Powertrain Modeling, Design, and Integration for the World’s Fastest Electric Vehicle

THESIS

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By
David W. Cooke, B.S.
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Master's Examination Committee:
Professor Giorgio Rizzoni, Advisor
Professor Marcello Canova
Abstract

For the past 20 years engineering students at the Ohio State University Center for Automotive Research have been designing, building, and racing electric vehicles. Over the past 15 years the team has focused on the development of the Buckeye Bullet series of landspeed racing vehicles to chase new speed records for EV’s. Throughout history, automotive technology has been born on the racetrack and the students of the Buckeye Bullet racing team have used this concept to push the performance limits of electric vehicle technology. In 2010 the team developed a partnership with EV manufacture Venturi Automobiles to form the Venturi Buckeye Bullet Racing Team. The team’s current mission is to chase 400 MPH and set the ultimate landspeed record regardless of class utilizing an electric vehicle. For the first time in 100 years an electric vehicle will challenge the ultimate speed performance of the internal combustion engine.

This document begins with a high level view of the development process for the VBB3 electric landspeed vehicle with a focus on the development of the 2 megawatt electric powertrain and energy storage systems. Next a detailed look into the specification, design, construction, and integration of each of the key powertrain components is presented. A section on the development of specialized test benches for high speed, high torque motors is included. The document concludes with a review of the results to date and future work remaining to achieve the 400 MPH program goal.
Dedication

This document is dedicated to my parents for their extraordinary dedication to, involvement in, and support of all aspects of my life. I am eternally grateful for their extreme sacrifices in the name of their children's success. They have always been and will always be my greatest inspiration in life.
Acknowledgments

I would first like to acknowledge the Buckeye Bullet team members past, present, and future who have dedicated countless hours to this intensive program in the pursuit of world landspeed records. A special thanks goes to the following individuals for key technical contributions that made this thesis possible: Robert (RJ) Kromer, Evan Maley, LingChang Wang, Luke Kelm, Casie Clark, Carrington Bork, Josh Terrell, Kevin Kaschube, and Matt Little. I would also like to recognize the dedicated VBB3 support team and next generation of team leaders, Michael Johanni, Ross Johnstal, and Drew Browning. I would also like to thank the team leaders that mentored me when I was a new student including: Isaac Harper, Ed Hillstrom, Ben Sinsheimer, Kevin Ponziani, and Kim Stevens.

I cannot say enough thanks to the Buckeye Bullet team advisor and my faculty advisor and mentor Dr. Giorgio Rizzoni. His 20+ year support of this team as well as my academic and professional development have been an immense influence to my time at OSU and my future career development. I would also like to thank Dr. Marcello Canova and Dr. Shawn Midlam-Mohler for their support of my thesis and the technical development of the VBB3. Additionally, key support has been provided by the research and support staff of the Center for Automotive Research including Julie Haywood, Darrin Orr, Donald Butler, Don Williams, Joanna Pinkerton, Holly Henley, John Kabat, and Frank Ohlemacher. I would
like to thank the Ohio State University and all of its leaders who provide the platform to participate in this one-of-a-kind program.

This project would not be possible without the generous support of all of our program partners and donors. I would especially like to thank Gildo Pallanca Pastor for his immense and unwavering support of our team and passion for the future of the electric automobile. He is a daily inspiration to the team. A special thanks goes to the entire team at Venturi Automobiles. From the technical development of the vehicle and powertrain to cooking pasta for our team for dinner at the track, the team from France has been an amazing partner though it all. I would also like to thank key sponsors, A123 Systems, Brian Moorhead, TRC, EWI, Josh Chance, The Mathworks, The OSU Honda Partnership Program, American Traction Systems, Hewland Engineering, Aerodine Composites, Timken, the Ohio Super Computer Center, Dassault Systemes, and the OSU College of Engineering.

A very special thank you to Roger Schroer for more than 10 years of dedication to the team and willingness to not only drive whatever vehicle we put in front of him, but also to help to maximize the potential of the vehicle and the team. Working with Roger is truly a privilege and has been one of my greatest joys over the past 10 years. Finally, I would like to thank Brittney Tipton for her tremendous support of the team and my personal dream to participate at the highest level. She has provided loving support of all of my goals and put up with many late nights that transform into early mornings at the workshop for more than 6 years. She has not only tolerated this time encompassing project, but also worked to help out in any way possible. Form holding the umbrella over cockpit to shade Roger between runs to cooking lunch for 50, she has always been there to support the team.
Vita

January 1\textsuperscript{st}, 1986 ............................................Born, Columbus, Ohio

June 2004 ...........................................................Logan Elm High School, Circleville, OH
   Class Valedictorian

December 2004 to Present ..................................Member, Buckeye Bullet Team
   Center for Automotive Research
   OSU

June, 2005 to June 2012 ......................................Student Research Associate,
   Center for Automotive Research
   OSU

2007 to 2010 ......................................................Engineering Intern,
   Honda
   Research and Development

2010 to 2012 ......................................................Engineering Intern,
   Venturi
   Automobiles

June, 2012 ..........................................................B.S Mechanical Engineering, with
   Distinction, The Ohio State University

July, 2012 to May 2015 .......................................Graduate Fellow, The Ohio State University
   Center for Automotive Research

May, 2015 ..........................................................M.S Mechanical Engineering, the Graduate
   School, The Ohio State University

Fields of Study

Major Field: Mechanical Engineering
# Table of Contents

Abstract ............................................................................................................................... ii

Dedication .......................................................................................................................... iii

Acknowledgments .............................................................................................................. iv

Vita ..................................................................................................................................... vi

List of Tables ...................................................................................................................... x

List of Figures .................................................................................................................... xi

Chapter 1: Introduction ...................................................................................................... 1

1.1: Program History ...................................................................................................... 1

1.1.1: “The Smokin’ Buckeye” ................................................................................... 1

1.1.2: Buckeye Bullet 1 .............................................................................................. 2

1.1.3: Buckeye Bullet 2 .............................................................................................. 4

1.1.4: Venturi Buckeye Bullet 2.5 .............................................................................. 5

1.2: Landspeed Racing .................................................................................................... 8

1.3: Motivation, the Venturi Buckeye Bullet 3 ............................................................ 12

1.4: Thesis Objectives .................................................................................................. 14

vii
4.3: Inverter Detailed Design ........................................................... 68
4.4: Gearbox Detailed Design ........................................................ 70
4.5: Powertrain Complete Axle Detailed Design ......................... 75

Chapter 5: Powertrain Manufacture, Assembly, and Integration .... 81

Chapter 6: Powertrain Test Bench .................................................. 88
6.1: Buckeye Bullet 2 - 2007 Test Bench ....................................... 89
6.2: Venturi Buckeye Bullet 3 - 2012 Inverter Development Test Bench ................. 92
6.3: Venturi Buckeye Bullet 3 - 2013 Axle Test Bench .................... 95

Chapter 7: Results to Date and Conclusions .............................. 101

Chapter 8: Future Work .............................................................. 109

Bibliography ............................................................................... 112
List of Tables

Table 1: Wheel-Driven Runs Over 400 MPH (1st per Vehicle) ........................................ 13
Table 2: BB1 vs BB2 Defining Variable Parameter Values ............................................ 32
Table 3: Defining Parameter Conceivable Range ............................................................ 34
Table 4: Initial Inverter Requirements ............................................................................. 51
Table 5: Battery Pack Final Specifications ...................................................................... 63
List of Figures

Figure 1: "Smokin' Buckeye" - Formula Lightning Series Vehicle – 1993 to 2001........ 2
Figure 2: Buckeye Bullet 1 – 314 MPH – NiMH Batteries – 2001 to 2004............... 3
Figure 3: Buckeye Bullet 2 Packaging................................................................. 4
Figure 4: Buckeye Bullet 2 – 303 MPH – Hydrogen Fuel Cell – 2006 to 2009........ 5
Figure 5: Venturi Buckeye Bullet 2.5 – 308 MPH – Li-Ion Batteries – 2010......... 7
Figure 6: Bonneville Salt Flats, Utah............................................................... 8
Figure 7: Landspeed Racing Course Layout..................................................... 11
Figure 8: Original Concept of the Venturi Buckeye Bullet 3 (VBB3)................. 14
Figure 9: Landspeed Vehicle Development Process ....................................... 19
Figure 10: BulletSim Module Implementation [1]........................................... 26
Figure 11: Top Level Simulink Implementation of BulletSim [1]....................... 27
Figure 12: Model Parameter Inputs ................................................................. 29
Figure 13: Fixed and Variable Simulation Parameters...................................... 31
Figure 14: Aerodynamic Drag and Rolling Resistance Forces.......................... 33
Figure 15: Early Concept of VBB3 Packaging.................................................. 36
Figure 16: Battery Cycling (Charge/Discharge) Equipment............................... 39
Figure 17: Battery Cell Compressions Test Fixture in an Environmental Chamber... 40
Figure 18: A123 Module Packaging Design (Courtesy of A123 Systems Inc.) .......................... 41
Figure 19: Module Thermal Operating Validation .................................................................. 42
Figure 20: Electrical Layout of Battery Pack ...................................................................... 43
Figure 21: Battery Cell (left), Module (middle), “Blade Pack” of Modules (right) .............. 43
Figure 22: Ideal Torque (at the wheels) vs. Motor RPM ..................................................... 45
Figure 23: Ideal Motor Power vs. Motor RPM .................................................................. 45
Figure 24: Absolute Maximum Performance Potential of VBB3 ...................................... 47
Figure 25: Wheel Torque vs. Wheel Speed for Various Motor Designs ............................... 48
Figure 26: Venturi Production AC IPM Motor Package .................................................... 49
Figure 27: Performance Potential of VBB3 with Motor Technology Selected .................. 50
Figure 28: Early Prototype of ATS Inverter ........................................................................ 52
Figure 29: Axle Layout - 4 Motors per Axle – Linear Arrangement ................................. 55
Figure 30: Axle Layout - 4 Motors per Axle – 2 x 2 Arrangement ................................. 55
Figure 31: Axle Layout - 3 Motors per Axle – Linear Arrangement ................................. 57
Figure 32: 2 Motors per Axle – Linear Arrangement ....................................................... 58
Figure 33: Battery Pack High Voltage Schematic – “Inverter Pack” - (¼ Vehicle) ............ 60
Figure 34: Battery Management Housing Final Packaging Design .................................. 62
Figure 35: Battery Axle Pack Final Design – 4 Blade Packs ............................................ 63
Figure 36: IPM Motor Exploded Rendering [6] ................................................................. 64
Figure 37: Style of IPM Motor Cartridge Supplied To Student Team .............................. 65
Figure 38: Custom Motor Shaft Development .................................................................. 66
Figure 39: CAD Image of Custom Venturi / OSU Motor Design ...................................... 67
Figure 62: Transmission and Suspension Assembly ......................................................... 87
Figure 63: 1st Powertrain Fitment in VBB3 Chassis ....................................................... 87
Figure 64: CAD Model of Buckeye Bullet 2 Motor Test Bench ..................................... 91
Figure 65: Buckeye Bullet 2 Motor Test Bench Installation ............................................. 91
Figure 66: CAD Model of 2013 Inverter Development Test Bench .............................. 94
Figure 67: 2013 Inverter Development Test Bench Installation ...................................... 94
Figure 68: High Voltage Schematic for Axle Test Bench ............................................... 96
Figure 69: CAD Model of 2013 VBB3 Axle Test Bench .................................................. 97
Figure 70: Test Bench Drive Shaft / Flex Coupling Installation .................................... 98
Figure 71: Magtrol In-Line Torque Transducer .............................................................. 98
Figure 72: 2013 Axle Test Bench – Complete Installation .............................................. 99
Figure 73: Axle Test Bench Cooling Cart ....................................................................... 100
Figure 74: Early Road Test at Transportation Research Center (TRC) ............................ 101
Figure 75: Desired Salt Flats Appearance (from the End of the Access Road) ............... 103
Figure 76: 2013 Salt Flats Appearance (from the End of the Access Road) .................... 103
Figure 77: 2013 Testing at Wendover Airport Due to Rain .......................................... 104
Figure 78: 2013 Salt Flats Appearance (from the End of the Access Road) .................... 105
Figure 79: 2014 Racing Run ~260 MPH ...................................................................... 106
Figure 80: Run Simulation Based on 2014 Conditions .................................................. 107
Figure 81: 2014 Top Speed Run (Data – Based On Wheel RPM) .................................... 108
Figure 82: VBB3 Team on the Salt Flats After 2014 Racing Attempts ............................ 111
Chapter 1: Introduction

1.1: Program History

For the past 22 years, students at The Ohio State University's Center for Automotive Research have been designing, building, and racing electric vehicles. Over the years, the vehicles and competitors have changed, but the mission of the team has remained the same. The primary goal of the team is to provide a truly unique opportunity for students to apply their engineering knowledge outside the classroom, and to develop the next generation of automotive engineering leaders. The second mission of the team is to take the powertrain technology of tomorrow and test it to the ultimate limits today, showing the world that green technologies of the future can still be rooted in performance. The ecologically friendly innovations of the auto industry do not have to bring an end to racing, merely a revolution. Pushing the technologies on the race track today helps us to understand and improve the production products of tomorrow.

