A Systematic Approach to Hybrid Electric Vehicle Modeling

THESIS

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By

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ABSTRACT

The modeling and simulation of vehicles is an essential stage in the design process. Early design stages focus on energy-modeling, where many component dynamics are ignored and the models only compute the energy flow through the models. This allows for quick simulations and changing of component parameters, but as the design process progresses, a need for more detailed models arises. This thesis focuses on modeling and simulations of subsystems that are unique to hybrid electric vehicles, the battery, electric machine, and inverter. Battery modeling was divided into three subsystems, electrical, thermal and aging. Electrical models predict the battery voltage and state of charge. Thermal models predict the battery temperature. Aging models predict the loss in capacity and increase in resistance. The different combinations of battery, electric machine, and inverter models were simulated using a vehicle simulator of a wheel loader. The differences in fuel consumption, simulation time, battery SOC and battery capacity loss were analyzed and compared. The causes of the differences were determined, and the impact of each model fidelity was systematically and objectively evaluated.
DEDICATION

To my parents.
ACKNOWLEDGEMENTS

First, I would like to thank my advisor, Giorgio Rizzoni. His overall guidance helped me through school and finding my passion.

I would also like to thank the other team members on this project, Qadeer Ahmed, Bharatkumar Hegde, and C.G Cantemir. They each played a vital role in the project, and this thesis wouldn’t be what it is without them.

I would like to thank the Cummins side of the project, Vivek Sujan, Pinak Tulpule, Kenny Follen, and Gary Parker. The discussions we held and questions that were asked modeled this project.

Finally, I would like to thank Lorenzo Serrao, although I have never met him. The simulator he built during his time at Ohio State saved me countless hours of modeling, and the detail level in his simulator manual allowed me to understand how it operated without spending an excessive amount of time staring at a computer screen.
VITA

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FIELDS OF STUDY

Major Field: Mechanical Engineering
# TABLE OF CONTENTS

ABSTRACT ......................................................................................................................... ii
DEDICATION ...................................................................................................................... iii
ACKNOWLEDGEMENTS ................................................................................................. iv
VITA ....................................................................................................................................... v
TABLE OF CONTENTS ..................................................................................................... vi
LIST OF TABLES .............................................................................................................. viii
LIST OF FIGURES .......................................................................................................... xi
CHAPTER 1: INTRODUCTION ......................................................................................... 1
  1.1 Motivation ................................................................................................................. 1
  1.2 Hybrid Electric Vehicle Modeling ........................................................................... 4
  1.3 Vehicle Simulators .................................................................................................. 6
  1.4 Overview of Thesis ................................................................................................. 8
CHAPTER 2: OVERVIEW OF BATTERY MODELS .................................................. 10
  2.1 Overview of Battery Modeling .............................................................................. 10
  2.2 Electrical Models .................................................................................................... 12
  2.3 Thermal Models ..................................................................................................... 15
  2.4 Aging Models ......................................................................................................... 22
  2.5 Interconnected Battery Model ................................................................................ 25
  2.6 Battery Model Fidelities ........................................................................................ 27
CHAPTER 3: OVERVIEW OF ELECTRIC DRIVE MODELS ................................ 29
  3.1 Overview of Electric Drive System ....................................................................... 29
  3.2 Electric Motor Modeling ......................................................................................... 32
  3.3 Inverter Modeling ................................................................................................... 37
  3.4 Electric Drive System Fidelities ............................................................................. 41
LIST OF TABLES

Table 1- Electric Machine Model Capabilities ................................................................. 14
Table 2- Thermal Model Capabilities .................................................................................. 22
Table 3- Aging Model Capabilities .................................................................................. 24
Table 4- Battery Model Fidelities ................................................................................... 27
Table 5- Battery Subsystem Fidelities ............................................................................. 27
Table 6- Electric Machine Model Capabilities ................................................................. 36
Table 7- Switching Table for Ideal Switching Inverter ....................................................... 38
Table 8- Inverter Model Capabilities ............................................................................... 41
Table 9- EDS Model Fidelities ......................................................................................... 42
Table 10- Engine Data .................................................................................................... 44
Table 11- Transmission Data ............................................................................................ 45
Table 12- Battery Pack .................................................................................................... 53
Table 13- Comparison of Conventional and Hybrid Vehicle Fuel Consumption ............ 59
Table 14- Battery Model Combinations ................................................................. 63
Table 15- Different Combinations of Electric Drive System Models .................. 64
Table 16- Results of Simulations to be Compared ............................................. 65
Table 17- Battery Notation .................................................................................. 73
Table 18- EDS Notation ...................................................................................... 73
Table 19- Vehicle Fuel Consumption with Different Model Fidelities ............... 74
Table 20- Simulation Run Time .......................................................................... 77
Table 21- Battery Capacity Loss ......................................................................... 80
Table 22- Change in SOC ................................................................................... 82
Table 23- Time-Step Fuel Consumption .............................................................. 87
Table 24- Time-Step Simulation Time ................................................................. 87
Table 25- Battery Capacity Loss ......................................................................... 89
Table 26- Battery Aging- Fuel Consumption ..................................................... 91
Table 27- Battery Aging- Capacity Loss .............................................................. 91
Table 28- Change in SOC ................................................................................... 92
Table 29- Parameterization Study- Fuel Consumption [kg] .................................. 95
Table 30- Parameterization Study- Loss in Battery Capacity [-] ........................................... 97

Table 31- Vehicle Drive Cycle- Fuel Economy ................................................................. 99

Table 32- Vehicle Drive Cycle- Battery Capacity Loss ............................................... 100

Table 33- Vehicle Drive Cycle- Change in SOC ......................................................... 100
LIST OF FIGURES

Figure 1- World Energy Consumption [1]................................................................. 2

Figure 2- US Energy Consumption for Source and Sector [2]................................. 3

Figure 3- Fuel Economy Prediction of Hybrid Vehicles [3]...................................... 4

Figure 4- Interconnected Battery Subsystems .......................................................... 11

Figure 5- Advantages and Disadvantages of Different Modeling Levels.................. 12

Figure 6- Randle’s Circuit for ECM Battery Modeling.......................................... 13

Figure 7- Boundary Value Problem [13]................................................................... 16

Figure 8- Heat Generated in Reduced-Order Model [13]........................................ 17

Figure 9- Reduced-Order Model Temperature Comparison [13]......................... 18

Figure 10- Liquid-Cooled Battery Thermal Diagram............................................. 19

Figure 11- Interconnected Battery Pack Structure [15]......................................... 20

Figure 12- Thermal Circuit Diagram for a Battery Cell [15]................................. 21

