes to their aerodynamic drag was simulated. The battery SOC obtained from the control models were compared with the baseline model battery SOC to identify the magnitude of loss not considered. The model efficiency (η_{model}) was then estimated by taking the ratio of final battery SOC of Baseline model to Control model. For simulation under the HWFET, and Custom driving schedules:

$$\eta_{model} = \frac{SOC_{baseline}}{SOC_{Control}} \quad \dots (3.1)$$

Preliminary control simulations were run under the HWFET, and Custom cycle for both model – 1 and model – 2 where their final SOC values were identical at 97.8%, and 93.28 respectively, which is higher than the final SOC values of 95.37%, and 87.11% for the baseline model simulated under the HWFET, and Custom cycles. Control simulation results are shown on figure 3.30.

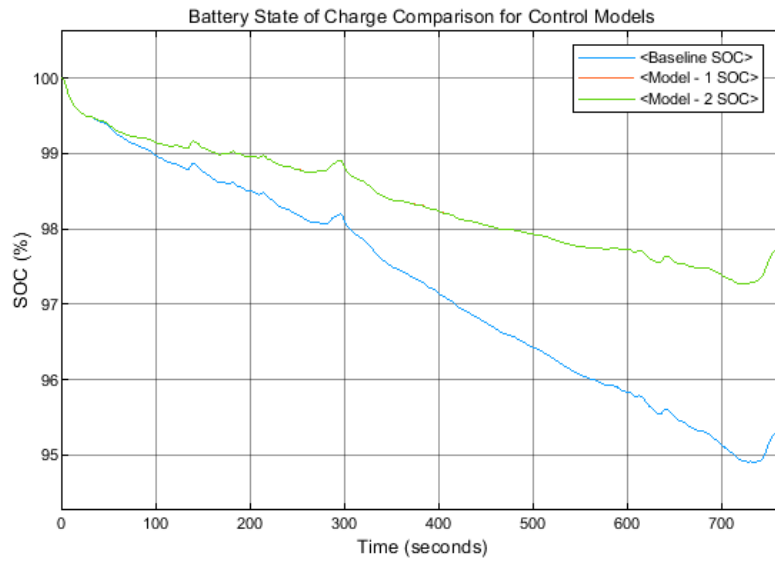


Figure 3.30: Preliminary Control Simulation SOC Results

The model Efficiencies were estimated using expression (3.1). The final battery state of charge values of baseline model, Model – 1, and Model – 2 obtained from the control simulation conducted, listed in table 3.11 are used in computing the model efficiencies under varying driving schedules. The estimated/computed model efficiencies are then used to correct Simulink® model errors in order to obtain accurate model results.

Model Efficiency Under HWFET drive cycle:

$$\eta_{model\ HWFET} = \frac{SOC_{baseline}}{SOC_{Control}} = \frac{95.37}{97.8}$$

$$\eta_{model\ HWFET} = 0.9752 \text{ or } 97.52\%$$

Model Efficiency under the custom drive cycle:

$$\eta_{model\ Custom} = \frac{SOC_{baseline}}{SOC_{Control}} = \frac{87.11}{93.28}$$

$$\eta_{model\ Custom} = 0.9339 \text{ or } 93.39\%$$

Table 3.11: Preliminary Control Model Simulation Results

	HWFET Cycle SOC (%)	Custom Cycle SOC (%)
Baseline Model	95.37	87.11
Model – 1	97.8	93.28
Model – 2	97.8	93.28

3.2.10 Extended Vehicle Range Estimation

The extended model Driving range was computed using the SOC_{actual} difference from baseline model SOC, Simulink® model travelled distance, and total battery discharge percentage for the implemented drive cycle. Expression (3.2) was used to estimate the extended range.

$$Extended\ Driving\ Range = \frac{SOC_{actual\ diff\ from\ baseline} \times Simulink\ model\ travelled\ distace}{Total\ \%discharge_{Baseline}} \dots (3.2)$$

CHAPTER FOUR

RESULTS AND DISCUSSIONS

In this chapter result obtained from CFD and physical modelling simulation performed on ANSYS Fluent® and MATLAB Simulink® softwares respectively are discussed. Multiple figures and tables are used for clear and concise result representations and discussions. Discussed simulation results are for the following three models:

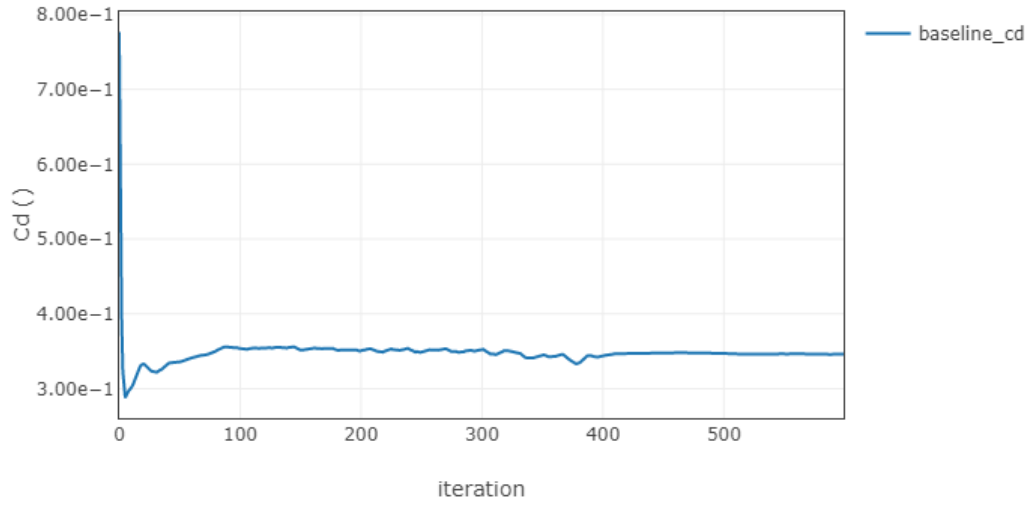
1. Baseline vehicle model: vehicle model with no ERS onboard.
2. Model – 1: vehicle model with HAWT augmented ERS onboard.
3. Model – 1: vehicle model with Savonius rotor VAWT augmented ERS onboard.

4.1 CFD Simulation Results

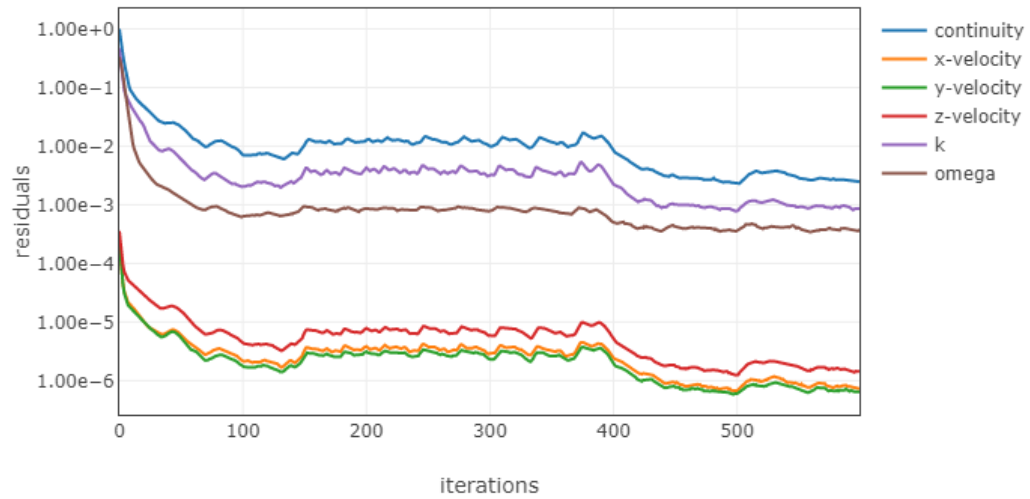
The CFD simulation performed in ANSYS Fluent® was a three-dimensional steady state on incompressible flows. The turbulence modelling was accomplished by employing the SST K- ω turbulence model. All CFD simulation results were obtained with computation performed with identical global & local mesh sizing, turbulence model, and boundary condition for common components used in all models. Components which are model specific were assigned appropriate local mesh sizes and boundary conditions. The models were simulated under 100 *km/hr* (27.78 *m/s*) freestream conditions. Second order upwind discretization was used for solving model residual convergences to set absolute criterion over 600 iterations.

4.1.1 Baseline Model Results

Baseline model residual and drag coefficient convergence plots are shown in figure 4.1. The residuals of x, y and z velocities along with omega (ω) and k values converged to absolute criteria of 1e-3 before the end of 600 iterations. Even though the continuity residuals did not converge to absolute value of 1e-3 within 600 iterations, it can be deduced that after the 400th iteration continuity residuals exhibit gradual but steady convergence to 1e-3. To reach the set absolute value requires additional iterations. But due to the computational resources and time available the above deduction was assumed to be true. This deduction will hold true for all models.



(a)

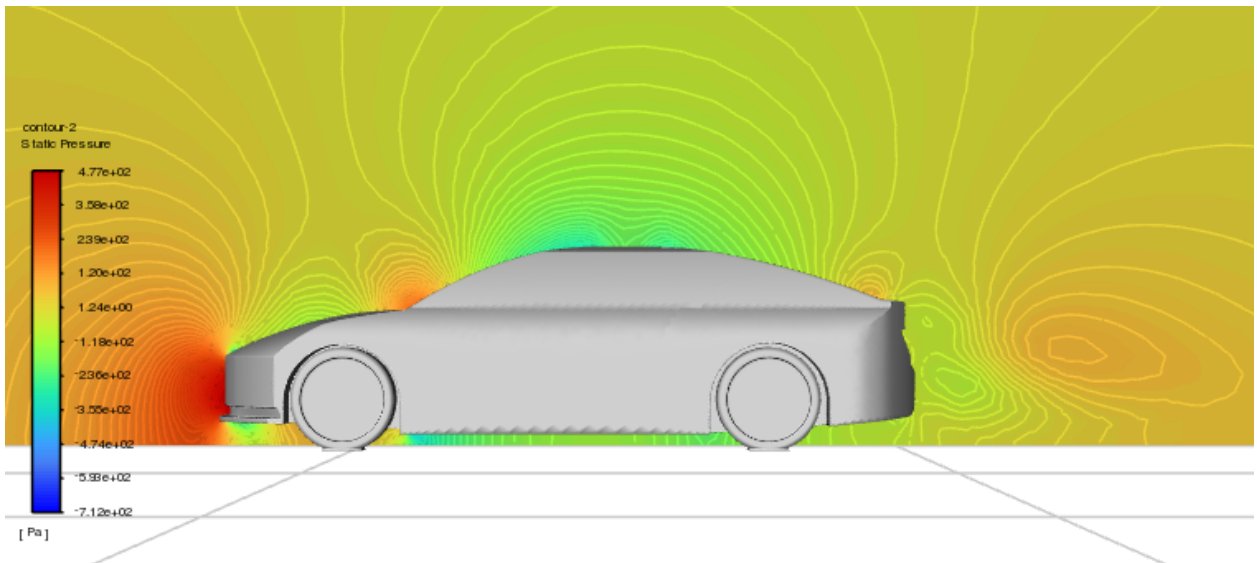


(b)

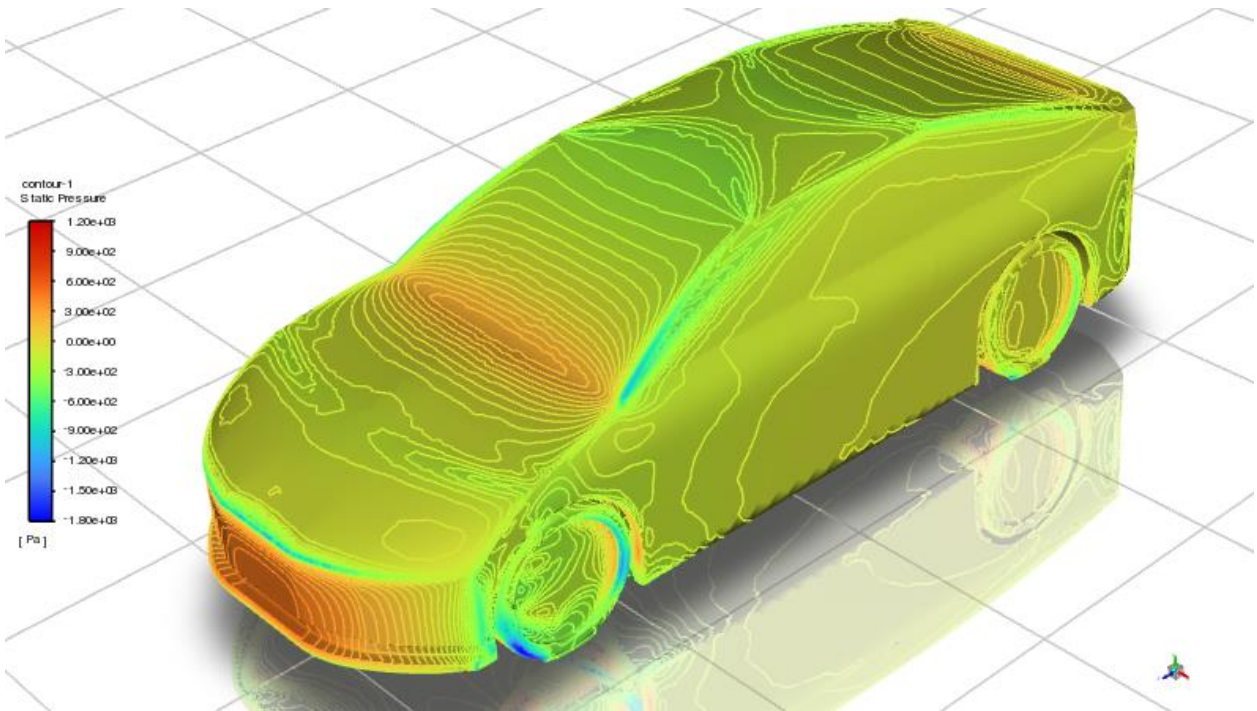
Figure 4.1: Baseline model convergence history plots of (a) Residuals, and (b) Drag Coefficient

From figure 4.1 it can be seen that the drag coefficient plot converges before the 600th iteration which is an indication of an accurate and converged simulation results have been reached. The drag coefficient (C_D) of the baseline model at 100 km/hr after 600 iteration was 0.3463876.

The pressure and Velocity distributions over the surface of the baseline model were further analyzed to show important flow characteristics.



(a)

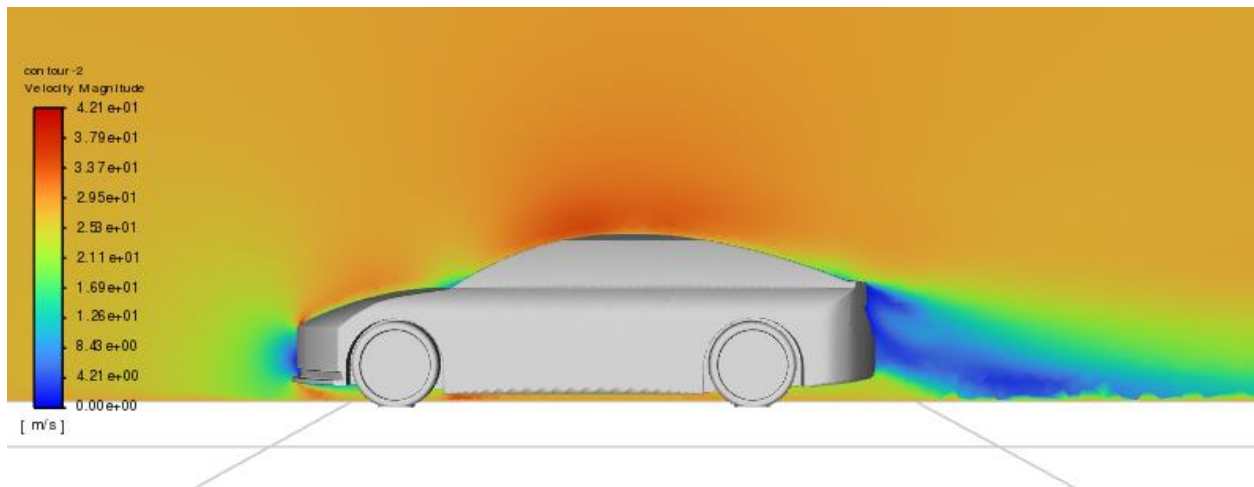


(b)

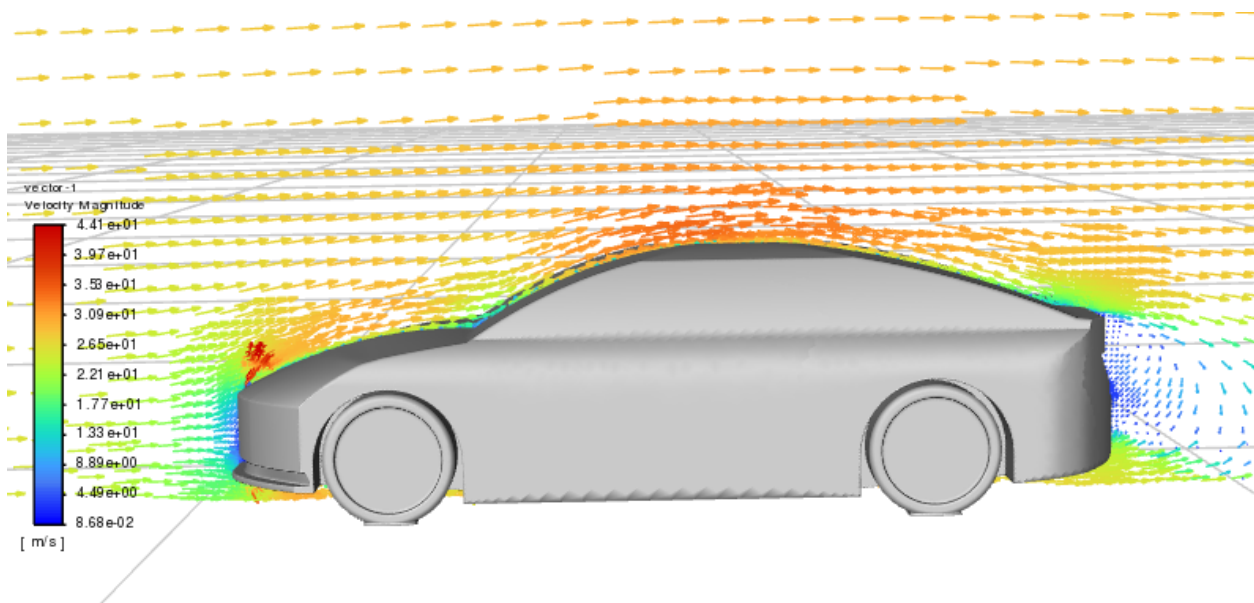
Figure 4.2: Static Pressure Contours for Baseline Model

Static pressure contours shown on figure 4.2 show the high and low-pressure areas that are the causes for force developments on the model surfaces. High pressure areas marked with red color can be seen at the front end of the vehicle, Cowell, and at the junction where the rear window and boot lid meet. Low pressure area marked with blue and light green colors can be seen in areas

where the flow separates at sharp edges having lowest values and gradually increasing section on surface that come after the edges.



(a)



(b)

Figure 4.3: Velocity Distributions on Baseline Model

Velocity distribution on the baseline model surface shown on figure 4.3, shows areas where flow velocities maximum and minimum values across the model surface. On the baseline model the flow velocities reduce to zero at the front end where the flow interacts with blunt face, and at the rear end of the model where the flow separates from the model surface. Maximum velocities are created where there are steep edges on the vehicle model. On the baseline model velocities increase to maximum value of 42m/s at the front-end edge of the hood and roof. The increased velocity

magnitudes of the flow will then even out to freestream velocity as they travel downstream the model surfaces. The velocity distribution contours displayed on figure 4.3 were with color legend representing low end values with blue, higher end values with red and the rest in-between.

Flow separation regions with reversed flow velocities of up to 2 m/s on the baseline model are depicted on figure 4.4.

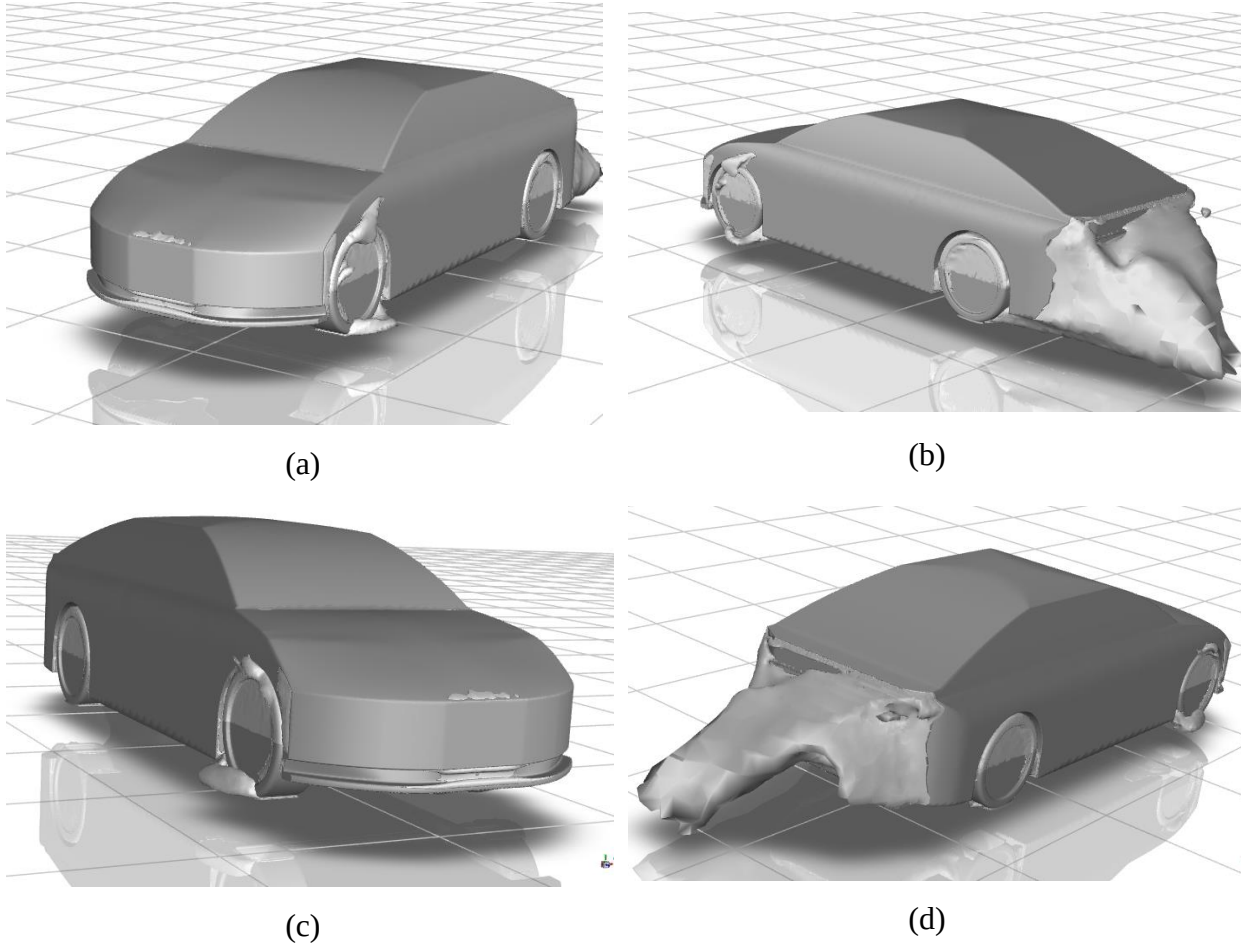
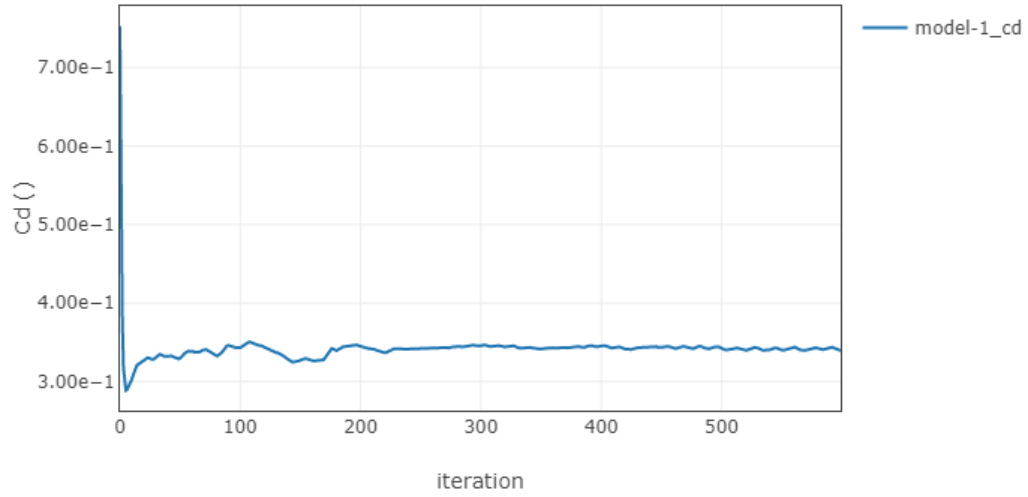


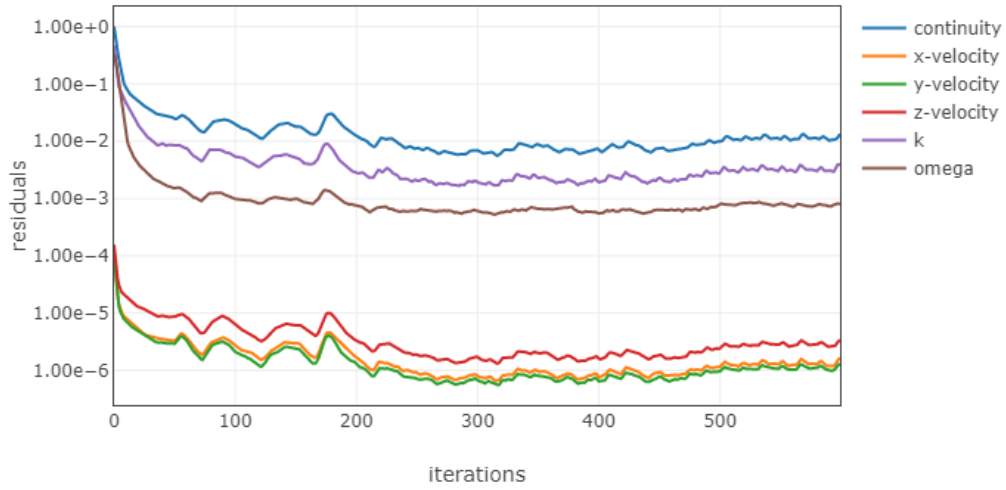
Figure 4.4: Flow Recirculation Regions on the Baseline Model

4.1.2 Model – 1 Results

Similar to the baseline model in addition to continuity, the k residual needs iteration more than 600 to converge to absolute criterion of $1\text{e-}3$. But from the steady plot of the drag coefficient value, it can be understood that the obtained results are analytically sound and accurate. Figure 4.5 shows the convergence histories of residual and drag coefficient.



(a)



(b)

Figure 4.5: Convergence History of Model – 1 (a) Drag Coefficient, and (b) Residuals

The drag coefficient of model – 1 at 100 *km/hr* after 600 iterations was 0.3394422.

Model-1 has two distinct features that make it different from the baseline model. When looking at the front end there is a square shaped opening that pierces into the body work. The second feature is the two openings on each side of the model just behind the wheel arches. The square opening at the front is the starting point for an underbody Y-shaped ducting with two exits on both sides of the vehicle. This ducting is used to accommodate the installation of the energy recovery system utilizing a HAWT.

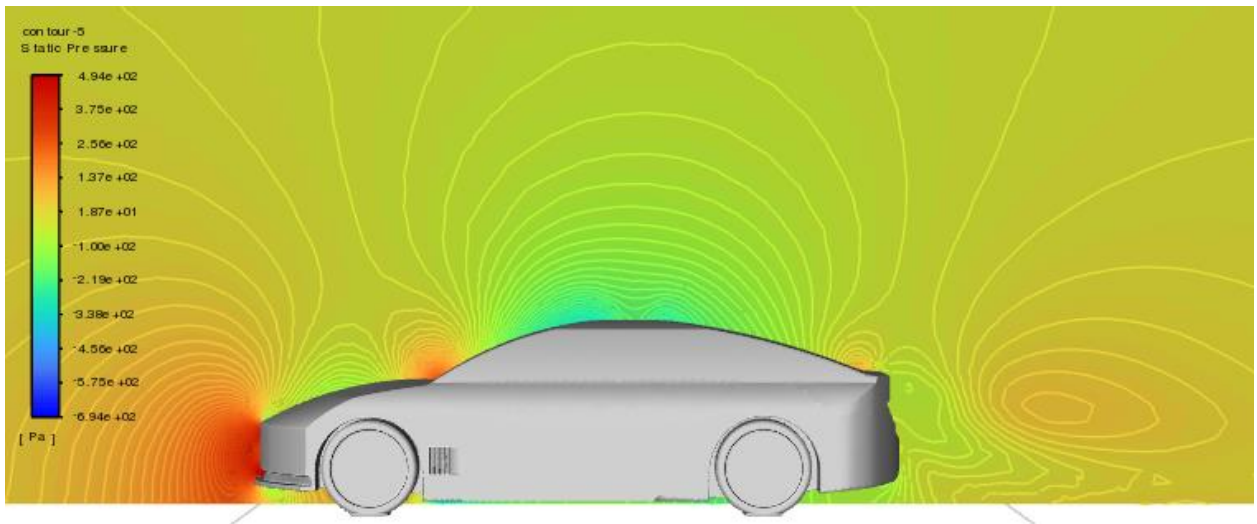


Figure 4.6: Static Pressure Distribution on Model-1

When observing figure 4.6 static pressure distributions occur at identical location on both model-1 and baseline model surfaces. Instead of large area of high static pressure origin observed on the baseline model front end were reformed into localized pressured origin segments on model – 1. This reform is the result of flows being directed into the opening. The wake structure behind the model had reduce low pressure area when compared with the baseline model. What the flows look like inside the ducting can be seed of figure 4.7.