1.1.1: “The Smokin’ Buckeye”

The OSU electric racing program began in 1993 with an open wheel formula style car named “The Smokin’ Buckeye”. This vehicle raced in an inner-collegiate series called “Formula Lightning.” The vehicle is pictured in Figure 1 below.
The team was incredibly successful in this series, winning more than half of all the races held and every national championship that was awarded. In 2001 due to lack of battery technology progression and lack of funding the Formula Lightning series ended. While many teams disbanded, the OSU team began to investigate a new way to apply their passions for electric vehicles and racing.

1.1.2: Buckeye Bullet 1

The teams’ expertise in pushing batteries to their limits, as well developing and integrating custom electric motors drove them to dream about other demonstration electric vehicle [EV] projects they could develop. After some discussion with the teams’ motor manufacturer, it was decided that chasing the ultimate speed record for an electric vehicle could be a very rewarding challenge. This set the team off to develop a mathematical
model based simulator to prove the challenge was feasible with the available technology. This simulation exercise is the basis for everything the team has done for the past 15 years and sets the ground work for this thesis. In 2001 the team used the simulator to determine that exceeding the existing land speed record of 245 MPH for an electric vehicle was possible and kick started the Buckeye Bullet series of vehicles. After 3 short years of designing, building, and upgrading the vehicle, the Buckeye Bullet 1 [BB1] made its way to a U.S. record of 314 MPH and became the first EV over 300 MPH. This vehicle was powered by a Ni-MH battery pack and a custom AC induction motor. The BB1 can be seen in Figure 2 below. While the BB1 exceeded the FIA World Record of 245 MPH it was not run under the international rules and thus only holds a U.S. SCTA record, not a World Record. The U.S. record still stands as of May, 2015.

Figure 2: Buckeye Bullet 1 – 314 MPH – NiMH Batteries – 2001 to 2004
1.1.3: Buckeye Bullet 2

Following the success of the BB1 program the team decided to continue the EV Speed record, but add in a new challenge. As of 2004 the BB1 was using one of the best battery technologies available and there was not much performance improvement to be found by developing a new battery vehicle. The team pivoted its efforts into developing an electric vehicle with a new power source, hydrogen fuel cells. After several years of preforming H2 fuel cell research and building a program with the ideal technical partners, the team began the development of the Buckeye Bullet 2 [BB2] in 2006. Ballard Power Systems provided the fuel cell stacks which were repurposed from a fuel cell bus program, and Ford Motor Company assisted in the integration of the hydrogen systems. OSU, Ballard, and Ford worked together to push the 250 kW production fuel cell system to over 600 kW of continuous power. The OSU team designed the rest of the vehicle around this power source and in the end developed a state of the art landspeed vehicle platform capable of more than 300 MPH. The layout of the BB2 vehicle and the final vehicle on the salt flats can be seen in Figure 3 and Figure 4.

Figure 3: Buckeye Bullet 2 Packaging
After 3 intense years of testing, tuning, and “Hot Rodding” the fuel cell systems the vehicle completed FIA certified World Record at 303 MPH in 2009. The record represented an increase of more than 210 MPH from the previous fuel cell record and an achievement that still stands as of May, 2015.

1.1.4: Venturi Buckeye Bullet 2.5

Following the hugely successful BB2 program the team was as eager as ever to continue to develop the next generation of landspeed records. After the 5 year break from working with battery power, the team found that there had been huge developments in the industry. Ni-MH battery technology was no longer the king of large format batteries in terms of energy and power densities. At the end of the BB1 2004 lithium ion [Li-ion] batteries were
just starting to become amiable in small formats for high end portable electronics, and
could have never been efficiently scaled to a landspeed vehicle pack. By 2009 the Li-ion
industry was booming, and a multitude of chemistries was available with more being
introduced each month. Most importantly, the batteries were available in large formats
appropriate for automotive use. With this exciting new technology on the forefront of
development, the team set up to develop an all new vehicle based on Li-ion technology.
While in principal it was time to develop a new vehicle from the ground up for the new
mission, the team realized that they needed to gain some experience in working with
modern batteries and most importantly, selection from the many available battery
chemistries. During 2009 and early 2010 the team worked with a large number of battery
suppliers to obtain samples of their offerings for comparison. The team then utilized the
advanced battery testing equipment at the OSU Center for Automotive Research where the
OSU motorsports programs are co-located, to put the various batteries through the rigorous
cycles of a landspeed race. After hundreds of race cycles were run under various
conditions, the team decided to partner with A123 Systems on the development of a
landspeed racing battery pack. To speed the time to the test track, an initial pack was
developed as a replacement for the hydrogen fuel cell systems in the BB2 and integrated
into the vehicle leaving nearly every other system the same including the chassis, body,
motor, and other mechanical systems. The variable frequency motor drive [inverter] was
upgraded to a more modern model. This upgraded vehicle / test mule was dubbed VBB2.5.
The V added to this vehicles name represented a new program partnership that was founded
during this era. Venturi Automobiles, a small electric vehicle company based in Monaco,
shared in the dream of breaking electric landspeed records and joined the effort. This key technological and financial partnership led to the founding of the Venturi Buckeye Bullet Racing Team. Together with Venturi the team headed to the salt flats in 2010 with the VBB2.5 to collect data on the A123 battery systems and overall vehicle performance. During this outing, the team had a chance to race the VBB2.5 against the existing electric vehicle world record of 245 MPH and was able to blow that record away. After only a few days of testing the vehicle set a new FIA World Record of 306 MPH. The vehicle had far more performance potential, but available time at the race track did not allow the team to continue to push the performance of the test vehicle. The critical job of battery validation had been completed which was the primary mission of the program. The VBB2.5 can be seen in Figure 5 below.

![Venturi Buckeye Bullet 2.5](image)

Figure 5: Venturi Buckeye Bullet 2.5 – 308 MPH – Li-Ion Batteries – 2010
1.2: Landspeed Racing

For as long as man has been on this earth, there has been a drive to complete. From the earliest days of mobility, the daredevils of each era have pushed the technology of the day to the limits of speed. From the chariot races in ancient grease to modern Bonneville speed trials, the race track has always been a birthplace for mobility innovation. Landspeed racing is quite different from any other form of racing. Many herald it as "The last pure form of grassroots motorsports." Each year thousands of gear-heads travel to the Mecca of landspeed racing, The Bonneville Salt Flats, in Utah. The flats is a 50 square mile, dry lake bed. Each winter the entire area floods, becoming a salt lake, but in the late spring and summer the water recedes leaving a perfectly flat salt surface. The salt flats are so large they can be identified from space. The area is shown below in Figure 6.

Figure 6: Bonneville Salt Flats, Utah
Automobile racing at Bonneville dates back to the turn of the 20th century. Early enthusiasts used the flats as a safe place to test their designs to the limits without risk to bystanders. As technology progressed and top vehicle speeds moved from 25 MPH to 50 MPH, and eventually over 100 MPH, racing in city streets became quite dangerous. As the hot-rodgers of Southern California looked for a more remote place far from the city and the attention of law enforcement, they found the Salt Flats to be an ideal location to push their cars to the limit. In the 1950's an official yearly hot rod speed trail event was created named Bonneville Speedweek. The event is managed by the Southern California Timing Association [SCTA]. Each year more than 500 teams bring cars spanning hundreds of categories to compete at Speedweek, the largest of 5 major events that take place on the flats. There is quite literally a class for any type of powered vehicle, including numerous Frankenstein creations that didn't even begin as automobiles. From showroom stock OEM cars to fighter jet fuel tanks with a seat and motor bolted inside, if it can move under its' own power it has probably raced at Bonneville.. Aside from the location, the track, and the cars, the most unique part of the landspeed racing community is the relationship between the competitors. Most other forms of racing have a very closed feel, with development happening behind locked doors and limited access pits at the track. The rules of the racing body are very specific and hinder engineering creativity. Slight advantages from minor changes in tuning is all that separate first and last place so the winning configurations are highly guarded. The Bonneville experience is quite the opposite. Though there is a rule book, nearly all of the rules are dictated by safety and great work is taken to make sure that creativity is not limited, but instead encouraged. The majority of
the rules are simply to classify the vehicles into the various categories. At the track the pits are completely open and the competitors are more than willing to discuss their designs, experiences, and trade secrets. It is not uncommon to see the current record holder coaching a competitor and suggesting design improvements, or even taking parts from their own vehicle to help repair a competitor’s vehicle so they can have a shot at a new record.

There are many different sanctioning bodies which grant landspeed records. In the United States, the sanctioning body which grants national records is the SCTA. Internationally sanctioned records are granted by the FIA (Federation Internationale de l'Automobile). Records are always based on the average of two runs, a qualifying run in which the previous record must be surpassed by at least 0.001 mile per hour, and a record run which occurs after a successful qualifying run. The specific rules of vehicle classification, track layout, and record certification vary greatly among sanctioning bodies. The course layout for national and international records are shown in Figure 7.
The key differences between the SCTA and FIA records are time limit, course length, and travel direction. For event efficiency, due to the high number of competitors, the SCTA runs occur in one direction and the record run following a qualifying run happens the next day after 4 hours is given to service the car prior to impound. The track is a fixed length of 5 timed miles. In contrast the FIA course is a 2 way track that can be as long as physically possible with a single timed mile in the middle. Due to the geographic limits at Bonneville, the FIA course can end up with anywhere from a 4 to 5.5 mile approach to the timed mile compared to the fixed 4 mile approach of the SCTA course. This presents a big advantage to the longer FIA course. The challenge comes from the other major difference,
the time limit. During the FIA run the entire 2 way attempt must happen inside of 60 minutes. This means that after the run the vehicle must be slowed, brought into the pits, serviced, taken back to the track and raced to speed all within an hour. This extremely compressed cycle becomes a key defining factor in the design of all vehicle systems as will be discussed in Chapter 4.