Figure 13- Battery Model Setup [15]....................................................................... 25
Figure 14 - Electric Drive System ................................................................. 30
Figure 15 - Electric Drive System Fidelities .................................................. 31
Figure 16 - Complete Electric Drive System Model Structure ....................... 32
Figure 17 - EDS block for Efficiency Model of Electric Machine .................... 33
Figure 18 - EDS Block of DQ-Axis Model ...................................................... 34
Figure 19 - EDS Block of 3-Phase Model ....................................................... 35
Figure 20 - Inverter Modeling ........................................................................ 37
Figure 21 - Inverter Diagram ......................................................................... 38
Figure 22 - Wheel Loader .............................................................................. 43
Figure 23 - Conventional Wheel Loader Architecture .................................... 44
Figure 24 - Vehicle Velocity Profile ................................................................. 45
Figure 25 - Vehicle Velocity Profile Used During Simulation ......................... 46
Figure 26 - Vehicle Weight Duty Cycle ............................................................ 46
Figure 27 - Engine Load Torque from Shovel .................................................. 47
Figure 28 - Load on Engine ........................................................................... 47
Figure 29 - Example of Forward Simulator ..................................................... 48
Figure 30- Conventional Vehicle Velocity with P=3 ............................................. 49

Figure 31- Conventional Vehicle Velocity with P=10 .......................................... 50

Figure 32- Engine Speed Comparison for P=10 and P=3 ....................................... 50

Figure 33- Engine Torque Comparison for P=10 and P=3 ....................................... 51

Figure 34- Engine Torque Comparison for P=10 and P=3 ....................................... 52

Figure 35- Hybrid Vehicle Architecture ..................................................................... 53

Figure 36- Percentage of Regenerative Braking Available ....................................... 54

Figure 37- Conventional Vehicle Control Diagram ..................................................... 55

Figure 38- Hybrid Vehicle Control Diagram ............................................................... 55

Figure 39- Regenerative Braking ................................................................................ 56

Figure 40- Percent EM Usage ................................................................................... 58

Figure 41- Vehicle Supervisory Controller ................................................................. 58

Figure 42- Hybrid Vehicle Speed Trace .................................................................... 59

Figure 43- Electric Machine Efficiency Map ............................................................... 60

Figure 44- Battery SOC ............................................................................................ 61

Figure 45- Battery C-Rate ........................................................................................ 61
Figure 46- Electrical Subsystem Calibration- Current .................................................. 66
Figure 47- Electrical Subsystem Calibration- Voltage .................................................. 66
Figure 48- Electrical Subsystem Calibration- Battery SOC ........................................ 67
Figure 49- Electrical Subsystem Calibration- Heat Generated .................................... 68
Figure 50- Thermal Subsystem Calibration- Temperature .......................................... 69
Figure 51- Aging Subsystem Calibration- Capacity Loss ........................................... 70
Figure 52- Electric Drive System Calibration- Torque .............................................. 71
Figure 53- Electric Machine Calibration- Speed ....................................................... 72
Figure 54- Electric Machine Torque ........................................................................ 75
Figure 55- Electric Machine Torque ........................................................................ 75
Figure 56- EM with Inverter Torque ....................................................................... 76
Figure 57- EM with Inverter Torque ....................................................................... 77
Figure 58- Boxplot of Simulation Time ................................................................. 78
Figure 59- Boxplot of Simulation Time ................................................................. 79
Figure 60- Boxplot of Capacity Loss ..................................................................... 80
Figure 61- Boxplot of Capacity Loss ..................................................................... 81
Figure 62- Boxplot of Capacity Loss ................................................................. 81
Figure 63- Difference in Capacity Loss Algorithms ........................................... 82
Figure 64- Box Plot of Change in SOC ................................................................. 83
Figure 65- Box Plot of Change in SOC ................................................................. 84
Figure 66- Boxplot of Simulation Time ................................................................. 88
Figure 67- Boxplot of Simulation Time ................................................................. 88
Figure 68- Boxplot of Battery Capacity Loss ....................................................... 90
Figure 69- Battery Capacity Loss .................................................................... 92
Figure 70- Change in SOC ................................................................................ 93
Figure 71- Shovel Torque Profiles ................................................................. 94
Figure 72- Vehicle Mass Profiles ................................................................... 95
Figure 73- Boxplot of Fuel Consumption ......................................................... 96
Figure 74- Boxplot of Battery Capacity Loss ..................................................... 97
Figure 75- Low Speed Drive Cycle ................................................................. 98
Figure 76- High Speed Drive Cycle ................................................................ 99
CHAPTER 1: INTRODUCTION

1.1 Motivation

As the world progresses technologically, an increasing amount of energy is consumed. Increasing the efficiency of primary energy consumers provides a potential offset to the increase in energy consumption. A graph of the world energy consumption from 1990-2040 is shown in Figure 1.
The world energy consumption is projected to increase by over 400 quadrillion Btu by 2040. Most of this growth is seen in Non-OECD regions, however OECD regions are still projected to increase in energy consumption. The U.S. energy consumption by source and sector is shown in Figure 2.
The energy consumption by sector shows that 26.9% of the energy consumed in the U.S. is used for transportation purposes. Of this 26.9%, 92% comes from petroleum, while 3% comes from natural gas and 5% comes from renewable energy sources. Therefore, the majority of the energy used in transportation is non-renewable. This makes transportation a large sector to see improvements in energy consumption. Additionally, 71% of petroleum is used in transportation, meaning that increasing the efficiency of energy usage in transportation would decrease the overall petroleum consumption by a similar margin. The projected fuel economy of various electrified vehicles is shown in Figure 3.
As the degree of electrification in the vehicle increases, the fuel economy increases. However, for the vehicle to have an increase in fuel economy, it has to be designed properly.

1.2 Hybrid Electric Vehicle Modeling

Modeling is extremely important for the system level design of vehicles, including hybrid-electric vehicles. Modeling typically reduces the cost and overall time associated with the design process. Simulators can be modified and used for comparison purposes much easier and quicker than prototypes. For these reasons, vehicle modeling and simulation is a tool that is utilized by many research organizations and companies to design vehicles.
As early as 1997, computer simulations were used to predict maximum acceleration and fuel economy measures over various drive cycles [4]. Bryon Wasacz developed a vehicle simulator based off of The Ohio State University FutureCar Challenge vehicle. The simulator was designed to be modular, meaning that each component, such as the engine or transmission, is contained within a single subsystem with only that component. This allows a single component to be changed easily and without impacting other components in the simulator. The individual models of the components are energy-based, so that the individual dynamics of components are assumed negligible as compared to the entire vehicle.

In this simulator, a driver with a throttle was modeled, similar to a human driver and an accelerator pedal. This forces the driver to change the speed of the vehicle in accordance to a desired velocity profile, as opposed to calculating the loads on the drivetrain given the speed. The simulator now must take corrective action if it falls off the desired velocity trace, similar to a real-world driver controlling an actual vehicle. This style of simulator that uses a driver and torque requests to determine speed is called a ‘forward’ simulator. This differs from a backwards simulator that constrains the vehicle speed to a given cycle, which by doing so doesn’t incorporate the system dynamics into the model.