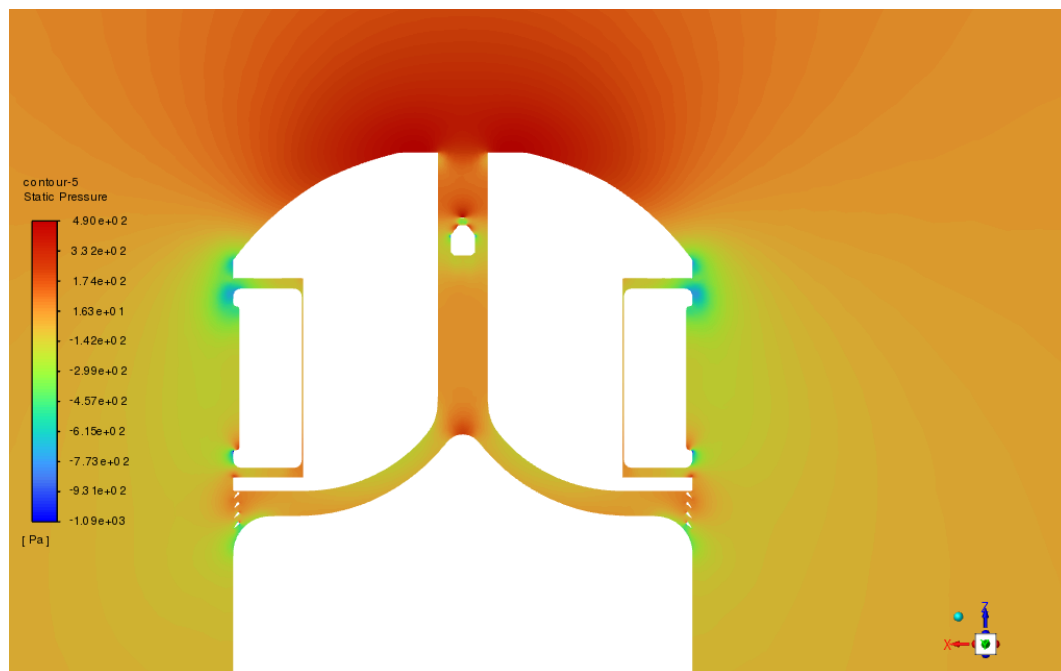
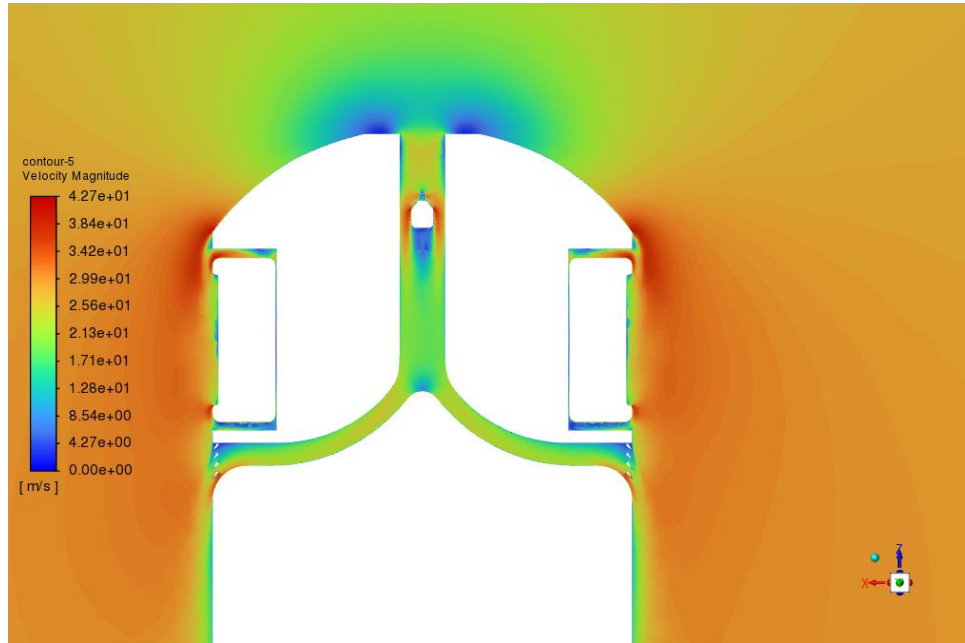
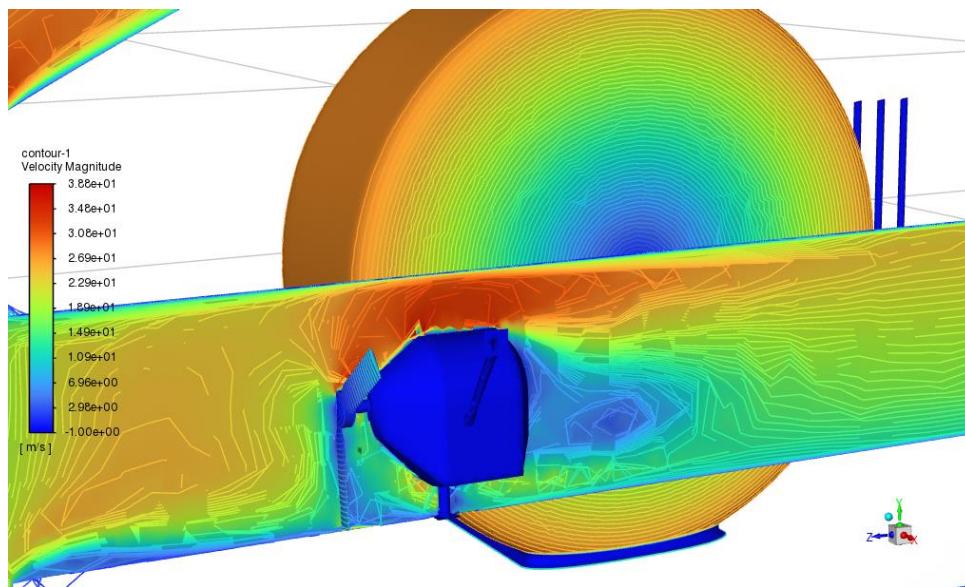


Figure 4.7: Static Pressure Distribution Inside the Ducting on Model-1

When looking at the pressure distribution inside model-1 ducting high static pressure areas are found on the rotor faces, nacelle front, and at the Y-junction fillet. Another high-pressure area is at the ducting exits on the un-filleted side, which is the result of flow separation dissipates/converges to the freestream pressure.



(a)



(b)

Figure 4.8: Velocity Distribution Inside Model-1 Ducting (a) Top View, and (b) Side View

Velocity distribution contours on figure 4.8, further support the observation made from the pressure contour. Inside the ducting the flow accelerates towards the turbine rotor, and then imparts portion of its kinetic energy to the rotor and flows downstream over and under the turbine nacelle. The flow that impacts the turbine moves at a relatively low speed to downstream, while flows that do not directly impact the rotor continue to accelerate through the narrow opening between the turbine nacelle and ducting wall. Localized flow separation occurs behind the turbine nacelle. The turbine rotor blades were assigned rotating boundary condition. The blade's angular velocity was estimated using the tip speed ratio obtained from the respective literatures it was adopted from. The velocity contours that exist on the blade surface shows the wind speed at the turbine rotor wall. The turbine rotor has rotating boundary condition with angular velocity of 95.46 rad/sec at rotation axis origin of $x=0$ m, $y=0.419926$ m and $z=-0.3023702$ m.

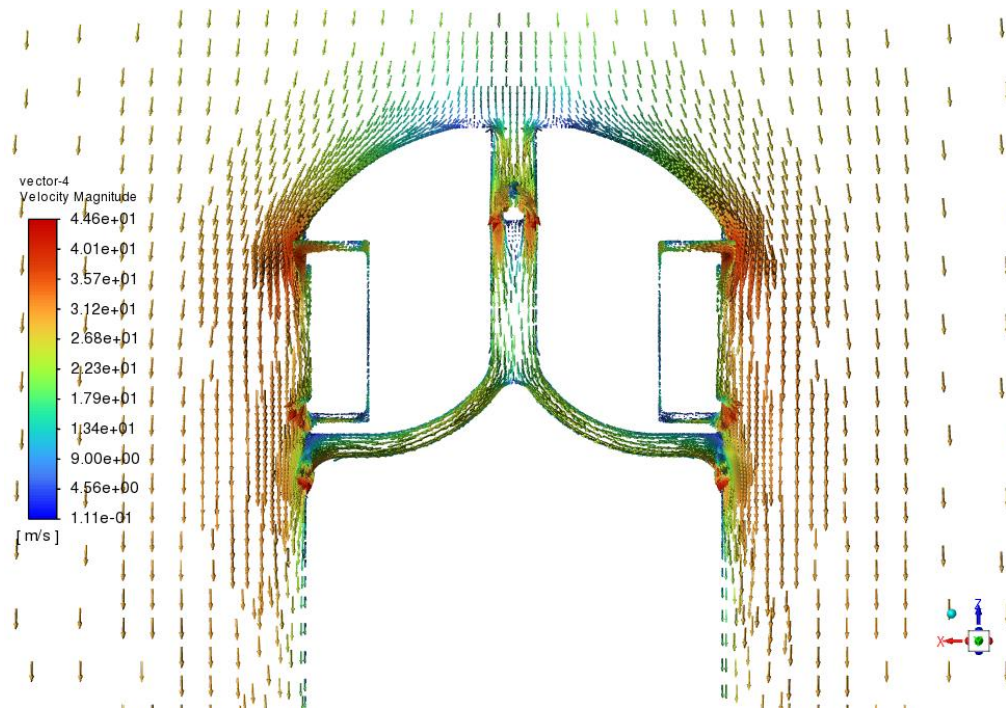


Figure 4.9: Flow Vector Plot Inside Model-1 Ducting

As can be seen from the vector plots on figure 4.9, the chaotic flow behind the ERS assembly transition into a more stable and uniform flow in the diverging ducts. At the exits the flow in the direction of the square end starts separation before reaching the end of the exit, while the flow in the direction of the filleted end remains attached until it reaches the edge of the exit.

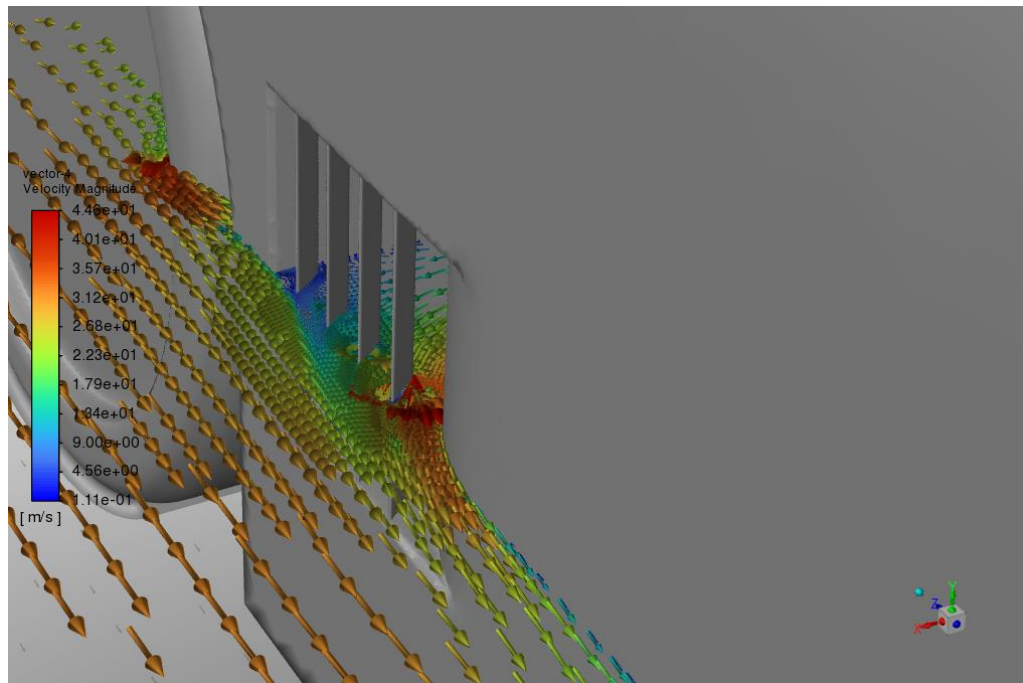


Figure 4.10: Flow Conditions at Ducting Exits

In section 3.2.1.2 it was stated that symmetric airfoil flow treatment device implementation at flow exits were for the purpose of improving the exit flow merging capabilities to the freestream flow. The benefit to this device can readily be observed in figure 4.10, in which the exit flow merges to the extremal flow with minimal disturbance. The exit flow interaction over the entire height of the exit can be seen on figure below.

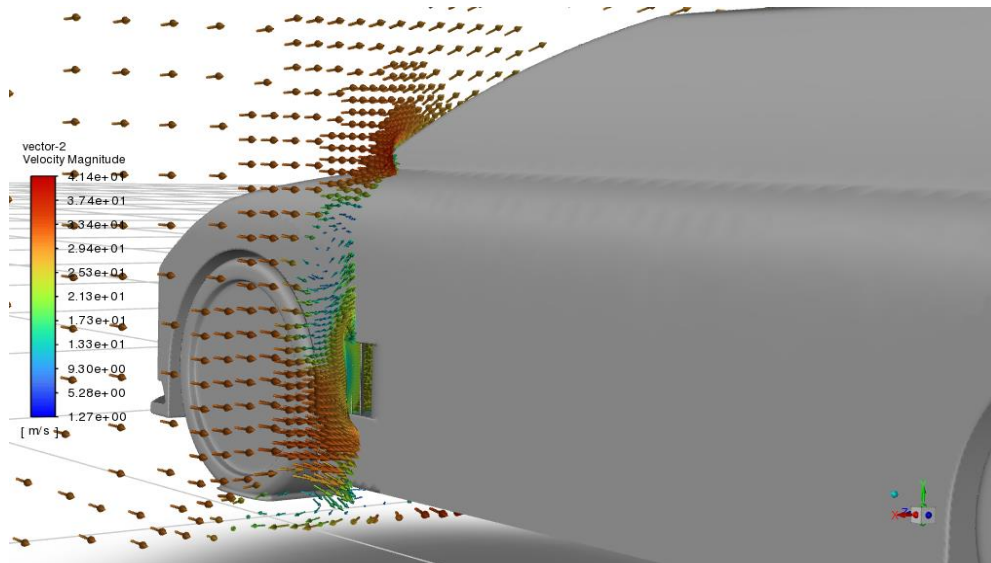
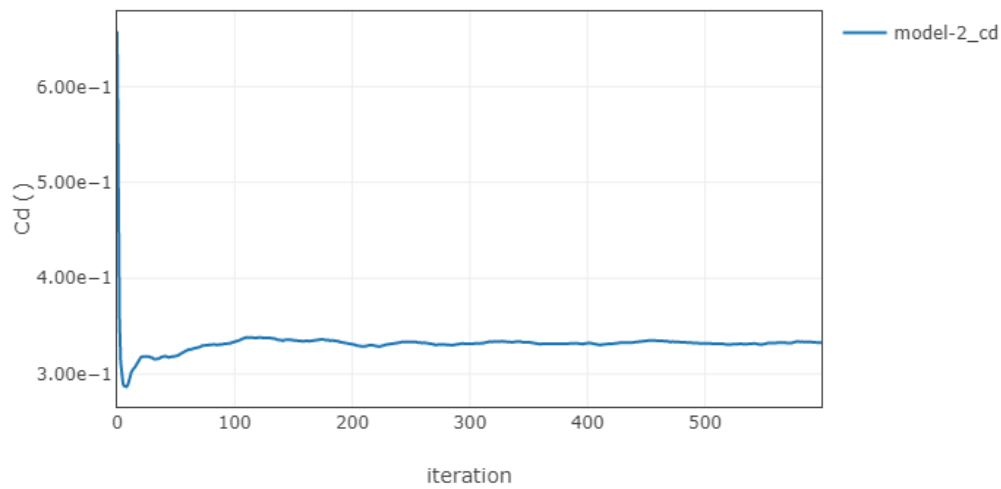


Figure 4.11: Exit Flow Interaction with Freestream Flow

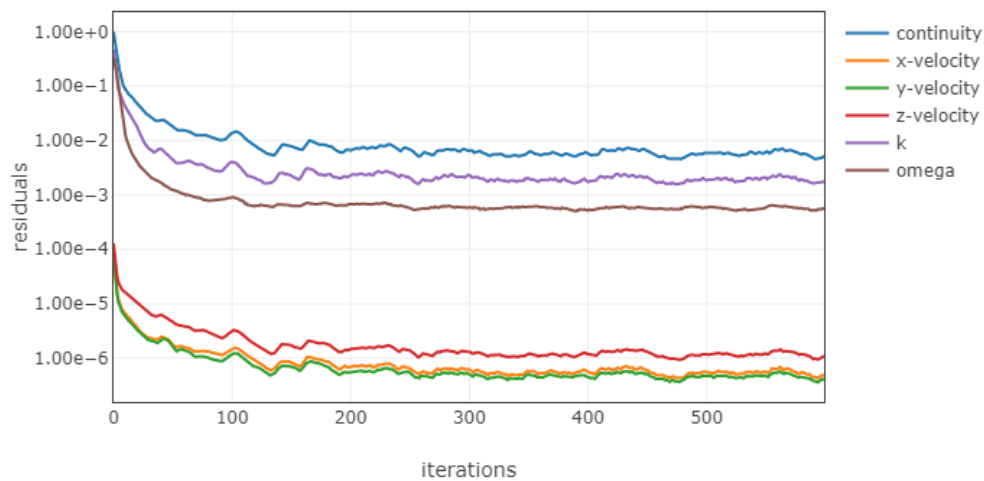
The flow that remains attached to the top wall follows the exit edge fillet upward and joins the incoming external flow at an undesirable angle. This flow phenomenon leads to the creation of an unwanted vortex, shown on figure 4.11. The upward moving exit flow drags the closest free stream flows with it, and also disturbs the flow located above the ducting exits. As the exit flow velocities increase with vehicle speed the additional flow disturbance may hinder the drag coefficient improvement to the baseline model.

4.1.3 Model – 2 Results

Residual and drag coefficient convergence histories for model – 2 are shown on figure 4.12.



(a)



(b)

Figure 4.12: Convergence History of Model – 2 (a) Drag Coefficient, and (b) Residuals

The drag coefficient of model-2 at 100 km/hr after 600 iteration was 0.3328318.

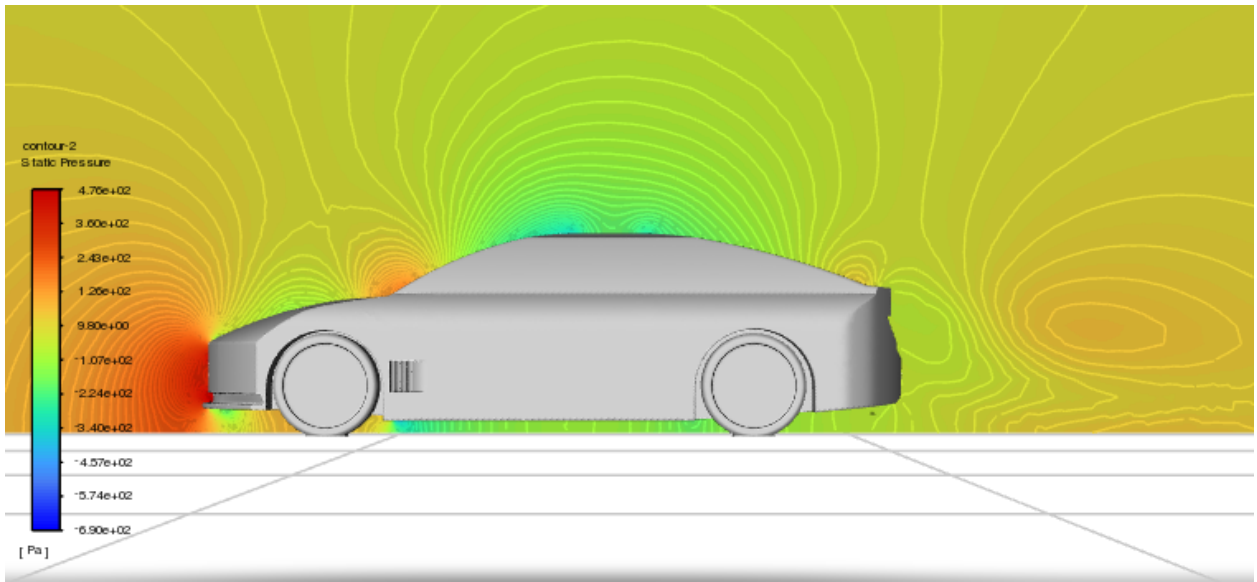


Figure 4.13: Static Pressure Distribution for Model-2

Model – 2 employs a two bucket savonius rotor as energy recovery device. The pressure distribution across the vehicle surface exhibits relatively identical distributions when viewing figure 4.13. Peak pressures occur at the front end of the vehicle, Cowell and rear window flow separation edge.

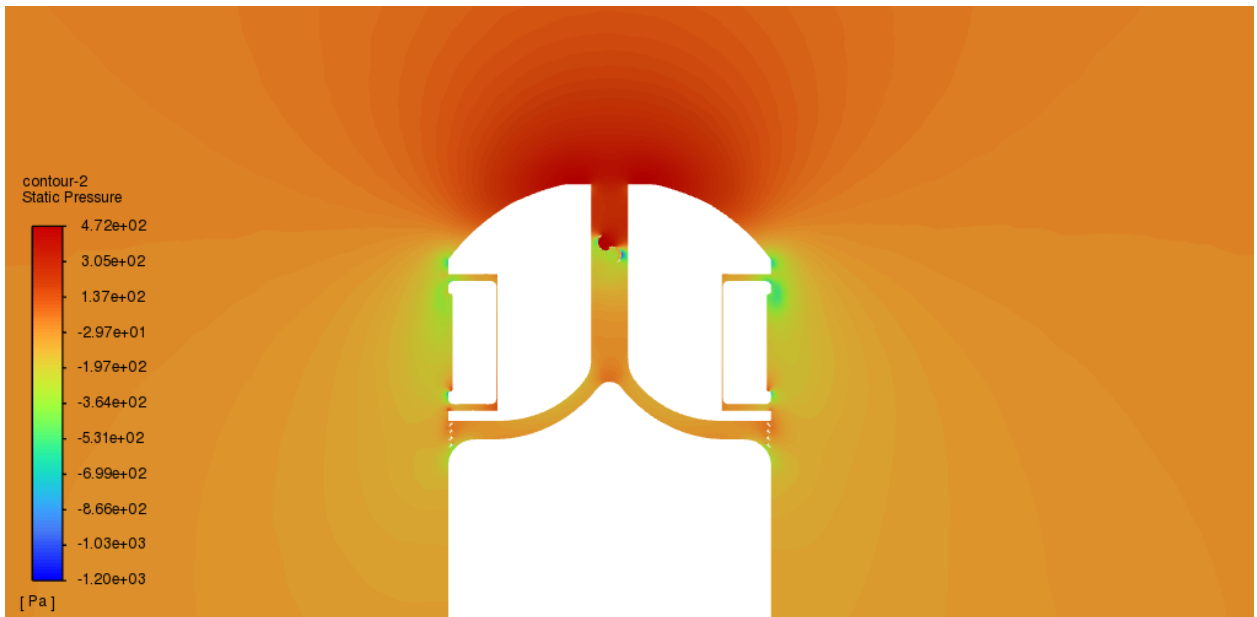
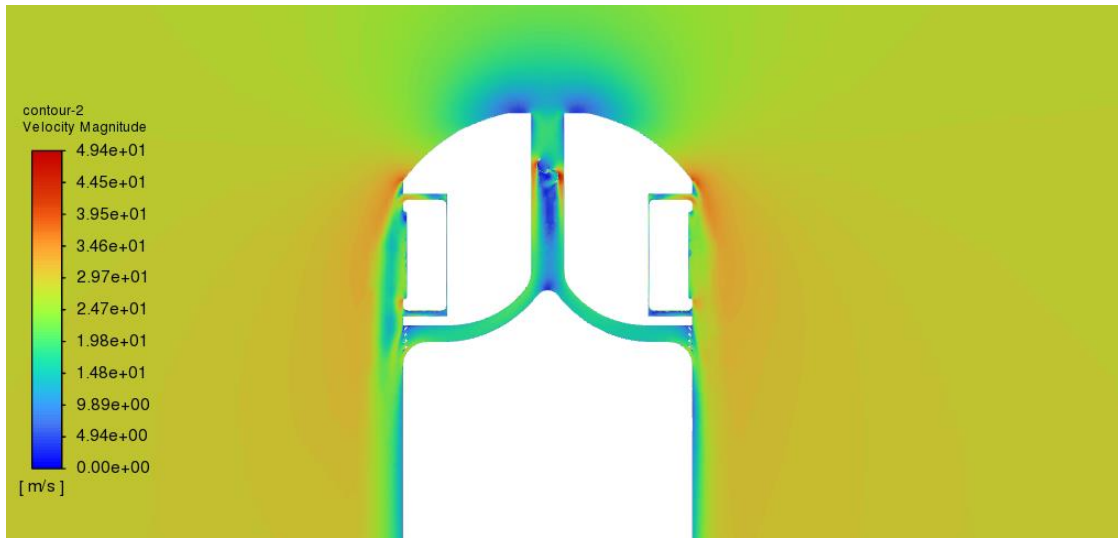
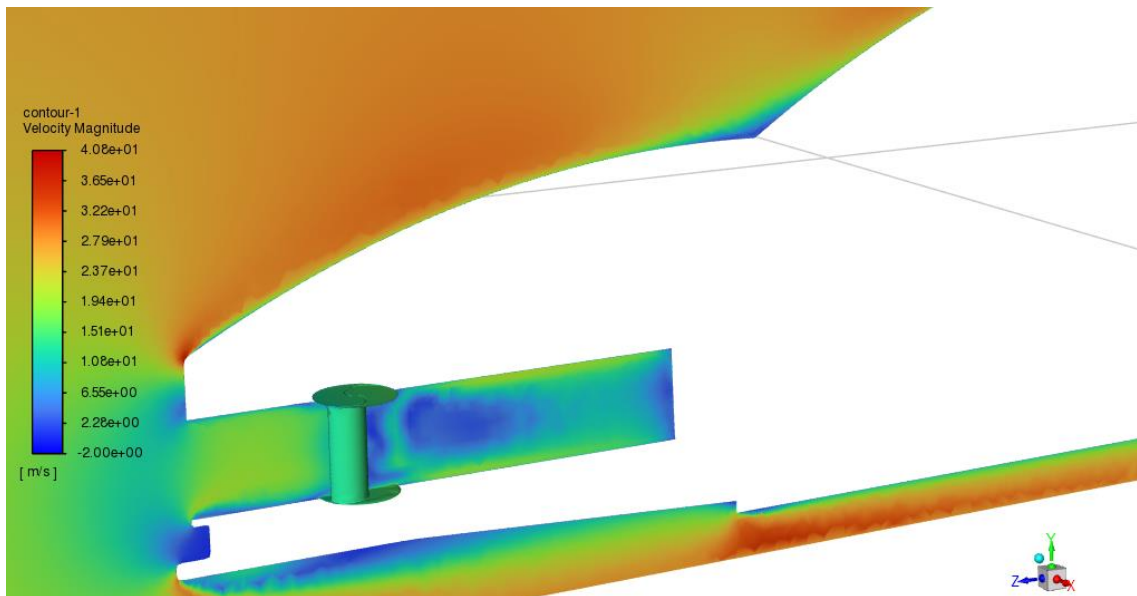


Figure 4.14: Static Pressure Distribution Inside the Ducting on Model-2

Model – 2 has a slightly larger duct where a Savonius rotor energy recovery device (savonius rotor) is placed at 60° angles to the incoming flow direction. Due to the solid construction of the turbine rotors flow that impacts the rotor at steep angles to the normal experience stagnation, while well angled flow drift over the rotor surfaces and pass-through opening between the rotor and wall as observed on figure 4.14. The rotor rotates in the counter clockwise direction. As a result of the rotor direction of rotation an area of flow separation can be observed on the right rotor.



(a)



(b)

Figure 4.15: Velocity Distribution Inside Model-2 Ducting (a) Top View, and (b) Side View

Observing the velocity distribution inside the ducting of model-2 flow velocities accelerate to maximum velocity magnitudes when the flow is through openings between rotor and wall faces. Decelerated flows also come through turbine rotor overlap opening attached to the inside of the right rotor blade with induced swirling motion. From the flow velocity distributions on figure 4.15 (b), it can be observed that the flow on the Savonius rotor wall has velocity magnitudes above 0 m/s. This increased for velocities at the rotor wall are the results of the assigned rotating boundary conditions to the Savonius rotor. The turbine rotor has rotating boundary condition with angular velocity of 95.46 rad/sec at rotation axis origin of $x=0$ m, $y=0.4196$ m and $z=-0.404$ m. When observing the immediate flow behind the rotor a large wake region can be observed as seen on figure 4.16.

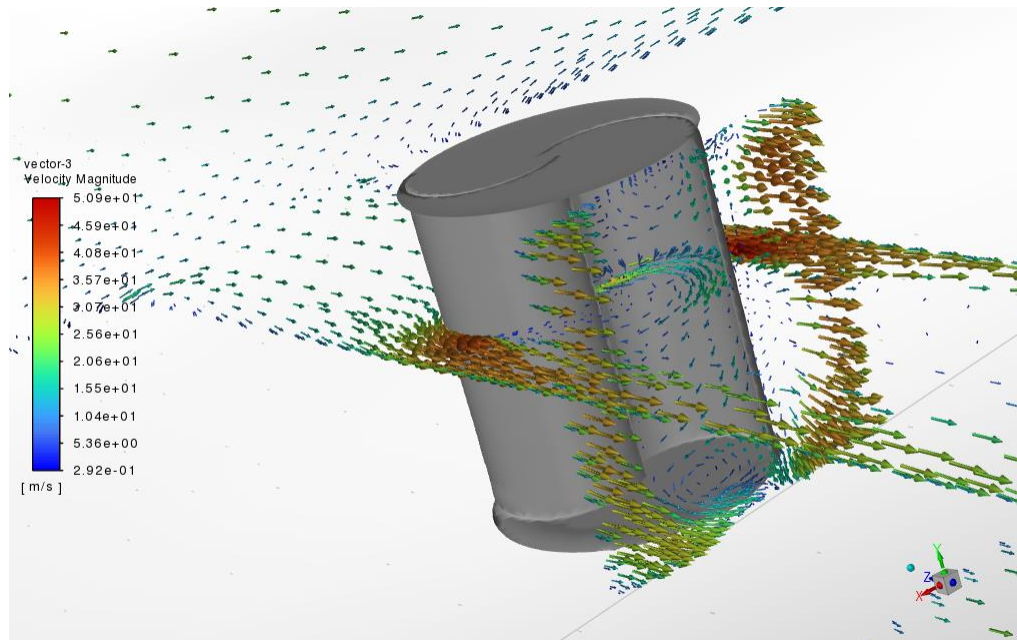


Figure 4.16: Flow Patterns Behind the Savonius Rotor

The vector plot on figure 4.16, shows the formation of two counter rotating vortices at the top and bottom of the rotor which are the results of the incoming swirl flow from opening at the eye of the Savonius rotor.