1.3: Motivation, the Venturi Buckeye Bullet 3

As of 2010 the team had accomplished a number of outstanding feats in the landspeed racing community including:

- Having the All-Time Most Successful Electric Formula Racing Program
- Producing 3 Student Designed Vehicles, All With Top Speeds Over 300 MPH
- Holding All National and International Top Speed Records for Battery Vehicles
- Holding All National and International Top Speed Records for Fuel Cell Vehicles
- Producing the Fastest Student Designed Automotive Vehicle of Any Power Type

While the team was quite proud of these accomplishments, there was a drive to continue to expand the program to even higher levels of performance. It was quite a feat to have “the fastest electric” vehicle and “the fastest student” vehicle, but the team began to ask what does it take to be “the fastest PERIOD.” The answer to this question in the context of wheel-driven landspeed race cars, is to exceed 400 MPH. At Bonneville the first digit of a record is really the defining class of the vehicle, and after many years in the 300 MPH club the team decided to chase the panicle of landspeed racing, the 400 MPH club. To give
a brief idea of what this accomplishment means each of the wheel-driven vehicles that have
a run, not even a record, over 400 MPH are listed in Table 1 below. More men have walked
on the moon than driven a landspeed vehicle over 400 MPH.

Table 1: Wheel-Driven Runs Over 400 MPH (1st per Vehicle)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Team</th>
<th>Year</th>
<th>Speed</th>
<th>Powered By</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluebird CN7</td>
<td>Donald Campbell</td>
<td>1964</td>
<td>403.100</td>
<td>1 Engine, TurboShaft, 4WD</td>
</tr>
<tr>
<td>Goldenrod</td>
<td>Summers Brothers</td>
<td>1965</td>
<td>409.277</td>
<td>4 Engine, Unblown, 4WD</td>
</tr>
<tr>
<td>Speed-O-Motive</td>
<td>Al Teague</td>
<td>1991</td>
<td>409.86</td>
<td>1 Engine, Blown, Fuel, 2WD</td>
</tr>
<tr>
<td>Turbinator</td>
<td>Team Vesco</td>
<td>2001</td>
<td>458.440</td>
<td>1 Engine, TurboShaft, Fuel, 4WD</td>
</tr>
<tr>
<td>Spirit of Auto Power</td>
<td>Nolan &amp; Rick White</td>
<td>2002</td>
<td>413.000</td>
<td>2 Engine, Blown, Fuel</td>
</tr>
<tr>
<td>Burkland s 411</td>
<td>Burkland Family</td>
<td>2008</td>
<td>415.896</td>
<td>2 Engine, Blown, Fuel, 4WD</td>
</tr>
<tr>
<td>Spirit of Rett</td>
<td>Charles Nearburg</td>
<td>2010</td>
<td>414.316</td>
<td>1 Engine, Unblown, Fuel, 2WD</td>
</tr>
<tr>
<td>Speed Demon</td>
<td>Poteet and Main</td>
<td>2010</td>
<td>404.562</td>
<td>1 Engine, Blown, Fuel, 2WD</td>
</tr>
<tr>
<td>Spectre SpeedLiner</td>
<td>Spectre</td>
<td>2010</td>
<td>408.000</td>
<td>1 Engine, Blown, Gas, 2WD</td>
</tr>
</tbody>
</table>

This 400 MPH goal set the stage for all future design direction of the program. The
question shifted from “what is the best battery for the job to maximize speed” to what will
it take to get to 400 MPH. It became clear from day 1 that the team’s previous methods of
customizing and optimizing existing technology would not provide enough performance
to reach the 400 MPH goal. Each vehicle system would have to be evaluated form the
ground up and optimized to the mission. This new program was named the Venturi Buckeye Bullet 3 and began with the initial concept shown below in Figure 8.

Figure 8: Original Concept of the Venturi Buckeye Bullet 3 (VBB3)

1.4: Thesis Objectives

The complete program lifecycle for the VBB3 from concept to retirement is an incredibly involved process with extensive research in nearly every facet of vehicle technology. By the end of racing in 2016 the total program will have encompassed more than 6 years and involved approximately 10 graduate students and 50 undergraduate students. The author of this thesis has severed as the team leader and held overall responsibility for the technical aspects of the vehicle development since day 1 of the VBB3 program. Due to this wide spanning responsibility across all vehicle systems, it is the intent of this document to present the overall process of developing the powertrain for the vehicle. This document builds upon the work done by the past and current graduate students and focuses on the
selection and integration of powertrain components. It also presents key work of the author in the development of several different powertrain test benches. The primary objective of this thesis is to provide a historical record of the overall development process for future team members to use as a guide in the development of next generation vehicles.

1.5: Thesis Summary

This document is organized into 5 key topics spanning 8 chapters. First an introduction to the project and work completed thus far is presented in Chapters 1. Next in Chapter 2 the tools and methods used to define vehicle components and to simulate vehicle performance are introduced. The 3rd section spans Chapters 3 through 5 and presents the methods used to define the powertrain architecture and to develop the final designs of each component. The 4th section focuses on the development of a test bench to simulate full power race runs with the vehicle powertrain. The final section spanning Chapters 7 and 8, present the results to date and planned future work.

1.6: Program Literature Review

As discussed above, the work presented in this thesis is a summary of the modeling, design, and integration of the powertrain for the VBB3. The challenge of reaching 400 MPH required close examination of each vehicle system, and optimization to the unique mission profile. The vast majority of the literature relevant to landspeed racing, and specifically electric landspeed race vehicle development, has been produced by the Buckeye Bullet
team. Each of the teams’ nine graduate students who participated in the development of VBB3 held primary responsibility for one or more of the vehicle systems. Eight of the nine graduate students were undergraduate members of the team who continued on to a graduate degree, specializing in their vehicle system. By the end of 2015, eight master’s theses, as well as several technical papers focusing on this work will have been published. The scope of this thesis covers the overall strategy and implementation of the key powertrain technologies. The detailed development of each of these systems can be found in the respective master’s thesis and technical papers.

As will be presented in the following sections, the foundation of all of the teams’ work is the mathematical model of the vehicle, or “Buckeye Bullet Simulator.” This work is introduced in a 2008 thesis by Benjamin Sinsheimer, and heavily expanded upon in a 2014 thesis by Robert [RJ] Kromer. RJ’s work in the development of a highly modular vehicle simulator provided the key tool for all design, analysis, and optimization exercise for each system of the VBB3.

A great deal of the development work on the energy storage system (battery pack) was completed by the author of this thesis during the course of an undergraduate honors thesis. That document goes into great depth on the topic of battery chemistry selection, race profile determination, power and energy specifications, and system design concepts. The energy storage sections of this document are presented as a follow up effort to the work covered in that thesis.

Other critical support work referenced in this thesis has been documented in previous theses completed by Carrington Bork on the subject of vehicle packaging and layout with
regards to aerodynamic optimization, Cassie Clark on the subject of Aerodynamic optimization, and Austin Krohn on the subject of inverter control methodology. An upcoming thesis will be published by Evan Maley on the subject of landspeed vehicle dynamics, suspension design and integration, and performance analysis. Key relevant non-thesis work on vehicle systems has been carried out by Luke Kelm on motor packaging and cooling design, LingChang Wang on battery packaging, and Josh Terrell on battery pack testing. Each of these documents, and development efforts has provided the critical foundation upon which this thesis is built.
Chapter 2: Tools and Methods

Over the past 15 years the Buckeye Bullet team has developed an iterative design methodology for landspeed vehicle development. This process began informally out of necessity, but over time has developed into a formal cycle which the team follows closely. The process is constantly refined and improved with special focus on implementing cutting edge computer simulation tools for the development of each vehicle system. This chapter presents the tools and methods used by the team to conceive, design, build, and test landspeed racing vehicles.

2.1: Model Based Design Process

From the foundation of our first landspeed effort in 2001 the team has used dynamic systems methods and model based design as the basis for our vehicle programs. Our development cycle can be split into distinct phases. Each phase of vehicle development begins with computer simulation of the system model utilizing a tool developed by the team called BulletSim. In general the modeling and simulation exercises with BulletSim feed detailed, system specific CAE simulations including packaging studies with computer aided design [CAD], aerodynamic simulation with computational fluid dynamics [CFD], strength and materials studies with finite element analysis [FEA], and further detailed performance design utilizing BulletSim. The detailed design exercises of each phase then
feeds prototyping exercise of the systems, and finally in each phase physical testing is completed. This process can be seen in flow chart from in Figure 9 below. Each line represents a phase of vehicle development, each color a type of activity.

![Figure 9: Landspeed Vehicle Development Process](image)

### 2.1.1: Development Phase 1 – Component Research

The first phase contains the initial component research. Widely ranging baseline simulations allow the team to narrow in on the type of vehicle to be built and provide a very rough idea of basic system parameters. It is during this phase that the type of components and the scale of overall vehicle size and power are determined. Once the simulations are complete broad system parameters are identified to allow for component research. Next, the available components and technologies already on the market, or soon
to be released prototypes are studied for fit with the program goals. Where feasible, completely custom components are considered and analyzed for use in the vehicle. Once target components are specified, samples are built or obtained for physical testing. Physical testing of each potential vehicle component is key, as very few devices are rated for the duty cycles seen in landspeed racing. Steady state parameters and limits mean nothing when the application calls for 90 seconds of full power followed by a long period of rest. Each potential vehicle component is put through race cycles and re-rated for use in the Buckeye Bullet. This test data feeds the next phase of the process. Phase one of the process has traditionally taken each of our vehicle teams approximately 1 year to complete.

2.1.2: Development Phase 2 – Detailed Design

The component testing data feeds the modeling exercise at the start of phase 2. Updating the broad simulation model with specific vehicle parameters provides confirmation that appropriate systems were selected and the vehicle can meet performance targets. This stage of simulation also helps to size many system components, and a wide variety of components that may have been neglected for simplification of the phase 1 model. As an example, this stage allows analysis of various gear ratios to optimize the torque curve of the motor selected during component specification. The 2nd round of modeling feeds the detailed design of the complete vehicle. During this stage CAD, CFD, FEA, and BulletSim are used quite iteratively to develop a digital model the entire vehicle from both a 3D packaging and a performance analysis standpoint. This iterative design process is one of the most time consuming stages of the development process as it starts over each time a
component is changed. Once the proposed design is locked in, prototype components added or modified since phase 1 as well as sub-system prototypes are built and then tested. This test data feeds phase 3 of the project. This phase of the project can vary highly in completion time based on the number of components being studied and the number of major design changes. It would typically represent 1 year but stretched to nearly 2 years for the VBB3 based on an extreme number of powertrain component changes along the way.

2.1.3: Development Phase 3 – Build and Test

The sub-system test date feeds a 3rd round of simulation with BulletSim. The goal during this round of simulation is to update the models as accurately as possible to reflect the final vehicle design, and to simulate full Bonneville race runs. This exercise allows the team to confirm the design decisions and the overall performance prior to the major commitment to build the vehicle. At this point the vehicle is 100% designed but the first steel tube of the chassis has not yet been cut. With the successful completion of the simulation and the agreement of faculty advisors and program partners, this locks in the vehicle design freeze and kicks off the vehicle build. This phase of the project traditionally occupies one to two years of time depending on program funding and desired timeline of the external program partners. At the end of phase 3 the complete vehicle is tested on the race track. At the time of the writing of this document, the VBB3 program has just completed this phase of development.
2.1.4: Development Phase 4 – Optimize and Race

The final phase of vehicle development focuses on the testing, improvement, and ultimately racing of the vehicle. The phase once again begins with simulation, but this time to compare phase 3 track data with performance simulations. Any discrepancies between simulation and test data must be closely studied and corrected. Discrepancies could indicate one of two possibilities. First they could expose a modeling error that is corrected based on imperial data, or second they could indicate a lack of component performance which can help to target systems that were not implemented correctly or are being underutilized. The vehicle speeds are slowly increased and track vs. simulation data is studied for correlation through the entire process. The team works to implement any necessary modifications as they arise during the testing process. Test tracks available in Ohio allow the vehicle to be tested to approximately 100 MPH. Once this maximum speed is reached and all known vehicle issues are corrected, the team moves operations to the Bonneville Salt Flats and continues the quest to 100 MPH. Because the salt flats are only available during a limited time in the summer, the team usually can only make one racing event per year. Issues that arise above 100 MPH that were not encountered at the test track can take time to identify and correct, so it is expected that this phase of the process will take more than 1 racing season and may span up to 3 years.
2.2: Development of the Landspeed Vehicle Simulator

The Buckeye Bullet simulator [BulletSim] referenced above is a multi-domain mathematical model of each of the vehicle components built in the Matlab/Simulink software package. For the purposes of this document BulletSim is treated as an existing and complete engineering tool used to produce simulations and study component feasibility. A basic introduction to the principals of the simulator are presented in this section. A detailed description of the governing equations and implementation of the simulator can be found the Robert Kromer’s master’s thesis which is cited in the bibliography of this document.