Once developed, vehicle simulators can be used in many stages of the vehicle design process. One common use of vehicle simulators is to analyze a specific component in the vehicle powertrain. A study was performed that analyzed the impact of an
electrically-variable transmission (EVT) on the vehicle powertrain, as compared to conventional and parallel HEV vehicle configurations [5]. This study used the different transmission models combined with control strategies suited for each powertrain configuration to show significant improvements in fuel economy using an EVT.

Another common use of vehicle simulators is in control development. This requires the models produce accurate outputs, yet also run fast enough to be implemented in real-time. In 1997, a vehicle simulator was used to develop a supervisory control strategy using neural networks and fuzzy logic [6]. In 1999, an approach to determining an optimal control strategy focusing on energy management was developed using dynamic programming [7]. This tool determines the optimal power output of components, such as the engine or electric machine, to achieve a certain goal, such as minimizing fuel consumption. In 2004, an optimal control strategy for a known vehicle cycle was developed using Pontryagin’s minimum principle, and then adapted to be used when the future drive cycle isn’t known [8]. In 2009, Lorenzo Serrao implemented and compared three optimal control strategies, dynamic programming, Pontryagin’s minimum principle, and equivalent consumption method, using energy flow through a vehicle simulator [9].

1.3 Vehicle Simulators

The earliest publically available vehicle simulation tool is Advanced Vehicle Simulator (ADVISOR), which was developed in 1994 at the National Renewable Energy Laboratory (NREL) [10]. ADVISOR is a Matlab/Simulink based simulator that allows
the user to customize vehicle parameters and replace existing component models with more detailed models. However, ADVISOR uses quasi-static energy-based models and a backwards simulator that constrains component speeds based on the drive cycle. This is opposed to a forwards simulator, which uses a driver and a throttle input so the vehicle can track the desired drive cycle. The component models within ADVISOR are based on energy flow through the components. The components largely use empirical data to determine the model outputs.

Since 1999, Argonne National Laboratory (ANL) has worked with the Partnership for a New Generation of Vehicles (PHGV) to maintain the hybrid vehicle simulation software called PNGV Systems Analysis Toolkit (PSAT) [11]. PSAT is a Matlab/Simulink based simulator that allows the user to customize the vehicle architecture and each component. PSAT differs from ADVISOR because PSAT is a forward simulator, meaning that a driver controls throttle and brake inputs in a way which causes the vehicle to follow a drive cycle. This allows the implementation of more advanced component models, such as the modeling of engine start/stop and gear shifts. The individual component models in PSAT track the energy flow through each component, similar to ADVISOR.

Gamma Technologies maintains a simulator called GT-Suite. GT-Suite contains many different simulation technologies, including a vehicle powertrain simulation named GT-Drive. GT-Drive can incorporate models from other GT-Suite tools [12]. This allows the use of complex models, such as the engine models created using GT-Power, to also
be used in GT-Drive vehicle simulations. This increase in fidelity provides additional information about the system, which can be used to make important decisions in the later stages of the design process.

1.4 Overview of Thesis

This thesis explores the development of a tool that use a hierarchy of different levels of model fidelity to systematically create a vehicle level simulator based on the user’s needs. In this thesis, we focus on modeling and simulation of subsystems that are unique to HEVs. An overview of the chapters contained in this thesis is provided below.

- Chapter 2- Overview of Battery Modeling
  - Describes battery subsystem models
    - Electrical
    - Thermal
    - Aging
  - Describes interconnected battery model
- Chapter 3- Overview of Electric Drive Modeling
  - Describes electric machine models
  - Describes inverter models
- Chapter 4- Vehicle Simulator
  - Describes vehicle simulator that was used
- Chapter 5- Fidelity Study
  - Evaluates system level impact of different models
• Chapter 6- Additional Studies
  o Describes additional studies that were performed

• Chapter 7- Conclusion
  o Describes significance of work and future work
CHAPTER 2: OVERVIEW OF BATTERY MODELS

2.1 Overview of Battery Modeling

The modeling of a battery pack focuses on three different subsystems, electrical dynamics, thermal dynamics, and aging dynamics. These three battery systems are interconnected, as shown in Figure 4.
The electrical subsystem requires a set of parameters and initial conditions to be used, but can be operated without other battery subsystems. The thermal subsystem requires the electrical subsystem to determine the heat generated by the battery pack. The aging subsystem requires the temperature from the thermal subsystem and the state of charge from the electrical subsystem.

Each of the three systems can be modeled at either the cell level, the module level, or the pack level. The cell level models the interactions between the cells by modeling each cell in the pack as a different model. This allows the model to account for manufacturing variability and variations in cell parameters during usage. The module level models the interaction between modules, similar to the cell level. Pack level models assumes that
every cell in the pack has identical parameters and states. The advantages and disadvantages of each level of modeling are shown in Figure 5.

![Dynamical Sub-systems](image)

- **Electrical Subsystem**
  - Equivalent Circuit
  - Electrochemical
- **Thermal Subsystem**
  - Numerical Models (FEM, CFD)
  - Spatially-reduced and Reduced-order Models
  - Lumped-capacitance Dynamic Models
- **Aging Subsystem**
  - Physics based approach
  - Semi-Empirical approach
- **Battery Management System**
  - Voltage management system
  - Current management system
  - Safety and diagnostic system
  - Cell balancing system
  - Thermal Management system

**Figure 5- Advantages and Disadvantages of Different Modeling Levels**

The modeling accuracy and understanding of the system dynamics increases as the amount of interaction modeled between the components increases. However, the modeling effort, complexity, and calibration effort increase greatly when modeling the interactions.

**2.2 Electrical Models**

The electrical subsystem is typically modeled in one of two ways. The first models the electrochemical dynamics within the battery cells. This can be simplified into
one dimensional flow to determine the battery voltage given an input current profile. The second method represents the battery using Randle’s circuits. This is a low order approximation of partial differential equations and doesn’t represent resistors or capacitors in the cell itself. Only the latter will be discussed in this document.

**Equivalent Circuit Method for Battery Modeling**

The Randle’s circuit that is used in cell voltage approximations is shown in Figure 6.

![Randle’s Circuit for ECM Battery Modeling](image)

**Figure 6- Randle’s Circuit for ECM Battery Modeling**

A 0th order model only takes the low frequency resistance, $R_0$, into account. A first order model includes the low frequency resistance and the first RC circuit. This process can be repeated to produce an $n^{th}$ order battery model consisting of $n$ RC circuits and a low frequency resistance. These parameters depend on the operating conditions of the cell, such as the state of charge (SOC), direction of current (charging, discharging), and the cell temperature. This battery model uses the current demand and the battery temperature.
to determine the voltage, SOC, and heat generated by the battery. This is done using Kirchhoff’s Laws and Power Laws, as shown for a 1\textsuperscript{st} order model in Equations 1, 2, 3, and 4.

\[ V_{cell} = V_{OC} - R_0 I - V_C \quad [1] \]

\[ \frac{dV_{RC}}{dt} = \frac{I}{C} - \frac{V_{RC}}{RC} \quad [2] \]

\[ I_{R1} = I - \frac{dV_{RC}}{dt} C \quad [3] \]

\[ P_{gen} = (I^2 \ast R_0 + I_{R1}^2 \ast R_1) \ast N \quad [4] \]

**Electrical Model Capabilities**

The electric machine models are compared in Table 1.