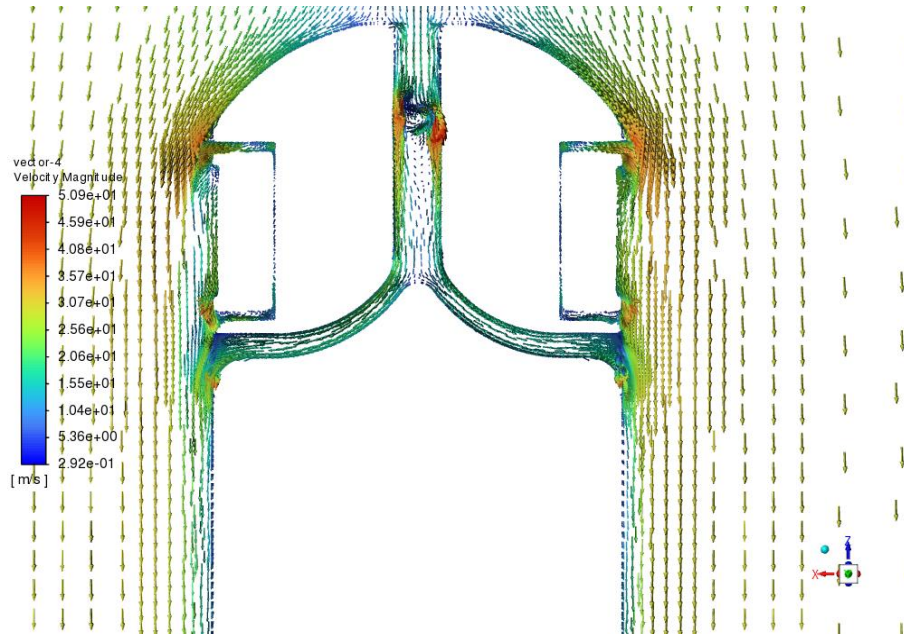


Figure 4.17: Flow Vector plot Inside Model-1 Ducting

The flow inside the ducting of model-2 has identical flow patterns with model-1 (i.e., similar attached and separated flow areas), though be it at lower flow velocities. Slow and lower volume flows exist inside of ducting of model-2 when compared with model-1.

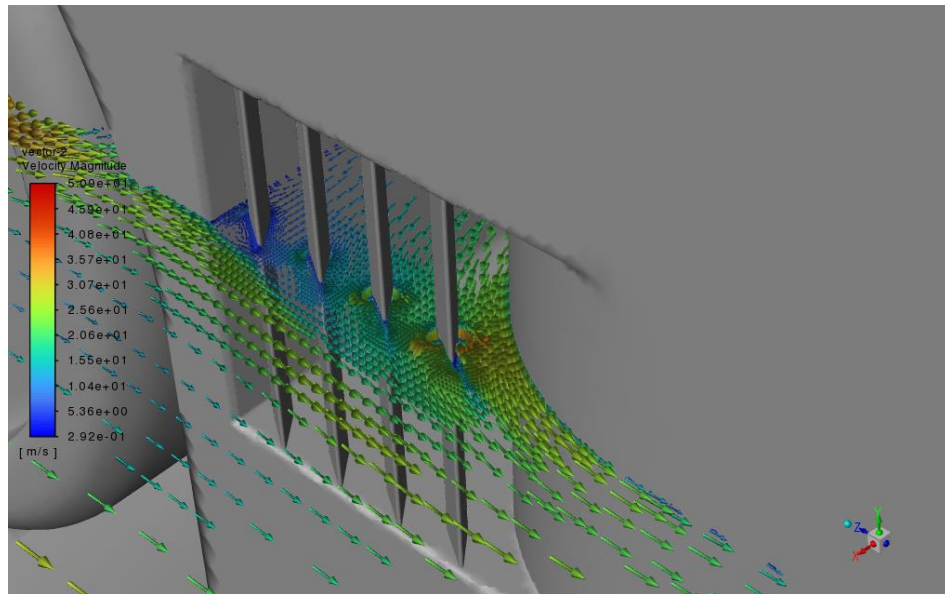


Figure 4.18: Flow Conditions at Ducting Exit

The low-speed exit flows of model-2 show a much better merging characteristics compared to the high velocity merging exit flows of model-1. The flow merging properties of the two models can

also be seen on flow patterns downstream of the exits shown on figures 4.17 and figure 4.9 ducting vector for model – 1, and model – 2. On model-2 disturbance to the flow downstream to the exits is minimal and close to the walls of the model. On the other hand, the flows on model – 1 are more magnified, propagating wider into the free stream flow. These propagated disturbances are more inclined to generate vortices due to their high velocity and low-pressure flow properties.

The vortex generated due to the exit flow that remain attached to the top wall surfaces on model-2 has a relatively smaller wake and low vortex velocity magnitudes when compared with model-1, as shown on figure 4.19.

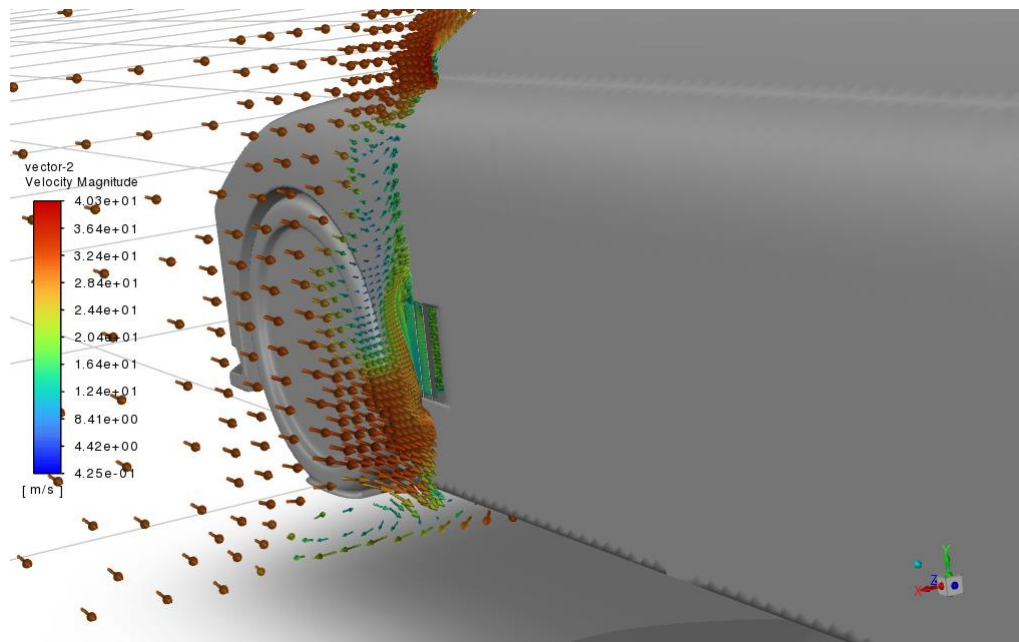


Figure 4.19: Exit Flow Interaction with Freestream Flow for Model – 2

4.1.4 Model Comparisons

The drag coefficient obtained from CFD simulations using ANSYS Fluent® for each model is summarized in the figure below.

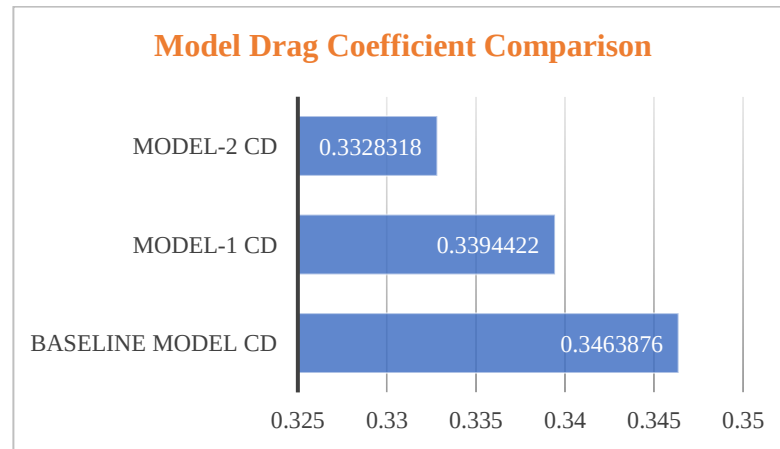


Figure 4.20: Comparison of Model Drag Coefficients

From figure 4.20 it was understood that both model – 1 and model – 2 designs result in reduced baseline model drag coefficient. Model – 2 resulted in higher drag coefficient reduction when compared with model – 1. From the results analyzed in the preceding sections, the higher aerodynamic performance of model – 2 is a result of reduced flow disturbance at the exits when compared with the higher volume and rapid flowing exit flow conditions of model – 1 which do not exhibit the smooth merging that exist on model – 2. Improvement to the drag coefficient of baseline model were summarized on table 4.1.

Table 4.1: Drag Coefficient Improvement from Baseline Model

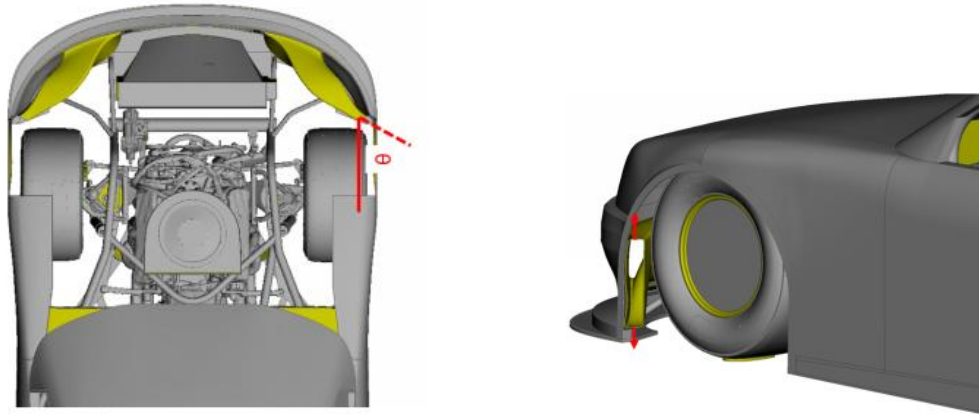
	Model-1			Model-2		
Baseline Cd	Model Cd	Difference form Baseline	%Diff from Baseline	Model Cd	Difference form Baseline	%Diff from Baseline
0.3463876	0.3394422	-0.006946	-2.01%	0.3328318	-0.01356	-3.914%

When compared with the baseline model both model – 1 and model – 2 have reduced drag coefficients. Model – 1 exhibited drag coefficient improvement of 2.01%, and model – 2 had improvement level of 3.941 % lower than the baseline model at 100km/hr.

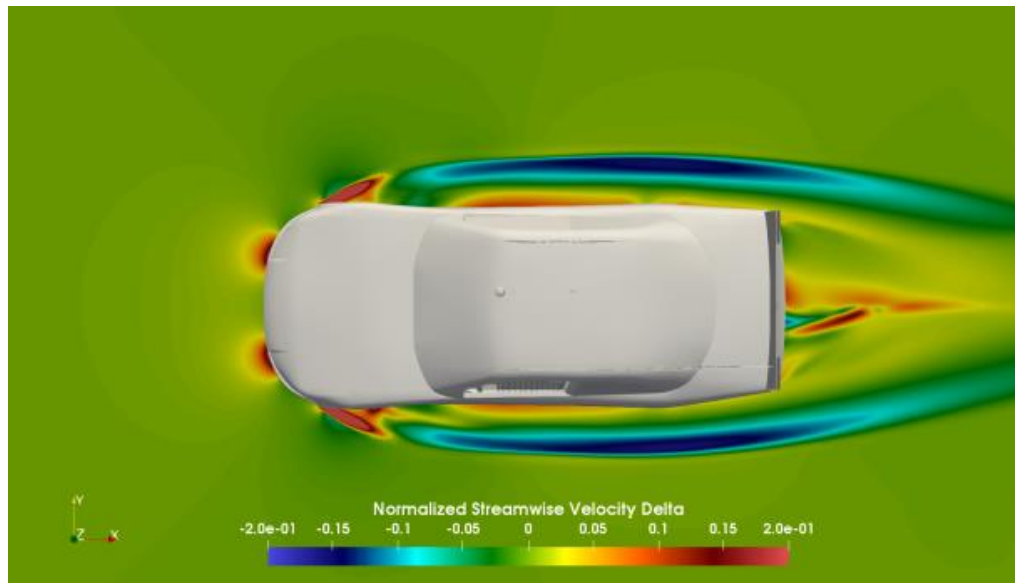
4.1.5 CFD Result Validation

There aren't any identical previous works to validate the model as a whole. A study by Jacuzzi & Granlund, 2019, studied the effect of front end passive flow ducting and its effect on isolated vehicle, and on following vehicle when platooning. The CFD simulation by Jacuzzi & Granlund,

2019, was conducted at inlet boundary condition of 89.4m/s (200 miles per hour), during which drag coefficient deltas were observed to be positive for different arrangements. Closer angling of the exit flows to the parallel of the induction flow resulted in improved vehicle drag characteristics. In the current study it can also be seen that for increased exit flow velocities the drag coefficient showed deterioration, which is the case for model – 1.



(a)



(b)

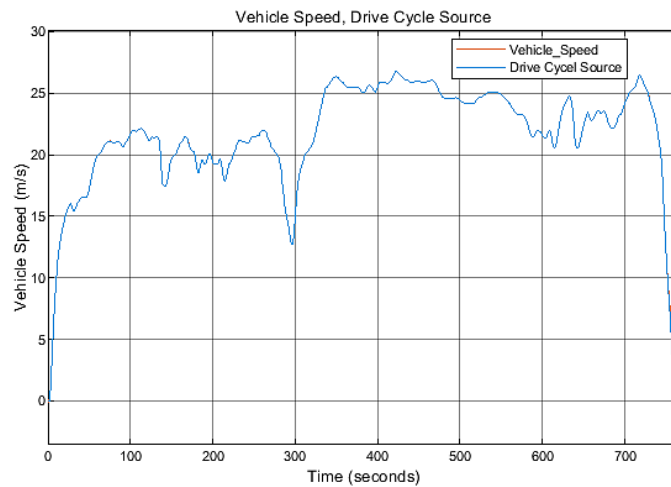
Figure 4.21 : Passive Blown Duct, (a) Placement and Design, and (b) Normalized Streamwise Velocity Delt Contour of Ducted Model (Jacuzzi & Granlund, 2019)

4.2 Simulink® Physical Modelling Results

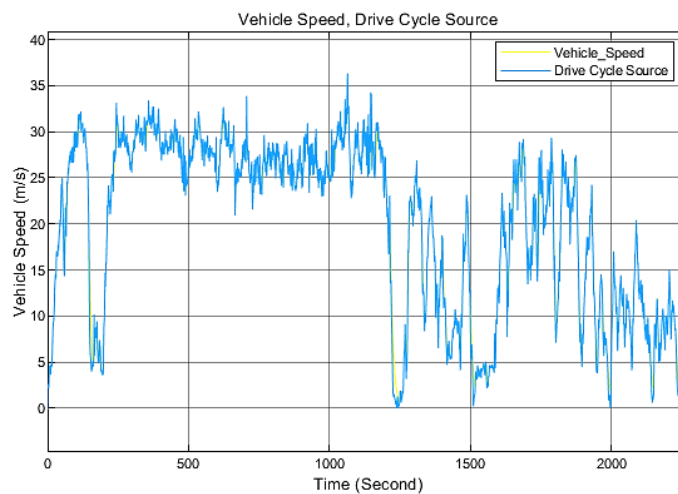
The physical model simulations were performed using the MATLAB Simulink® software using model blocks obtained from Simscape™ libraries. The physical modeling involved constructing models for the EV and ERS which take input datas related to wind, vehicle, and Energy recovery systems. The physical models are simulated under two drive cycles, namely the Highway Fuel Economy Test (HWFET) which is and EPA standard driving schedule and A custom driving schedule derived from road test preformed.

4.2.1 Baseline Model Results

The modeled EV Baseline model was tested under both the HWFET and Custom cycles. The baseline model's response on figure 4.22 shows the drive cycle speed tracking efficiency.



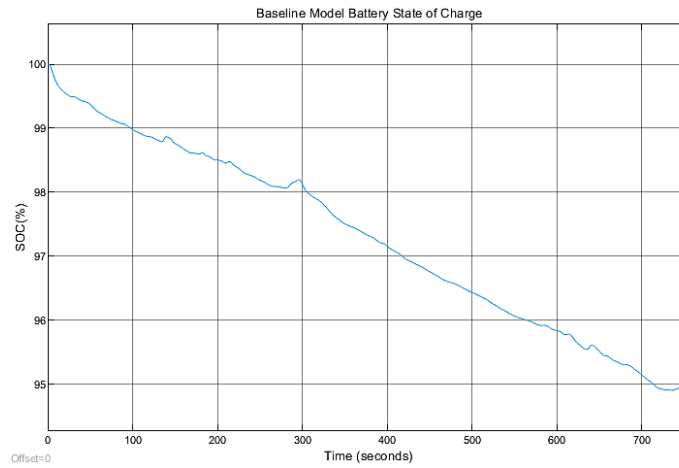
(a)



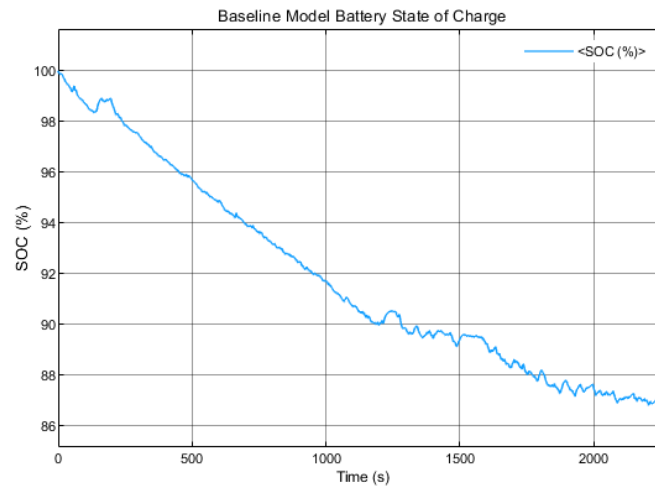
(b)

Figure 4.22: Baseline Speed tracking efficiency, (a) HWFET, and, (b) Custom Cycle

The final battery state of charge of the baseline model after simulation under the HWFET and custom cycles were 95.37% and 87.11% respectively. The rise and fall seen in the results is due to the motor controller used which enables regenerative braking.



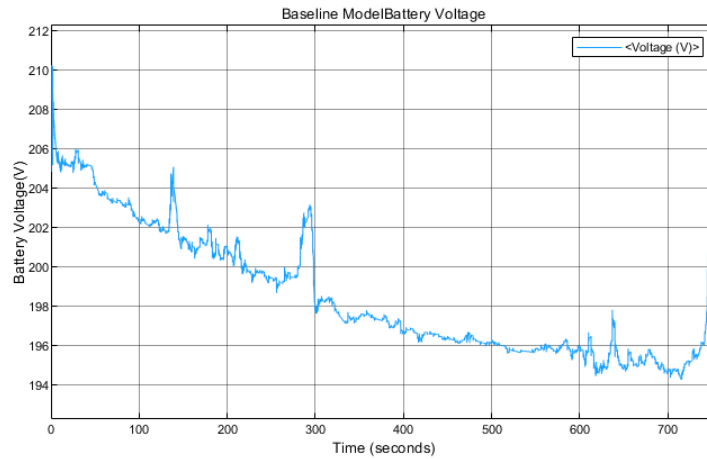
(a)



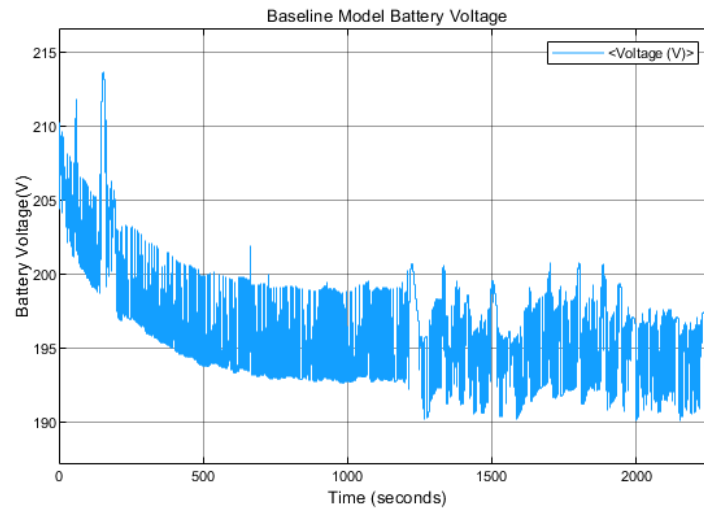
(b)

Figure 4.23: Battery SOC of Baseline Model Under, (a) HWFET, and (b) Custom Cycle

The battery voltage of baseline model drops to final values of 201V for HWFET cycle and 195.7V for the custom cycle. Voltage level spikes seen in the result on figure 4.24 are due to the regenerative braking action.



(a)



(b)

Figure 4.24: Baseline Model Battery Voltage, (a) HWFET, and (b) Custom Cycle

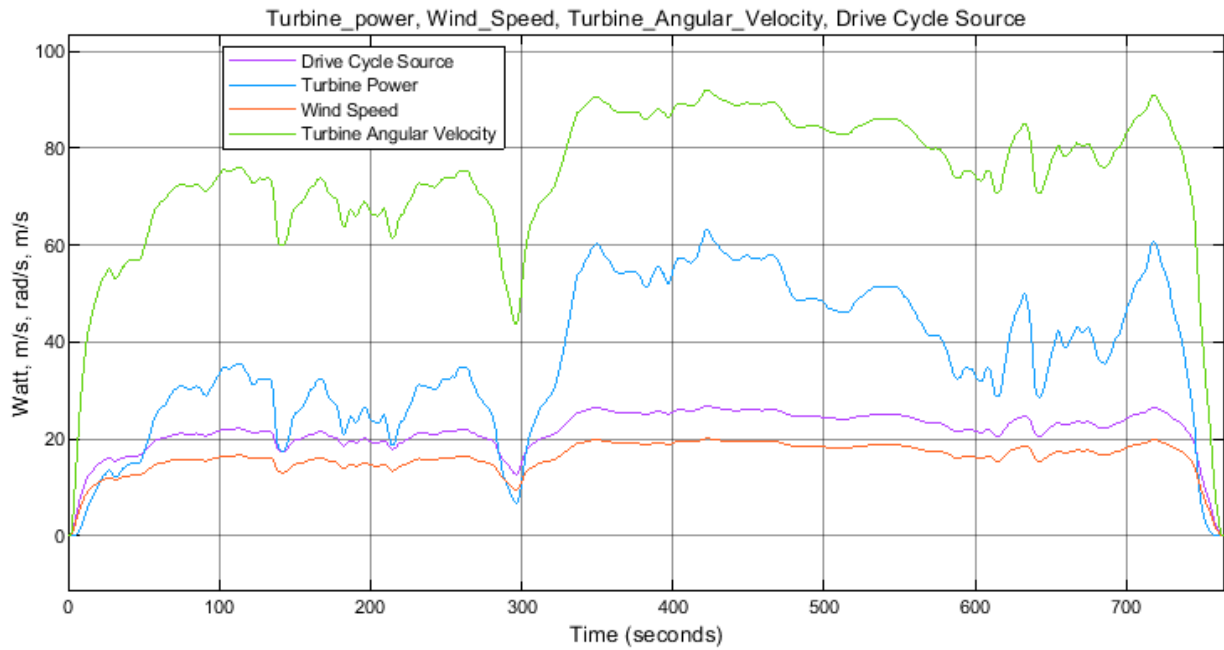
Table 4.2: Baseline Model Result Summary

HWFET		Custom Cycle	
Battery SOC (%)	Battery Voltage (V)	Battery SOC (%)	Battery Voltage (V)
95.37	201	87.11	195.7

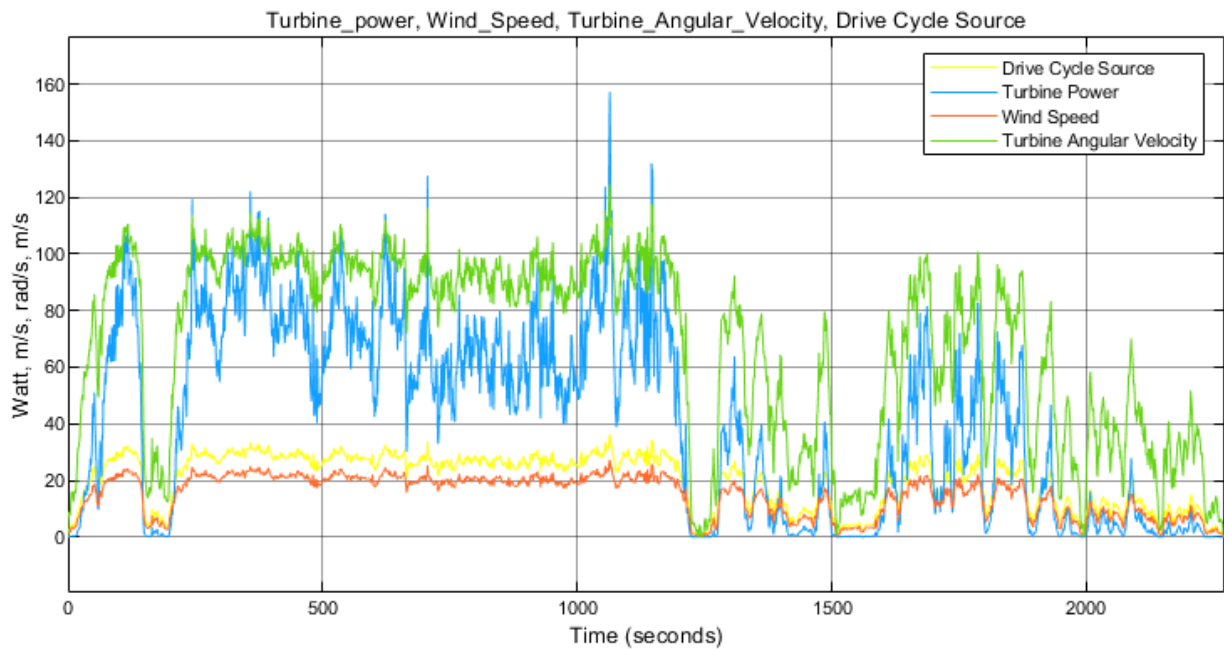
4.2.2 Model – 1 Results

The model (model – 1) integrated the EV model and ERS model discussed in section 3.2.5. In addition to baseline model performance characteristics, the model computes the ERS performance characteristics for considered input parameters of a HAWT and PMSG components, and ambient

conditions. Computed ERS output include turbine power, wind speed, turbine angular velocity, and rectifier output.



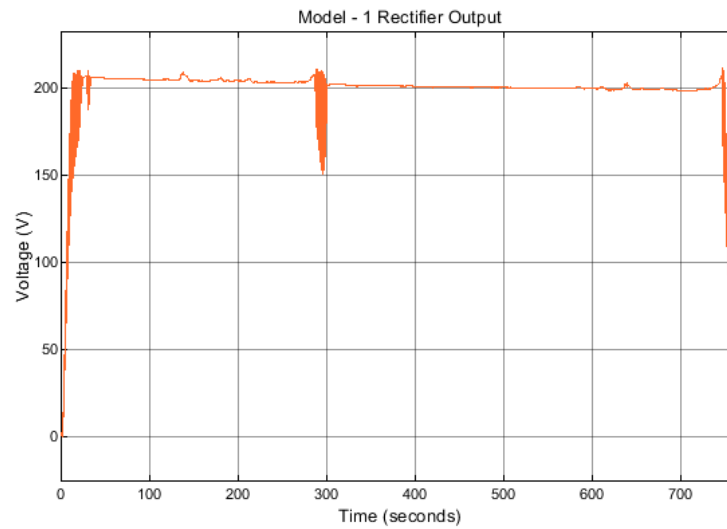
(a)



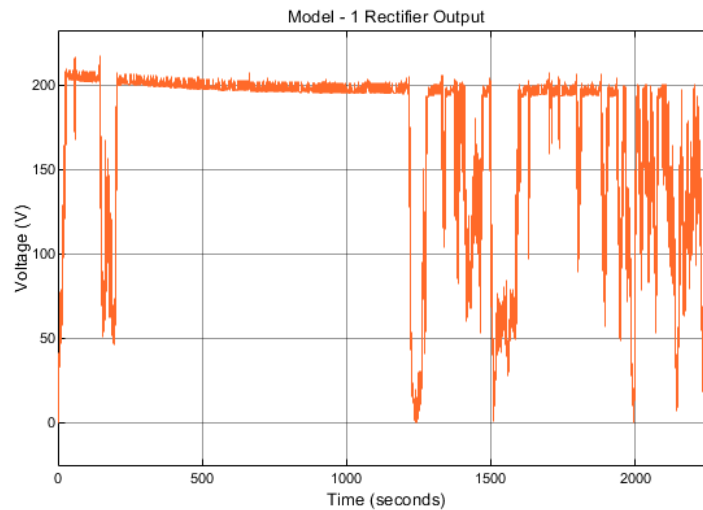
(b)

Figure 4.25: Model -1 ERS Mechanical Outputs Under, (a) HWFET, and (b) Custom Cycle

From figure 4.25 it can be seen that the model computes the ERS mechanical results for implemented driving schedules. The ERS mechanical output were computed from adopted design parameters and drive cycle source speed.