The core operating principle of any dynamic system vehicle model is Newton’s 2\textsuperscript{nd} law. The sum of the forces acting on an object is equal to the mass times the acceleration of the object, Equation 1. This equation can be manipulated and integrated to produce a statement of velocity in terms of forces and mass acting on the vehicle as seen in Equation 2 below. The single goal of the BulletSim model is to help the team maximize velocity, so the component section process is quite simply an exercise to maximize the force acting to accelerate the vehicle while minimizing the mass.

\[ \sum F = ma \]  
\[ velocity = \int_0^t a = \int_0^t \frac{\sum F}{m} \]
For the study of dynamic vehicle systems the sum of the forces action on the system is made up of 5 parts as shown in Equation 3. First, the tractive force is a measure of the force being applied at coupling between the tire and the ground which is propelling the vehicle forward. From this force the four load forces are subtracted. These traditionally include aerodynamic drag, rolling resistance, load due to grade or slope of the road, and accessory load of the vehicles auxiliary systems.

\[ \sum F_{\text{tractive}} - F_{\text{aero}} - F_{\text{rolling}} - F_{\text{grade}} - F_{\text{accessory}} \]  

Equations 4 – 7 present the load equations in more detail as used in the Bullet sim. Aerodynamic drag is divided by air density, a non-dimensional performance coefficient governed by the shape of the vehicle called the coefficient of drag, the frontal or wetted area of the vehicle, and the vehicle velocity. Rolling resistance is defined by a non-dimensional performance coefficient governed by friction losses in the bearings and tires called the coefficient of rolling resistance and the vehicle velocity. For the purposes of a landspeed vehicle operating on the salt flats the road grade can be neglected, and there are no mechanical accessory loads connected to the motor shaft. There are electrical accessory loads, but these are handled with a separate isolated low voltage battery system that does not in any way effect vehicle power or performance, so this load is also neglected.
\[ F_{\text{aero}} = \frac{1}{2} \rho V^2 C_d A \]  
(4)

\[ F_{\text{rolling}} = C_{rr} V \]  
(5)

\[ F_{\text{grade}} \sim 0 \]  
(6)

\[ F_{\text{accessory}} \sim 0 \]  
(7)

In summary the entire vehicle performance can be modeled by implementing equation 8.

\[
velocity = \int_0^t \frac{F_{\text{tractive}} - F_{\text{aero}} - F_{\text{rolling}}}{m}
\]  
(8)

It can immediately be recognized mathematically, as one might intuitively expect, that to maximize velocity you must increase tractive force at the wheels while decreasing aerodynamic drag, rolling resistance, and overall mass. While the statement above might seem obvious, the key is understanding how to balance the inherent tradeoff between maximizing vehicle power and minimizing mass and losses. The BulletSim model provides the critical tool to be able to analytically answer this question across an infinite range of vehicle architectures.
The key to the BulletSim tool is its modular design. Early versions of this tool dating back to 2001 were organized in a way that made it very difficult to swap out individual component models. It is an extremely difficult task to modify even small systems. The focus of the R. Kromer edition of the model, was to implement each piece of the system as a completely separate block.

![Figure 10: BulletSim Module Implementation](1)

The hierarchy of BulletSim is set in 3 levels as shown in Figure 10 below. Level one is the top level master simulator that manages interactions between the sub-models. At level 2 the model is broken down into 4 key components. The sub model is the driver model which captures the driver’s intent and commands. Next is the powertrain dynamics model which contains all of the sub models of powertrain components and outputs the overall power capability of the system at any given time. The 3rd sub model is the vehicle dynamics block. This is where the losses due to aerodynamics and rolling resistance are calculated as well as the maximum possible torque transfer.
capability between the tire and ground or grip. Finally, the track sub model sets up the particular racing course and boundaries. Each level 2 sub model is completely independent and can be substituted without changing any of the other level 2 models. Level 3 is where the actual component models are implemented. Each level 3 model is constructed as the base unit of a component so multiple components of the same type can be utilized, and once again each model is independent of every other level 3 model. Once the component models were built, this highly modular construction allowed the user to switch from a single motor, single battery, front wheel drive vehicle to a 6 motor, 6 battery, 4 wheel drive vehicle in a matter of seconds. The Simulink Implementation of the top level model is shown in Figure 11 below.

![Figure 11: Top Level Simulink Implementation of BulletSim [1]](image)

Another very powerful part of this tool is that the simulator was built to be run “backwards” or “forwards” meaning that the simulator can be fed driver commands and a run simulated, or track data can be fed into the model and performance metrics can be back calculated. This is a key component to phase 4 testing and tuning.
2.3: Defining Parameters

While the implementation of the detailed equations defining all of the vehicle systems is an intense process, the overall performance of the vehicle is defined by only a handful of key parameters. It takes extreme accuracy to model all of the dynamics that allow for a very high level coloration between simulator and track data, but the majority of the complexity comes from capturing dynamics that have a very moderate effect on the baseline performance. Some of the most troubling systems to model include tire growth, clutch position and operation, brake drag, and real time traction control response. Additionally, a number of parameters related to stability and safety must be modeled and monitored, but do not affect the vehicle acceleration performance in a significant way.

When approaching the design from an initial broad specification viewpoint, it is important to focus on optimizing comments based on the metrics that have the greatest effect on vehicle acceleration, which are not always the first parameters one might assume. This section presents an overview of the key parameters that define performance as well as a look into which are fixed and which can be tuned.

By examining the complete equations that drive the BulletSim simulation tool, one can extract the variable parameters and defining coefficients. A summary of all of the defining coefficients by vehicle system can be seen in Figure 12 below.
While there are nearly 30 parameters listed in the web above, nearly half can be lumped together and described as the packaging size and total weight of the vehicle. An additional 5 of these parameters can be combined and summarized as the power output of the vehicle. Considering the lumped mass, volume, and power parameters, the overall vehicle performance can be summarized by:

- Frontal Area
- Total Packaging Volume
- Total Vehicle Mass
- Powertrain Torque / Power Output
- Size of Cockpit and Height of the Wheel / Tire
While this list is still represents a large range of potential vehicle designs, it can be further simplified but considering which design variables are effectively fixed due to outside requirements. A major example of this is the driver area / cockpit of the vehicle. In a completely optimal design exercise it would make sense to consider very small vehicle packages and potentially to automate the vehicle to eliminate the need for a driver. Due to the rules of Bonneville racing, and the mission of the team, a driver will always be present in the vehicle. If the requirement to have a driver is set, the team has an additional self-enforced requirement to make that driver as safe as possible regardless of performance sacrifices. This means packaging the driver in a non-aerodynamically-optimal seating position and having a significant safety structure around the driver. If the driver’s position and cockpit are consider fixed in size regardless of the vehicle design, a minimum cross section, and thus frontal area of the vehicle has been pre-established. As it turns out this required cross section is large enough that a very significant amount of power is needed to overcome the resultant aerodynamic losses and immediately eliminates many small vehicle designs. With the large cross section already fixed, it becomes the goal of the team to package all other vehicle systems within the defined cross section as not to further decrease aerodynamic performance. This precedent sets key defining parameters for the sizing of all the systems.

The goal of the team was to build a simulator that could sweep all possible vehicle configurations from a very small, light, efficient, lower power vehicle to a very large, high
power solution. To complete this exercise all of the fixed parameters were estimated, and the rest of the parameters were defined in reference to the single parameter of motor power. Therefore with a sweep of motor power, all resultant vehicle designs were considered. The size and volume of each variable component was calculated in reference to the motor power and appropriate overall vehicle parameters were implemented into the model. A listing of the fixed and variable parameters considered are shown in Figure 13.

<table>
<thead>
<tr>
<th>Variables Scaled With Motor Power</th>
<th>“Fixed” Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>• CdA</td>
<td>• Coefficient of Rolling Resistance</td>
</tr>
<tr>
<td>• Battery Power / Energy</td>
<td>• Overall Volume and Mass:</td>
</tr>
<tr>
<td>• Overall Package Volume and Mass</td>
<td>• Cockpit</td>
</tr>
<tr>
<td>• Batteries</td>
<td>• Parachutes</td>
</tr>
<tr>
<td>• Motors</td>
<td>• Auxiliaries</td>
</tr>
<tr>
<td>• Inverters</td>
<td>• Safety Systems</td>
</tr>
<tr>
<td>• Transmissions</td>
<td>• Tire Height</td>
</tr>
<tr>
<td>• Brakes / Suspension</td>
<td>• Coefficient of Friction of the Salt Flats</td>
</tr>
<tr>
<td>• Cooling</td>
<td></td>
</tr>
</tbody>
</table>

Figure 13: Fixed and Variable Simulation Parameters

As can be seen above the extremely complex vehicle simulation model can really be reduced to a few key parameters that define the vast majority of the vehicle’s performance window. When you further simplify the model by eliminating parameters that are effectively fixed due to competition rules or team requirements the list of high level design variables is actually quite small.
Table 2 below presents these key parameters for the Buckeye Bullet 1 and Buckeye Bullet 2 vehicles. BB1 was a very lightweight, small frontal area, and relatively low power vehicle. Due to the complexity and size of the hydrogen fuel cell systems, BB2 was significantly heavier and larger in all dimensions. BB2 was nearly 50% heavier than BB1, had a 22% larger frontal area and an 8% higher coefficient of drag. The 18% added power of BB2 was able to help the vehicle overcome this larger size and achieve top speeds within a few percent of the BB1.