**Table 1- Electric Machine Model Capabilities**

<table>
<thead>
<tr>
<th>Models</th>
<th>Trnst</th>
<th>SS</th>
<th>CCA</th>
<th>DSA</th>
<th>BMS</th>
<th>PSC</th>
<th>FDP</th>
<th>MIL</th>
<th>SIL</th>
<th>HIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equiv. Circuit</td>
<td>( m )</td>
<td>( 0 )</td>
<td>( \times )</td>
<td>( \checkmark )</td>
<td>( \times )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \times )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>Model</td>
<td>( 1 )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td></td>
</tr>
</tbody>
</table>

The 0\textsuperscript{th} order electrical model doesn’t model transient responses, but models the steady state response of the battery voltage. The 1\textsuperscript{st} order model tracks both the steady state and transient responses. Neither model performs a chemical component analysis (CCA) or detailed system analysis (DSA), because neither model is based on first principles. The
0th order model shouldn’t be used for battery management system (BMS) control design or fault diagnosis (FDP) because it lacks accurate transient response, but the 1st order model can be used for BMS design and fault diagnosis. Both models can be used for supervisory controller design because they both accurately predict the battery SOC. Both models can also be used for model in the loop (MIL), software in the loop (SIL), and hardware in the loop (HIL) simulations because they run at real-time speed.

2.3 Thermal Models

A variety of techniques exist to model the thermal subsystem of a battery cell. These models take the heat generated by the battery and the temperature of the coolant flowing through the battery and determine the battery temperature. The finite element method (FEM) breaks down the cell into a grouping of small elements and calculates the temperature of each element. First principles models are created by using model order reduction techniques on partial differential equations that describes the temperature at different points on the cells. Lumped parameter models are created by assuming the cell to be one lumped element with homogeneous parameters, including temperature. The latter two methods will be discussed further.

First Principles Model with Model Order Reduction

The first principles model derives partial differential equations in the form of a boundary value problem (BVP) for the cell, as shown in Figure 7.
The equation that describes the cell temperature is shown in Equation 5 [14].

\[
\frac{\partial^2 T(x,t)}{\partial x^2} + \frac{1}{k} \frac{\partial Q(t)}{\partial t} = \frac{1}{\alpha} \frac{\partial T(x,t)}{\partial t} \tag{5}
\]

The problem is simplified using symmetry to develop boundary conditions. The boundary conditions of the system and symmetry are added to the BVP and are shown in Equations 6 and 7.

\[
\left. \frac{\partial T(r,t)}{\partial r} \right|_{r=R} = -\frac{h}{k} \left( T(R,t) - T_{air}(t) \right) \tag{6}
\]

\[
\left. \frac{\partial T(r,t)}{\partial r} \right|_{r=0} = 0 \tag{7}
\]

The system is described using a linear PDE, so the problem will be solved using the Laplace transform. The transformed BVP is shown in Equations 8, 9, and 10.

\[
\frac{d^2 T(r,s)}{dr^2} + \frac{1}{r} \frac{dT(r,t)}{dr} - \frac{1}{k} Q(s) = -\frac{1}{k} T(s) \tag{8}
\]

\[
\left. \frac{dT(r,t)}{dr} \right|_{r=R} = -\frac{h}{k} \left( T(R,t) - T_{air}(t) \right) \tag{9}
\]
\[
\frac{dT(r,t)}{dr} \bigg|_{r=0} = 0 \tag{10}
\]

Where \( a^2 = \frac{\rho c_p s}{k} \). Once the general solution is found, the temperature at the center and surface can be found by evaluating the solution at \( r=0 \) and \( r=R \), respectively. Then, the solution can be reformatted as a system, as shown in Equation 11 [13].

\[
\begin{bmatrix}
T(0, s) \\
T(R, s)
\end{bmatrix} =
\begin{bmatrix}
G_{11}(s) & G_{12}(s) \\
G_{21}(s) & G_{22}(s)
\end{bmatrix}
\begin{bmatrix}
\dot{q}(t) \\
T_{\text{air}}(t)
\end{bmatrix} \tag{11}
\]

Where the matrix \( G(s) \) contains transfer functions that are derived using the boundary conditions and Equation 5. The model then uses Equation 12 to determine the boundary temperature of the battery cell.

\[
\frac{dT_{\text{Bound}}}{dt} = \frac{Q_{\text{gen}} - hA(T_{\text{Batt}} - T_{\text{Coolant}})}{MC} \tag{12}
\]

The model was then compared to the results of an FEM simulation. The heat generation profile is shown in Figure 8.

![Figure 8- Heat Generated in Reduced-Order Model [13]](image)
The resultant temperature profile of the model is shown in Figure 9.

![Figure 9- Reduced-Order Model Temperature Comparison [13]](image)

The reduced-order model calculates the battery temperature at the surface and the center with similar accuracy as the FEM model. This model produces accurate results, however, the development and calibration of the model is time-consuming.

**Lumped Parameter Model for Liquid-Cooled System**

Lumped-parameter thermal models assume that all of the bodies have homogeneous thermal properties, including temperature. This means that every point on the battery is assumed to be the same temperature. The lumped-parameter liquid-cooled model represents the system shown in Figure 10.
Coolant flows by the cooling plate, through the heat exchanger, and to the fluid reservoir. Air flows through the heat exchanger, and heat is transferred from the Coolant to the air. Heat generated by the battery is then transferred to the Coolant. The temperature of the battery is calculated using Equation 13.

\[
\dot{T}_b = \frac{Q_{\text{gen}}}{C_b} - \frac{T_b - T_{w1}}{R_p C_b}
\]  

[13]

The temperature of the coolant throughout the cycle is shown in Equations 14, 15, and 16.

\[
\dot{T}_{w1} = \frac{m_v}{M_w} (T_{w3} - T_{w1})
\]  

[14]

\[
\frac{T_{w2} - T_a}{r} = \dot{m}_p C_w (T_{w2} - T_{w3})
\]  

[15]
\[
\frac{T_{b} - T_{w1}}{R_p} = \dot{m}_p C_w (T_{w2} - T_{w1})
\]  

[16]

**Higher-Order Lumped-Parameter Model for Interconnected Battery**

The interconnected battery model calculates the temperature of the cells within the battery, which are arranged in the format shown in Figure 11.