(a)

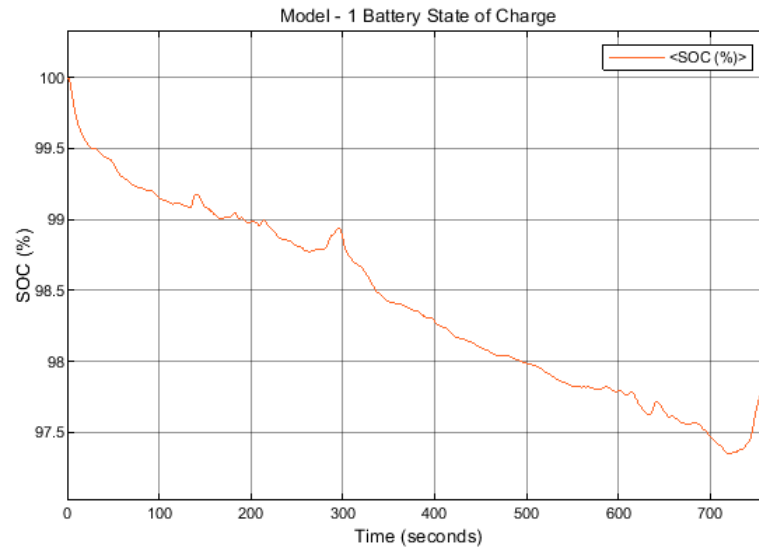


(b)

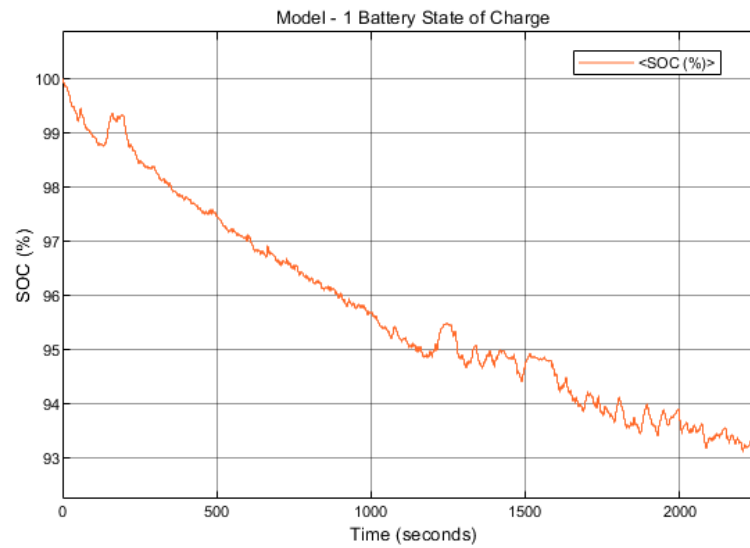
Figure 4.26: Model -1 Rectifier Terminal Voltage Under, (a) HWFET, and (b) Custom Cycle

The conversion of the mechanical output from the wind turbine is performed by the ERS electrical system. The PMSG used produced AC voltage which was then rectified using full wave bridge rectifier. As can be seen from figure 3.26 the rectifier performed satisfactory jobs of producing

smooth DC voltages at rectifier terminal for wind speed fluctuations above 10m/s for both driving schedules.



(a)

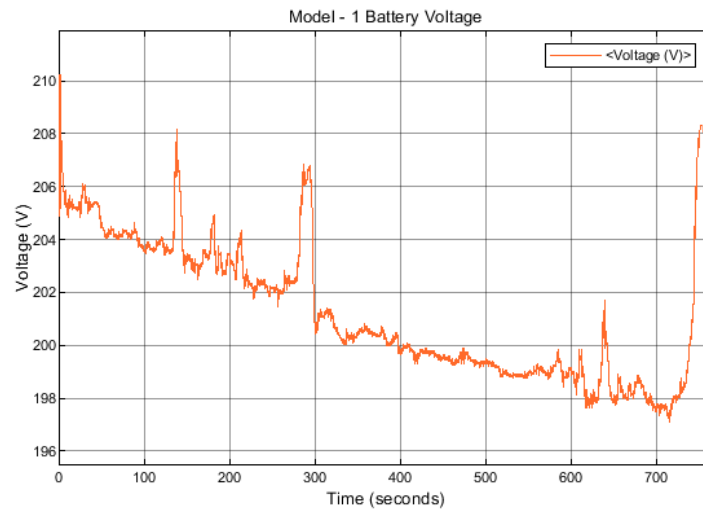


(b)

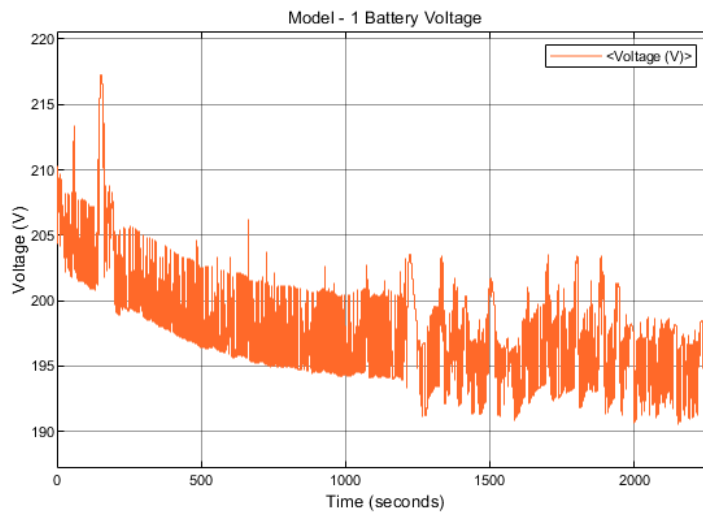
Figure 4.27: Battery SOC of Model – 1 Model Under, (a) HWFET, and (b) Custom Cycle

The DC voltage output from the rectifier seen of figure 4.27 was used to charge the EV's battery. The final battery SOC in model – 1 for simulation performed under the HWFET and Custom cycles were 97.89%, and 93.4% respectively when compared with the baseline results. Model – 1 benefited from increase SOC. Similarly, the final battery voltage valued were observed for the

HWFET and Custom cycles to be 205.5V and 196.3V respectively, which are higher values when compared with their respective results from the baseline model. The voltage fluctuation observed on Figure 2.28 (b), is due to rapid frequency of vehicle speed changes resulting in rapid discharging and charging.



(a)



(b)

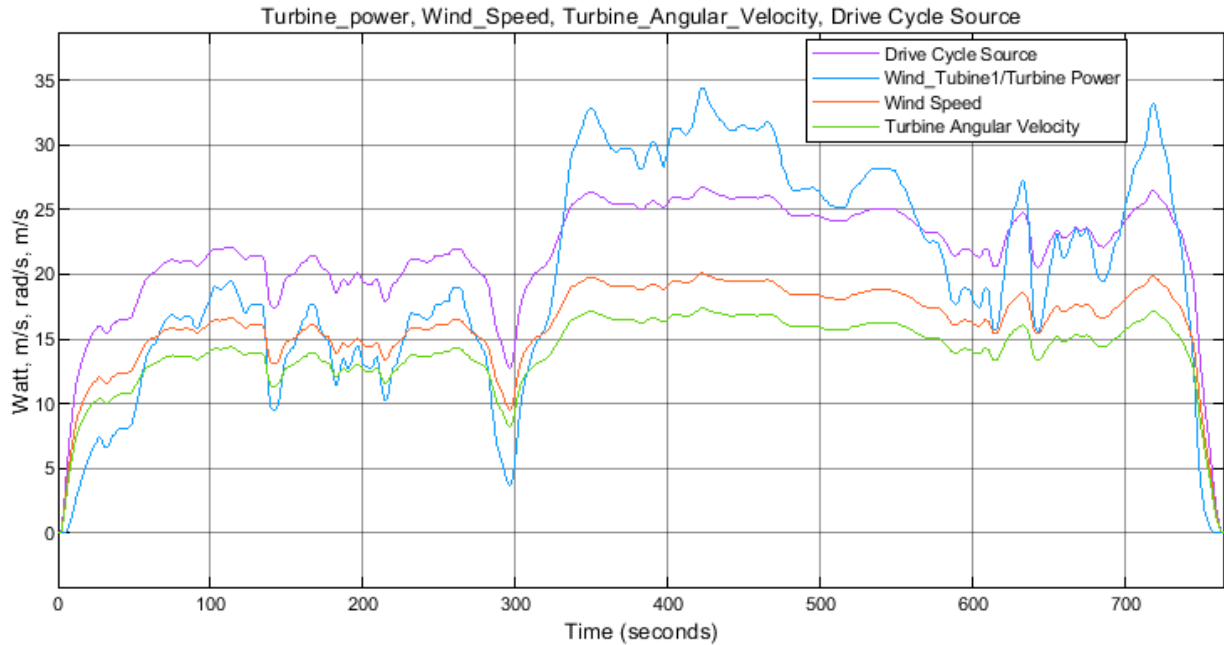
Figure 4.28: Model – 1 Battery Voltage Under, (a) HWFET, and (b) Custom Cycle

Table 4.3: Model – 1 Result Summary

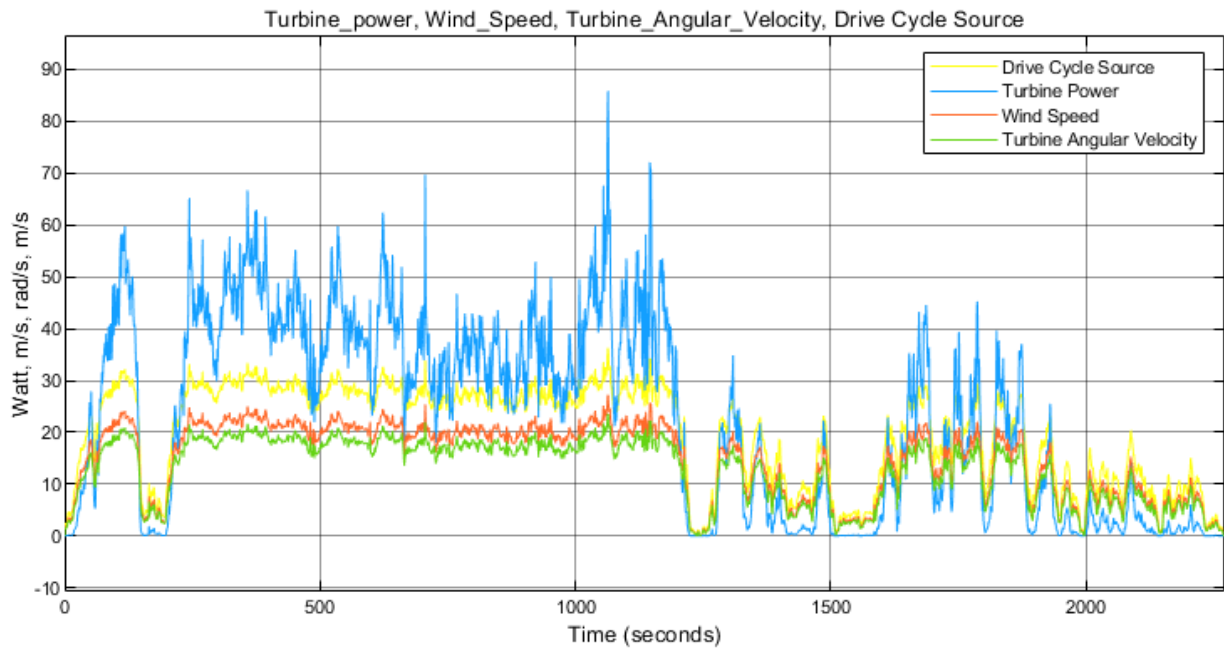
HWFET		Custom Cycle	
Battery SOC (%)	Battery Voltage (V)	Battery SOC (%)	Battery Voltage (V)
97.84	205.5	93.4	196.3

4.2.3 Model – 2 Results

Similar to model – 1, model – 2 integrates the EV model and the ERS. This model computed ERS performance characteristics for considered input parameters of a Savonius rotor wind turbine, PMSG components, and ambient conditions. The model computed similar mechanical and electrical performance characteristics values as model – 1.



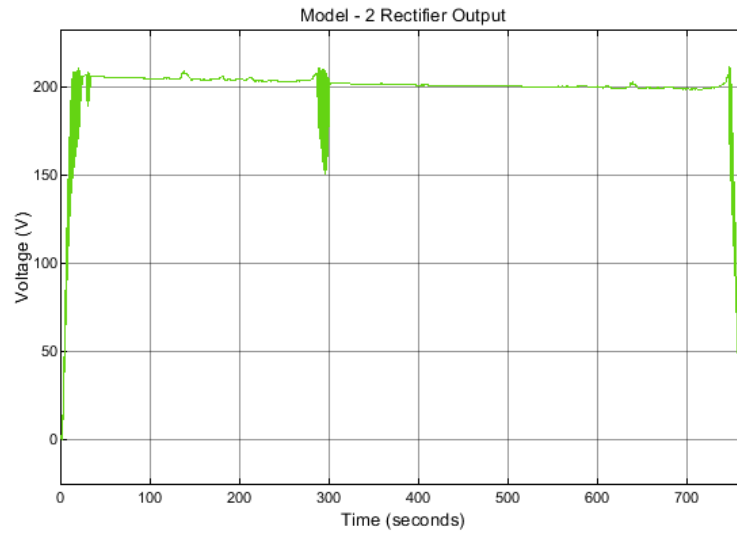
(a)



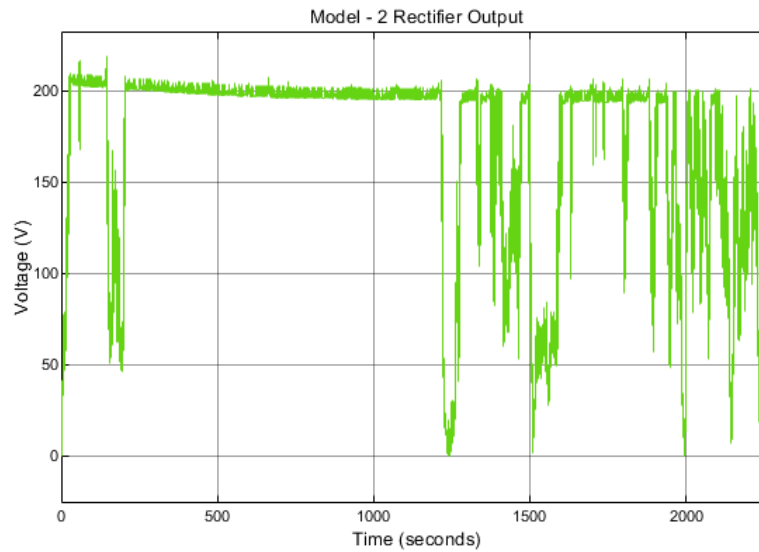
(b)

Figure 4.29: Model – 2 ERS Mechanical Outputs Under, (a) HWFET, and (b) Custom Cycle

Form figure 4.29, it can be seen that the turbine angular velocity and power produced had significantly reduced values when compared with model – 1 output.



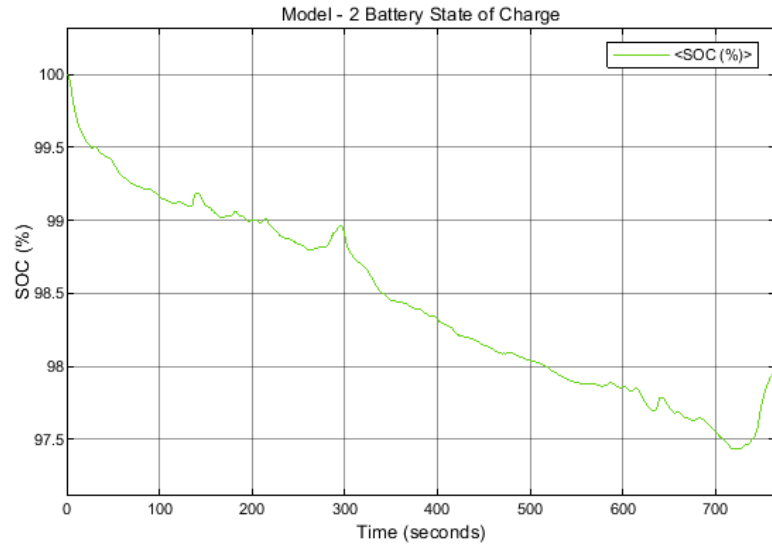
(a)



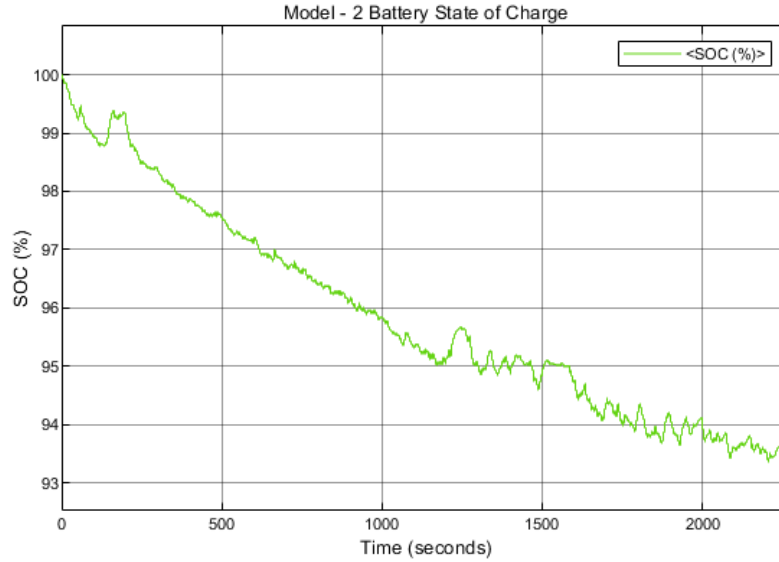
(b)

Figure 4.30: Model – 2 Rectifier Terminal Voltage Under, (a) HWFET, and (b) Custom Cycle

From the rectifier output observed on figure 4.30, it is understood that the full wave bridge rectifier used was able to produce smooth DC voltage at the rectifier terminal while operating under the moderate wind speed fluctuation. The rectifier terminal voltage was then used to charge the EV's battery.



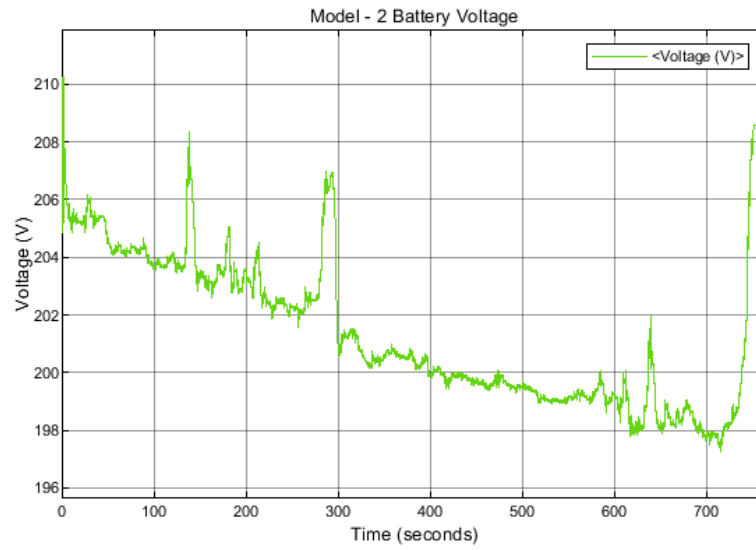
(a)



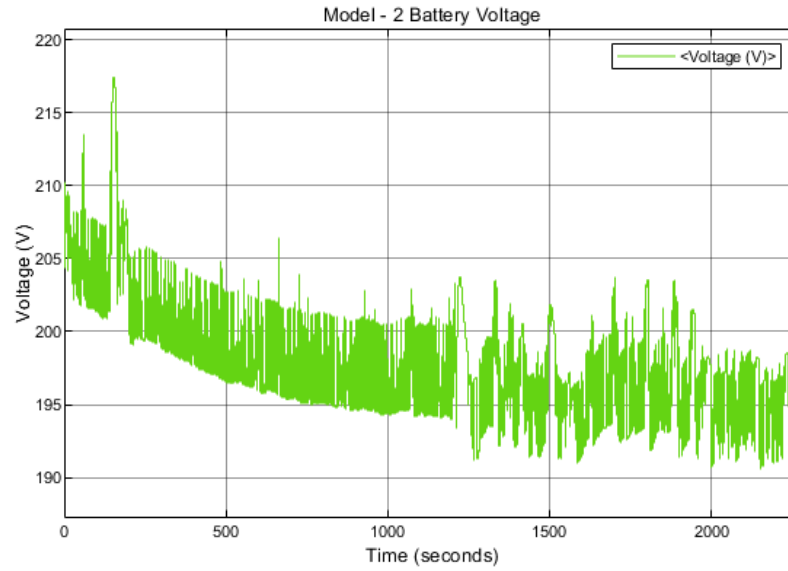
(b)

Figure 4.31: Battery SOC of Model – 2 Model Under, (a) HWFET, and (b) Custom Cycle

Model – 1's battery SOC for simulation performed under the HWFET and custom cycle were 97.98%, and 93.65% respectively. Comparing these final SOC values with baseline model, model – 2 benefits from increased battery SOC values as can be seen on figure 4.31. Final battery voltages given on figure 4.32 were for simulation under the HWFET, and Custom Cycle with values of 205.7V and 196.4V respectively.



(a)



(b)

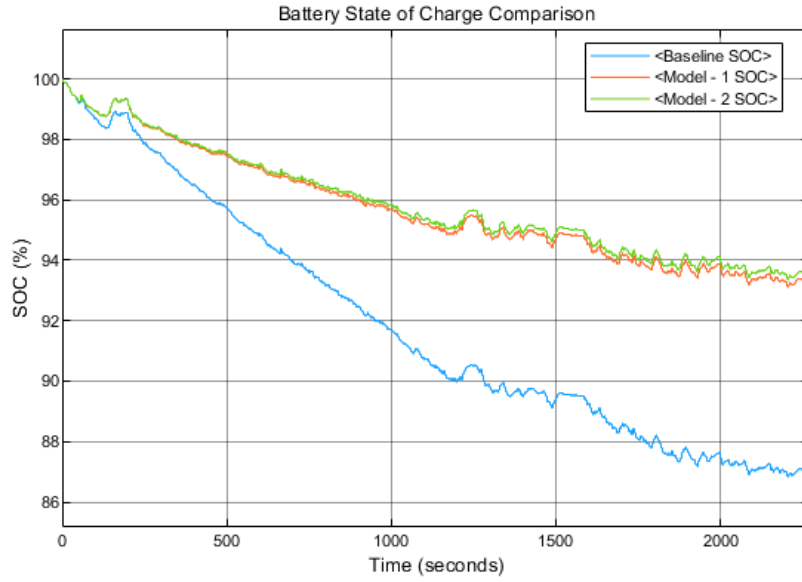
Figure 4.32: Model – 2 Battery Voltage Under, (a) HWFET, and (b) Custom Cycle

Table 4.4: Model – 2 Result Summary

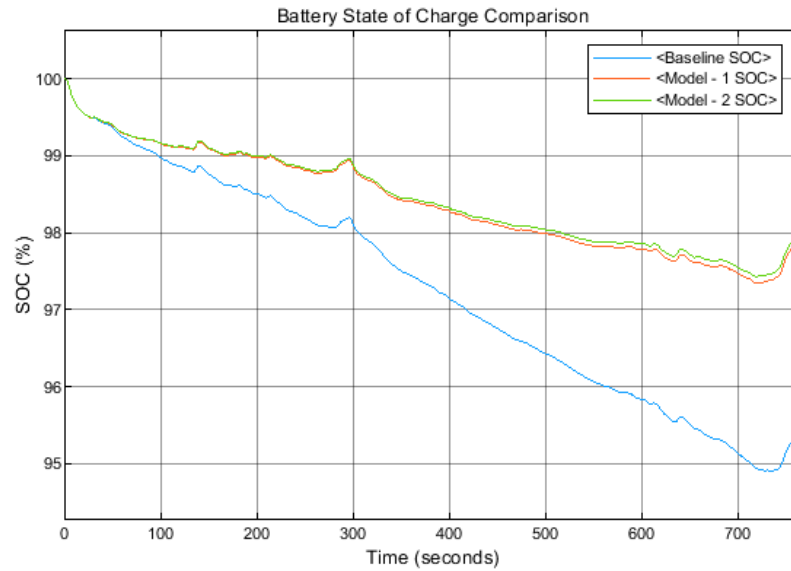
HWFET		Custom Cycle	
Battery SOC (%)	Battery Voltage (V)	Battery SOC (%)	Battery Voltage (V)
97.98	205.7	93.65	196.4

4.2.4 Model Comparison

The battery SOC values of each model obtained from the physical model simulation are shown on figure 4.33 for both HWFET and custom drive cycles.



(a)



(b)

Figure 4.33: Model SOC Comparison Under, (a) HWFET, and (b) Custom Cycle

From figure 4.33 it can be observed that both model – 1, and model – 2 benefits from increased final battery SOC values when compared to the baseline models; simulated under the HWFET and Custom cycles. When comparing model – 1, and model – 2 separately model – 2 benefits from the lower Cd value which resulted in a higher SOC Value Compared to model – 1 SOC values.

Table 4.5: Battery State of Charge for Each Model

	HWFET Cycle SOC (%)	Custom Cycle SOC (%)
Baseline Model	95.37	87.11
Model – 1	97.84	93.4
Model – 2	97.98	93.65

4.2.5 Actual Model Results

Battery SOC values obtained from model – 1 and model – 2 were subject to correction factor (model efficiency correction), as discussed in section 3.2.9. the model system efficiency given in section 3.2.9 will be used to calculate the actual SOC values of the models. Model efficiencies were computed for models under the HWFET Cycle and custom cycle. The calculated model efficiencies were 0.9752 under the HWFET and 0.9339 under the custom cycle.

$$SOC_{actual} = \eta_{model} * SOC$$

Where, SOC – is the battery state of charge obtained from physical model simulation, and η_{model} – is model efficiency computed in section 3.2.9.

Table 4.6: Actual Battery SOC Gained After Model Efficiency Correction

	HWFET Cycle			Custom Cycle		
	SOC (%)	SOC _{actual} (%)	Diff from Baseline (%)	SOC (%)	SOC _{actual} (%)	Diff from Baseline (%)
Baseline	95.37	-	-	87.11	-	-

Model – 1	97.84	95.414	+0.044	93.4	91.08	+0.1163
Model – 2	97.98	95.55	+0.18	93.65	91.33	+0.35

The extended vehicle range was computed using expression (3.2). The extended model driving ranges are given on table 4.7.

Table 4.7: Extended Driving Range Estimations

	HWFET Cycle Extended Range (km)	Custom Cycle Extended Range (km)
Model – 1	0.157	0.643
Model – 2	0.397	1.216

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The energy recovery potential of a vehicle front mounted wind energy recovery system was numerically investigated employing computational fluid dynamics (CFD), and physical model simulations. Multiple previous works were reviewed from which front mounted energy recovery system (ERS) was found to be realizable and practical implementation. The study implemented energy recovery system augmented with two wind generator variations of a 190mm diameter horizontal axis wind turbine, and a 208mm diameter Savonius rotor with aspect ratio of 1, with designated in study nomenclatures of model – 1, and model – 2 respectively. To accommodate the placement of the ERS a Y – shaped ducting with diverging exits on both sides of the baseline model was constructed through the front under body of the baseline electric vehicle model.

Three-dimensional models were generated using SOLIDWORKS 2017. The CFD simulations were conducted on a full-scale Tesla model S EV as a baseline using the ANSYS Fluent® 2021 R2. The shear stress transport $k-\omega$ turbulence model was used for all CFD simulations which consisted of both stationary and rotating boundary conditions. After performing the CFD simulation it was observed that both model – 1, and model – 2 resulted in reduced vehicle drag coefficient when compared with the baseline model. The baseline model had drag coefficient of 0.3463876, while model – 1 showed 2.01 % improvement, and model – 2 showed 3.914% improvement from the baseline model drag coefficient value at 100km/hr vehicle speed.

Physical model of baseline EV and ERS integrated models were constructed in the MATLAB Simulink® software. The physical modelling simulations were conducted under the EPA's highway fuel economy test (HWFET) driving cycle and a custom driving cycle derived from road tests conducted from Bishoftu, Ethiopia to Adama, Ethiopia. The energy recovery performances of the physical models were examined from the final battery state of charge (SOC), and voltage values. As a result of better improvement in drag coefficient model – 2 managed to recover the maximum amount of battery charge level of +2.61% at final battery SOC of 97.89% for the HWFET cycle, and +6.54% at final battery SOC of 93.65% for the custom cycle. In making sure that the models did not violate any physics/physical laws preliminary control simulations discussed

in section 3.2.9 were implemented for model efficiency corrections. The extended driving range of the models was estimated from expression in section 3.2.10.

Taking the model efficiency correction into account, model – 2 managed to increase the battery SOC level of the baseline model by +0.18% to final SOC_{actual} of 95.55% when simulated under the HWFET cycle, and +0.35% to final SOC_{actual} of 91.33% when simulated under the custom cycle. The estimated extended range for model – 2 was 0.397km when simulated under the 16.53km HWFET cycle, and 1.216km when simulated under the 44.8km custom cycle.

- Even though be it at varying magnitudes, all model were able to recover energy resulting in improved vehicle range. From the improvement in the drag coefficient, it was possible to conclude that energy can be recovered by redirecting the incoming flow through a ducting provided under the front end of the vehicle.
- Considering the sole point of aerodynamic performance gains the model with savonius augmented ERS (model – 2) showed better recovery potential.
- Ducting exit flow conditions greatly affected the improvement to the model drag coefficient in which for exit flow conditions with higher velocity magnitudes resulting in increased drag coefficient/lower improvements.
- Finally, form the physical model simulations under varied drive cycles it was understood that vehicle travelling longer distances at higher speeds would benefit to the utmost extent.

5.2 Recommendations

- Computing machines (computers) with high processing speed and capacities are suggested for a more accurate finding. These types of computers will contribute to the improvement of mesh quality and the reduction of processing time/duration when conducting CFD analysis.
- If computational resources lack for physical model simulation in MATLAB Simulink®, instead of running the powergui solver block with continuous solver setting it is recommended to use the discrete solver with timestep of 1e-4 second discretization or lower to reduce computation time and resource needed for simulation.
- In order to make sure complete data logging when running physical model simulation in Simulink®, the computing machines should at least have 12GB of RAM memory.

- To avoid simulation data loss, it is recommended to save .data and .case files for ANSYS Fluent® simulations, and logging Simulink® simulation scope data in to the MATLAB workspace where it can be extracted manually.
- The results obtained in the current research work only reflected on the effects of the ERS used to vehicle aerodynamic drag alterations. Future work that incorporates the system's mechanical and electrical efficiencies could be conducted.
- Future studies could design the wind turbines for implementation. In the present work the wind turbines implemented were adopted from previous works and their size dictated the subsequent designs for implementations. Designing custom turbines could give future researchers flexibilities in the implementations. Also, using other more efficient turbine designs such as helical savonius turbines instead of the conventual bucket rotor type, suggested by Mandal et al., 2020; or implementing cylindrical cowling for performance improvements on the savonius turbine model, suggested by Kothe et al., 2019. Additionally, turbine placement parametric studies should be conducted to study the effects of ERS placement.
- More advanced power electronic systems and controls could be modelled in the MATLAB environment to improve the performance and reliability of current system models which are representative of basic schemes. In order to achieve reliable and accurate designs multi-discipline cooperative works should be conducted.
- Experimental works to validate the results could be done either in the wind tunnel using hardware in the loop (HIL) test or conducting road test by constructing road worthy prototypes.