Table 2: BB1 vs BB2 Defining Variable Parameter Values

<table>
<thead>
<tr>
<th>Value</th>
<th>Units</th>
<th>BB1</th>
<th>BB2</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tractive Power Capability</td>
<td>kW</td>
<td>500</td>
<td>600</td>
<td>18%</td>
</tr>
<tr>
<td>Vehicle Mass</td>
<td>Lbs.</td>
<td>4000</td>
<td>6200</td>
<td>48%</td>
</tr>
<tr>
<td>Cd</td>
<td>Unitless</td>
<td>0.124</td>
<td>0.134</td>
<td>8%</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>Square Feet</td>
<td>7.37</td>
<td>9.15</td>
<td>22%</td>
</tr>
<tr>
<td>Maximum Vehicle Speed</td>
<td>MPH</td>
<td>321</td>
<td>303</td>
<td>-6%</td>
</tr>
</tbody>
</table>

To help quantify the relative effects of rolling resistance and aerodynamic drag, parameters between the BB1 and BB2 were selected and simulation was extended to 450 MPH. Figure 14 below shows the magnitude of the rolling and aero drag forces for this exercise.
For a vehicle with performance characteristics similar to the previous buckeye Bullet vehicles, it can be seen that below 100 MPH aerodynamic drag can nearly be neglected completely. By 225 MPH drag force has reached the same magnitude as rolling resistance. In the 300 MPH range where the previous Buckeye Bullet vehicles have operated drag force is about double that of rolling resistance. As the vehicle approaches 500 MPH drag force has increased to nearly five times the rolling resistance force. This concept illustrates the increasing importance of drag force, and its key defining components frontal area, and Cd, as vehicle speed targets are increased.
Expanding on the idea of control of the defining parameters it is important to understand the realistic limits on these parameters. Based on the teams’ sizing exercises and studies of potential vehicle configurations, the following bounds were applied to each key parameter as seen in Table 3

Table 3: Defining Parameter Conceivable Range

<table>
<thead>
<tr>
<th>Value</th>
<th>Units</th>
<th>Minimum</th>
<th>Maximum</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tractive Power Capability</td>
<td>kW</td>
<td>200</td>
<td>2000</td>
<td>164%</td>
</tr>
<tr>
<td>Vehicle Mass</td>
<td>Lbs.</td>
<td>1000</td>
<td>8000</td>
<td>156%</td>
</tr>
<tr>
<td>Cd</td>
<td>Unitless</td>
<td>0.120</td>
<td>0.140</td>
<td>15%</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>Square Feet</td>
<td>7.0</td>
<td>12.0</td>
<td>53%</td>
</tr>
<tr>
<td>Coefficient of Friction</td>
<td>Unitless</td>
<td>0.3</td>
<td>0.6</td>
<td>67%</td>
</tr>
</tbody>
</table>

An immediate take away of these parameter bounds is that the largest range of control falls within the vehicle power and vehicle mass parameters. The team can exercise a great level of control over the overall size and power of the vehicle. Another widely spanning parameter is the coefficient of friction of the salt flats where tractive grip can vary nearly 70%. While this is not in the direct control of the team, selection the appropriate salt conditions for racing (and a bit of luck with the weather), can lead to a significant performance improvement for traction limited vehicles. On the other hand the aerodynamic parameters show much less variance. While both frontal area and Cd are direct multipliers of the drag equations and play a huge role in the performance of the vehicle, they can are very difficult to modify. From one of the best cars ever seen on the salt flats to one of the worst streamliner body shapes the Cd variance is only around 15%. Thousands of hours are spent in CFD and wind tunnel exercises to make extremely small
gains in Cd. Frontal area is a bit more flexible, and becomes the second most important vehicle parameter to overall vehicle power. Reducing either the frontal area or the Cd by 10% has the same net effect on the aerodynamic drag, but it is much more feasible to improve the frontal area by 10% than the Cd. It is critically important to focus on the smallest possible frontal area from day one of the design. Due to self-imposed safety requirements the team defined the frontal area of the vehicle by the driver cell and worked to keep all possible components inside of this pre-defined box.

2.4: Early Design Targets

Based on the Phase 1 first pass simulations, and the concepts presented in the previous section for dominant parameters, clear trends in the simulations results emerged. The team identified the following high level design targets as the moved into the component research phase.

- Maximize overall vehicle power until the maximum vehicle weight is reached (limited by tire load supporting capabilities)
- Implement a four wheel drive system to take advantage of the maximum possible traction due to dimension salt flats conditions
- Place the driver at the center of gravity of the vehicle for safety considerations
- Set the vehicle width based on the minimum possible width of an appropriate driver safety cell
- Set the vehicle height based on the tire height and drivers head
- Limit maximum battery voltage to 1000V for safety considerations
• Maximize the battery power density above all other component parameters
• Precisely match battery capacity to mission profile to minimize pack weight
• Minimize driveline complexity (transmission / motor configuration), utilize a single speed gear reduction box if possible

An early concept of the vehicle packaging is shown in Figure 15 below.

Figure 15: Early Concept of VBB3 Packaging
Chapter 3: Powertrain Architecture

With a broad idea of the relative sizing of the vehicle and the target power levels, the next step was to identify optimal components for each part of the powertrain. This chapter details the required and preferred specifications of each system as well as the search for appropriate suppliers and technical partners to assist as needed in the design, manufacture, and integration of these components.

3.1: Energy Storage Requirements

Based on the study of a wide range of commercially available system components for all aspects of the powertrain, it became clear early on the process that the volume and mass of the battery pack would be the single greatest performance variable in the vehicle design. It goes without saying that maximizing volumetric and gravimetric energy and power density of any electric vehicle battery pack is important, but initial component studies showed that the battery pack could account for as much as 60% of the vehicle mass and volume.

Due to program partnerships and technology development, it was critical to announce a battery supplier partnership very early in the program. This need pulled the team slightly out of the ideal design cycle, but the battery pack, more than any other system, could reasonably be scaled to fit the final vehicle design. With this directive in mind the team
set up to study all of the available battery technologies circa 2009-2010. The selection process of a chemistry and a supplier is outside of the scope of this document but is covered in detail in the author’s undergraduate thesis which was published in 2012. This project included carrying out hundreds of simulated race runs on battery cycling equipment at the Center for Automotive Research and comparing overall battery pack energy storage, power delivery, and relative size and mass. The equipment shown in Figure 16 and Figure 17 was used to complete this testing. By the end of the undergraduate research project, A123systems had been selected as the battery supplier due to superior testing results with their HEV line battery cells. A123systems had been selected as the battery supplier due to superior testing results with their HEV line battery cells.
Figure 16: Battery Cycling (Charge/Discharge) Equipment
A123 committed to providing cells commercially packaged into modules as seen in Figure 18. The overall battery packaging design, high voltage architecture, BMS packaging and integration and system DFMA were left to the team.
Results from initial pack sizing exercise showed that the battery pack could deliver the required power and energy for 3 to 5 sequential racing runs in line with the FIA racing duty cycle, without exceeding the allowable temperature. An early version of this study is shown in Figure 19 below.
With the cell technology fixed and a broad testing background supporting the cell’s ability to be packaged in a configuration conducive to the vehicle goals, the team moved forward with a highly adaptable packaging design which could be easily scaled to meet the final series and parallel configuration of cells which would be tuned to meet the voltage and energy requirements of the final vehicle architecture. The proposed electrical layout is shown in Figure 20. The modular “Blade Pack” packaging concept is shown in Figure 21.
With this highly scalable system defined, the team moved forward with the rest of the powertrain development. Once the final vehicle power and energy needs were defined the back configuration could be finalized.
3.2 Electric Motor Requirements

Initial simulations defined the overall scale of the vehicle, and showed a trend towards maximizing the total motor power, regardless of the weight and volume penalty. The next stage of motor specification required collecting information on what motor technology existed, or could reasonably be built for the VBB3 vehicle. At this point in the process Venturi Automobiles became a highly technical program partner and took primary responsibility for conceiving the electric motor. The student team worked closely with Venturi to consider all possible options for motor development.

The first stage required setting the ideal specifications of the motor. The BulletSim simulation tool was used to back calculate the ideal torque at the wheels of the vehicle based on broadly defined overall system parameters. This exercise produced the torque and power requirements shown in Figure 22 and Figure 23.
Figure 22: Ideal Torque (at the wheels) vs. Motor RPM

Figure 23: Ideal Motor Power vs. Motor RPM

45
Because the torque is defined as the maximum possible tractive force at the wheel, the torque slightly increases with downforce (total effective vehicle weight) until the power limited region of operation is reached. From the beginning of the project it was a goal of the program partners to demonstrate the torque capabilities and favorable power curves of electric machines by utilizing a single reduction gearbox, not a multi-speed transmission. In this case the reduction ratio selected could help to shift the torque curve required at the motor, but because the overall operating speed of the motor had to be scaled to match vehicle speed there was limited flexibility in this ratio. For the purposes of this exercise a 1.6:1 gear reduction was assumed and a motor maximum speed of 10,500 RPM was simulated. Utilizing the optimal torque and power curves shown above the simulator showed an absolute maximum performance window for the vehicle of 489 MPH during a US record run and 518 MPH during an FIA record attempt as seen in Figure 24.
The results of this simulation drove the OSU / Venturi partnership to target a motor solution that could supply approximately 1 megawatt of power and 1800 Nm of torque to each axle. From this point the work transitioned from an engineering design exercise to a supplier investigation. Venturi and OSU put forth a great deal of effort to study different solutions including options in 3 major categories 1) Utilizing multiple integrated copies of the Buckeye Bullet 2 motor, 2) Purchasing an off the shelf commercial solution to integrate, or 3) developing a completely custom motor from the ground up. Over a two year period 14 drastically different motor designs were considered spanning all three of these categories. A summary of the torque vs speed curves of each of these potentially viable solutions is presented in Figure 25 below.
Figure 25: Wheel Torque vs. Wheel Speed for Various Motor Designs

The ideal torque curve determined during optimization simulation is shown as marker 1 in the figure. Marker 3 represents the torque curve of 4 coupled Buckeye Bullet 1/2 induction motors. From a performance standpoint this was an interesting solution, but at 4 times the mass of more modern, commercially available motor designs. Marker 2 represents a completely custom motor solution from Venturi based on a scaled up design of their production AC internal permanent magnet vehicle motors. Marker 4 represents integration of 4 instances of the current Venturi production vehicle motor which is also of an AC IPM design. For each of these 12 possible solutions the team went through a complete design exercise to study the rest of the vehicle including battery pack sizing, vehicle packaging, and gearbox design. After this intense analysis it was decided that the ideal solution for
performance was to develop the purpose-built Venturi motor (marker #2) but that due to timing constraints and the desire to race before the motor could be manufactured, it was most practical to implement a custom package featuring 4 instances of the existing Venturi motor technology (marker #4). It was agreed at this point that the rest of the vehicle would be developed with the performance potential to support not only the selected motor, but also, the increased power needed for the custom Venturi motor (marker 2). This would allow the possibility of upgrading the motor in the future without requiring any other vehicle changes, which would leave the potential for significantly increased performance. An image of the existing Venturi motor and custom transmission is shown below.

Figure 26: Venturi Production AC IPM Motor Package

Implementing the parameters of this design with 2 coupled motors per axle into the BulletSim, allowed the team update the performance potential of the vehicle as seen in
Figure 27. As expected, the deviation from the ideal torque and power curves lowered the overall vehicle performance but still showed the ability to exceed 440 MPH with proper system implementation. The team and sponsors determined that 400 MPH + was the initial goal of the program and decided to move forward with the implementation of this powertrain, with the hope to expand to a slightly more powerful motor once the performance potential of the existing package was realized.

![Figure 27: Performance Potential of VBB3 with Motor Technology Selected](image)

3.3: Inverter Requirements

It was agreed from the foundation of the OSU Venturi partnership that ground up inverter design was outside the scope of either existing partner and that the two would work together to find the correct technical partner to add to the team. Motor selection was carried out under the assumption that an appropriate inverter could be paired to each of the motor
designs, without putting forth the detailed development of a specific inverter for each of the 12 motor options. The team was careful to make sure this assumption was valid at each stage of design, but did not kick off the development of an inverter until after the motor section was complete. The known power potential of the motor coupled with simulation allowed the team to finalize the battery pack configuration. Between reasonably fixed battery and motor requirements, the search for an inverter was defined by the parameters listed in Table 4.