![Figure 11 - Interconnected Battery Pack Structure](image)

[Figure 11- Interconnected Battery Pack Structure [15]]

The problem can be reformatted using thermal circuits, as shown in Figure 12.
The temperature of each cell is calculated using Equation 12.

\[
\frac{dT_{\text{cell},i}}{dt} = \frac{\dot{Q}_{\text{cell},i}}{R_u} - \frac{T_{\text{channel},i-1} - T_{\text{cell},i}}{R_u} - \frac{T_{\text{channel},i+1} - T_{\text{cell},i}}{R_{cc}} - \frac{T_{\text{cell},i-1} - T_{\text{cell},i}}{R_{cc}}
\]

[12]

The temperature in the thermal channels is calculated using Equation 13.

\[
T_{\text{channel},i} = T_{\text{air}} + \frac{\dot{Q}_{\text{cell},i} + \dot{Q}_{\text{cell},i+1}}{c_p \cdot m_{\text{air}}}
\]

[13]

This approach is nearly identical to the above lumped parameter approach. However, this model accounts for heat transfer between multiple cells and channels, as opposed to only modeling the heat transfer between the pack and the fluid that removes heat from the pack.

**Thermal Model Capabilities**

The thermal models are compared in Table 2.
<table>
<thead>
<tr>
<th>Models</th>
<th>Trnst</th>
<th>SS</th>
<th>DSA</th>
<th>BMS</th>
<th>PSC</th>
<th>FDP</th>
<th>MIL</th>
<th>SIL</th>
<th>HIL</th>
</tr>
</thead>
<tbody>
<tr>
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<td>✓</td>
<td>x</td>
<td>✓</td>
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<tr>
<td>Lumped Para.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>model</td>
<td>High</td>
<td>order</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>order</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All three thermal models accurately predict both steady state and transient temperatures in the battery. Therefore, all three models can be used for BMS, supervisory controller, and fault diagnosis development. However, on the higher order lumped parameter model is the only one that performs a detailed system analysis, because it tracks the temperature of every cell. All three models can be used in MIL and SIL simulations, however only the reduced order and low-order models can be used in HIL simulations. This is because the higher-order model fails to run in real time.

### 2.4 Aging Models

Battery aging models take the SOC, current profile, C-Rate, and battery temperature as inputs and calculate the loss in energy the battery can hold or the loss in power the battery can deliver. Battery aging can be modeled using first principles equations or an empirical approach. These two methods can also be combined to develop
a semi-empirical approach. Two different semi-empirical approaches are discussed further.

**Semi-Empirical Aging Model for HEV Applications**

The semi-empirical aging model uses a combination of experimental data and first-principle equations to determine the aging characteristics of the battery. The HEV model calculates the loss in capacity of the battery using Equation 14.

\[
Q_{Loss} = (\alpha \cdot SOC + \beta) \cdot \exp\left(\frac{-Ea + C \cdot Rate}{RT}\right) \cdot Ah^z
\]  

[14]

Where \(\alpha, \beta, C, Ea, and z\) are calibrated parameters that are determined experimentally.

This model also contains a severity factor map. Severity factor maps assist in solving the optimal control problem by providing a value that can be used in the cost function, similar to how engine fuel maps are used. The severity factor map provides the relative stress on the battery given the temperature, SOC, and C-Rate. However, this model doesn’t calculate the increase in resistance that occurs over the life of the battery.

**Semi-Empirical Aging Model for PHEV Applications**

The semi-empirical aging model for PHEV applications uses a similar technique to determine the loss in cell capacity. This is shown in Equation 15.

\[
Q_{Loss} = (\alpha_c + \beta_c \cdot Ratio^b + \gamma_c (SOC_{min} - SOC_0)^c) \cdot \exp\left(\frac{-Ea}{RT}\right) \cdot Ah^z
\]  

[15]
\( \alpha_c, \beta_c, b, \gamma_c, c, E_a, \text{ and } z \) are calibrated parameters that are determined experimentally.

This loss in capacity can then be fed back into the electrical subsystem so the model can predict the long term aging of a battery. Similar to Equation 15, this model predicts the increase in internal resistance of the battery, as shown in Equation 16.

\[
R_{inc} = (\alpha_R + \beta_R (SOC_{min} - SOC_0)^{c_R} + \gamma_R) \cdot \exp\left[ d(CR_0 - CR_{eq}) + e(SOC_{min} - SOC_0) \right] \cdot \exp\left( -\frac{E_{aR}}{R_g T} \right) \cdot Ah \tag{16}
\]

\( \alpha_R, \beta_R, C_R, \gamma_R, c, \text{ and } E_{aR} \) are calibrated parameters that are determined experimentally.

This increase in resistance can be fed back into the electrical subsystem to analyze the decrease in power over the life of the battery. However, this model doesn’t include a severity factor map, which can be used to determine when the operating conditions of the battery can have accelerated aging effects.

**Aging Model Capabilities**

The aging model capabilities are shown in Table 3.

<table>
<thead>
<tr>
<th>Models</th>
<th>Trnst</th>
<th>SS</th>
<th>CCA</th>
<th>DSA</th>
<th>BMS</th>
<th>PSC</th>
<th>FDP</th>
<th>MIL</th>
<th>SIL</th>
<th>HIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi Empirical Model</td>
<td>✓</td>
<td>✓</td>
<td>✘</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

[24]
Both aging models are semi-empirical. They capture the transient and steady state effects of aging on the battery pack, so they can be used for BMS, supervisory controller, and fault diagnosis design. However, they don’t capture the chemical analysis or the detailed system analysis. They have a quick enough simulation time so that they can be used in MIL, SIL, and HIL simulations.

2.5 Interconnected Battery Model

The interconnected battery model takes the difference between cells into account. The temperature differences between cells leads to SOC differences, which impacts the performance of the battery pack. The setup of the interconnected battery model is shown in Figure 13.

![Figure 13- Battery Model Setup](image)

The model was developed using prismatic cells, with cooling channels between each cell. String 1 consists of cells 1-S, where S is the number of cells per string. String 2 would then consist of cells S+1-2S, and so on for P strings in the battery pack. There are SxP
number of cells per battery pack, meaning there are SxP models of cells, making the cell calculations much more computationally demanding. The total voltage of the pack is determined by summing the voltages of the cells in any string, as shown in Equation 17.

\[ V_{pack} = \sum_{n=1}^{n=S} V_n \]  \hfill [17]

Each of the P strings has the same voltage in the pack, due to Kirchhoff's Laws. Since the cell states within each string differ, identical currents through each string produce different voltages. In order for the interconnected model to obey Kirchhoff's Laws, a different current is required through each of the strings in the pack. These currents can be solved for using Equations 18, 19, 20, and 21 in the example of a 4P12S battery pack.

\[ I_1 + I_2 + I_3 + I_4 = I \]  \hfill [18]

\[ \sum E_{0,1-12} - I_1 \sum R_{0,1-12} - \sum V_{C,1-12} = \sum E_{0,13-24} - I_2 \sum R_{0,13-24} - \sum V_{C,13-24} \]  \hfill [19]

\[ \sum E_{0,25-36} - I_3 \sum R_{0,25-36} - \sum V_{C,25-36} = \sum E_{0,13-24} - I_2 \sum R_{0,13-24} - \sum V_{C,13-24} \]  \hfill [20]

\[ \sum E_{0,25-36} - I_3 \sum R_{0,25-36} - \sum V_{C,25-36} = \sum E_{0,37-48} - I_4 \sum R_{0,37-48} - \sum V_{C,37-48} \]  \hfill [21]

There will be P number of equations for any given battery pack.
2.6 Battery Model Fidelities

The battery model fidelities are described at two different levels. The top level compares pack and interconnected models, as shown in Table 4.