REFERENCES

- Alexandera, V.-M. (2006). Electric power systems: A Conceptual Introduction. In *IEEE Press*. John Wiely & Sons, LTD. https://doi.org/10.1007/978-3-662-44160-2_2
- ANSYS®. (2009). Ansys fluent 12.0 - Theory Guide. In *Theory Guide* (Issue April). ANSYS Inc. <http://orange.engr.ucdavis.edu/Documentation12.0/120/FLUENT/flth.pdf>
- ANSYS®. (2016). *ANSYS FLUENT 17.0 - Theory Guide*. SAS IP, Inc. http://www.afs.enea.it/project/neptunius/docs/fluent/html/th/main_pre.htm
- Bangi, V. K. T., Chaudhary, Y., Guduru, R. K., Aung, K. T., & Reddy, G. N. (2017). Preliminary investigation on generation of electricity using micro wind turbines placed on a car. *International Journal of Renewable Energy Development*, 6(1), 75–81. <https://doi.org/10.14710/ijred.6.1.75-81>
- Blackwell, B. F., Sheldahl, R. E., & Feltz, L. V. (1977). Wind Tunnel Performance Data for Two- and Three-Bucket Savonius Rotors. *Sandia National Labratories Report*. <https://doi.org/10.2514/3.47966>
- Cable, M. (2009). *An Evaluation of Turbulence Models for the Numerical Study of Forced and Natural Convective Flow in Atria*. May, 1–136.
- Cakir, M. (2012). CFD study on aerodynamic effects of a rear wing/ spoiler on a passenger vehicle. “*Unpublished*” *Masters Thesis Submitted to Santa Clara University*, 1–72.
- Chauvin, A., & Benghrib, D. (1989). Drag and lift coefficients evolution of a Savonius rotor. *Experiments in Fluids*, 8(1–2), 118–120. <https://doi.org/10.1007/BF00203076>
- Collis, S. S., Joslin, R. D., Seifert, A., & Theofilis, V. (2004). Issues in Active Flow control: Theory, Control, Simulation, and Experiment. *Progress in Aerospace Science*, 40, 237–289. <https://doi.org/10.1016/j.paerosci.2004.06.001>
- Ernest H., W. (1993). *History of the Electric Automobile*. SAE International.
- Fathabadi, H. (2019). Possibility of Utilizing Wind Turbine to Recover a Portion of the Kinetic Energy Losses of a Car. *IEEE Transactions on Vehicular Technology*, 68(9), 8663–8670.

<https://doi.org/10.1109/TVT.2019.2931192>

- Ferdous, S. M., Bin Khaled, W., Ahmed, B., Salehin, S., & Ghani Ovy, E. (2011). Electric Vehicle with Charging Facility in Motion using Wind Energy. *Proceedings of the World Renewable Energy Congress – Sweden, 8–13 May, 2011, Linköping, Sweden, 57*, 3629–3636. <https://doi.org/10.3384/ecp110573629>
- Feudjio Nguefack, M. C., Mtopi Fotso, B. E., & Fogue, M. (2022). Optimization of the position of Savonius turbines mounted on a hybrid vehicle by CFD analysis. *International Journal of Green Energy, 19*(7), 757–774. <https://doi.org/10.1080/15435075.2021.1961262>
- Feudjio Nguefack, M. Carlos, Fotso, B. M., Talawo, R.-C., & Fogue, M. (2019). Aerodynamic Analysis of an Electric Vehicle Equipped With Horizontal Axis Savonius Wind Turbines. *International Journal of Recent Trends in Engineering & Research, 05*(06), 17–26. <https://doi.org/10.23883/ijrter.2019.5057.lkaxl>
- Fitzgerald, A. E., Charles, K. J., & Stephen, U. D. (2003). *Electric Machinery* (Sixth Edit). McGraw-Hill Companies, Inc.
- Gaunaa, M., Øye, S., & Mikkelsen, R. (2009). Theory and Design of Flow Driven Vehicles Using Rotors for Energy Conversion. *European Wind Energy Conference and Exhibition 2009, EWEK 2009, 7*, 4693–4702.
- Gil-García, I. C., García-Cascales, M. S., Dagher, H., & Molina-García, A. (2021). Electric vehicle and renewable energy sources: Motor fusion in the energy transition from a multi-indicator perspective. *Sustainability (Switzerland), 13*(6), 1–19. <https://doi.org/10.3390/su13063430>
- Hegde, S. S., Thamban, A., Ahmed, A., & Arun, M. (2016). Chassis mounted single stage impulse turbine for wind energy harvesting on a cruising transport vehicle. *IEEE Region 10 Humanitarian Technology Conference, R10-HTC 2015 - Co-Located with 8th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management, HNICEM 2015*. <https://doi.org/10.1109/R10-HTC.2015.7391870>
- Hucho, W.-H. (Ed.). (1990). *Aerodynamics of road vehicles*. Butterworth-Heinemann.

- Iqbal, H. (2021). Electric and Hybrid Vehicles: Design Fundamentals. In *Angewandte Chemie International Edition*, 6(11), 951–952. (Third). CRC Press.
- Jacuzzi, E., & Granlund, K. (2019). Passive flow control for drag reduction in vehicle platoons. *Journal of Wind Engineering and Industrial Aerodynamics*, 189(June 2019), 104–117. <https://doi.org/10.1016/j.jweia.2019.03.001>
- Jiyuan, T., Guan-Heng, Y., & Chaoqun, L. (2018). *Computational Fluid Dynamics: A Practical Approach* (Thrid Edit). Butterworth-Heinemann.
- Joseph, K. (1995). *Race Car Aerodynamics: Designing For Speed* (Revised Se). Bentley Publishers.
- Joseph, K. (2016). *AUTOMOTIVE AERODYNAMICS*. John Wiely & Sons, Ltd.
- Kamoji, M. A., Kedare, S. B., & Prabhu, S. V. (2008). Experimental investigations on single stage, two stage and three stage conventional Savonius rotor. *INTERNATIONAL JOURNAL OF ENERGY RESEARCH*, 32, 877–895. <https://doi.org/10.1002/er.1399>
- Kassem, Y. (2018). Computational study on vertical axis wind turbine car: static study. *Modeling Earth Systems and Environment*, 4(3), 1041–1057. <https://doi.org/10.1007/s40808-018-0461-x>
- Khan, S. A., Sufiyan, S. A., George, J. T., & Ahmed, N. (2013). Analysis of Down-Wind Propeller Vehicle. *International Journal of Scientific and Research Publications*, 3(4), 3–6.
- Kosasih, B., & Tondelli, A. (2012). Experimental study of shrouded micro-wind turbine. *Procedia Engineering*, 49(December), 92–98. <https://doi.org/10.1016/j.proeng.2012.10.116>
- Kothe, L. B., Möller, S. V., & Petry, A. P. (2019). Numerical and experimental study of a helical Savonius wind turbine and a comparison with a two-stage Savonius turbine. *Renewable Energy*. <https://doi.org/10.1016/j.renene.2019.10.151>
- Lanfrit, M. (2005). Best Practice Guidelines for Jandling Automotive External Aerodynamics with FLUENT. *Fluent*, 1–14.
- Laughton, M. A., & Warne, D. J. (2003). *Electrical Engineer 's Reference Book* (Sixteenth).

Newnes.

Launder, B. E., & Spalding, D. B. (1972). *Lectures in Mathematical Models of Turbulence*. Academic Press.

Letcher, T. M. (2017). *Wind Energy Engineering: A Handbook for Onshore and Offshore Wind Turbines* (T. M. Letcher (Ed.)). Academic Press.

Liansheng, L., Fanxin, K., Xue, L., Yu, P., & Qinglong, W. (2015). A review on electric vehicles interacting with renewable energy in smart grid. *Renewable and Sustainable Energy Reviews*, 51, 648–661. <https://doi.org/10.1016/j.rser.2015.06.036>

Mandal, A. K., Rana, K. B., & Tripathi, B. (2020). Environmental Effects Experimental study on performance improvement of a Savonius turbine by equipping with a cylindrical cowling. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 00(00), 1–19. <https://doi.org/10.1080/15567036.2020.1772907>

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2009). *Wind Energy Explained: Theory, Design and Application* (Second Edi). John Wiley & Sons, Ltd.

Mathew, S. (2006). *Windy Energy Fundamentals: Fundamentals, Resource Analysis and Economics*. Springer International Publishing.

Mathieu, R., Patrick, G., & Azeddine, K. (2008). Drag reduction by flow separation control on a car after body. *International Journal for Numerical Methods in Fluids*. <https://doi.org/10.1002/fld>

Mehrdad, E., Yimin, G., & Ali, E. (2010). *Modern Electric, Hybrid Electric and Fuel Cell Vehicles: Fundamental, Theory and Design* (Second). CRC Press.

Menter, F. R. (1993). Zonal Two Equation k-w Models Turbulence for Aerodynamic Flows. *AIAA Paper 93-2906*, 1–22.

Miri, I., Fotouhi, A., & Ewin, N. (2021). Electric vehicle energy consumption modelling and estimation - A case study. *International Journal of Energy Research*, 45(1), 501–520. <https://doi.org/10.1002/er.5700>

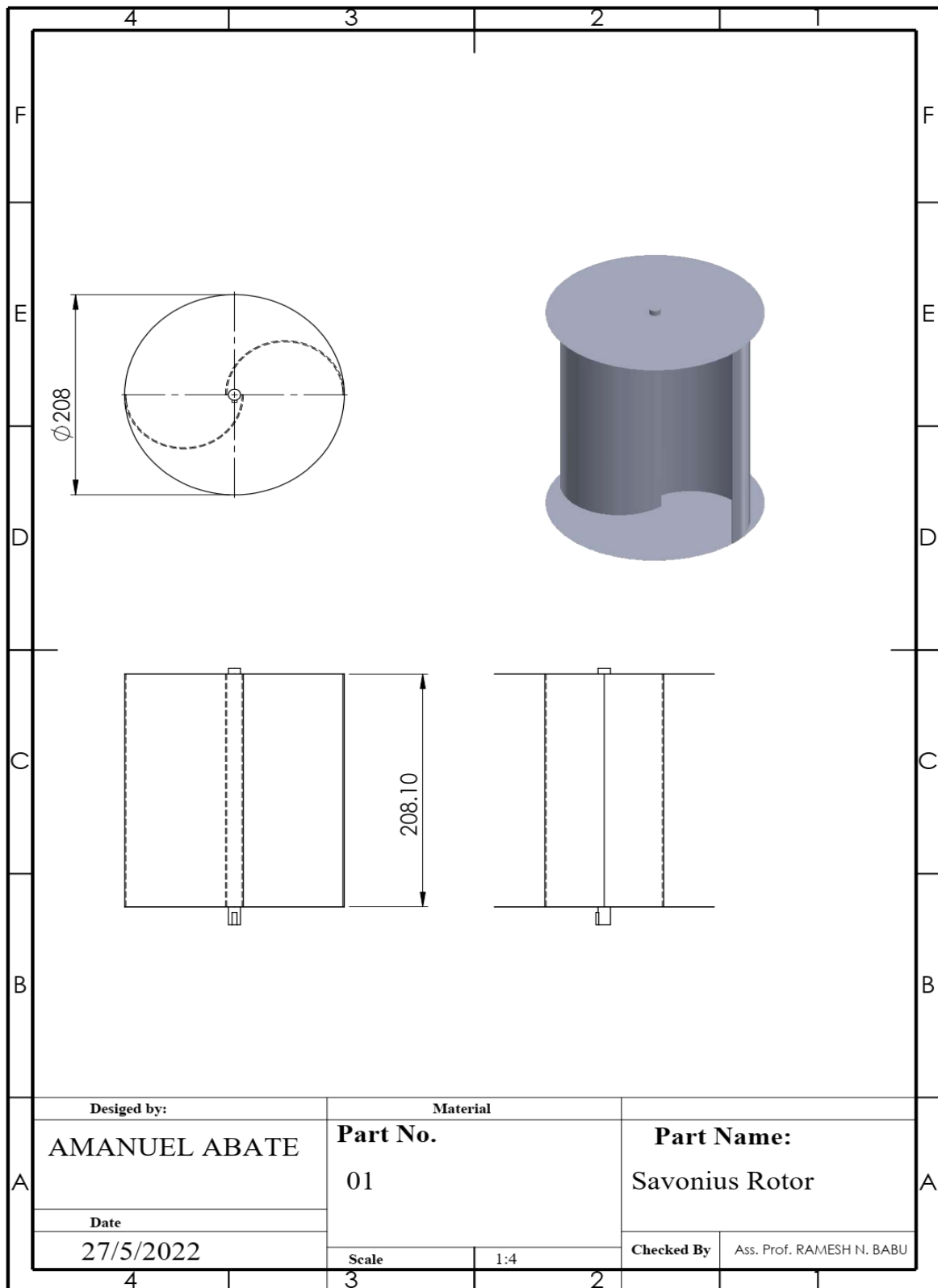
- Mohamed, G.-H., Andrew, P., & Jean-Paul, B. (Eds.). (1998). *Flow Control: Fundamentals and Practices*. Springer International Publishing. <https://www.amazon.fr/Flow-Control-Fundamentals-Mohamed-Gad-el-Hak/dp/3540639365>
- Naama, F. Z., Zegaoui, A., Benyessad, Y., Kessaissia, F. Z., Djahbar, A., & Aillerie, M. (2019). Model and simulation of a wind turbine and its associated permanent magnet synchronous generator. *Energy Procedia*, 157(2018), 737–745. <https://doi.org/10.1016/j.egypro.2018.11.239>
- Nasser, H. (2014). Vehicle Dynamics Conversion into Power (Dynapower). *AASRI Procedia*, 7, 32–37. <https://doi.org/10.1016/j.aasri.2014.05.025>
- Ned, M., Tore, M. U., & William, P. R. (2003). *Power Electronics: Converters, Applications, and Design* (Third Edit). John Wiely & Sons, Ltd. <https://doi.org/10.1017/CBO9780511544828.039>
- Oleg, Z. (2010). *Essential Computational Fluid Dynamics*. John Wiely & Sons, Ltd.
- Paraschivoiu, I. (2002). *Wind Turbine Design With Emphasis on Darrieus Concept*. Polytechnic International Press.
- Pramod, J. (2011). *Wind Energy Engineering*. McGraw-Hill Companies, Inc.
- Quartey, G., & Adzimah, S. K. (2014). Generation of Electrical Power by a Wind Turbine for Charging Moving Electric Cars. *Journal of Energy Technologies and Policy*, 4(3), 19–29.
- Quintal-Palomo, R. E., Gwozdziwicz, M., & Dybkowski, M. (2019). Modelling and co-simulation of a permanent magnet synchronous generator. *COMPEL - The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, 38(6), 1904–1917. <https://doi.org/10.1108/COMPEL-12-2018-0501>
- Randall, S. (2007). *Fundamentals of Power Electornics with Matlab*. Charles River Media.
- Rathore, N. S., & Panwar, N. L. (2022). *Fundamentals of Renewable Energy*. CRC Press. <https://doi.org/10.1201/9781003245643>
- Rubio, F., & Llopis-Albert, C. (2019). Viability of using wind turbines for electricity generation

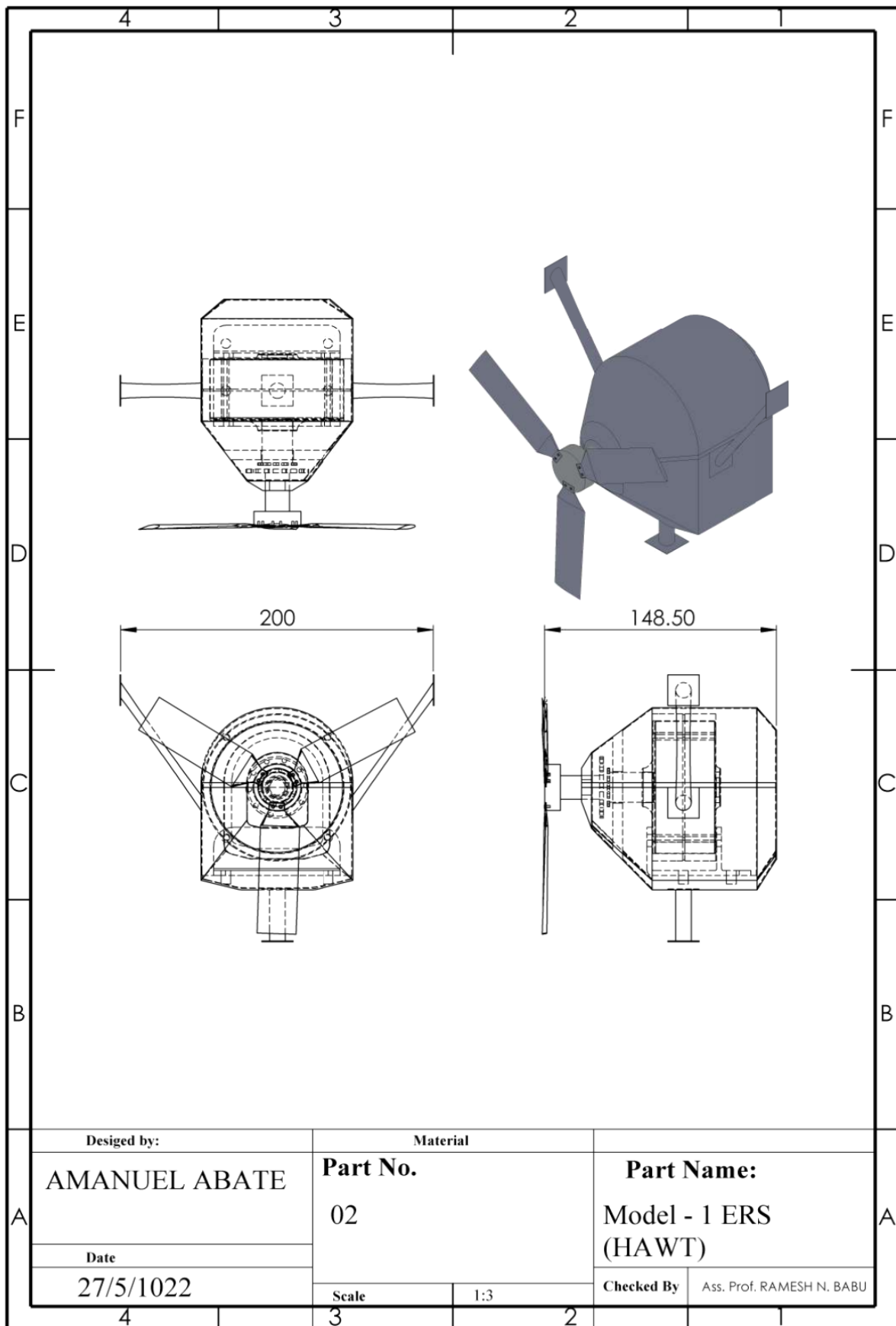
- in electric vehicles. *Multidisciplinary Journal for Education, Social and Technological Sciences*, 6(1), 115. <https://doi.org/10.4995/muse.2019.11743>
- Rubio, F., & Llopis-Albert, C. (2021). Analysis of the use of a wind turbine as an energy recovery device in transport systems. *Mathematics*, 9(18). <https://doi.org/10.3390/math9182265>
- Sciencedaily. (2008). *Wind-powered "Ventomobile" Places First in Race*. <https://www.sciencedaily.com/releases/2008/08/080827104702.htm>
- Shih, T. H., Liou, W. W., Shabbir, A., Yang, Z., & Zhu, J. (1995). A new k- ϵ eddy viscosity model for high reynolds number turbulent flows. *Computers and Fluids*, 24(3), 227–238. [https://doi.org/10.1016/0045-7930\(94\)00032-T](https://doi.org/10.1016/0045-7930(94)00032-T)
- Sofian, M., Nurhayati, R., Rexca, A. J., Syariful, S. S., & Aslam, A. (2014). An evaluation of drag coefficient of wind turbine system installed on moving car. *Applied Mechanics and Materials*, 660, 689–693. <https://doi.org/10.4028/www.scientific.net/AMM.660.689>
- Spalart, P. R., & Allmaras, S. . (1994). A one-equation turbulence model for aerodynamic flow. *La Recherche Aéronautique*, 5–21. https://turbmodels.larc.nasa.gov/Papers/RechAerosp_1994_SpalartAllmaras.pdf
- Stephen, J. C. (2005). *Electric Machinery Fundamentals* (Fourth Edi). McGraw-Hill Companies, Inc.
- Tesla.Inc. (2012). *Tesla Model S Owner's Manual*.
- Theraja, B. L., & Theraja, A. K. (2005). *A Textbook of Electrical Technology: Vol. I*. S. Chand & Company LTD.
- Thomas, S. (2016). *Aerodynamics of Road Vehicles* (Fifth Edit). SAE International.
- Tony, B., David, S., Nick, J., & Ervin, B. (2001). *Wind Energy Hand Book*. John Wiley & Sons, LTD.
- Vaughn, N. (2011). *Introduction to Renewable Energy* (G. Abbas (Ed.)). CRC Press.

- Wagner, H.-J., & Mathur, J. (2018). Introduction to wind energy systems: Basics, Technology and Operation. In *EPJ Web of Conferences* (Third, Vol. 189). Springer International Publishing. <https://doi.org/10.1051/epjconf/201818900005>
- Wendt, J. F. (Ed.). (2009). *Computational Fluid Dynamics - An Introduction* (Third Edit). Springer.
- Wilcox, D. C. (1993). *Turbulence modeling for CFD-DCW Industries*. DCW Industries, Inc.
- Wired. (2012). *Wind-Powered Vehicle Can Also Travel Upwind Faster Than the Wind*. <https://www.wired.com/2012/07/wind-powered-car-upwind/>
- Yakhot, V., & Orszag, S. A. (1986). Renormalization Group Analysis of Turbulence. I. Basic Theory. *Journal of Scientific Computing*, 1(1).
- Zahir Hussain, M., Anbalagan, R., Jayabalakrishnan, D., Naga Muruga, D. B., Prabhahar, M., Bhaskar, K., & Sendilvelan, S. (2020). Charging of car battery in electric vehicle by using wind energy. *Materials Today: Proceedings*, 45. <https://doi.org/10.1016/j.matpr.2020.08.341>
- Zoran, S. (2012). *New Generation Electric Vehicles*. InTech.
- Zou, Y., & He, J. (2016). Comprehensive modeling, simulation and experimental validation of Permanent Magnet Synchronous generator wind power system. *IEEE - 52nd Industrial and Commercial Power Systems Technical Conference, 2016-June*, 1–9. <https://doi.org/10.1109/ICPS.2016.7490241>

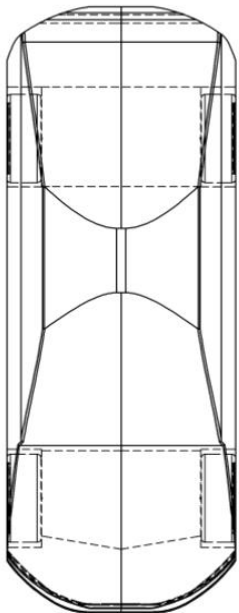
APPENDICES

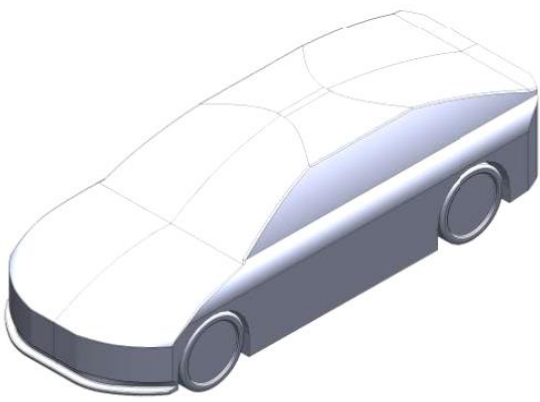
Appendix A: Model Drawings

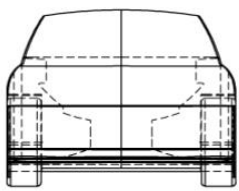


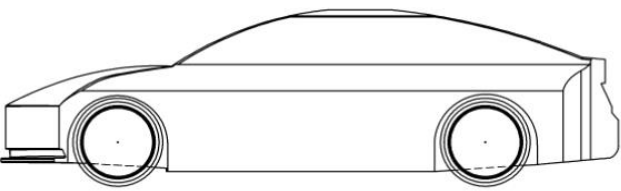


	4	3	2	
F				
E				
D				
C				
B				
A				





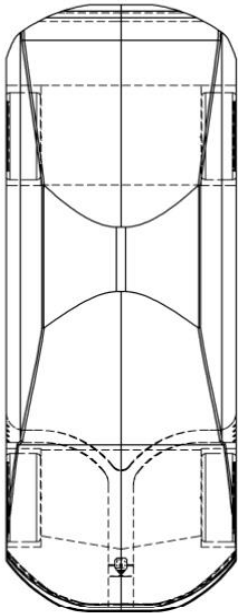




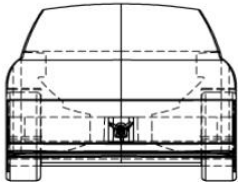
Designed by:	Material			
AMANUEL ABATE	Part No. 03		Part Name: Baseline Model	
Date				
27/05/2022	Scale	1:50	Checked By	Ass. Prof. RAMESH N. BABU
4	3	2		

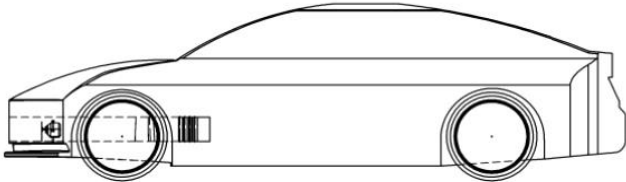
	4	3	2		
F					F
E					E
D					D
C					C
B					B
A	Designed by:		Material		A
	AMANUEL ABATE		Part No.		
	Date		04		
	27/5/2022		Scale 1:50		
	4	3	2		
			Part Name:		
			Modified Baseline Model		
			Checked By	Ass. Prof. RAMESH N. BABU	

	4	3	2	
F				
E				
D				
C				
B				
A				



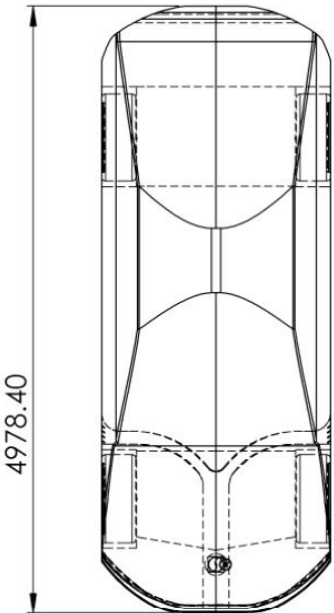
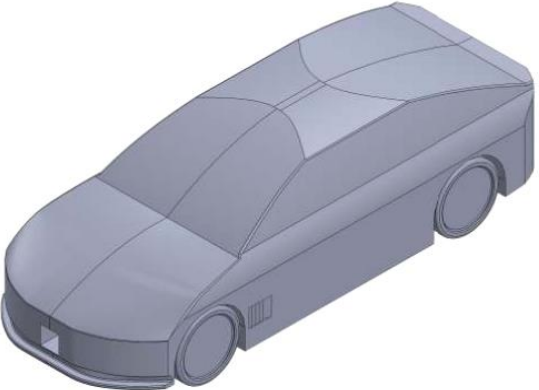
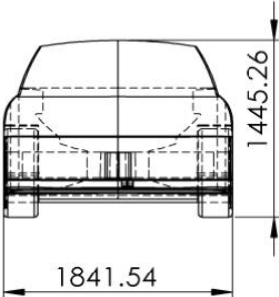
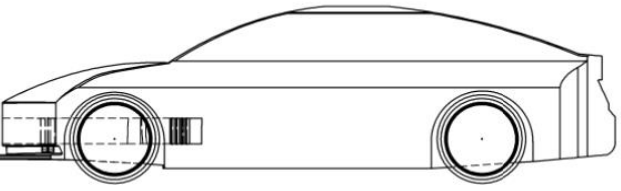






Designed by:	Material		Part Name:	
AMANUEL ABATE	Part No. 05		Model -1	
Date				
27/05/2022	Scale	1:50	Checked By	Ass. Prof. RAMESH N. BABU

4	3	2		
---	---	---	--	--

	4	3	2	1																											
F						F																									
E						E																									
D	 					D																									
C						C																									
B	 					B																									
A	<table border="1"> <tr> <td>Designed by:</td> <td colspan="2">Material</td> <td colspan="2"></td> </tr> <tr> <td>AMANUEL ABATE</td> <td colspan="2">Part No.</td> <td colspan="2">Part Name:</td> </tr> <tr> <td></td> <td colspan="2">06</td> <td colspan="2">Model - 2</td> </tr> <tr> <td>Date</td> <td colspan="2"></td> <td colspan="2"></td> </tr> <tr> <td>27/5/2022</td> <td>Scale</td> <td>1:50</td> <td>Checked By</td> <td>Ass. Prof. RAMESH N. BABU</td> </tr> </table>					Designed by:	Material				AMANUEL ABATE	Part No.		Part Name:			06		Model - 2		Date					27/5/2022	Scale	1:50	Checked By	Ass. Prof. RAMESH N. BABU	A
Designed by:	Material																														
AMANUEL ABATE	Part No.		Part Name:																												
	06		Model - 2																												
Date																															
27/5/2022	Scale	1:50	Checked By	Ass. Prof. RAMESH N. BABU																											
	4	3	2	1																											