Table 4: Initial Inverter Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Voltage (Max)</td>
<td>V</td>
<td>900</td>
</tr>
<tr>
<td>DC Voltage (Min)</td>
<td>V</td>
<td>600</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>Hz</td>
<td>8,000 +</td>
</tr>
<tr>
<td>AC Current</td>
<td>Arms</td>
<td>600</td>
</tr>
<tr>
<td>Motor Control Support</td>
<td>Type</td>
<td>IPM</td>
</tr>
<tr>
<td>Power (90s rating)</td>
<td>kW</td>
<td>500</td>
</tr>
<tr>
<td>Weight Target</td>
<td>Lbs.</td>
<td>100</td>
</tr>
<tr>
<td>Control Interface</td>
<td>Type</td>
<td>CAN</td>
</tr>
</tbody>
</table>

After an exhaustive search of many suppliers, it was determined that the vast majority of existing technology that could support advanced IPM motor control techniques and was aimed at the automotive market, could not support the high voltage (500 Vdc+) requirements of the team. On the other hand, any companies that specialized in HV operation most commonly worked with drastically different types of electric machines. The inverters for the BB1 and BB2 projects were supplied by Saminco Inc. which specialized in heavy duty mining equipment and rail car applications. Due to the extremely high power applications Saminco’s product offerings went well into the voltage range
required by the VBB3, but they were traditionally quite heavy units. The team approached Saminco with the required specifications for the 4 VBB3 motors. Saminco referred the team to its new affiliate company American Traction Systems [ATS]. The business model of ATS was to implement Saminco technology as well as their own new technology into custom engineered solutions for the transit industry including automotive and rail applications. This development made for the perfect partner for the VBB3 program as the team now had access to the historically strong Saminco technology, but with the willingness to customize the inverter to our application. During the initial meeting ATS presented their new prototype PML-3-900L product which is shown in Figure 28. This product’s initial specifications met or could reasonably be assumed to be upgraded to all the VBB3 inverter requirements.

Figure 28: Early Prototype of ATS Inverter
After the presentation of this product the VBB3 team worked to form a technical partnership with ATS and began the development of the custom inverter for the VBB3 with this product as a starting point.

3.4: Gearbox Requirements

In contrast to the inverter development strategy of delaying the design until a motor and battery had been selected, a completely custom gearbox was developed for each of the 12 motor implementation proposals. This work was exhaustive but necessary to confirm that each of the proposed motor architectures could be implemented into the vehicle. While crucially important, the gearbox is less focused on the demonstration of new technology, and more of a trivial exercise in core machine design principals. The single largest challenge of gearbox design is reducing the overall size and mass while maintaining the ability to reliably transmit the torque. The initial electric motor proposals were based on implementing many small motors that were commercially available. Proposals spanned from 1 to 4 separate motors to be implemented into each axle and the power to combine in the gearbox. These complex motor arrangements lead to many “what if” gearbox design questions which were outside the scope of the team’s knowledge. At this point the team approached many potential suppliers with a few of the custom designs to obtain a quote to develop the internals of the box and to manufacture prototypes. After working with several suppliers the team found that their long term partner Hewland Engineering had the technical capability to design and validate nearly any custom design and could do so at the most attractive price. A partnership was formed with Hewland to conceive a multitude of
gearbox designs, and to help to develop the final box once a motor was selected. The following broad requirements were identified for the project:

- Transaxle Layout (Ring and Pinion used to output power at 90 degrees)
- Narrowest possible design as #1 priority to reduce frontal area
- Approximately 1.8:1 final drive ratio (sizes ring gear and box size)
- Load bearing case to support
  - Suspension mounting and reaction loads
  - Steering mounting
  - Structural member of chassis
- Recessed CV / tripod joint integration
- Auxiliary input shaft for braking system
- Integrated overrunning clutch
- Integrated Pneumatic shifting (for multi-speed gearbox)
- Integrated data acquisition sensors
  - RPM
  - Clutch Position
  - Gear Position
  - Temperature

With these design criteria in mind the team set out to develop various gearbox concepts. Two different prototypes for 4 motor per axle designs are shown in Figure 29 and Figure 30 below.
Figure 29: Axle Layout - 4 Motors per Axle – Linear Arrangement

Figure 30: Axle Layout - 4 Motors per Axle – 2 x 2 Arrangement

55
The first design integrates the motors in a linear fashion with 2 motors on each side of the box. This design had great benefits in frontal areal, but significantly extended the overall vehicle length and wheel base. The 2nd 4 motor design involved mounting all the motors in a two by two arrangement facing the center axis of the vehicle and utilizing helical gears to combine and transmit all of the torque. This design is compact from a vehicle length standpoint and removes a ring gear from the design, but has a large frontal area, and requires excellent control of the torque production of the motors to prevent damaging the gears. The single shaft designs showed a slight edge in this regard by forcing the rotors to the same speed at all times.

As time progressed the motor design moved towards larger single motor units which only required 3 motors per axle. With these larger units the only feasible solution, with regard to frontal area minimization, was to place them in a common shaft, linear arrangement as seen in below.
Once a final motor design was selected, the power of the individual motor units allowed the team to reduce the layout to 2 motors per axle. An early concept of this arrangement is shown in Figure 32 below.
This layout represented the final direction of the gearbox and the first step in defining the custom packaging requirements of the system.
Chapter 4: Detailed Design of Powertrain Systems

Once the requirements, specifications, and technical partners were established as presented in Chapter 3, the program moved from Phase 1 into Phase 2, detailed design. The goal of this stage of the program was to work with the technical partners, prototype test samples, and the VBB3 engineering team, to transform a list of goals into completely designed and analyzed products ready for construction. This chapter covers this transformation process.

4.1: Energy Storage Detailed Design

Heading into the detailed design phase, the battery pack was more complete than any other vehicle component. At this point the cell technology, battery management systems [BMS], and mechanical packaging had been pre-determined during the specification phase. The remaining tasks to complete were the detailed design and analysis of the mechanical packaging systems, integration of the BMS packaging system, and evaluation of the HV system layout with regards to operating modes and safety.

The battery packs were arranged in “Blade Packs” which consisted of 10 modules placed in series. This produced an overall Blade architecture of 250 series cells and 1 parallel cell. This arrangement was chosen to meet the voltage requirements of the motor while producing the maximum possible current a single series loop of batteries and BMS could
handle. Each of these prototype cells can produce 425 A of current. While the ideal pack layout to match one battery pack to one inverter would have been 250 series and 2 parallel, this would have led to 850 A of pack output which exceeds the current capability of all the pack level components. As such the blades were constructed as single parallel cell units and at the inverter level two blade packs were put in parallel to combine the power feeding one inverter. This architecture presented a number of new design considerations to the process. A schematic of the HV layout is shown in Figure 33 below.

Figure 33: Battery Pack High Voltage Schematic – “Inverter Pack” - (¼ Vehicle)
This system, dubbed an “inverter pack” required some top level circuit protection and control consideration. It was important to prevent the parallel blade packs from charging each other so an “anti-balance diode was placed in the power path. In a production vehicle this would be an unacceptable solution as it would prevent regenerative breaking from charging the packs, but the VBB3 does not utilize any reverse current flow, so this was an acceptable solution. Battery pack charger ports were implemented behind the diodes so that battery charging could take place though an external connector. At this stage an additional power contactor was integrated at the output of the inverter pack adding a level of safety and control that could be independently commanded from the vehicle controller, outside of the battery pack control loop. From a controls standpoint the BMS software had to be modified to reflect that fact that two separate battery packs were powering one device. A number of the BMS self-check protocols were violated when one battery pack was allowed to pre-charge the system before the other back was initialized. As such a new master / slave protocol was developed to give one blade in each of the inverter packs supervisory control and allow the other blade to reference the master’s signals.

The final stages of battery pack design consisted of finalizing the mechanical packaging of the blade packs as well as the BMS housings. A great deal of effort was applied to reduce the packaging weight to less than 10% of the total battery system weight. As such advanced composite structures were designed and validated for structural integrity utilizing FEA analysis. The final BMS housing and Blade Pack structures can be seen in Figure 34 and
Figure 35 below. The final specifications of the complete 2.8 megawatt capable battery pack can be found in Table 5. The table presents the key specifications at the cell, blade pack, inverter pack, and vehicle level.

Figure 34: Battery Management Housing Final Packaging Design
Table 5: Battery Pack Final Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Vehicle Pack</th>
<th>Axle Pack</th>
<th>Blade Pack</th>
<th>Cell</th>
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<tr>
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<td>#</td>
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<td>2</td>
<td>8</td>
<td>2000</td>
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<tr>
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<td>825</td>
<td>825</td>
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<tr>
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<td>700</td>
<td>700</td>
<td>2.8</td>
</tr>
<tr>
<td>Maximum Current</td>
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<td>3400</td>
<td>1700</td>
<td>425</td>
<td>425</td>
</tr>
<tr>
<td>Maximum Power</td>
<td>kW</td>
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<td>1,400</td>
<td>350</td>
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</tr>
<tr>
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<td>Lbs.</td>
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<td>1750</td>
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<tr>
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<td>kWh</td>
<td>92.4</td>
<td>46.2</td>
<td>11.5</td>
<td>0.05</td>
</tr>
</tbody>
</table>
4.2 Electric Motor Detailed Design

As described in section 3.2, the first generation motor technology to be used in the VBB3 was selected and the Venturi team took primary responsibility for delivery of the motor internals. All of the electromagnetics and internal machine design considerations were implemented by Venturi and their suppliers. The component to be delivered to the OSU team to integrate was a cartridge style internal permanent magnet motor [IPM]. An exploded view rendering of an extremely similar production motor can be seen in Figure 36 below. The stator is based on a laminated steel core with proprietary winding technology. The rotor consists of a steel hub with slots to accept neodymium rare earth magnets. The rotor rides on bearings which are only designed to support the mass of the rotor, not any additional shafts of axial motor loads. The cartridge assembly was shipped to OSU in configuration similar to that shown in Figure 37 below.

Figure 36: IPM Motor Exploded Rendering [6]
While the motor cartridge provided to the team included all of the key electromagnetic operational elements, it was far from ready to integrate into the VBB3. The student team took primary responsibility for developing the dual cartridge – axle motor system to be used in the race vehicle. This effort required development of a custom housing system, cooling system, rotor shaft, shaft links, and high footage connection box.

The production motor was to design to be used in a single motor configuration. This means the shaft was sized for the torque of a single motor. In the VBB3 application the motor could be overdriven as much as 100% over stock torque output for short periods and with two motors connected in series this lead to up to four times to total rated torque on all of the associated shafts and splines. The team was able to obtain factory specification for the production shaft and reverse engineered the material design and factor of safety using FEA
analysis. This factor of safety was set as the minimum requirement of the custom VBB3 shaft. Implementation of this high strength shaft was non-trivial as the existing rotor design could not be modified so the team had to work within the given maximum diameters. Images of the shaft design process can be seen in Figure 38.

![Figure 38: Custom Motor Shaft Development](image)

With the shaft specified the team focused on the development of a custom casing system. The case was built in a modular way to reduce the total number of unique parts. The casing system was designed to interface with the cartridge systems, support the additional mass and torque loading of 2 coupled motors, and to integrate very low profile, custom high
voltage and cooling connections. Images of the CAD design of the motor and a cross section of the design can be seen in Figure 39 and Figure 40.

Figure 39: CAD Image of Custom Venturi / OSU Motor Design
4.3: Inverter Detailed Design

Primary responsibility for the detailed design of the inverter resided with the supplier, American Traction Systems Inc. The specifications presented in section 3.3 were agreed upon among OSU, Venturi, and ATS. The development process was reasonably hands-off for the OSU team, but frequent design reviews were held, and troubleshooting activities were approached in partnership. The inverter development took place primarily at the ATS facility in Florida. To aid in development of the inverter the OSU team designed in implemented a custom motor / inverter test bench at the ATS facility. The design of this
test bench is covered in Chapter 6.2. In image of the 1st development inverter can be seen in Figure 41 below.

![Development of ATS / Venturi Inverter](image)

Figure 41: Development of ATS / Venturi Inverter

While this product had been conceived by ATS prior to the VBB3 team approach, it was found that this was truly a brand new product in need of a great deal of development work. Over the course of a very iterative 18 month development process the teams worked together to find solutions to a large number of issues including:

- Reliable Operation over 800 Vdc
- Voltage Limits of Gate Driver Circuit
- Switching Frequency Implementation
- Electrical Noise Procured by High Switching Frequencies
- Early Development Firmware Bugs
- Peer to Peer Communication Protocol (axle inverters working together)
- IGBT Overheating
• Cooling System Design Flaws

• System DFMEA

As of the writing of this document, all of the above issues have been addressed and appropriate solutions implemented and tested. Through a very large amount of work on the ATS side, the inverters have morphed from an unreliable pre-production concern, to a fully reliable, extreme performance racing part. Further work to push the inverters to their limits is covered in Chapter 6.