Table 4- Battery Model Fidelities

<table>
<thead>
<tr>
<th>Battery Model Fidelity</th>
<th>Battery Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Interconnected Cell Model</td>
</tr>
<tr>
<td>Low</td>
<td>Pack Model</td>
</tr>
</tbody>
</table>

Table 4 shows that interconnected battery pack models are a higher fidelity than pack level models. This is due to the modeling of interactions between the cells. The second level of battery fidelities can be described for each subsystem and is shown in Table 5.

Table 5- Battery Subsystem Fidelities

<table>
<thead>
<tr>
<th>Battery Fidelity Level</th>
<th>Battery Model</th>
<th>Electrical</th>
<th>Thermal</th>
<th>Aging</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>1st Order</td>
<td>Reduced-Order</td>
<td>HEV</td>
<td>PHEV</td>
</tr>
<tr>
<td>Low</td>
<td>0th Order</td>
<td>Lumped Parameter</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A 1st order electrical battery model is a higher fidelity than a 0th order model because the 1st order model includes the presence of dynamics. The reduced-order thermal model is a higher fidelity compared to the lumped parameter due to the nature of the models. The reduced-order model doesn’t assume the temperature throughout the pack is homogeneous, however, it does assume that the other thermal properties are
homogeneous. The aging models are both at the same fidelity level. Both models use a semi-empirical approach, however, the formulas that are used are slightly different.
3.1 Overview of Electric Drive System

Modeling the electric drive system of a vehicle consists mainly of two different physical components, the electric machine and the inverter. However, there is a supervisory controller and an electric drive controller that impact the performance of each component. A schematic that shows how these systems interact is shown in Figure 14.
The supervisory controller takes the driver input, electric machine torque, and system temperature to determine the torque request to the electric drive controller. The supervisory controller turns the torque request from the supervisory controller into the three-phase current switching request or electric machine torque, depending on electric machine model. The inverter takes the switching request from the electric drive controller to determine the voltage and current supplied to the electric machine. The electric machine model takes this voltage and current and provides the torque to the system. The advantages and disadvantages of different modeling fidelities are shown in Figure 15.

Figure 14- Electric Drive System
The modeling accuracy and understanding of the system dynamics increase as the fidelity increases. However, the modeling effort, complexity, calibration effort, and computational cost all increase and the adaptability of the model decreases as fidelity increases. An overview of the electric drive system model structure is shown in Figure 16.
The Electric Drive System (EDS) block determines the torque produced by the model, which is then checked using the maximum and minimum torque limits of the electric machine at a given speed. After the delivered torque is calculated, the speed, the inverter efficiency, and the electric machine efficiencies are used to determine the electrical power that is consumed or produced.

### 3.2 Electric Motor Modeling

There are three main methods of modeling an electric machine for hybrid drive purposes. The first method uses neglects the dynamics of the machine and inverter, and instead uses efficiency maps to determine the electrical power consumed given a certain mechanical power load. The second method takes the electrical dynamics of the machine into consideration using the dq-axis. The third method takes the electrical dynamics into...
account, similar to the second method, but models the actual three-phase current in the electric machine. All three modeling techniques will be discussed below.

**Efficiency-Based Modeling of an Electric Machine**

The diagram of the EDS block for the efficiency modeling of an electric machine is shown in Figure 17.

![Figure 17- EDS block for Efficiency Model of Electric Machine](image)

The electrical dynamics of the system aren’t captured, so the requested torque is equal to the delivered torque, assuming that the torque is within the minimum and maximum limits. Efficiency maps are then used to determine the electric power consumed by the EM, given the speed of the machine and the torque request.

**DQ-Axis Modeling of an Electric Machine**

A diagram of the EDS block for a DQ-Axis model is shown in Figure 18.
The DQ-Axis model consists of four main blocks. The first of these blocks converts the torque request into a current request for the controller, as shown by Equation 22 and 23.

\[
I_q = \frac{2}{3P*\lambda_m} T_{\text{request}}
\]  \hspace{1cm} [22]

\[
I_d = 0
\]  \hspace{1cm} [23]

The controller then uses two PI controllers to determine the necessary voltages, given the actual current and requested current. The third block calculates the current through the motor given the voltages, as shown in Equations 24 and 25.

\[
\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q - \omega_e \frac{L_d}{L_q} i_d - \omega_e \frac{\psi_m}{L_q}
\]  \hspace{1cm} [24]

\[
\frac{d}{dt} i_d = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \omega_e \frac{L_q}{L_d} i_q
\]  \hspace{1cm} [25]

The torque produced by the electric machine is then calculated using the current through the machine, as shown in Equation 26.
\[ T_e = 1.5P[\lambda_m i_q + (L_q - L_d) i_d i_q] \]  \[26\]

The addition of Equations 24 and 25 adds two states to the model, which adds dynamics into the production of torque.

**3-Phase Modeling of an Electric Machine**

A diagram of the EDS block for a 3-Phase model is shown in Figure 19.

![Figure 19 - EDS Block of 3-Phase Model](image)

The 3-Phase model consists of eight different blocks, three of which are unique. The transformation from a two-axis model to a three-phase model is done through Clark’s and Park’s transformation, as shown in Equation 27.

\[
\begin{bmatrix} v_q \\ v_d \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}
\]  \[27\]

The two additional unique blocks will be expanded upon in the following section. The current and torque calculations are identical to the DQ-Axis model, with the only
difference being the controller, inverter model, and conversions so that the inverter model can be used with the DQ-Axis electric machine model. Therefore, the dynamics present in the 3-Phase model are identical to the dynamics present in the DQ-Axis model.

**Electric Machine Model Capabilities**

The electric machine model capabilities are shown in Table 6.