Appendix B: Mesh Detail

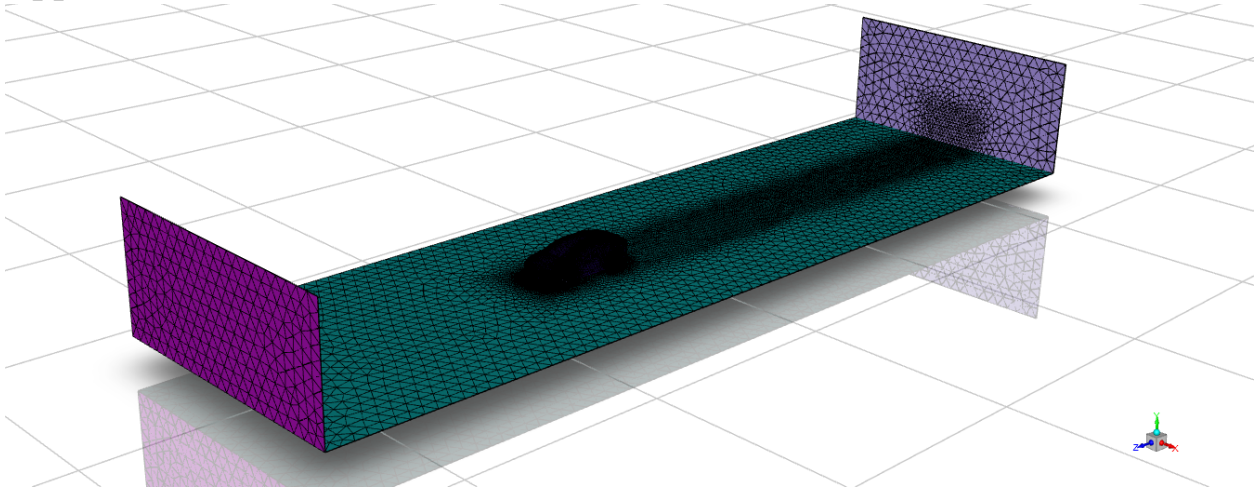


Figure B.1: Model – 1 Surface Mesh

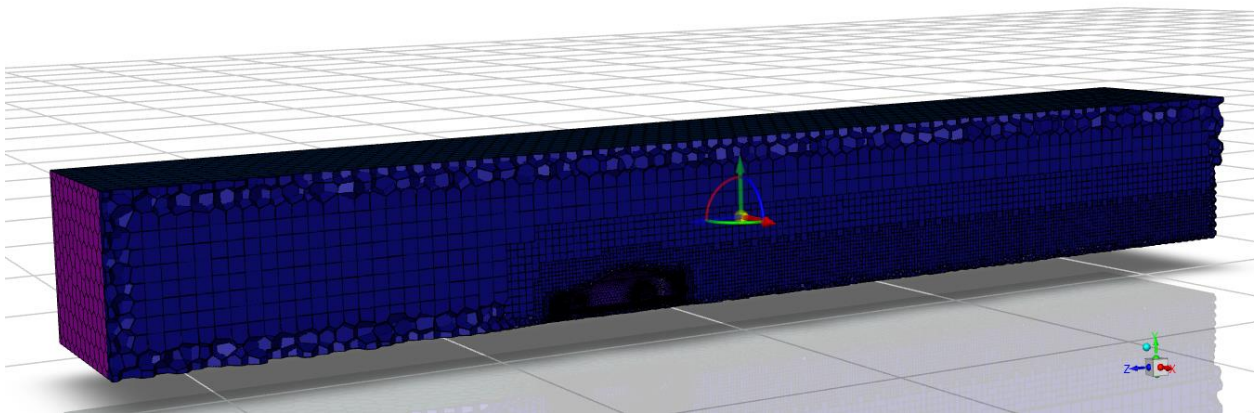


Figure B.2: Model – 1 Volume Mesh

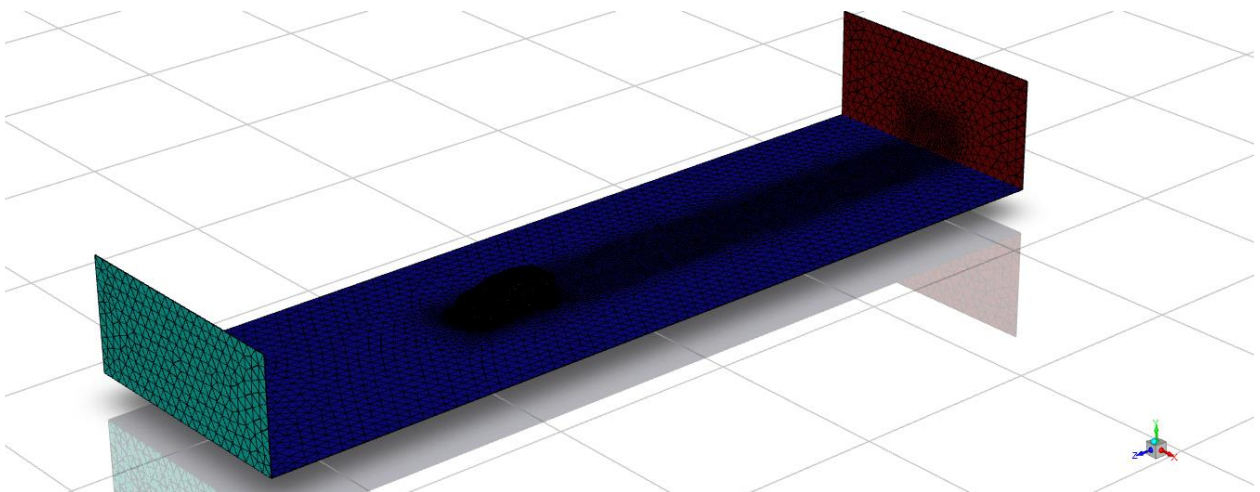


Figure B.3: Model – 2 Surface Mesh

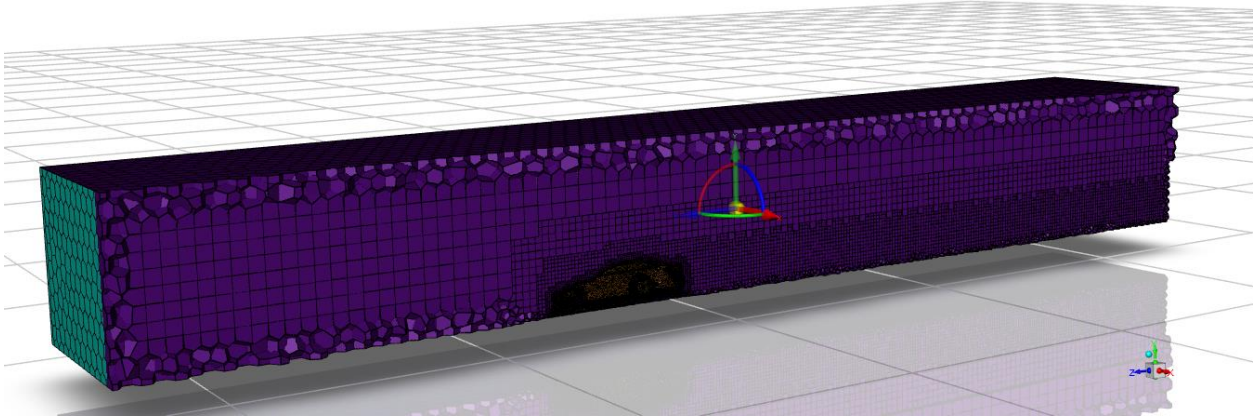


Figure B.4: Model – 2 Volume Mesh

Appendix C: Simulink® Block Parameters

This section contains information about parameters for model block obtained from the Simscape™ library.

The Simulink to PS Converter block: this block converts the dimensionless input Simulink® signal into a physical signal (PS). This block is used to connect Simulink® sources or other Simulink® blocks to other blocks that take physical signals.



Figure C.1: Simulink to PS Converter Block

The PS to Simulink Converter block: this block converts input physical signal (PS) into the dimensionless Simulink® signal.



Figure C.2: PS to Simulink Converter Block

Longitudinal Driver: The Longitudinal Driver block implements a longitudinal speed-tracking controller. Based on reference and feedback velocities, the block generates normalized acceleration and braking commands that can vary from 0 through 1. The block can be used to model the dynamic response of a driver or to generate the commands necessary to track a longitudinal drive cycle.

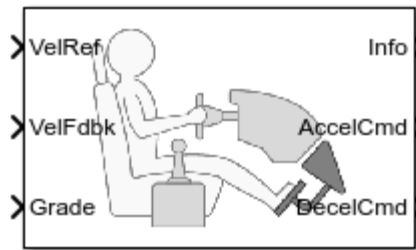


Figure C.3: Longitudinal Driver Block

The following are the settings for the Longitudinal Driver Block:

- Proportional Gain (K_p): 100
- Integral Gain (K_i): 20
- Velocity feed forward (K_{ff}): 0.05
- Grade Feed forward: 0.01

DC Motor: This block represents the electrical and torque characteristics of a DC motor. The block assumes that no electromagnetic energy is lost, and hence the back-emf and torque constants have the same numerical value when in SI units. Motor parameters can either be specified directly, or derived from no-load speed and stall torque.



Figure C.4: DC Motor Block

The following are the setting for the DC motor block:

- Armature inductance: 12e-6H
- No load speed: 42000rpm
- Rated speed: 38000rpm
- Rated load: 100kW
- Voltage: 180V

Battery Block: The Battery block implements a generic dynamic model that represents most popular types of rechargeable batteries. The parameters of the equivalent circuit on which the block is based on can be modified to represent a specific battery type and its discharge characteristics.

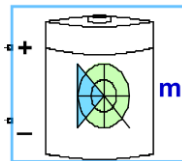


Figure C.5: Battery Block

The followings are the settings for the battery block:

- Type: Lithium: Ion
- Nominal Voltage: 180V
- Rated capacity: 472.2Ah
- Initial SOC: 100%

Controlled PWM Voltage Source: This block creates a Pulse-Width Modulated (PWM) voltage across the PWM and REF ports. The output voltage is zero when the pulse is low, and is equal to the Output voltage amplitude parameter when high.

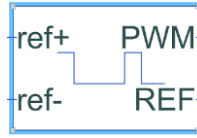


Figure C.6: Controlled PWM Voltage Source Block

The followings are the settings for the Controlled PWM Voltage block:

- PWM frequency: 1000Hz
- Simulation model: Averaged
- Output amplitude: 1V

H – Bridge: This block represents an H-bridge motor drive block. The block can be driven by the Controlled PWM Voltage block in PWM or Averaged mode. In PWM mode, the motor is powered if the PWM port voltage is above the Enable threshold voltage. In Averaged mode, the PWM port voltage divided by the PWM signal amplitude parameter defines the ratio of the on-time to the PWM period. Using this ratio and assumptions about the load, the block applies an average voltage to the load that achieves the correct average load current. The Simulation mode parameter value must be the same for the Controlled PWM Voltage and H-Bridge blocks.

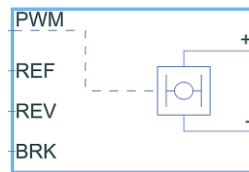


Figure C.7: H – Bridge Block

If the REV port voltage is greater than the Reverse threshold voltage, then the output voltage polarity is reversed. If the BRK port voltage is greater than the Braking threshold voltage, then the output terminals are short circuited via one bridge arm in series with the parallel combination of a second bridge arm and a freewheeling diode. Voltages at ports PWM, REV and BRK are defined relative to the REF port.

The followings are the settings for the Controlled PWM Voltage block:

- Power supply: Internal
- Simulation model: Averaged
- Regenerative Braking: enabled
- Enable threshold voltage: 0.001V
- Output amplitude: 1V
- Reverse threshold voltage: 0.01V
- Braking threshold voltage: 0.01V
- Output voltage amplitude: 180V
- Total bridge resistance: 0.1 ohm
- Freewheel diode resistance: 0.1 ohm

Vehicle Body Block: represents a two-axle vehicle body in longitudinal motion. The block accounts for body mass, aerodynamic drag, road incline, and weight distribution between axles due to acceleration and road profile. The vehicle does not pitch or move vertically relative to the ground.

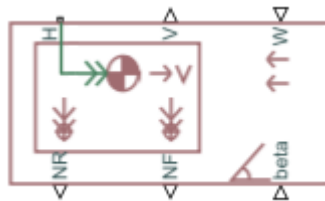


Figure C.8: Vehicle Body Block

Connection H is the mechanical translational conserving port associated with the horizontal motion of the vehicle body. The resulting traction motion developed by tires should be connected to this port. Connections V, NF, and NR are physical signal output ports for vehicle velocity and front and rear normal wheel forces, respectively. Wheel forces are considered positive if acting downwards. Connections W and beta are physical signal input ports corresponding to headwind speed and road inclination angle, respectively.

The followings are the settings for the vehicle body block:

- Mass: 2027 kg
- Number of wheels per axle: 2
- Horizontal distance from CG to front axle: 1.6m
- Horizontal distance from CG to rear axle: 1.361m

- CG height above ground: 0.46m
- Frontal area: 3.111948 m²
- Drag coefficients: 0.3463876 for baseline, 0.3394422 for model – 1, and 0.3328318 for model – 2.
- Initial velocity: 0km/hr

The Permanent Magnet Synchronous Machine Block: represents the PMSM block that operates in either generator or motor mode. The mode of operation is dictated by the sign of the mechanical torque (positive for motor mode, negative for generator mode). The electrical and mechanical parts of the machine are each represented by a second-order state-space model. The sinusoidal model assumes that the flux established by the permanent magnets in the stator is sinusoidal, which implies that the electromotive forces are sinusoidal. The trapezoidal model assumes that the winding distribution and flux established by the permanent magnets produce three trapezoidal back EMF waveforms.

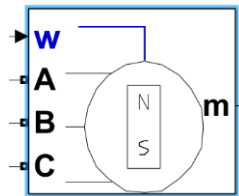


Figure C.9: Permanent Magnet Synchronous Machine Block

The port assigned w is the mechanical input port, A, B, and C are block AC phase output ports, and m is a Simulink signal output containing block measurement signals.

The followings are the settings for the PMSM block:

- Number of phases: 3
- Back EMF Waveform: Sinusoidal
- Rotor Type: Round
- Mechanical input: Speed w
- Preset model: 20Nm, 300Vdc, 2200 rpm – 33.9Nm

Appendix D: Wind Speed Data

No.	Time	Wind Speed (km/hr)
0	15:43:15	7.34
1	15:43:16	7.09
2	15:43:17	7.20
3	15:43:18	6.30
4	15:43:19	8.49
5	15:43:20	11.77
6	15:43:21	13.46
7	15:43:22	13.21
8	15:43:23	13.03
9	15:43:24	11.77
10	15:43:25	10.44
11	15:43:26	12.60
12	15:43:27	13.68
13	15:43:28	13.64
14	15:43:29	12.96
15	15:43:30	14.58
16	15:43:31	18.32
17	15:43:32	22.50
18	15:43:33	25.34
19	15:43:34	26.42
20	15:43:35	26.67
21	15:43:36	28.04
22	15:43:37	29.01
23	15:43:38	33.19
24	15:43:39	36.50
25	15:43:40	39.20
26	15:43:41	40.28
27	15:43:42	42.01
28	15:43:43	40.42
29	15:43:44	41.29
30	15:43:45	47.52
31	15:43:46	49.03
32	15:43:47	48.96
33	15:43:48	47.34
34	15:43:49	47.62
35	15:43:50	47.59
36	15:43:51	51.12
37	15:43:52	49.35
38	15:43:53	49.35
39	15:43:54	52.48

40	15:43:55	54.10
41	15:43:56	55.72
42	15:43:57	55.11
43	15:43:58	58.71
44	15:43:59	56.95
45	15:44:00	59.36
46	15:44:01	60.55
47	15:44:02	67.50
48	15:44:03	70.05
49	15:44:04	70.05
50	15:44:05	67.53
51	15:44:06	71.92
52	15:44:07	64.33
53	15:44:08	64.11
54	15:44:09	58.78
55	15:44:10	58.28
56	15:44:11	47.26
57	15:44:12	43.66
58	15:44:13	41.76
59	15:44:14	41.29
60	15:44:15	49.64
61	15:44:16	55.51
62	15:44:17	62.74
63	15:44:18	56.73
64	15:44:19	59.90
65	15:44:20	53.74
66	15:44:21	63.97
67	15:44:22	63.21
68	15:44:23	70.74
69	15:44:24	69.91
70	15:44:25	70.77
71	15:44:26	72.64
72	15:44:27	75.02
73	15:44:28	73.26
74	15:44:29	74.95
75	15:44:30	77.47
76	15:44:31	76.39
77	15:44:32	78.69
78	15:44:33	79.20
79	15:44:34	77.32
80	15:44:35	80.42
81	15:44:36	79.05

82	15:44:37	77.76
83	15:44:38	76.64
84	15:44:39	76.68
85	15:44:40	81.39
86	15:44:41	78.91
87	15:44:42	76.68
88	15:44:43	80.24
89	15:44:44	81.75
90	15:44:45	79.81
91	15:44:46	76.78
92	15:44:47	78.51
93	15:44:48	86.14
94	15:44:49	86.36
95	15:44:50	80.17
96	15:44:51	82.47
97	15:44:52	86.61
98	15:44:53	86.00
99	15:44:54	81.39
100	15:44:55	81.72
101	15:44:56	81.90
102	15:44:57	85.39
103	15:44:58	86.07
104	15:44:59	84.99
105	15:45:00	81.46
106	15:45:01	83.59
107	15:45:03	88.52
108	15:45:04	90.57
109	15:45:05	91.80
110	15:45:06	87.22
111	15:45:07	91.98
112	15:45:08	90.75
113	15:45:09	91.83
114	15:45:10	90.10
115	15:45:11	90.82
116	15:45:12	91.98
117	15:45:13	92.70
118	15:45:14	86.50
119	15:45:15	88.05
120	15:45:16	88.30
121	15:45:17	87.73
122	15:45:18	88.05
123	15:45:19	89.28

124	15:45:20	86.97
125	15:45:21	84.74
126	15:45:22	86.47
127	15:45:23	82.76
128	15:45:24	85.89
129	15:45:25	85.21
130	15:45:26	86.11
131	15:45:27	87.37
132	15:45:28	87.22
133	15:45:29	84.96
134	15:45:30	81.79
135	15:45:31	81.36
136	15:45:32	81.64
137	15:45:33	80.71
138	15:45:34	77.36
139	15:45:35	75.02
140	15:45:36	74.12
141	15:45:37	76.53
142	15:45:38	72.86
143	15:45:39	65.23
144	15:45:40	64.47
145	15:45:41	56.16
146	15:45:42	47.19
147	15:45:43	33.62
148	15:45:44	25.09
149	15:45:45	21.13
150	15:45:46	17.71
151	15:45:47	15.98
152	15:45:48	15.62
153	15:45:49	14.25
154	15:45:50	12.20
155	15:45:51	11.48
156	15:45:52	11.91
157	15:45:53	12.49
158	15:45:54	13.24
159	15:45:55	14.76
160	15:45:56	12.88
161	15:45:57	13.75
162	15:45:58	13.82
163	15:45:59	14.36
164	15:46:00	29.30
165	15:46:01	16.34

166	15:46:02	19.29
167	15:46:03	20.19
168	15:46:04	22.82
169	15:46:05	25.30
170	15:46:06	21.96
171	15:46:07	22.06
172	15:46:08	23.50
173	15:46:09	26.53
174	15:46:10	27.10
175	15:46:11	23.43
176	15:46:12	17.38
177	15:46:13	17.35
178	15:46:14	14.86
179	15:46:15	14.07
180	15:46:16	14.47
181	15:46:17	14.36
182	15:46:18	17.82
183	15:46:19	21.27
184	15:46:20	20.01
185	15:46:21	19.47
186	15:46:22	18.36
187	15:46:23	14.79
188	15:46:24	11.44
189	15:46:25	11.73
190	15:46:26	12.24
191	15:46:27	11.34
192	15:46:28	10.51
193	15:46:29	10.87
194	15:46:30	10.87
195	15:46:31	10.29
196	15:46:32	10.51
197	15:46:33	13.06
198	15:46:34	22.10
199	15:46:35	26.56
200	15:46:36	26.60
201	15:46:37	31.03
202	15:46:38	34.66
203	15:46:39	42.33
204	15:46:40	37.90
205	15:46:41	42.69
206	15:46:42	45.46
207	15:46:43	45.03
208	15:46:44	49.06

209	15:46:45	52.88
210	15:46:46	54.61
211	15:46:47	63.32
212	15:46:48	59.94
213	15:46:49	63.50
214	15:46:50	67.93
215	15:46:51	69.55
216	15:46:52	69.04
217	15:46:53	66.45
218	15:46:54	63.03
219	15:46:55	64.94
220	15:46:56	62.02
221	15:46:57	60.55
222	15:46:58	61.16
223	15:46:59	64.51
224	15:47:00	65.23
225	15:47:01	67.28
226	15:47:02	71.85
227	15:47:03	72.50
228	15:47:04	73.18
229	15:47:05	72.75
230	15:47:06	71.10
231	15:47:07	72.18
232	15:47:08	67.57
233	15:47:09	79.92
234	15:47:10	78.84
235	15:47:11	80.74
236	15:47:12	79.34
237	15:47:13	76.93
238	15:47:14	77.90
239	15:47:15	79.74
240	15:47:16	79.05
241	15:47:17	82.36
242	15:47:18	90.43
243	15:47:19	95.40
244	15:47:20	88.16
245	15:47:21	91.36
246	15:47:22	91.58
247	15:47:23	88.99
248	15:47:24	88.84
249	15:47:25	86.68
250	15:47:26	84.16
251	15:47:27	81.36

252	15:47:28	86.00
253	15:47:29	82.11
254	15:47:30	84.06
255	15:47:31	84.27
256	15:47:32	83.30
257	15:47:33	81.21
258	15:47:34	81.79
259	15:47:35	82.26
260	15:47:36	84.60
261	15:47:37	86.61
262	15:47:38	82.90
263	15:47:39	84.20
264	15:47:40	85.35
265	15:47:41	86.32
266	15:47:42	84.49
267	15:47:43	83.16
268	15:47:44	86.68
269	15:47:45	91.36
270	15:47:46	83.77
271	15:47:47	85.89
272	15:47:48	83.41
273	15:47:49	81.72
274	15:47:50	82.62
275	15:47:51	81.39
276	15:47:52	83.70
277	15:47:53	84.96
278	15:47:54	82.29
279	15:47:55	85.57
280	15:47:56	85.32
281	15:47:57	80.06
282	15:47:58	80.35
283	15:47:59	79.56
284	15:48:00	83.05
285	15:48:01	78.91
286	15:48:02	81.97
287	15:48:03	81.00
288	15:48:04	79.52
289	15:48:05	79.52
290	15:48:06	75.81
291	15:48:07	76.21
292	15:48:09	74.41
293	15:48:10	76.50
294	15:48:11	76.93

295	15:48:12	75.70
296	15:48:13	75.42
297	15:48:14	73.58
298	15:48:15	78.40
299	15:48:16	76.53
300	15:48:17	79.84
301	15:48:18	80.31
302	15:48:19	80.24
303	15:48:20	79.99
304	15:48:21	81.72
305	15:48:22	83.91
306	15:48:23	83.12
307	15:48:24	80.85
308	15:48:25	83.77
309	15:48:26	83.91
310	15:48:27	84.20
311	15:48:28	86.90
312	15:48:29	89.13
313	15:48:30	90.18
314	15:48:31	87.48
315	15:48:32	85.10
316	15:48:33	85.82
317	15:48:34	88.23
318	15:48:35	87.73
319	15:48:36	89.06
320	15:48:37	88.48
321	15:48:38	88.38
322	15:48:39	91.65
323	15:48:40	85.71
324	15:48:41	86.47
325	15:48:42	85.46
326	15:48:43	86.00
327	15:48:44	83.05
328	15:48:45	82.87
329	15:48:46	83.37
330	15:48:47	87.73
331	15:48:48	85.75
332	15:48:49	87.62
333	15:48:50	86.65
334	15:48:51	84.42
335	15:48:52	82.04
336	15:48:53	86.07
337	15:48:54	82.36

338	15:48:55	82.69
339	15:48:56	86.40
340	15:48:57	85.89
341	15:48:58	86.79
342	15:48:59	90.97
343	15:49:00	90.54
344	15:49:01	86.54
345	15:49:02	82.04
346	15:49:03	80.24
347	15:49:04	80.35
348	15:49:05	86.76
349	15:49:06	89.85
350	15:49:07	89.71
351	15:49:08	89.31
352	15:49:09	88.48
353	15:49:10	89.89
354	15:49:11	89.13
355	15:49:12	90.25
356	15:49:13	90.86
357	15:49:14	96.15
358	15:49:15	93.24
359	15:49:16	91.40
360	15:49:17	89.85
361	15:49:18	88.48
362	15:49:19	89.64
363	15:49:20	88.70
364	15:49:21	91.51
365	15:49:22	90.93
366	15:49:23	89.20
367	15:49:24	87.33
368	15:49:25	89.20
369	15:49:26	88.59
370	15:49:27	91.36
371	15:49:28	92.55
372	15:49:29	94.21
373	15:49:30	89.17
374	15:49:31	91.08
375	15:49:32	94.28
376	15:49:33	91.98
377	15:49:34	85.21
378	15:49:35	86.54
379	15:49:36	88.09
380	15:49:37	86.54

381	15:49:38	89.02
382	15:49:39	86.47
383	15:49:40	84.49
384	15:49:41	84.49
385	15:49:42	83.41
386	15:49:43	86.00
387	15:49:44	87.08
388	15:49:45	89.02
389	15:49:46	87.66
390	15:49:47	85.60
391	15:49:48	91.98
392	15:49:49	93.63
393	15:49:50	92.19
394	15:49:51	89.74
395	15:49:52	87.37
396	15:49:53	86.68
397	15:49:54	84.20
398	15:49:55	82.51
399	15:49:56	80.46
400	15:49:57	80.17
401	15:49:58	81.25
402	15:49:59	79.99
403	15:50:00	77.36
404	15:50:01	80.71
405	15:50:02	83.19
406	15:50:03	82.04
407	15:50:04	82.62
408	15:50:05	79.34
409	15:50:06	83.05
410	15:50:07	81.14
411	15:50:08	80.74
412	15:50:09	79.16
413	15:50:10	79.41
414	15:50:11	81.72
415	15:50:12	82.04
416	15:50:13	83.41
417	15:50:14	86.65
418	15:50:15	81.61
419	15:50:16	81.54
420	15:50:17	83.77
421	15:50:18	83.41
422	15:50:19	83.26
423	15:50:20	82.51

424	15:50:21	79.74
425	15:50:22	79.27
426	15:50:23	81.75
427	15:50:24	81.25
428	15:50:25	81.14
429	15:50:26	81.46
430	15:50:27	80.24
431	15:50:28	81.75
432	15:50:29	81.46
433	15:50:30	81.32
434	15:50:31	85.21
435	15:50:32	82.65
436	15:50:33	87.08
437	15:50:34	80.64
438	15:50:35	84.85
439	15:50:36	84.45
440	15:50:37	85.21
441	15:50:38	84.45
442	15:50:39	86.00
443	15:50:40	84.56
444	15:50:41	83.26
445	15:50:42	81.36
446	15:50:43	79.74
447	15:50:44	81.97
448	15:50:45	86.54
449	15:50:46	88.05
450	15:50:47	89.56
451	15:50:48	90.28
452	15:50:49	87.62
453	15:50:50	85.75
454	15:50:51	83.12
455	15:50:52	86.50
456	15:50:53	84.02
457	15:50:54	87.33
458	15:50:55	86.65
459	15:50:56	86.61
460	15:50:57	82.94
461	15:50:58	84.45
462	15:50:59	79.92
463	15:51:00	80.64
464	15:51:01	79.66
465	15:51:02	78.26
466	15:51:03	83.37

467	15:51:04	80.82
468	15:51:05	79.84
469	15:51:06	85.46
470	15:51:07	79.27
471	15:51:08	77.72
472	15:51:09	81.86
473	15:51:10	79.20
474	15:51:11	77.36
475	15:51:12	72.57
476	15:51:13	72.18
477	15:51:14	70.34
478	15:51:15	71.56
479	15:51:16	74.77
480	15:51:17	84.70
481	15:51:18	75.85
482	15:51:19	67.75
483	15:51:20	68.07
484	15:51:21	68.07
485	15:51:22	72.36
486	15:51:23	79.02
487	15:51:24	72.50
488	15:51:25	66.45
489	15:51:26	77.14
490	15:51:27	69.66
491	15:51:28	71.31
492	15:51:29	69.37
493	15:51:31	71.78
494	15:51:31	71.38
495	15:51:33	69.80
496	15:51:34	71.92
497	15:51:35	72.36
498	15:51:36	75.60
499	15:51:37	74.66
500	15:51:38	78.91
501	15:51:39	76.24
502	15:51:40	74.95
503	15:51:41	80.89
504	15:51:42	75.88
505	15:51:43	76.03
506	15:51:44	77.72
507	15:51:45	76.89
508	15:51:46	78.22
509	15:51:47	78.84

510	15:51:48	78.15
511	15:51:49	77.04
512	15:51:50	79.92
513	15:51:51	81.90
514	15:51:52	77.97
515	15:51:53	82.69
516	15:51:54	85.24
517	15:51:55	83.84
518	15:51:56	81.10
519	15:51:57	82.51
520	15:51:58	85.10
521	15:51:59	89.96
522	15:52:00	90.61
523	15:52:01	89.71
524	15:52:02	86.47
525	15:52:03	85.89
526	15:52:04	84.16
527	15:52:05	84.99
528	15:52:06	86.76
529	15:52:07	86.90
530	15:52:08	85.89
531	15:52:09	83.66
532	15:52:10	85.71
533	15:52:11	90.97
534	15:52:12	92.70
535	15:52:13	89.35
536	15:52:14	91.69
537	15:52:15	89.85
538	15:52:16	87.87
539	15:52:17	88.16
540	15:52:18	87.04
541	15:52:19	85.71
542	15:52:20	83.37
543	15:52:21	83.05
544	15:52:22	84.02
545	15:52:23	81.61
546	15:52:24	80.82
547	15:52:25	77.47
548	15:52:26	81.36
549	15:52:27	83.01
550	15:52:28	84.09
551	15:52:29	83.70
552	15:52:30	81.90

553	15:52:31	82.47
554	15:52:32	75.56
555	15:52:33	76.21
556	15:52:34	80.35
557	15:52:35	82.62
558	15:52:36	83.41
559	15:52:37	82.51
560	15:52:38	79.27
561	15:52:39	80.06
562	15:52:40	80.82
563	15:52:41	82.36
564	15:52:42	82.80
565	15:52:43	83.41
566	15:52:44	85.17
567	15:52:45	82.69
568	15:52:46	78.15
569	15:52:47	81.10
570	15:52:48	79.56
571	15:52:49	81.36
572	15:52:50	80.89
573	15:52:51	77.07
574	15:52:52	80.06
575	15:52:53	82.11
576	15:52:54	80.10
577	15:52:55	78.66
578	15:52:56	81.00
579	15:52:57	79.59
580	15:52:58	79.70
581	15:52:59	81.50
582	15:53:00	79.59
583	15:53:01	79.92
584	15:53:02	79.56
585	15:53:03	79.16
586	15:53:04	78.30
587	15:53:05	78.94
588	15:53:06	78.66
589	15:53:07	79.66
590	15:53:08	79.95
591	15:53:09	79.34
592	15:53:10	79.45
593	15:53:11	73.65
594	15:53:12	76.50
595	15:53:13	77.86

596	15:53:14	78.15
597	15:53:15	84.70
598	15:53:16	71.96
599	15:53:17	70.16
600	15:53:18	71.28
601	15:53:19	67.57
602	15:53:20	69.55
603	15:53:21	68.58
604	15:53:22	71.17
605	15:53:23	69.44
606	15:53:24	75.60
607	15:53:25	71.53
608	15:53:26	75.99
609	15:53:27	75.49
610	15:53:28	77.50
611	15:53:29	79.66
612	15:53:30	84.06
613	15:53:31	84.09
614	15:53:32	83.12
615	15:53:33	82.54
616	15:53:34	83.37
617	15:53:35	87.12
618	15:53:36	88.45
619	15:53:37	89.89
620	15:53:38	89.31
621	15:53:39	91.29
622	15:53:40	94.03
623	15:53:41	93.60
624	15:53:42	90.61
625	15:53:43	88.59
626	15:53:44	88.45
627	15:53:45	87.08
628	15:53:46	89.85
629	15:53:47	83.70
630	15:53:48	88.70
631	15:53:49	89.17
632	15:53:50	88.30
633	15:53:51	85.96
634	15:53:52	81.64
635	15:53:53	84.42
636	15:53:54	82.87
637	15:53:55	82.29
638	15:53:56	81.72