4.4: Gearbox Detailed Design

With the general layout of the box defined, several additional components had to be integrated with, and packaged around the gearbox with very tight constraints to minimize frontal area. Each design iteration of the box had to place equal weight on both the internal design and performance of the gearbox, as well as the integration into the chassis and with the surrounding systems. Two of the most important systems that had to be co-developed with the gear box were the suspension and brakes. The use of fully independent suspension as well as high speed friction brakes are a design requirement of the student team based on safety and performance and must be included. As discussed in Chapter 2, the frontal area of the vehicle is one of the most important parameters of the vehicle design, and it is critical that the suspension and brake system design does not increase the required frontal area of the vehicle beyond the existing width of the driver cell and the height of the tire. An image of the transmission packaging model as it started to take shape is shown in Figure 42.
In parallel with the transmission design, the design of the independent suspension progressed. The suspension featured parallel A-arms, custom 7000 RPM uprights, push rod activated coil over dampers, tie rods / tow bars, and an anti-roll bar. All of this is packaged in a 26” total track width. An image of the suspension design is shown in Figure 43 below.
The other key system that had to be finalized prior to the transmission was the braking system. The team implemented a high speed friction break system into the BB2 with great success and hoped to implement a similar system into the VBB3. The brake team worked with the supplier to size the brakes for the new vehicle which was heavier and traveling at much high speeds. As a result the overall brake package volume was increased significantly, and could no longer be packaged within the wheels without widening the vehicle. To avoid increase the frontal area of the vehicle the team worked with Hewland
to ingrate an auxiliary shaft into the gearbox to allow for in-board breaking though the gearbox. The design of this system is shown in Figure 44 below. Internal to the box the auxiliary shaft was integrated into the power shaft though a gear, so the torque and speed amplification of the break system could be tuned independently of wheel speed. An early mockup of the brake integration into the gearbox is shown in Figure 45.

Figure 44: VBB3 Aircraft Break – Carbon/Carbon Disk Pack Design.
As the mechanical design of the suspension, brakes, and motor interface were defined and frozen, the gearbox case was updated to allow for seamless integration. The final CAD model of the box that was sent to production is shown in Figure 46 below.
4.5: Powertrain Complete Axle Detailed Design

With the detailed design of all the components complete, a final round of system level integration checks were performed. A schematic of the final axle component layout is shown in Figure 47. For review, the power path begins with four separate battery blade packs. Two packs are placed in a parallel master/slave configuration to provide DC power to each inverter. Each inverter provides AC power using frequency control to one electric motor. The two electric motors on the axle are mechanically coupled on a common shaft in a common housing. The motor output shaft connects to the transmission input shaft which features an integrated mechanical overrunning clutch. Internal to the transmission are 2 gear ratios, a ring and pinion final drive, and an auxiliary input brake shaft. The CV
joint drives shafts then connect the transmission to the wheel hubs. Two of these axle drive systems are integrated into the vehicle, one at each end.

Figure 47: Powertrain Schematic for 1 Axle

The overall vehicle packaging layout can be seen in Figure 48 below and a rendering of the integrated powertrain can be seen in Figure 49.
Figure 48: Final Proposed Vehicle Layout

Figure 49: Rendering of Integrated Powertrain
Based on the power level integrated into the vehicle a target of 7500 lbs. was established for total vehicle weight. The complete weight of the race-ready vehicle came in at 7900 lbs. The majority of the additional weight came from the final inverters each being 50 lbs. over their target as well as the need for some additional auxiliary control electronics that were implemented over the course of the vehicle development. The motor, inverter and transmission represent less than 20% of the total vehicle weight. The battery pack makes up approximately 45% of the total vehicle weight. The detailed breakdown of the vehicle weight can be seen in Figure 50. A detail view of the powertrain weight breakdown is shown in Figure 51.

![Vehicle Weight Breakdown](image)

**Complete Vehicle Weight 7900 lbs.**

Figure 50: Vehicle Weight Breakdown
Renderings of the vehicle design in exploded and assembled views can be seen in Figure 52 and Figure 53.
Figure 52: Exploded View Rendering of Final VBB3 Design

Figure 53: Rending of Final VBB3 Design
Chapter 5: Powertrain Manufacture, Assembly, and Integration

Once the specifications were set, components selected, and detailed designs of custom parts finalized, the next phase of development was to prototype, build, assemble, and integrate each component. These processes are presented in this chapter.

The 2000 battery cells were assembled into 25 cell modules at A123 systems. This process includes the mechanical assembly of the cells and packaging and the welding of the module level bus bars. The completed modules were shipped to OSU and are pictured in Figure 54 below.

Figure 54: Delivery of Assembled A123 Battery Modules
The next stage of the battery pack build was to assembly modules into the OSU developed carbon fiber tubs and bolt them into place as seen in Figure 55 and Figure 56. The final phase of battery pack assembly was to build the battery management system housing and wire all of the components as seen in Figure 57.

Figure 55: Assembly of Battery Packaging “Blade Tubs”
Figure 56: Final Assembly of 1 Battery “Blade” Pack

Figure 57: Battery Management System Assembly
Next the motors were assembled. The custom housings and shafts were designed to the level of final production drawings by the team. Due to the complexity and sheer quantity of machining work the majority was sent to outside machine shops. Once the Venturi-supplied motor cartridges as well as all the custom machined parts were delivered to the shop, assembly took place at OSU – CAR. The machined housings can be seen in Figure 58. Custom tooling for the assembly process was designed and built at OSU. The bearings were fit to the shafts, and then the shafts and cartridges were installed into the housings. The housings of the two motors for each axle were then fitted together as seen in Figure 59. After each motor was assembled precision alignment was verified for concentricity, shaft alignment, and shaft center height as seen in Figure 60.
Figure 59: Motor Assembly

Figure 60: Motor Alignment
After the motors were assembled the next major project was transmission, brake, and suspensions assembly. The transmissions were supplied by Hewland based on the team’s design and specification. They arrived as completely assembled units. The suspension and brake parts were custom produced by OSU. The majority of the machined parts were made in house with outsourced help for EDM, Spline, and coating work. The completed brake parts can be seen in Figure 61 below. The production transmission with the suspension A-arms and uprights installed can be seen in Figure 62 below.
When all of the components of the powertrain were assembled and inspected, the final step was to assembly the complete driveline and integrate it into the vehicle. The initial fitment of the entire powertrain can be seen in Figure 63 below.

Figure 62: Transmission and Suspension Assembly

Figure 63: 1st Powertrain Fitment in VBB3 Chassis
Chapter 6: Powertrain Test Bench

As presented in Chapter 2, the ability to test, validate, and push the performance of each vehicle component is critical to the optimal development of the vehicle systems. This is especially true for all of the components of the driveline. Each of the 4 critical systems presented in this document are either one off custom parts for the VBB3 application or are highly specialized production directives. It is crucial to have a platform to test each component with the ability to:

- Record Baseline Performance and Specifications for Simulation
- Validate Manufacturing and Assembly of Each Prototype Part
- Innovate, Implement, and Prove Advanced Technology
- Isolate Powertrain Component Test from Full Vehicle Reliance
- Complete Longer Durability Cycles Than Road Testing Would Allow

While the need for powertrain testing capabilities is well demonstrated, finding the appropriate testing solution has presented a challenge for the Buckeye Bullet team since the beginning of the program. The author of this thesis has held primary responsibility for the development of all powertrain testing activities since 2006 with the BB1/BB2 motor
A variety of solutions have been considered, developed, and implemented. This chapter presents a few of the key developments during the past 10 years and focuses on the development of 2 different test benches related to VBB3 motor and inverter development.

6.1: Buckeye Bullet 2 - 2007 Test Bench

During the BB1 program the team had very limited ability to test the electric motor independently from the complete vehicle. The vast majority of motor and inverter tuning took place in the vehicle. This method of operation was far from ideal as track time is highly limited and all of the results are based on highly variable battery pack voltage. At the start of the BB2 program it was decided that the BB1 motor would be used in the BB2 vehicle, but that a significant effort to optimize the motor and inverter performance would be required to meet vehicle performance goals. This decision produced the demand of the first dedicated motor test bench. The test bench was required to be able to be operated both on site at OSU CAR as well as at remote motor testing and inverter development facilities.

Each time the team has faced a need to test a vehicle motor, a few common issues have arisen. Two key reoccurring problems in any of the test setups investigated are 1) limited DC power supply at many testing facilities including OSU CAR and 2) highly limited RPM capabilities from any test bench that can handle the power of Buckeye Bullet motors. The first problem can be addressed by either selection one of the few facilities that can supply the needed power, or by utilizing the vehicle’s power source during the testing. While it is preferred to separate motor and battery pack testing for independent optimization, the
two can be tested effectively together, with some additional nuance to recharge the batteries between each run.

As to the second key challenge, test bench RPM, the majority of commercially accessible electric motor based dynamometers that can handle 500+ kW of power are designed to test large industrial motors which typically spin at very low RPMs, commonly less than 2,000 RPM. Historically, the Buckeye Bullet motors of interest have operated between 10,000 and 14,000 RPM. While high RPM high power test benches do exist, especially in the gas turbine field, they are usually not based on load from an electric motor, but instead a water brake, eddy current, or similar design which does not allow for the capability of full racing run simulation due to distinct step-wise operating points. Even if a full power, full speed capable testing facility is identified, it is not practical to do long term development projects off site. Specific high power runs might be possible to complete during a brief travel to an off-site facility but it is immensely time consuming and expensive to move the entire operation off-site each time a change needs to be tested.

With these numerous considerations in mind, a modular and portable platform was developed to house the BB2 motor, transmission, and inverter. The components could be aligned with precision in the workshop and then transported to any testing facility and quickly installed with only one custom driveline coupler required in each case. To address the issue of different dynamometer load motor speeds, two different gearboxes were implemented in-line with the test setup, one has 2 gears and the other 5 for a total of 10
possible reduction ratios. A CAD model of the setup as designed for the OSU dynamometer cell is shown in Figure 64 below. Figure 65 shows a photo of the installation in use.

Figure 64: CAD Model of Buckeye Bullet 2 Motor Test Bench

Figure 65: Buckeye Bullet 2 Motor Test Bench Installation
Overall, this modular test bench was very effective at meeting the goals laid out during the
design phase of the BB2, and was utilized for many hours of testing both on-site at OSU
and at external testing facilities. Several short documents in the form of technical papers
have been written on the detailed development of the modular test bench, gear box
selection, and shaft and coupling sizing and manufacture.

While the BB2 test bench was effective for short term development need and highly
portable, there were a couple of key problems. The largest issue was the frequent damage
to any and all gearboxes utilized in the setup. Electric motors have the ability to produce
full torque at 0 RPM and can deliver the torque quite quickly. In a testing environment,
this means that any small control issues or unintended torque fluctuation can rip all of the
teeth form a gear instantly. Moving forward it was the hope to eliminate gear reductions
from the assembly and to focus on full speed operation.