<table>
<thead>
<tr>
<th>Models</th>
<th>Trnst</th>
<th>SS</th>
<th>DSA</th>
<th>CLA</th>
<th>EMLC</th>
<th>PSC</th>
<th>FDP</th>
<th>MIL</th>
<th>SIL</th>
<th>HIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Map based model</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
</tr>
<tr>
<td>DQ Axis model</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
</tr>
<tr>
<td>3ø DQ Axis model</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
</tr>
</tbody>
</table>

The map based electric machine model tracks the steady state response and not the transient torque response. Therefore, it cannot be used for the electric machine level controller (EMLC) development, unlike the DQ-Axis and 3-Phase models. However, all models provide an accurate enough torque response for powertrain supervisory controller development. Additionally, the DQ-Axis and 3-Phase models cannot be used in HIL simulations because they cannot be run in real-time.
3.3 Inverter Modeling

Inverter modeling consists of two parts, the controller and the inverter itself, as shown in Figure 20.

![Figure 20- Inverter Modeling](image)

The controller determines the switching logic that is fed into the inverter model. The controller is modeled using three relays, which switch on when the magnitude of the current demand through a phase is large enough. The states of the other three switches are then determined using the compliment of the first three switches.

The diagram of an inverter is shown in Figure 21.
The inverter consists of six switches that switch in a pattern to make the desired 3-Phase current. All of the inverters modeled in this study are modeled with this design. The switching table is shown in Table 7.

Table 7- Switching Table for Ideal Switching Inverter

<table>
<thead>
<tr>
<th>Switch Signals</th>
<th>$V_a$</th>
<th>$V_b$</th>
<th>$V_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>$V_{dc}/2$</td>
<td>$-V_{dc}/2$</td>
<td>$-V_{dc}/2$</td>
</tr>
<tr>
<td>110</td>
<td>$V_{dc}/2$</td>
<td>$V_{dc}/2$</td>
<td>$-V_{dc}/2$</td>
</tr>
<tr>
<td>010</td>
<td>$-V_{dc}/2$</td>
<td>$V_{dc}/2$</td>
<td>$-V_{dc}/2$</td>
</tr>
<tr>
<td>011</td>
<td>$-V_{dc}/2$</td>
<td>$V_{dc}/2$</td>
<td>$V_{dc}/2$</td>
</tr>
<tr>
<td>001</td>
<td>$-V_{dc}/2$</td>
<td>$-V_{dc}/2$</td>
<td>$V_{dc}/2$</td>
</tr>
<tr>
<td>101</td>
<td>$V_{dc}/2$</td>
<td>$-V_{dc}/2$</td>
<td>$V_{dc}/2$</td>
</tr>
<tr>
<td>000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>111</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 7 refers to the states of the upper switches (T1, T3, and T5). The lower switches are compliments of the upper switches. The details of the four different inverter models are elaborated on below.

**Efficiency-Based Modeling of an Inverter**

An inverter can be modeled using an efficiency value, similar to an electric machine. The efficiency is multiplied by the electric machine efficiency when determining the power request from the electric drive system, as shown in Equation 28.

\[
\eta_{EDS} = \eta_{EM}\eta_{INV}
\]

This efficiency is also often included in the EM efficiency map. Therefore, instead of having two different efficiencies, \(\eta_{EM}\) and \(\eta_{INV}\), only one efficiency map, \(\eta_{EDS}\), is used. This neglects all dynamics present in the inverter.

**Ideal Switches**

The ideal switching inverter model assumes ideal switches, capacitors, and diodes, meaning that the resistance through the switch is zero. The model consists solely of switches that determine what the voltage through the switch is. This model neglects losses in the inverter switching dynamics, but does model the inverter switching dynamics. Therefore, the voltage, current, and torque through the electric machine fluctuate.

**IGBT**

An IGBT, or an insulated-gate bipolar transistor, acts as an electronic switch. It has both high speed switching performance as well as large current processing performance [16]. Switching power loss and speed both impact the fuel economy and
performance of electrified vehicles, therefore development of accurate models to predict device performance is important. The IGBT inverter model consists of six SimPowerSystems IGBT models connected in an arrangement similar to Figure 21. The model includes resistances within the IBGTs, so the system dynamics and losses are both modeled.

**MOSFET**

A MOSFET, or metal-oxide-semiconductor field-effect transistor, acts as an electronic switch, similar to an IGBT. MOSFETs have many applications within the vehicle, including within the electric drive system [17]. The MOSFET model consists of six SimPowerSystems MOSFET models connected in an arrangement similar to Figure 21. Similar to the IGBT model, the resistance is included, so both system dynamics and losses are modeled.

**SimPower Systems**

The SimPower Systems model consists of the generic Universal Bridge model in SimPower Systems. This model can be set to MOSFET, IGBT, or ideal switches. For the purposes of this study, this model is set to MOSFET. This will allow direct comparison between the inverter modeled as a combination of six MOSFET models, and the inverter modeled as a single MOSFET inverter.

**Inverter Model Capabilities**

The inverter model capabilities are described in Table 8.
Table 8- Inverter Model Capabilities

<table>
<thead>
<tr>
<th>Models</th>
<th>Trnst</th>
<th>SS</th>
<th>DSA</th>
<th>CLA</th>
<th>EMLC</th>
<th>PSC</th>
<th>FDP</th>
<th>MIL</th>
<th>SIL</th>
<th>HIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency based model</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
</tr>
<tr>
<td>Ideal Switch based 3ø</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
</tr>
<tr>
<td>Inverter Model</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
<td>☒</td>
</tr>
</tbody>
</table>

The inverter efficiency model only tracks the steady state response, unlike the ideal switch and component-based models. For this reason, the component and ideal switching models are the only models that can be used for EMLC development. However, the dynamics are so fast that all models can be used for supervisory controller development.

The inverter switching dynamics operate in the microseconds, so these models don’t run in real time. However, special equipment, such as the DS5202 I/O board, can be used to run these models in HIL simulations.

3.4 Electric Drive System Fidelities

The electric drive system model fidelities are compared in Table 9.
The electric drive system fidelities are compared separately for the electric machine and the inverter. The lowest fidelity for both components is the efficiency map. The DQ-Axis model includes the electric machine system dynamics, however, the 3-Phase model is a higher fidelity because it includes the actual currents and voltages that are present in the system. The component level models are higher fidelity than the ideal switch model, because they include the inverter resistance and other parameters in the model, as well as the switching dynamics.
4.1 Conventional Vehicle Architecture and Components

The vehicle in this system level analysis is a wheel loader, shown in Figure 22.

Figure 22- Wheel Loader

The system level architecture of the conventional wheel loader is shown in Figure 23.
A hydraulic pump is attached to the engine through a gear train connected to the crankshaft. This gear train is connected to a torque converter, which connects to an automatic transmission, and then through the final drive to the wheels. The hydraulic pump powers the shovel, as well as other hydraulic loads, which are lumped together. The engine is described in Table 10.