639	15:53:57	85.21
640	15:53:58	86.47
641	15:53:59	89.74
642	15:54:00	87.87
643	15:54:01	81.72
644	15:54:02	80.71
645	15:54:03	82.54
646	15:54:04	78.30
647	15:54:05	81.79
648	15:54:06	80.71
649	15:54:07	81.79
650	15:54:08	82.51
651	15:54:09	82.51
652	15:54:10	79.52
653	15:54:11	81.72
654	15:54:12	80.31
655	15:54:13	82.54
656	15:54:14	82.36
657	15:54:15	84.34
658	15:54:16	84.45
659	15:54:17	88.45
660	15:54:18	82.65
661	15:54:19	82.29
662	15:54:20	76.21
663	15:54:21	67.96
664	15:54:22	60.22
665	15:54:23	64.47
666	15:54:24	68.43
667	15:54:25	71.53
668	15:54:26	74.19
669	15:54:27	74.77
670	15:54:28	69.94
671	15:54:30	72.72
672	15:54:31	76.64
673	15:54:32	73.94
674	15:54:33	75.06
675	15:54:34	70.59
676	15:54:35	73.40
677	15:54:36	73.87
678	15:54:37	72.39
679	15:54:38	74.73
680	15:54:39	72.25
681	15:54:40	73.87

682	15:54:41	73.40
683	15:54:42	72.50
684	15:54:43	73.29
685	15:54:44	73.58
686	15:54:45	72.18
687	15:54:46	76.96
688	15:54:47	77.83
689	15:54:48	74.77
690	15:54:49	76.50
691	15:54:50	82.36
692	15:54:51	79.45
693	15:54:52	78.40
694	15:54:53	78.91
695	15:54:54	80.71
696	15:54:55	83.30
697	15:54:56	77.50
698	15:54:57	81.36
699	15:54:58	83.95
700	15:54:59	81.90
701	15:55:00	79.16
702	15:55:01	76.75
703	15:55:02	84.16
704	15:55:03	82.51
705	15:55:04	97.56
706	15:55:05	85.50
707	15:55:06	82.36
708	15:55:07	81.32
709	15:55:08	78.40
710	15:55:09	77.43
711	15:55:10	77.58
712	15:55:11	80.49
713	15:55:12	73.98
714	15:55:13	73.33
715	15:55:14	73.44
716	15:55:15	71.85
717	15:55:16	70.74
718	15:55:17	70.20
719	15:55:18	72.86
720	15:55:19	72.36
721	15:55:20	76.10
722	15:55:21	71.67
723	15:55:22	77.07
724	15:55:23	73.98

725	15:55:24	63.21
726	15:55:25	62.10
727	15:55:26	64.47
728	15:55:27	67.93
729	15:55:28	67.24
730	15:55:29	72.90
731	15:55:30	71.78
732	15:55:31	76.24
733	15:55:32	69.66
734	15:55:33	77.68
735	15:55:34	70.34
736	15:55:35	76.50
737	15:55:36	70.84
738	15:55:37	73.29
739	15:55:38	76.82
740	15:55:39	77.47
741	15:55:40	78.12
742	15:55:41	76.42
743	15:55:42	76.39
744	15:55:43	78.62
745	15:55:44	73.58
746	15:55:45	73.44
747	15:55:46	69.84
748	15:55:47	75.16
749	15:55:48	75.56
750	15:55:49	75.56
751	15:55:50	79.30
752	15:55:51	75.06
753	15:55:52	66.88
754	15:55:53	72.64
755	15:55:54	69.26
756	15:55:55	68.32
757	15:55:56	69.12
758	15:55:57	67.75
759	15:55:58	66.63
760	15:55:59	73.98
761	15:56:00	75.06
762	15:56:01	74.73
763	15:56:02	76.14
764	15:56:03	77.07
765	15:56:04	78.30
766	15:56:05	80.10
767	15:56:06	85.39

768	15:56:07	82.11
769	15:56:08	76.78
770	15:56:09	78.37
771	15:56:10	76.75
772	15:56:11	73.69
773	15:56:12	74.77
774	15:56:13	76.93
775	15:56:14	73.44
776	15:56:15	72.46
777	15:56:16	74.08
778	15:56:17	79.05
779	15:56:18	76.35
780	15:56:19	81.36
781	15:56:20	77.72
782	15:56:21	81.46
783	15:56:22	83.01
784	15:56:23	78.80
785	15:56:24	79.74
786	15:56:25	81.39
787	15:56:26	75.60
788	15:56:27	78.15
789	15:56:28	80.10
790	15:56:29	80.20
791	15:56:30	74.41
792	15:56:31	75.06
793	15:56:32	78.94
794	15:56:33	78.51
795	15:56:34	80.10
796	15:56:35	77.32
797	15:56:36	83.01
798	15:56:37	82.40
799	15:56:38	82.47
800	15:56:39	80.56
801	15:56:40	80.24
802	15:56:41	78.94
803	15:56:42	80.46
804	15:56:43	76.60
805	15:56:44	74.80
806	15:56:45	79.84
807	15:56:46	76.21
808	15:56:47	71.71
809	15:56:48	74.77
810	15:56:49	75.70

811	15:56:50	82.80
812	15:56:51	78.37
813	15:56:52	78.66
814	15:56:53	82.04
815	15:56:54	82.15
816	15:56:55	82.69
817	15:56:56	79.92
818	15:56:57	78.15
819	15:56:58	80.06
820	15:56:59	77.43
821	15:57:00	78.40
822	15:57:01	73.47
823	15:57:02	76.28
824	15:57:03	75.20
825	15:57:04	71.71
826	15:57:05	74.80
827	15:57:06	74.26
828	15:57:07	72.46
829	15:57:08	69.40
830	15:57:09	77.22
831	15:57:10	72.21
832	15:57:11	73.00
833	15:57:12	79.30
834	15:57:13	72.36
835	15:57:14	68.90
836	15:57:15	75.56
837	15:57:16	75.88
838	15:57:17	79.41
839	15:57:18	80.60
840	15:57:19	82.65
841	15:57:20	79.16
842	15:57:21	79.99
843	15:57:22	79.66
844	15:57:23	78.84
845	15:57:24	79.30
846	15:57:25	80.74
847	15:57:26	83.44
848	15:57:27	82.76
849	15:57:28	79.09
850	15:57:29	78.22
851	15:57:30	76.03
852	15:57:31	73.11
853	15:57:32	74.48

854	15:57:33	72.86
855	15:57:34	74.77
856	15:57:35	75.81
857	15:57:36	75.42
858	15:57:37	74.52
859	15:57:38	76.35
860	15:57:39	73.29
861	15:57:40	69.62
862	15:57:41	69.44
863	15:57:42	70.63
864	15:57:43	79.81
865	15:57:44	81.00
866	15:57:45	72.57
867	15:57:46	67.96
868	15:57:48	72.10
869	15:57:49	76.53
870	15:57:50	75.31
871	15:57:51	73.69
872	15:57:52	74.12
873	15:57:53	73.00
874	15:57:54	71.31
875	15:57:55	69.98
876	15:57:56	68.43
877	15:57:57	68.68
878	15:57:58	69.51
879	15:57:59	67.82
880	15:58:00	69.44
881	15:58:01	69.55
882	15:58:02	68.76
883	15:58:03	72.50
884	15:58:04	73.83
885	15:58:05	77.76
886	15:58:06	71.64
887	15:58:07	73.87
888	15:58:08	73.72
889	15:58:09	74.26
890	15:58:10	74.08
891	15:58:11	77.14
892	15:58:12	79.81
893	15:58:13	82.00
894	15:58:14	82.11
895	15:58:15	78.51
896	15:58:16	77.36

897	15:58:17	73.26
898	15:58:18	74.88
899	15:58:19	76.68
900	15:58:20	74.12
901	15:58:21	68.68
902	15:58:22	70.84
903	15:58:23	75.06
904	15:58:24	69.40
905	15:58:25	74.01
906	15:58:26	75.56
907	15:58:27	82.00
908	15:58:28	84.74
909	15:58:29	83.80
910	15:58:30	84.56
911	15:58:31	80.06
912	15:58:32	76.93
913	15:58:33	80.74
914	15:58:34	85.86
915	15:58:35	84.99
916	15:58:36	83.37
917	15:58:37	84.16
918	15:58:38	82.51
919	15:58:39	83.66
920	15:58:40	87.08
921	15:58:41	89.02
922	15:58:42	79.30
923	15:58:43	81.50
924	15:58:44	80.31
925	15:58:45	77.97
926	15:58:46	77.43
927	15:58:47	67.28
928	15:58:48	82.04
929	15:58:49	78.91
930	15:58:50	77.32
931	15:58:51	72.72
932	15:58:52	79.56
933	15:58:53	82.65
934	15:58:54	76.24
935	15:58:55	77.97
936	15:58:56	77.22
937	15:58:57	75.81
938	15:58:58	82.76
939	15:58:59	81.21

940	15:59:00	72.86
941	15:59:01	72.90
942	15:59:02	74.37
943	15:59:03	72.93
944	15:59:04	78.69
945	15:59:05	79.41
946	15:59:06	75.60
947	15:59:07	81.46
948	15:59:08	84.60
949	15:59:09	76.39
950	15:59:10	80.20
951	15:59:11	87.33
952	15:59:12	83.59
953	15:59:13	74.95
954	15:59:14	76.42
955	15:59:15	77.50
956	15:59:16	71.56
957	15:59:17	72.75
958	15:59:18	70.92
959	15:59:19	74.52
960	15:59:20	68.76
961	15:59:21	74.73
962	15:59:22	70.48
963	15:59:23	73.44
964	15:59:24	72.90
965	15:59:25	74.59
966	15:59:26	75.06
967	15:59:27	71.78
968	15:59:28	70.99
969	15:59:29	74.19
970	15:59:30	70.20
971	15:59:31	68.11
972	15:59:32	66.20
973	15:59:33	68.97
974	15:59:34	69.62
975	15:59:35	72.72
976	15:59:36	69.01
977	15:59:37	66.24
978	15:59:38	69.80
979	15:59:39	72.18
980	15:59:40	70.30
981	15:59:41	74.26
982	15:59:42	71.71

983	15:59:43	70.05
984	15:59:44	73.04
985	15:59:45	75.45
986	15:59:46	75.85
987	15:59:47	80.42
988	15:59:48	80.35
989	15:59:49	79.59
990	15:59:50	76.10
991	15:59:51	75.81
992	15:59:52	72.07
993	15:59:53	76.10
994	15:59:54	74.95
995	15:59:55	74.12
996	15:59:56	72.86
997	15:59:57	74.12
998	15:59:58	72.10
999	15:59:59	71.31
1000	16:00:00	72.39
1001	16:00:01	70.63
1002	16:00:02	72.72
1003	16:00:03	71.46
1004	16:00:04	70.88
1005	16:00:05	81.86
1006	16:00:06	79.45
1007	16:00:07	87.08
1008	16:00:08	82.26
1009	16:00:09	73.15
1010	16:00:10	72.21
1011	16:00:11	75.06
1012	16:00:12	78.51
1013	16:00:13	82.22
1014	16:00:14	79.41
1015	16:00:15	73.83
1016	16:00:16	73.98
1017	16:00:17	83.55
1018	16:00:18	83.59
1019	16:00:19	80.96
1020	16:00:20	80.82
1021	16:00:21	81.75
1022	16:00:22	81.50
1023	16:00:23	82.76
1024	16:00:24	83.52
1025	16:00:26	85.06

1026	16:00:27	85.32
1027	16:00:28	88.34
1028	16:00:29	84.92
1029	16:00:30	87.12
1030	16:00:31	89.71
1031	16:00:32	89.28
1032	16:00:33	88.92
1033	16:00:34	87.48
1034	16:00:35	86.79
1035	16:00:36	83.77
1036	16:00:37	84.06
1037	16:00:38	90.93
1038	16:00:39	92.77
1039	16:00:40	85.32
1040	16:00:41	83.05
1041	16:00:42	87.80
1042	16:00:43	86.79
1043	16:00:44	82.90
1044	16:00:45	80.56
1045	16:00:46	82.36
1046	16:00:47	82.65
1047	16:00:48	84.49
1048	16:00:49	84.56
1049	16:00:50	81.46
1050	16:00:51	81.25
1051	16:00:52	85.64
1052	16:00:53	84.27
1053	16:00:54	88.48
1054	16:00:55	96.58
1055	16:00:56	90.14
1056	16:00:57	85.64
1057	16:00:58	91.15
1058	16:00:59	93.78
1059	16:01:00	88.70
1060	16:01:01	90.75
1061	16:01:02	93.49
1062	16:01:03	102.50
1063	16:01:04	104.60
1064	16:01:05	100.20
1065	16:01:06	91.87
1066	16:01:07	91.94
1067	16:01:08	94.35
1068	16:01:09	84.20

1069	16:01:10	83.70
1070	16:01:11	81.64
1071	16:01:12	78.94
1072	16:01:13	75.85
1073	16:01:14	74.01
1074	16:01:15	68.43
1075	16:01:16	67.82
1076	16:01:17	65.59
1077	16:01:18	66.88
1078	16:01:19	71.10
1079	16:01:20	66.60
1080	16:01:21	68.86
1081	16:01:22	70.30
1082	16:01:23	69.51
1083	16:01:24	75.81
1084	16:01:25	74.23
1085	16:01:26	78.51
1086	16:01:27	78.12
1087	16:01:28	79.30
1088	16:01:29	79.02
1089	16:01:30	82.62
1090	16:01:31	87.08
1091	16:01:32	81.25
1092	16:01:33	83.44
1093	16:01:34	82.65
1094	16:01:35	83.44
1095	16:01:36	85.89
1096	16:01:37	81.10
1097	16:01:38	87.04
1098	16:01:39	86.25
1099	16:01:40	89.35
1100	16:01:41	86.79
1101	16:01:42	82.54
1102	16:01:43	80.82
1103	16:01:44	76.93
1104	16:01:45	78.12
1105	16:01:46	79.70
1106	16:01:47	75.85
1107	16:01:48	78.62
1108	16:01:49	77.90
1109	16:01:50	74.88
1110	16:01:51	74.37
1111	16:01:52	74.62

1112	16:01:53	73.11
1113	16:01:54	76.93
1114	16:01:55	79.92
1115	16:01:56	78.01
1116	16:01:57	86.76
1117	16:01:58	79.92
1118	16:01:59	83.66
1119	16:02:00	90.10
1120	16:02:01	87.22
1121	16:02:02	87.19
1122	16:02:03	90.28
1123	16:02:04	82.76
1124	16:02:05	81.79
1125	16:02:06	81.86
1126	16:02:07	86.22
1127	16:02:08	84.74
1128	16:02:09	83.19
1129	16:02:10	85.89
1130	16:02:11	75.81
1131	16:02:12	82.36
1132	16:02:13	80.46
1133	16:02:14	88.16
1134	16:02:15	74.88
1135	16:02:16	72.00
1136	16:02:17	75.88
1137	16:02:18	91.87
1138	16:02:19	83.44
1139	16:02:20	78.55
1140	16:02:21	73.04
1141	16:02:22	73.98
1142	16:02:23	85.57
1143	16:02:24	83.91
1144	16:02:25	79.99
1145	16:02:26	98.67
1146	16:02:27	97.84
1147	16:02:28	98.13
1148	16:02:29	93.16
1149	16:02:30	78.66
1150	16:02:31	74.41
1151	16:02:32	81.39
1152	16:02:33	82.40
1153	16:02:34	82.65
1154	16:02:35	83.41

1155	16:02:36	82.94
1156	16:02:37	81.14
1157	16:02:38	74.26
1158	16:02:39	72.21
1159	16:02:40	71.78
1160	16:02:41	73.18
1161	16:02:42	73.54
1162	16:02:43	79.45
1163	16:02:44	86.76
1164	16:02:45	87.04
1165	16:02:46	89.06
1166	16:02:47	89.20
1167	16:02:48	88.30
1168	16:02:49	86.61
1169	16:02:50	88.20
1170	16:02:51	89.35
1171	16:02:52	83.26
1172	16:02:53	88.02
1173	16:02:54	83.95
1174	16:02:55	83.55
1175	16:02:56	80.74
1176	16:02:57	81.00
1177	16:02:58	83.44
1178	16:02:59	83.80
1179	16:03:00	81.61
1180	16:03:01	82.51
1181	16:03:02	77.47
1182	16:03:03	76.53
1183	16:03:04	81.75
1184	16:03:05	79.52
1185	16:03:06	79.95
1186	16:03:07	81.36
1187	16:03:08	78.94
1188	16:03:09	77.58
1189	16:03:10	78.80
1190	16:03:11	75.16
1191	16:03:12	67.50
1192	16:03:13	68.58
1193	16:03:14	65.77
1194	16:03:15	72.50
1195	16:03:16	78.80
1196	16:03:17	76.75
1197	16:03:18	78.22

1198	16:03:19	70.92
1199	16:03:20	71.92
1200	16:03:21	67.39
1201	16:03:22	66.96
1202	16:03:23	64.36
1203	16:03:24	59.68
1204	16:03:25	62.78
1205	16:03:26	61.52
1206	16:03:27	61.41
1207	16:03:28	53.46
1208	16:03:29	49.57
1209	16:03:30	48.06
1210	16:03:31	50.29
1211	16:03:32	52.27
1212	16:03:33	66.42
1213	16:03:34	62.92
1214	16:03:35	41.04
1215	16:03:36	39.16
1216	16:03:37	38.91
1217	16:03:38	39.96
1218	16:03:39	30.81
1219	16:03:40	29.05
1220	16:03:41	23.94
1221	16:03:42	20.80
1222	16:03:43	13.21
1223	16:03:44	8.28
1224	16:03:46	4.93
1225	16:03:47	4.03
1226	16:03:48	3.70
1227	16:03:49	3.56
1228	16:03:50	4.32
1229	16:03:51	3.85
1230	16:03:52	3.13
1231	16:03:53	2.77
1232	16:03:54	2.70
1233	16:03:55	1.29
1234	16:03:56	1.29
1235	16:03:57	2.34
1236	16:03:58	0.72
1237	16:03:59	0.00
1238	16:04:00	0.00
1239	16:04:01	3.49
1240	16:04:02	3.63

1241	16:04:03	2.62
1242	16:04:04	0.72
1243	16:04:05	0.00
1244	16:04:06	0.72
1245	16:04:07	0.72
1246	16:04:08	1.08
1247	16:04:09	1.51
1248	16:04:10	2.01
1249	16:04:11	5.04
1250	16:04:12	5.47
1251	16:04:13	5.43
1252	16:04:14	4.39
1253	16:04:15	1.76
1254	16:04:16	2.48
1255	16:04:17	2.84
1256	16:04:18	3.13
1257	16:04:19	4.96
1258	16:04:20	5.43
1259	16:04:21	4.96
1260	16:04:22	4.53
1261	16:04:23	6.98
1262	16:04:24	11.98
1263	16:04:25	16.20
1264	16:04:26	17.92
1265	16:04:27	17.82
1266	16:04:28	20.84
1267	16:04:29	26.24
1268	16:04:30	19.83
1269	16:04:31	17.13
1270	16:04:32	11.91
1271	16:04:33	9.10
1272	16:04:34	13.46
1273	16:04:35	12.06
1274	16:04:36	15.40
1275	16:04:37	22.50
1276	16:04:38	32.83
1277	16:04:39	41.14
1278	16:04:40	49.57
1279	16:04:41	48.56
1280	16:04:42	53.74
1281	16:04:43	59.14
1282	16:04:44	64.47
1283	16:04:45	64.44

1284	16:04:46	64.76
1285	16:04:47	65.52
1286	16:04:48	64.76
1287	16:04:49	66.34
1288	16:04:50	64.29
1289	16:04:51	63.57
1290	16:04:52	60.30
1291	16:04:53	64.58
1292	16:04:54	62.17
1293	16:04:55	61.16
1294	16:04:56	59.54
1295	16:04:57	56.88
1296	16:04:58	60.76
1297	16:04:59	60.84
1298	16:05:00	59.97
1299	16:05:01	61.88
1300	16:05:02	69.12
1301	16:05:03	69.62
1302	16:05:04	69.37
1303	16:05:05	72.75
1304	16:05:06	71.67
1305	16:05:07	70.45
1306	16:05:08	72.90
1307	16:05:09	74.66
1308	16:05:10	77.43
1309	16:05:11	68.76
1310	16:05:12	67.14
1311	16:05:13	67.57
1312	16:05:14	65.23
1313	16:05:15	67.14
1314	16:05:16	62.67
1315	16:05:17	65.48
1316	16:05:18	68.58
1317	16:05:19	63.68
1318	16:05:20	61.70
1319	16:05:21	68.97
1320	16:05:22	63.97
1321	16:05:23	65.88
1322	16:05:24	62.28
1323	16:05:25	65.52
1324	16:05:26	61.12
1325	16:05:27	59.58
1326	16:05:28	55.04

1327	16:05:29	54.10
1328	16:05:30	42.98
1329	16:05:31	35.85
1330	16:05:32	38.88
1331	16:05:33	35.35
1332	16:05:34	36.00
1333	16:05:35	36.32
1334	16:05:36	30.02
1335	16:05:37	27.61
1336	16:05:38	24.04
1337	16:05:39	28.47
1338	16:05:40	29.48
1339	16:05:41	26.71
1340	16:05:42	27.00
1341	16:05:43	31.03
1342	16:05:44	33.73
1343	16:05:45	35.56
1344	16:05:46	42.91
1345	16:05:47	45.86
1346	16:05:48	47.23
1347	16:05:49	47.01
1348	16:05:50	52.45
1349	16:05:51	53.06
1350	16:05:52	55.04
1351	16:05:53	57.63
1352	16:05:54	59.22
1353	16:05:55	59.43
1354	16:05:56	58.17
1355	16:05:57	60.04
1356	16:05:58	61.95
1357	16:05:59	63.28
1358	16:06:00	62.60
1359	16:06:01	64.72
1360	16:06:02	64.76
1361	16:06:03	66.24
1362	16:06:04	61.27
1363	16:06:05	60.30
1364	16:06:06	57.63
1365	16:06:07	54.61
1366	16:06:08	54.00
1367	16:06:09	53.06
1368	16:06:10	53.46
1369	16:06:11	50.07

1370	16:06:12	48.56
1371	16:06:13	45.79
1372	16:06:14	47.88
1373	16:06:15	46.83
1374	16:06:16	43.59
1375	16:06:17	30.13
1376	16:06:18	28.26
1377	16:06:19	33.04
1378	16:06:20	39.02
1379	16:06:21	35.60
1380	16:06:22	36.64
1381	16:06:23	38.66
1382	16:06:24	34.12
1383	16:06:25	26.96
1384	16:06:26	20.66
1385	16:06:27	18.75
1386	16:06:28	27.82
1387	16:06:29	32.11
1388	16:06:30	34.41
1389	16:06:31	31.46
1390	16:06:32	37.72
1391	16:06:33	38.48
1392	16:06:34	40.14
1393	16:06:35	46.40
1394	16:06:36	40.75
1395	16:06:37	40.68
1396	16:06:38	42.80
1397	16:06:39	41.94
1398	16:06:40	54.03
1399	16:06:41	51.40
1400	16:06:42	53.28
1401	16:06:43	41.36
1402	16:06:44	37.00
1403	16:06:45	35.10
1404	16:06:46	31.24
1405	16:06:47	34.56
1406	16:06:48	31.71
1407	16:06:49	34.45
1408	16:06:50	34.56
1409	16:06:51	32.58
1410	16:06:52	30.49
1411	16:06:53	28.98
1412	16:06:54	22.42

1413	16:06:55	21.06
1414	16:06:56	18.36
1415	16:06:57	13.50
1416	16:06:58	14.32
1417	16:06:59	14.11
1418	16:07:00	15.04
1419	16:07:01	20.01
1420	16:07:02	16.20
1421	16:07:03	17.28
1422	16:07:04	21.06
1423	16:07:05	19.87
1424	16:07:06	16.20
1425	16:07:07	17.35
1426	16:07:08	15.26
1427	16:07:09	16.41
1428	16:07:10	15.98
1429	16:07:11	15.48
1430	16:07:12	15.51
1431	16:07:13	15.40
1432	16:07:14	15.87
1433	16:07:15	18.75
1434	16:07:16	21.13
1435	16:07:17	21.16
1436	16:07:18	24.58
1437	16:07:19	21.92
1438	16:07:20	24.87
1439	16:07:21	25.02
1440	16:07:22	25.20
1441	16:07:24	24.76
1442	16:07:25	27.25
1443	16:07:26	26.42
1444	16:07:26	30.88
1445	16:07:28	30.45
1446	16:07:29	29.55
1447	16:07:30	25.88
1448	16:07:31	27.39
1449	16:07:32	28.11
1450	16:07:33	26.96
1451	16:07:34	26.74
1452	16:07:35	24.80
1453	16:07:36	23.25
1454	16:07:37	23.72
1455	16:07:38	26.10

1456	16:07:39	27.28
1457	16:07:40	26.38
1458	16:07:41	27.14
1459	16:07:42	21.24
1460	16:07:43	18.36
1461	16:07:44	20.48
1462	16:07:45	14.11
1463	16:07:46	11.88
1464	16:07:47	14.68
1465	16:07:48	24.44
1466	16:07:49	28.87
1467	16:07:50	29.48
1468	16:07:51	25.56
1469	16:07:52	25.20
1470	16:07:53	35.85
1471	16:07:54	36.68
1472	16:07:55	40.68
1473	16:07:56	48.96
1474	16:07:57	54.54
1475	16:07:58	46.69
1476	16:07:59	47.12
1477	16:08:00	45.75
1478	16:08:01	50.54
1479	16:08:02	47.80
1480	16:08:03	50.29
1481	16:08:04	52.02
1482	16:08:05	50.65
1483	16:08:06	53.35
1484	16:08:07	64.62
1485	16:08:08	66.70
1486	16:08:09	66.09
1487	16:08:10	60.87
1488	16:08:11	64.51
1489	16:08:12	63.14
1490	16:08:13	58.89
1491	16:08:14	55.26
1492	16:08:15	51.91
1493	16:08:16	45.54
1494	16:08:17	43.77
1495	16:08:18	37.40
1496	16:08:19	36.07
1497	16:08:20	37.15
1498	16:08:21	29.12

1499	16:08:22	20.98
1500	16:08:23	16.20
1501	16:08:24	15.40
1502	16:08:25	17.13
1503	16:08:26	19.98
1504	16:08:27	18.82
1505	16:08:28	15.80
1506	16:08:29	9.50
1507	16:08:30	5.90
1508	16:08:31	4.17
1509	16:08:32	0.54
1510	16:08:33	1.51
1511	16:08:34	2.77
1512	16:08:35	3.42
1513	16:08:36	3.78
1514	16:08:37	3.96
1515	16:08:38	4.96
1516	16:08:39	9.21
1517	16:08:40	11.48
1518	16:08:41	10.40
1519	16:08:42	8.85
1520	16:08:43	9.00
1521	16:08:44	9.00
1522	16:08:45	8.96
1523	16:08:46	11.88
1524	16:08:47	13.39
1525	16:08:48	10.62
1526	16:08:49	12.74
1527	16:08:50	11.59
1528	16:08:51	9.57
1529	16:08:52	10.18
1530	16:08:53	11.30
1531	16:08:54	9.93
1532	16:08:55	11.73
1533	16:08:56	12.34
1534	16:08:57	11.84
1535	16:08:58	12.09
1536	16:08:59	10.76
1537	16:09:00	9.39
1538	16:09:01	12.52
1539	16:09:02	11.62
1540	16:09:03	11.48
1541	16:09:04	11.70

1542	16:09:05	12.24
1543	16:09:06	12.74
1544	16:09:07	13.53
1545	16:09:08	12.74
1546	16:09:09	14.07
1547	16:09:10	12.67
1548	16:09:11	12.74
1549	16:09:12	10.51
1550	16:09:13	10.33
1551	16:09:14	11.62
1552	16:09:15	13.89
1553	16:09:16	14.58
1554	16:09:17	14.36
1555	16:09:18	10.94
1556	16:09:19	7.63
1557	16:09:20	6.22
1558	16:09:21	6.51
1559	16:09:22	8.17
1560	16:09:23	6.98
1561	16:09:24	6.69
1562	16:09:25	7.84
1563	16:09:26	10.08
1564	16:09:27	9.82
1565	16:09:28	11.48
1566	16:09:29	12.60
1567	16:09:30	13.53
1568	16:09:31	13.32
1569	16:09:32	13.17
1570	16:09:33	13.21
1571	16:09:34	12.60
1572	16:09:35	12.81
1573	16:09:36	12.74
1574	16:09:37	12.49
1575	16:09:38	13.39
1576	16:09:39	13.68
1577	16:09:40	13.64
1578	16:09:41	12.16
1579	16:09:42	12.88
1580	16:09:43	12.78
1581	16:09:44	11.88
1582	16:09:45	11.77
1583	16:09:46	11.01
1584	16:09:47	19.69

1585	16:09:48	23.43
1586	16:09:49	16.34
1587	16:09:50	12.52
1588	16:09:51	16.63
1589	16:09:52	20.70
1590	16:09:53	27.82
1591	16:09:54	27.61
1592	16:09:55	26.13
1593	16:09:56	26.38
1594	16:09:57	31.42
1595	16:09:58	36.57
1596	16:09:59	37.65
1597	16:10:00	37.00
1598	16:10:01	34.20
1599	16:10:02	38.55
1600	16:10:03	32.68
1601	16:10:04	34.63
1602	16:10:05	36.90
1603	16:10:06	44.64
1604	16:10:07	47.01
1605	16:10:08	48.24
1606	16:10:09	51.98
1607	16:10:10	55.04
1608	16:10:11	56.66
1609	16:10:12	61.48
1610	16:10:13	64.47
1611	16:10:14	67.28
1612	16:10:15	65.08
1613	16:10:16	59.04
1614	16:10:17	57.31
1615	16:10:18	53.53
1616	16:10:19	59.83
1617	16:10:20	57.09
1618	16:10:21	61.70
1619	16:10:22	51.51
1620	16:10:23	50.00
1621	16:10:24	50.07
1622	16:10:25	54.86
1623	16:10:26	55.26
1624	16:10:27	50.25
1625	16:10:28	49.10
1626	16:10:29	48.09
1627	16:10:30	47.91