6.2: Venturi Buckeye Bullet 3 - 2012 Inverter Development Test Bench

As the testing needs for the VBB3 powertrain components were identified, a wide variety
of potential testing methods were discussed. During the validation of a variety of potential
motors, the testing specifications ranged from 150 kW to more than 1,500 kW for a single
motor unit with speeds ranging from 10,000 to 14,000 RPMs and torque production ranging
from 100 Nm to more than 2000 Nm. As the process progressed, a need for two very
different benches emerged. There were requirements for both a long term low power single
motor bench for inverter development, as well as a short term, high power race run simulation bench to test the entire axle. Time constraints dictated that the inverter test bench was needed very quickly so that the development of the custom ATS inverter adapted to our motor technology could progress and meet overall project timing requirements. Based on the experience with the BB2 test bench, a specific testing setup was developed for use at ATS facility in Florida. While a direct drive full speed setup was preferred, time, budget, and available loading motors did not allow for this goal to be realized. ATS does extensive work with the D77 DC train motor and had the ability to use an on-site motor for the loading of our test bench. Utilizing existing equipment available from the Buckeye Bullet team, a modular test bench was designed and built to connect a single (1 or 4) VBB3 motor to the D77 load motor with an inline torque/speed transducer. Ironically the power ratings of the drive and absorbing motors were quite similar, despite a very large discrepancy in size, weight, and operation RPM. A CAD image of the ATS development bench is shown in Figure 66 and a picture of the installation is shown in Figure 67.
Figure 66: CAD Model of 2013 Inverter Development Test Bench

Figure 67: 2013 Inverter Development Test Bench Installation
The inverter development bench installed at ATS has been operational for more than 2 years and has undergone hundreds of hours of testing with no notable issues, only requiring periodic gear box lubrication. The bench has been used to the full VBB3 single motor raging of 10,500 RPM and the full torque rating.

6.3: Venturi Buckeye Bullet 3 - 2013 Axle Test Bench

While the quick turnaround ATS inverter bench was being built, a separate design for a full power axle motor test bench was developed. The goal was to be able to simulate full power Bonneville race runs on a complete axle motor at the OSU CAR facility. Aside from the cost and complexity of building such a setup, the single biggest hold up is that CAR does not have enough electrical service to power the VBB3 drive motors being tested as well as a dynamometer motor large enough to supply load torque, even if every other electrical device at CAR was powered down. After a great deal of investigation into industry solutions for similar problems, it was determent that the motors could be tested at full speed and power in a back to back configuration where two identical motors (VBB3 axle motors) are connected together by a rigid shaft with an inline torque transducer. The power produced by the absorbing motor could be circulated back to the drive motor. In this configuration, the full power of the motor does not need be supplied, only the mechanical and electrical losses of the system which account for less than 10% of the overall power. CAR owns and operates a 250 kW DC power supply for large battery pack cycling which fit the needs of the test bench quite nicely. The equipment layout and electrical schematic of this proposal is shown in Figure 68 below.
Once it was confirmed that the proposal to provide power in this method was feasible, the focused shifted to developing a highly modular test bench that could be used to test conceivably any motor the team might be interested in implementing into the VBB3. The design utilizing the VBB3 axle motors is shown in Figure 69 below.
The motors were placed on generic sleds which help to align the system, shown in orange above. The sleds were machined and precisely aligned with the axis of the bench. Any motor can be adapted to the bench by producing custom mounting brackets as shown in green above. At the center of the bench is a high accuracy in line torque transducer which also incorporates an encoder to measure shaft speed. The transducer is capable of 2000 Nm and 16,000 RPM. The motors are connected to the transducer though custom drive shafts and flexible disk stack coupling joints. Conventional universal and CV joints cannot handle the speeds required during motor testing. The transducer and flex couplings / drive shafts are shown in Figure 70 and Figure 71.
Figure 70: Test Bench Drive Shaft / Flex Coupling Installation

Figure 71: Magtrol In-Line Torque Transducer
The complete installation with a protective shield covering the rotating components is shown in Figure 72 below.

![Figure 72: 2013 Axle Test Bench – Complete Installation](image)

A key feature of the bench is the utilization of exact duplicates of all of the race vehicle control, data acquisition, power distribution, oil cooling, and water cooling systems. Utilization of these systems provides the opportunity to validate and improve each of them during the motor testing process. Additionally, highly accurate thermal simulations can be performed to validate racing condition thermal performance. They also provide spare parts of all critical systems during the racing season. A picture of one of the test bench cooling carts which features the same fluids, pumps, and lines as the vehicle is shown in Figure 73 below.
To date, the construction of the test bench is complete and initial operational validation runs to 10,000 RPM at 75% load have been completed to prove the mechanical function of the test bench. The ATS inverters have been away from the shop since the completion of the bench, but they are scheduled to return to OSU with 2015 upgrades just days after the completion of this document. Full power testing is scheduled to commence in the next 2 weeks.
Chapter 7: Results to Date and Conclusions

The vehicle was completely assembled for the first time in July of 2013. While many systems were still in a highly prototype / early integration stage, every component of the vehicle was mounted and operational. To align with the goal of debuting the vehicle on the Salt Flats for Speedweek 2013, the team headed to the Transportation Research Center to complete initial rolling tests of the complete vehicle. An image of early testing is shown in Figure 74 below.

Figure 74: Early Road Test at Transportation Research Center (TRC)
During the initial road tests the team was not focused on data acquisition or comparing track data to simulation results; the goal was much more humble, to successfully turn on all of the vehicle control systems and simultaneously command power through all 8 battery packs, 4 inverters, 4 motors, and 2 transmissions, to spin both axles. In fact at that time, the data acquisition system was not yet integrated into the CAN Bus. With small amounts of interment success it became clear that there was still a great deal of controls level work to do, the largest problem being noise on all of the signal and control data busses, despite great effort to isolate the systems. While it was clear that the vehicle was not ready to go 400 MPH, the team successfully operated the vehicle at humble power levels and began to show great progress in the tuning and development of the vehicle. The vehicle was completely built and provided quite an impressive display, so the decision was made to travel to Bonneville in September where the team could continue to develop the vehicle and complete initial shake down runs.

Just before the team departed for Utah, the salt flats experienced historic rainfall as a major storm system traveled across the western region of the USA leaving horrific floods in its wake. When one arrives at Bonneville, they hope to see the bright white glow of the flats as seen in Figure 75 below. This is the ideal view from the “end of the access road.” Instead we found the image seen in Figure 76.
Figure 75: Desired Salt Flats Appearance (from the End of the Access Road)

Figure 76: 2013 Salt Flats Appearance (from the End of the Access Road)
The team did not let the rain prevent program progress. Space was obtained in a hanger at the nearby Wendover Airport and around the clock development work continued on the vehicle. Eventually, the airport runways were used for full vehicle testing and promotional filming as seen in Figure 77.

![Figure 77: 2013 Testing at Wendover Airport Due to Rain](image)

The relentless electrical noise on the control systems buses coupled with extremely short test track distances limited vehicle speeds to under 100 MPH. While the test speeds were not impressive, first hurdles of complete system manufacture, integration, and hands off operation had been overcome.
During the following off-season, the team put a great deal of focus into troubleshooting operational problems with the inverters, isolation all sources of noise on the control and data busses, and reliable operation of all systems. These efforts paid off as 2014 track testing in Ohio showed great reliability improvements of all the electrical systems. In August of 2014 the team returned to Bonneville to re-attempt the debut of the VBB3 at Speedweek, this time with a much more capable vehicle. The day the team arrive in Utah the weather was ideal and the salt flats were completely dry. The night before racing, an unprecedented storm blew in and completely flooded the salt flats, eventually causing the racing event to be cancelled. This was the first time in 50 years that racing had been canceled 2 years in a row. While there was not as much water as the 2013 storm brought, the flats were still unusable, as can be seen in Figure 78.

![Figure 78: 2013 Salt Flats Appearance (from the End of the Access Road)](image-url)
While most competitors chose to return home, the VBB3 team had already made arrangements for a private testing event following Speedweek and decided to stay and monitor the weather. Two weeks after the rain storm, a large portion of the salt flats had dried up and was able to be used for testing. The conditions were far from optimal, but in the end the team was able to utilize 3 miles of track for acceleration testing. Figure 79 shows the vehicle at the end of a high speed test run. During the highly limited testing period the team focused on the reliable operation of all 4 motors simultaneously while limiting the maximum torque requested and staying in 1st gear. By the end of 3 days of testing, the vehicle was demonstrated at 70% total vehicle power limit on a very wet salt flats with an estimated coefficient between 0.2 and 0.3.

Figure 79: 2014 Racing Run ~260 MPH
During the test runs, limited data was available but the key performance parameters were logged and analyzed after the team returned to Ohio. The racing conditions were plugged into the vehicle simulator and the performance estimation shown in Figure 80 was produced.

![Run Simulation Based on 2014 Conditions](image)

**Figure 80: Run Simulation Based on 2014 Conditions**

With the limited torque and grip, the simulator estimated reaching 225 MPH in 2 miles and reaching the terminal velocity of 1st gear in approximately 3 miles. The actual run data is shown in Figure 81 below. The data was based on the wheel RPM which includes some error due to inconsistent tire growth, but in general the data showed a very high correlation with the expected acceleration performance. This was a very high level initial look at the
vehicle operation but it showed great promise for the vehicle performance potential. Stated simply, the vehicle reached 88% of the terminal velocity of the BB2 and VBB2.5 with less than 75% power on a ½ length track in 1\textsuperscript{st} gear. After two years of troubleshooting difficult problems in the workshop, followed by two years of being rained out of racing, this was a much needed boost in excitement for the team and has set the foundation for a very successful 2015 racing season.

Figure 81: 2014 Top Speed Run (Data – Based On Wheel RPM)
Chapter 8: Future Work

To date the team has accomplished a great deal in the specification, design, and build of the VBB3 vehicle. The vehicle construction is 100% complete and initial testing is underway. As the team moves into phase 4 of the development cycle as presented in Chapter 2, the focus of the program will shift to road testing of the complete vehicle and data analysis. The initial shake down runs completed in 2014 were focused on the functional operation of the vehicle and were carried out before the data acquisition system was fully functional. The first key to moving forward is to obtain as much vehicle test data as possible for analysis. During the off season the data acquisition system was fully implemented and as soon as the weather permits the vehicle is ready to continue test track development.

The next core area of future development is to utilize the full axle test bench to fully simulate racing conditions and optimize the system. To date the dominate use of the bench has been to troubleshoot inverter operational issues. With the inverters up to date and with all known operational issues resolved, the focus of the test bench development can shift back to optimizing the motor control and thermal systems for maximum vehicle performance.
Having the combination of low speed track data as well as full range powertrain test data will allow the final phase 4 simulations to be carried out, and the vehicle performance window to be verified prior to 2015 racing. This is a critical step toward estimating overall vehicle speed as well as to prepare for onsite diagnostics at the salt flats. This simulation will also allow the team to fine tune the race strategy including start line placement, target pre-race and post-race component temperatures, and required battery charging level between record runs.

While these additional tasks are all focused on the optimization of the existing vehicle, a longer term consideration of the team should be a large scale evaluation of each of the components to determine which currently limit the vehicle performance, as well as an investigation into the technology advancements which have occurred during the years the team was focused on the implementation of the current configuration. Based on data presented in section 4.2 alone, it is already known that the exiting vehicle performance window could be increased drastically by upgrading the motor. Every other component of the powertrain was specified to operate at a higher power level and was implemented accordingly. Additionally, all of the mechanical systems of the vehicle were developed to withstand 500 MPH operation so there is still quite a lot of room for expansion before a completely new platform will be required. By the time such a technology evaluation could take place, it is likely that there will be highly competitive battery technologies that could significantly reduce the mass and volume of the battery pack. While there is much work to do to reach 400 MPH with the existing vehicle before the team should dream of 500
MPH, these opportunities present an existing case for the dedicated students of the Venturi Buckeye Bullet Racing Team to consider a VBB3.5 or a completely new Buckeye Bullet 4.

Figure 82: VBB3 Team on the Salt Flats After 2014 Racing Attempts
Bibliography