1628	16:10:31	43.30
1629	16:10:32	22.24
1630	16:10:33	31.89
1631	16:10:34	36.82
1632	16:10:35	35.24
1633	16:10:36	31.60
1634	16:10:37	44.46
1635	16:10:38	44.17
1636	16:10:39	48.60
1637	16:10:40	53.38
1638	16:10:41	64.15
1639	16:10:42	61.70
1640	16:10:43	57.60
1641	16:10:44	58.57
1642	16:10:45	60.37
1643	16:10:46	59.00
1644	16:10:47	62.31
1645	16:10:48	59.43
1646	16:10:50	57.38
1647	16:10:51	52.56
1648	16:10:52	55.26
1649	16:10:53	64.90
1650	16:10:54	71.31
1651	16:10:55	70.38
1652	16:10:56	76.28
1653	16:10:57	77.76
1654	16:10:58	76.10
1655	16:10:59	70.09
1656	16:11:00	71.28
1657	16:11:01	69.69
1658	16:11:02	67.14
1659	16:11:03	67.57
1660	16:11:04	72.10
1661	16:11:05	76.89
1662	16:11:06	77.72
1663	16:11:07	71.24
1664	16:11:08	69.76
1665	16:11:09	71.38
1666	16:11:10	61.81
1667	16:11:11	67.14
1668	16:11:12	71.71
1669	16:11:13	76.75
1670	16:11:14	76.03

1671	16:11:15	79.09
1672	16:11:16	83.19
1673	16:11:17	79.92
1674	16:11:18	76.39
1675	16:11:19	75.56
1676	16:11:20	72.64
1677	16:11:21	74.01
1678	16:11:22	71.92
1679	16:11:23	72.46
1680	16:11:24	70.63
1681	16:11:25	82.00
1682	16:11:26	80.82
1683	16:11:27	82.90
1684	16:11:28	82.51
1685	16:11:29	81.54
1686	16:11:30	84.06
1687	16:11:31	82.26
1688	16:11:32	79.30
1689	16:11:33	75.74
1690	16:11:34	75.70
1691	16:11:35	76.14
1692	16:11:36	78.55
1693	16:11:37	65.23
1694	16:11:38	64.76
1695	16:11:39	59.58
1696	16:11:40	60.04
1697	16:11:41	53.82
1698	16:11:42	52.59
1699	16:11:43	50.07
1700	16:11:44	47.59
1701	16:11:45	41.76
1702	16:11:46	38.73
1703	16:11:47	40.89
1704	16:11:48	48.42
1705	16:11:49	48.85
1706	16:11:50	50.25
1707	16:11:51	44.71
1708	16:11:52	43.12
1709	16:11:53	43.09
1710	16:11:54	44.92
1711	16:11:55	44.92
1712	16:11:56	39.81
1713	16:11:57	48.81

1714	16:11:58	50.86
1715	16:11:59	48.81
1716	16:12:00	46.29
1717	16:12:01	44.56
1718	16:12:02	47.37
1719	16:12:03	48.70
1720	16:12:04	56.98
1721	16:12:05	65.95
1722	16:12:06	57.52
1723	16:12:07	57.31
1724	16:12:08	58.17
1725	16:12:09	66.99
1726	16:12:10	60.76
1727	16:12:11	55.11
1728	16:12:12	62.67
1729	16:12:13	62.02
1730	16:12:14	64.04
1731	16:12:15	65.52
1732	16:12:16	62.31
1733	16:12:17	53.49
1734	16:12:18	45.75
1735	16:12:19	42.73
1736	16:12:20	39.60
1737	16:12:21	42.01
1738	16:12:22	44.64
1739	16:12:23	52.74
1740	16:12:24	60.87
1741	16:12:25	73.94
1742	16:12:26	78.26
1743	16:12:27	75.06
1744	16:12:28	78.44
1745	16:12:29	72.21
1746	16:12:30	67.39
1747	16:12:31	66.85
1748	16:12:32	69.12
1749	16:12:33	72.50
1750	16:12:34	80.64
1751	16:12:35	80.35
1752	16:12:36	65.66
1753	16:12:37	68.36
1754	16:12:38	68.58
1755	16:12:39	71.31
1756	16:12:40	62.74

1757	16:12:41	60.08
1758	16:12:42	54.10
1759	16:12:43	60.62
1760	16:12:44	58.50
1761	16:12:45	56.19
1762	16:12:46	57.09
1763	16:12:47	59.58
1764	16:12:48	57.96
1765	16:12:49	57.09
1766	16:12:50	61.09
1767	16:12:51	63.50
1768	16:12:52	61.92
1769	16:12:53	61.12
1770	16:12:54	63.50
1771	16:12:55	65.01
1772	16:12:56	64.80
1773	16:12:57	74.66
1774	16:12:58	74.26
1775	16:12:59	67.64
1776	16:13:00	70.84
1777	16:13:01	68.76
1778	16:13:02	66.24
1779	16:13:03	62.85
1780	16:13:04	74.12
1781	16:13:05	72.21
1782	16:13:06	77.07
1783	16:13:07	72.79
1784	16:13:08	69.98
1785	16:13:09	82.36
1786	16:13:10	84.49
1787	16:13:11	83.70
1788	16:13:12	76.24
1789	16:13:13	73.29
1790	16:13:14	76.93
1791	16:13:15	71.17
1792	16:13:16	67.64
1793	16:13:17	63.79
1794	16:13:18	52.45
1795	16:13:19	46.08
1796	16:13:20	40.17
1797	16:13:21	47.66
1798	16:13:22	35.02
1799	16:13:23	32.00

1800	16:13:24	28.18
1801	16:13:25	20.77
1802	16:13:26	20.48
1803	16:13:27	22.21
1804	16:13:28	24.01
1805	16:13:29	26.71
1806	16:13:30	26.67
1807	16:13:31	28.33
1808	16:13:32	31.78
1809	16:13:33	33.66
1810	16:13:34	33.87
1811	16:13:35	34.81
1812	16:13:36	42.62
1813	16:13:37	40.10
1814	16:13:38	40.75
1815	16:13:39	39.52
1816	16:13:40	51.80
1817	16:13:41	48.56
1818	16:13:42	53.67
1819	16:13:43	60.15
1820	16:13:44	61.70
1821	16:13:45	64.04
1822	16:13:46	66.34
1823	16:13:47	72.61
1824	16:13:48	80.82
1825	16:13:49	74.52
1826	16:13:50	72.21
1827	16:13:51	73.54
1828	16:13:52	79.52
1829	16:13:53	78.40
1830	16:13:54	74.26
1831	16:13:55	72.57
1832	16:13:56	69.94
1833	16:13:57	72.25
1834	16:13:58	73.98
1835	16:13:59	71.42
1836	16:14:00	73.15
1837	16:14:01	77.04
1838	16:14:02	70.30
1839	16:14:03	72.07
1840	16:14:04	70.45
1841	16:14:05	68.22
1842	16:14:06	65.80

1843	16:14:07	62.96
1844	16:14:08	64.80
1845	16:14:10	66.06
1846	16:14:10	72.10
1847	16:14:12	62.56
1848	16:14:13	66.81
1849	16:14:14	67.96
1850	16:14:15	64.04
1851	16:14:16	60.08
1852	16:14:17	51.12
1853	16:14:18	53.20
1854	16:14:19	58.57
1855	16:14:20	63.61
1856	16:14:21	64.11
1857	16:14:22	63.86
1858	16:14:23	65.91
1859	16:14:24	64.44
1860	16:14:25	63.10
1861	16:14:26	61.23
1862	16:14:27	62.10
1863	16:14:28	66.60
1864	16:14:29	69.30
1865	16:14:30	68.72
1866	16:14:31	66.99
1867	16:14:32	65.95
1868	16:14:33	78.12
1869	16:14:34	76.93
1870	16:14:35	76.96
1871	16:14:36	77.58
1872	16:14:37	78.30
1873	16:14:38	79.05
1874	16:14:39	77.36
1875	16:14:40	73.58
1876	16:14:41	68.97
1877	16:14:42	61.56
1878	16:14:43	58.89
1879	16:14:44	58.68
1880	16:14:45	50.11
1881	16:14:46	47.70
1882	16:14:47	44.53
1883	16:14:48	39.70
1884	16:14:49	32.25
1885	16:14:50	28.33

1886	16:14:51	25.09
1887	16:14:52	20.48
1888	16:14:53	25.56
1889	16:14:54	26.42
1890	16:14:55	21.16
1891	16:14:56	18.54
1892	16:14:57	16.48
1893	16:14:58	16.34
1894	16:14:59	12.92
1895	16:15:00	13.21
1896	16:15:01	23.32
1897	16:15:02	21.42
1898	16:15:03	20.01
1899	16:15:04	23.36
1900	16:15:05	23.36
1901	16:15:06	29.98
1902	16:15:07	32.47
1903	16:15:08	34.52
1904	16:15:09	36.82
1905	16:15:10	39.63
1906	16:15:11	40.06
1907	16:15:12	42.40
1908	16:15:13	40.06
1909	16:15:14	46.08
1910	16:15:15	50.18
1911	16:15:16	50.40
1912	16:15:17	53.60
1913	16:15:18	47.80
1914	16:15:19	52.38
1915	16:15:20	49.50
1916	16:15:21	53.13
1917	16:15:22	49.78
1918	16:15:23	53.38
1919	16:15:24	49.39
1920	16:15:25	50.29
1921	16:15:26	53.78
1922	16:15:27	60.30
1923	16:15:28	57.27
1924	16:15:29	59.29
1925	16:15:30	62.67
1926	16:15:31	62.78
1927	16:15:32	60.98
1928	16:15:33	65.91

1929	16:15:34	69.80
1930	16:15:35	67.75
1931	16:15:36	53.85
1932	16:15:37	55.00
1933	16:15:38	50.40
1934	16:15:39	47.52
1935	16:15:40	39.20
1936	16:15:41	35.35
1937	16:15:42	36.43
1938	16:15:43	34.56
1939	16:15:44	33.48
1940	16:15:45	30.92
1941	16:15:46	25.95
1942	16:15:47	25.45
1943	16:15:48	23.47
1944	16:15:49	17.56
1945	16:15:50	12.63
1946	16:15:51	11.19
1947	16:15:52	11.70
1948	16:15:53	12.24
1949	16:15:54	10.94
1950	16:15:55	12.16
1951	16:15:56	18.25
1952	16:15:57	23.00
1953	16:15:58	27.72
1954	16:15:59	25.74
1955	16:16:00	24.98
1956	16:16:01	28.54
1957	16:16:02	31.89
1958	16:16:03	32.22
1959	16:16:04	38.41
1960	16:16:05	39.20
1961	16:16:06	39.52
1962	16:16:07	41.83
1963	16:16:08	40.28
1964	16:16:09	40.17
1965	16:16:10	39.02
1966	16:16:11	36.07
1967	16:16:12	35.28
1968	16:16:13	28.90
1969	16:16:14	21.60
1970	16:16:15	20.12
1971	16:16:16	19.29

1972	16:16:17	16.30
1973	16:16:18	19.98
1974	16:16:19	23.90
1975	16:16:20	22.93
1976	16:16:21	21.31
1977	16:16:22	19.65
1978	16:16:23	19.98
1979	16:16:24	21.81
1980	16:16:25	21.85
1981	16:16:26	20.23
1982	16:16:27	17.28
1983	16:16:28	17.02
1984	16:16:29	16.63
1985	16:16:30	14.58
1986	16:16:31	12.06
1987	16:16:32	8.49
1988	16:16:33	4.53
1989	16:16:34	2.41
1990	16:16:35	4.24
1991	16:16:36	3.99
1992	16:16:37	3.49
1993	16:16:38	3.78
1994	16:16:39	1.29
1995	16:16:40	0.00
1996	16:16:41	1.08
1997	16:16:42	4.57
1998	16:16:43	12.34
1999	16:16:44	17.92
2000	16:16:45	24.01
2001	16:16:46	25.84
2002	16:16:47	29.05
2003	16:16:48	30.13
2004	16:16:49	35.31
2005	16:16:50	43.84
2006	16:16:51	47.37
2007	16:16:52	48.96
2008	16:16:53	44.56
2009	16:16:54	41.22
2010	16:16:55	39.31
2011	16:16:56	37.90
2012	16:16:57	37.22
2013	16:16:58	38.16
2014	16:16:59	33.98

2015	16:17:00	30.99
2016	16:17:01	29.55
2017	16:17:02	29.34
2018	16:17:03	31.82
2019	16:17:04	23.32
2020	16:17:05	18.93
2021	16:17:06	17.89
2022	16:17:07	21.92
2023	16:17:08	27.00
2024	16:17:09	23.72
2025	16:17:10	25.66
2026	16:17:11	29.55
2027	16:17:12	31.78
2028	16:17:13	36.93
2029	16:17:14	36.64
2030	16:17:15	39.06
2031	16:17:16	39.20
2032	16:17:17	41.54
2033	16:17:18	39.67
2034	16:17:20	38.08
2035	16:17:20	33.04
2036	16:17:22	32.58
2037	16:17:23	32.47
2038	16:17:24	31.82
2039	16:17:24	34.52
2040	16:17:26	35.10
2041	16:17:27	37.65
2042	16:17:28	26.10
2043	16:17:29	28.98
2044	16:17:30	26.74
2045	16:17:31	21.52
2046	16:17:32	18.97
2047	16:17:33	20.59
2048	16:17:34	24.69
2049	16:17:35	26.38
2050	16:17:36	24.76
2051	16:17:37	26.96
2052	16:17:38	33.87
2053	16:17:39	35.71
2054	16:17:40	33.30
2055	16:17:41	30.99
2056	16:17:42	31.32
2057	16:17:43	31.89

2058	16:17:44	33.66
2059	16:17:45	32.14
2060	16:17:46	31.42
2061	16:17:47	31.68
2062	16:17:48	29.73
2063	16:17:49	26.89
2064	16:17:50	27.43
2065	16:17:51	23.22
2066	16:17:52	25.88
2067	16:17:53	23.00
2068	16:17:54	21.31
2069	16:17:55	19.47
2070	16:17:56	14.04
2071	16:17:57	11.88
2072	16:17:58	12.24
2073	16:17:59	16.74
2074	16:18:00	23.25
2075	16:18:01	28.00
2076	16:18:02	26.38
2077	16:18:03	30.67
2078	16:18:04	35.85
2079	16:18:05	39.24
2080	16:18:06	39.63
2081	16:18:07	42.33
2082	16:18:08	48.20
2083	16:18:09	47.44
2084	16:18:10	48.38
2085	16:18:11	53.31
2086	16:18:12	55.62
2087	16:18:13	58.78
2088	16:18:14	54.25
2089	16:18:15	54.43
2090	16:18:16	52.27
2091	16:18:17	47.44
2092	16:18:18	44.85
2093	16:18:19	45.57
2094	16:18:20	41.94
2095	16:18:21	36.25
2096	16:18:22	37.58
2097	16:18:23	35.31
2098	16:18:24	33.94
2099	16:18:25	37.72
2100	16:18:26	35.74

2101	16:18:27	39.70
2102	16:18:28	40.06
2103	16:18:29	39.78
2104	16:18:30	37.22
2105	16:18:31	32.94
2106	16:18:32	33.15
2107	16:18:33	33.37
2108	16:18:34	38.55
2109	16:18:35	32.97
2110	16:18:36	30.13
2111	16:18:37	30.99
2112	16:18:38	28.04
2113	16:18:39	29.59
2114	16:18:40	32.94
2115	16:18:41	30.31
2116	16:18:42	25.95
2117	16:18:43	24.04
2118	16:18:44	24.69
2119	16:18:45	23.32
2120	16:18:46	21.27
2121	16:18:47	25.09
2122	16:18:48	26.17
2123	16:18:49	25.95
2124	16:18:50	26.17
2125	16:18:51	21.09
2126	16:18:52	19.90
2127	16:18:53	24.12
2128	16:18:54	28.44
2129	16:18:55	26.24
2130	16:18:56	22.50
2131	16:18:57	20.48
2132	16:18:58	17.13
2133	16:18:59	23.18
2134	16:19:00	22.24
2135	16:19:01	20.48
2136	16:19:02	18.86
2137	16:19:03	14.22
2138	16:19:04	13.53
2139	16:19:05	12.60
2140	16:19:06	8.78
2141	16:19:07	5.76
2142	16:19:08	3.78
2143	16:19:09	2.55

2144	16:19:10	1.76
2145	16:19:11	2.26
2146	16:19:12	3.63
2147	16:19:13	2.70
2148	16:19:14	4.50
2149	16:19:15	5.11
2150	16:19:16	14.22
2151	16:19:17	21.67
2152	16:19:18	26.42
2153	16:19:19	25.23
2154	16:19:20	26.24
2155	16:19:21	19.98
2156	16:19:22	19.72
2157	16:19:23	18.54
2158	16:19:24	28.29
2159	16:19:25	27.54
2160	16:19:26	34.12
2161	16:19:27	34.20
2162	16:19:28	30.81
2163	16:19:29	27.28
2164	16:19:30	25.52
2165	16:19:31	21.24
2166	16:19:32	15.30
2167	16:19:33	14.54
2168	16:19:34	14.25
2169	16:19:35	19.83
2170	16:19:36	20.59
2171	16:19:37	15.40
2172	16:19:38	14.79
2173	16:19:39	20.30
2174	16:19:40	18.36
2175	16:19:41	19.58
2176	16:19:42	22.35
2177	16:19:43	25.20
2178	16:19:44	27.54
2179	16:19:45	28.15
2180	16:19:46	28.15
2181	16:19:47	31.14
2182	16:19:48	30.42
2183	16:19:49	28.26
2184	16:19:50	26.38
2185	16:19:51	24.48
2186	16:19:52	22.17

2187	16:19:53	21.99
2188	16:19:54	20.05
2189	16:19:55	18.10
2190	16:19:56	21.99
2191	16:19:57	29.01
2192	16:19:58	26.53
2193	16:19:59	26.96
2194	16:20:00	28.58
2195	16:20:01	26.31
2196	16:20:02	24.04
2197	16:20:03	22.86
2198	16:20:04	25.23
2199	16:20:05	26.53
2200	16:20:06	28.29
2201	16:20:07	34.34
2202	16:20:08	32.58
2203	16:20:09	36.43
2204	16:20:10	43.30
2205	16:20:11	41.43
2206	16:20:12	37.90
2207	16:20:13	36.90
2208	16:20:14	31.89
2209	16:20:15	24.26
2210	16:20:16	21.45
2211	16:20:17	24.04
2212	16:20:18	26.10
2213	16:20:19	28.87
2214	16:20:20	30.60
2215	16:20:21	30.16
2216	16:20:22	33.66
2217	16:20:23	29.88
2218	16:20:24	31.82
2219	16:20:25	32.22
2220	16:20:26	30.78
2221	16:20:27	29.77
2222	16:20:28	28.69
2223	16:20:29	26.96
2224	16:20:30	24.48
2225	16:20:31	24.22
2226	16:20:32	25.02
2227	16:20:33	22.86
2228	16:20:34	18.82
2229	16:20:35	18.21

2230	16:20:36	14.68
2231	16:20:37	9.82
2232	16:20:38	7.12
2233	16:20:39	5.97
2234	16:20:40	4.93
2235	16:20:41	4.24
2236	16:20:42	3.78
2237	16:20:43	4.50
2238	16:20:44	6.37
2239	16:20:45	7.34
2240	16:20:46	7.77

2241	16:20:47	7.34
2242	16:20:48	6.37
2243	16:20:49	5.58
2244	16:20:50	5.47
2245	16:20:51	8.28
2246	16:20:52	10.44
2247	16:20:53	9.97
2248	16:20:54	8.28
2249	16:20:55	7.09
2250	16:20:56	6.80
2251	16:20:57	9.25

2252	16:20:58	10.33
2253	16:20:59	12.09
2254	16:21:00	11.88
2255	16:21:01	11.30
2256	16:21:02	9.72
2257	16:21:03	8.13
2258	16:21:04	6.40
2259	16:21:05	5.11
2260	16:21:06	4.28
2261	16:21:07	4.42
2262	16:21:08	5.43

2263	16:21:09	5.25
2264	16:21:10	5.07
2265	16:21:11	4.57
2266	16:21:12	4.28
2267	16:21:13	3.49
2268	16:21:15	0.54
2269	16:21:16	0.54
2270	16:21:17	0.36
2271	16:21:18	2.01
2272	16:21:19	0

Appendix E: CFD Simulation Boundary Conditions

Table E.1: CFD Simulation Boundary Conditions

Inlet	
Velocity Specification Method	Magnitude, Normal to Boundary
Reference Frame	Absolute
Velocity Magnitude [m/s]	27.78
Supersonic/Initial Gauge Pressure [Pa]	0
Turbulent Specification Method	Intensity and Viscosity Ratio
Turbulent Intensity [%]	0.5
Turbulent Viscosity Ratio	2
Outlet	
Backflow Reference Frame	Absolute
Gauge Pressure [Pa]	0
Pressure Profile Multiplier	1
Backflow Direction Specification Method	Normal to Boundary
Turbulent Specification Method	Intensity and Viscosity Ratio
Backflow Turbulent Intensity [%]	0.5
Backflow Turbulent Viscosity Ratio	2
Backflow Pressure Specification	Total Pressure
Build artificial walls to prevent reverse flow?	no
Radial Equilibrium Pressure Distribution	no
Average Pressure Specification?	no
Specify targeted mass flow rate	no
Wall	
Tunnel walls	
Wall Motion	Stationary Wall
Shear Boundary Condition	Specified Shear
Wall Surface Roughness	0
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
X-component of shear stress [Pa]	0

Y-component of shear stress [Pa]	0
Z-component of shear stress [Pa]	0
Ground	
Wall Motion	Moving Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude [m/s]	27.78
X-Component of Wall Translation	0
Y-Component of Wall Translation	0
Z-Component of Wall Translation	-1
Define wall velocity components?	no
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Wheel Radii	
Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Wheel Front Right	
Wall Motion	Moving Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	yes
Define wall velocity components?	no
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Rotation Speed [rad/s]	76.94

X-Position of Rotation-Axis Origin [m]	-0.7782685
Y-Position of Rotation-Axis Origin [m]	0.3610298
Z-Position of Rotation-Axis Origin [m]	-0.940474
Wheel Rear Right	
Wall Motion	Moving Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	yes
Define wall velocity components?	no
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Rotation Speed [rad/s]	76.94
X-Position of Rotation-Axis Origin [m]	-0.7782685
Y-Position of Rotation-Axis Origin [m]	0.3610298
Z-Position of Rotation-Axis Origin [m]	-3.899574
Wheel Rear Left	
Wall Motion	Moving Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	yes
Define wall velocity components?	no
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Rotation Speed [rad/s]	76.94
X-Position of Rotation-Axis Origin [m]	0.7782685
Y-Position of Rotation-Axis Origin [m]	0.3610298
Z-Position of Rotation-Axis Origin [m]	-3.899574
Wheel Front Left	
Wall Motion	Moving Wall

Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	yes
Define wall velocity components?	no
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Rotation Speed [rad/s]	76.94
X-Position of Rotation-Axis Origin [m]	0.7782685
Y-Position of Rotation-Axis Origin [m]	0.3610298
Z-Position of Rotation-Axis Origin [m]	-0.940474
Savonius Rotor	
Wall Motion	Moving Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	yes
Define wall velocity components?	no
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Rotation Speed [rad/s]	18.04
X-Position of Rotation-Axis Origin [m]	0
Y-Position of Rotation-Axis Origin [m]	0.4196
Z-Position of Rotation-Axis Origin [m]	-0.404
Guide Vanes	
Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Vehicle Body	

Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Model – 1 Rotor	
Wall Motion	Moving Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	yes
Define wall velocity components?	no
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Rotation Speed [rad/s]	95.46
X-Position of Rotation-Axis Origin [m]	0
Y-Position of Rotation-Axis Origin [m]	0.419926
Z-Position of Rotation-Axis Origin [m]	-0.3023702
Turbine Nacelle (Model – 1)	
Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Nacelle Support (Model – 1)	
Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5

Appendix F: Publications



3rd Biennial International Conference

on

“Future Learning Aspects of Mechanical Engineering”

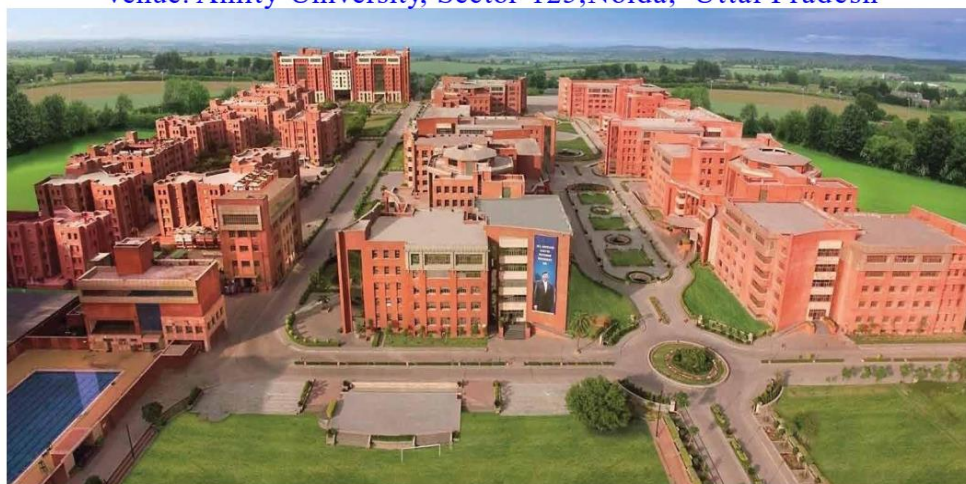
FLAME 2022

Organized By

Department of Mechanical Engineering
Amity School of Engineering and Technology
Amity University Uttar Pradesh, Noida

August 3rd -5th 2022

Venue: Amity University, Sector-125, Noida, Uttar Pradesh



AMITY UNIVERSITY UTTAR PRADESH, NOIDA CAMPUS

In Association with



- All the accepted papers will be indexed in the **SCOPUS** database.
- Selected and extended versions of papers will be published as Special Issue in Scopus/SCI/ESCI Indexed international journal of repute.

Conference website: <https://www.amity.edu/flame2022/>

Figure F.1: Brochure of the International Conference

From: FLAME-2022 <flame2022@easychair.org>
Date: Thu, May 26, 2022 at 10:53 AM
Subject: FLAME 2022 Notification for Paper Submission Number 325
To: Ramesh Babu Nallamothu <rbnallamothu@gmail.com>

Dear Author,

Submission Number 325

Title: Physical Modelling Based Study of Vehicle Mounted Wind Energy Recovery System

We would like to inform you that your manuscript has been reviewed and the reviewer's comments are appended at the bottom of this e-mail.

Based on the reviews received, your manuscript has been PROVISIONALLY accepted for presentation and publication in FLAME-2022. Please incorporate the reviewer's stated concerns and highlight the changes with RED in color and update the revised manuscript.

You are requested to send the following documents in the attachment to flame@amity.edu in a Zipped file (Paper Submission Number as a file name).

1. Revised Paper with Highlighted Changes in RED Colour (word file). File Name: Paper Submission Number _Draft.doc
2. Receipt of Registration Fee paid. File Name: (Paper Submission Number _Fee receipt.pdf).
3. Response to Reviewers (word file). File Name: Paper Submission Number _response.doc
4. Folder with all the figures (in TIFF format numbered as Fig.1, Fig.2, etc): Folder Name: Figures_ paper submission number
5. Camera Ready Paper (pdf and word, both files). File Name: Paper Submission Number _camera.doc and Paper Submission Number _camera.pdf
6. Permission request form. Ensure that all permissions have been obtained for any material within the manuscript which is not your original work, or (in most cases) is your own work but which you have previously published. File Name: Paper Submission Number _Permission

Kindly follow the submission guidelines while preparing the Camera-Ready paper mentioned on the conference website. <https://www.amity.edu/flame2022/call-for-paper.asp>

Figure F.2 : Conference Acceptance Notification

Physical Modelling Based Study of Vehicle Mounted Wind Energy Recovery System

Amanuel Abate¹, Ramesh Babu Nallamothu^{1*}

¹Mechanical Engineering Department, SoMCME, Adama Science and Technology University, Adama, Ethiopia.

Corresponding author: rbnallamothu@gmail.com, ramesh.babu@astu.edu

Abstract

Electric vehicles are the major contributors to the reduction of emissions from road vehicles. From previous studies this attribute of electric vehicles can further be strengthened by using vehicle mounted energy recovery systems. This study investigated the implementation of wind energy recovery system employing a 190mm HAWT mounted at vehicle front using physical model constructed in Simulink software for an EV operating under the HWFT driving schedule. The modeled EV was able to track the reference speed with maximum driver error of less than 0.5. The EV SOC for vehicle drag coefficients varied by +0.1 from the base model were 92.456% and 95.85% for reduced and increased Cd values. The energy recovery system was also developed and integrated with the EV model in MATLAB Simulink. The battery SOC of the Baseline and Integrated model were studied for which the integrated model resulted in net battery charge level gain of 2.15%.

Keywords: Electric Vehicle, MATLAB Simulink, Battery SOC, Wind Energy, Physical Model

Abbreviations: EVs – Electric Vehicles, ERS – Energy Recovery System, EV – Electric Vehicle, HAWT – Horizontal Axis Wind Turbine, SOC – State of Charge

INTRODUCTION

Electric vehicles were first used in public in the mid-nineteenth century [1]. Then after, over the years substantial advancements have been made to the electric vehicle. An electric vehicle has two characteristics: (i) a portable energy source and storage system that is electrochemical or electromechanical in nature, and (ii) solely electric traction.

The principal source of energy for these cars' electrical generation ranges from fossil fuels to solar energy [2].

There are several impediments to the adoption of this technology by market actors and the general public, the most significant of which are the high cost of purchasing an electric vehicle (EV), its limited range (range anxiety), and the prolonged time needed for charging [3].

One of the determining factors of an EV's environmental impact is the nature of the charging electrical energy source utilized. So, one obvious way to ensure the carbon neutrality of an EV is to implement renewable energy infrastructures that are the sources for EV charging.

1.1 Electric Vehicles and Renewable Energy

The transportation industry, which is primarily emitted in cities, accounts for more than 20% of worldwide greenhouse gas emissions. As a result, projects and research focusing on the integration of electric vehicles powered by renewables are considered a desirable solution for mitigating climate change and promoting the energy transition [4].

1.2 Wind Energy Devices on Automobiles

Wind turbines were not used as drive power sources in automobiles until the twenty-first century. [5] discussed three main schools or trends have developed in the use of wind power as a source of energy to move vehicles in general and the theoretical studies that have been carried out on its viability.

Harnessing the wind energy around the vehicle were implemented by vehicle mounted systems. Multiple researchers have studied this implementation for aerodynamic property alterations, [6]–[9] observing increase vehicle drag coefficient for roof mounted system and negligible to no changes to the vehicle drag coefficient for vehicle front mounted system.