Table 10- Engine Data

<table>
<thead>
<tr>
<th>Engine</th>
<th>Model</th>
<th>Size</th>
<th>Peak Power</th>
<th>Peak Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cummins ISB</td>
<td>5.9L</td>
<td></td>
<td>223kW @ 2500 RPM</td>
<td>895 Nm @ 1600 RPM</td>
</tr>
</tbody>
</table>

In the conventional vehicle, the only source of power for the hydraulic pump and vehicle is the engine; therefore all power to the pump and wheels needs to be produced by the engine. The transmission is described in Table 11.
Table 11- Transmission Data

<table>
<thead>
<tr>
<th>Gear</th>
<th>3R</th>
<th>2R</th>
<th>1R</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear Ratios</td>
<td>1.126</td>
<td>2.368</td>
<td>4.278</td>
<td>4.278</td>
<td>2.368</td>
<td>1.126</td>
<td>0.648</td>
</tr>
</tbody>
</table>

Note that the transmission has multiple gears in reverse, which is unusual for a vehicle simulation. However, due to the nature and use of a wheel loader, it can be necessary to use multiple gears while driving in reverse.

4.2 Vehicle Drive Cycle

The vehicle drive cycle is shown in Figure 24.

![Vehicle Velocity Profile](image)

**Figure 24- Vehicle Velocity Profile**

The velocity profile is low speed, with a maximum velocity of 11 km/hr and a total cycle time of 38 seconds. The velocity profile specifies both positive and negative velocities. In fact, the maximum vehicle velocity over the cycle is actually negative. However, due
to the nature of the simulator, negative vehicle speeds cannot be used. Therefore, the velocity profile that is used during simulation is shown in Figure 25.

![Vehicle Velocity Profile](image)

**Figure 25- Vehicle Velocity Profile Used During Simulation**

This vehicle velocity profile contains the absolute value of the profile shown in Figure 24. The vehicle weight duty cycle is shown in Figure 26.

![Vehicle Weight Duty Cycle](image)

**Figure 26- Vehicle Weight Duty Cycle**
The weight of the vehicle increases five tons from 11 seconds to 28 seconds, which simulates picking up dirt with the shovel and later dumping it. The torque on the engine from the shovel is shown in Figure 27.

![Hydraulic Torque (Nm)](image)

**Figure 27- Engine Load Torque from Shovel**

The hydraulic motor always requires at least 132 Nm due to the shovel, with a maximum loading of 555.8 Nm. The load on the engine due to other hydraulic loads is modeled using Figure 28.

![Load on Engine](image)

**Figure 28- Load on Engine**
The accessory hydraulic load on the engine is determined by the engine speed. However, the torque on the engine is around 50 Nm for the entire operating range of the engine.

**4.3 Description of Simulator**

The vehicle simulator is a forward-simulator, meaning that torque is the input and the vehicle speed is the output to the simulation, as shown in Figure 29.

![Figure 29- Example of Forward Simulator](image)

The speed of each component is a model state, which is the reason why a forward-simulator captures the dynamics present in the system. However, a forward simulator requires the presence of a well-tuned driver model so that the vehicle follows the requested drive cycle. A poorly tuned driver model may fail to follow the drive cycle. Therefore, when using a forward-simulator, it is important to always compare the simulated vehicle velocity against the desired vehicle velocity to ensure that the vehicle is meeting the performance requirements defined by the drive cycle.
4.4 Conventional Drive Cycle Results

The conventional wheel loader was simulated over the drive cycle. The vehicle velocity is shown in Figure 30.

![Figure 30- Conventional Vehicle Velocity with P=3](image)

The vehicle follows the desired velocity profile for the majority of the cycle. However, the vehicle doesn’t reach the peak velocity or come to a complete stop. Therefore, the proportional gain in the drive was increased from P=3 to P=10. The resultant vehicle velocity is shown in Figure 31.
The increase in proportional gain causes the vehicle to reach the peak speeds requested by the drive cycle as well as reach a complete. The more aggressive driver causes additional fluctuations in engine torque and speed, as compared to the less aggressive driver. The engine speeds are compared in Figure 32.
The engine speeds follow the same profile, because the vehicle velocities follow the same profile. However, the vehicle with \( P=10 \) has much larger fluctuations in engine speed, as compared to the vehicle with \( P=3 \). The torques produced by the engines are compared in Figure 33.

![Engine Torque Comparison for P=10 and P=3](image)

Figure 33- Engine Torque Comparison for P=10 and P=3

The engine torque fluctuates in a similar manor as the engine speed. The high proportional gain causes the driver model to request maximum torque from the engine one instant, and request zero torque from the engine the next instant. A closer look is shown in
In the first five seconds of the simulation with the aggressive driver, the engine oscillates from full torque to zero torque multiple times per second. While it is common for wheel loaders to be operated aggressively, the near instantaneous change from full-throttle to zero-throttle is unrealistic. Therefore, the smoother operating driver with P=3 will be used for the remainder of this study.

4.5 Hybrid Vehicle Architecture and Components

The vehicle was hybridized by connecting an electric machine to the gear train attached to the engine and hydraulic pump, as shown in Figure 35.
The electric machine is attached to an inverter and a battery pack. The electric machine can use regenerative braking to charge the battery pack, as well as supply power to the wheels through the gear train. The battery pack is described in Table 12.

Table 12- Battery Pack

| Battery Pack | 7.2 kWh | 43.2 V | 167 Ah |

The electric machine was sized based-off the maximum power capabilities of the battery. The maximum allowable current of the battery pack is a function of the capacity of the battery. The C-Rate of a battery defined as the amount of continuous current that can
discharge a battery in one hour. A C-Rate of two discharges a battery in half an hour. The electric-machine was sized to a peak power of 30 kW, so the battery C-Rate wouldn’t exceed 4.2. The amount of regenerative braking that a 30 kW motor can provide using the drive cycle shown in Figure 25 is shown in Figure 36.

![Figure 36- Percentage of Regenerative Braking Available](image)

A 30 kW motor can regenerate 65% of the possible energy to be regenerated in a given cycle. Every time the vehicle needs to apply more than 30 kW of braking energy, the vehicle must use the friction brakes, and that energy can’t be recovered. A larger machine would be able to regenerate a larger percentage of braking energy, but the battery would then see higher currents, which would be detrimental to the aging of the battery.
4.6 Hybrid Control Development

A conventional vehicle provides torque to the wheels through only the engine, as shown in Figure 37.

![Figure 37- Conventional Vehicle Control Diagram](image)

However, the hybrid vehicle has two sources of power, the engine and the electric machine. This creates a need for a supervisory controller to determine the torque split between the engine and electric machine, as shown in Figure 38.

![Figure 38- Hybrid Vehicle Control Diagram](image)
The supervisory controller takes the driver throttle signal and turns it into a torque request for the electric machine and a throttle signal for the engine. The two torques are then summed to get the torque provided to the wheels.

The supervisory controller is designed to be rule-based. It operates in two main modes, regenerative braking, when the engine produces zero torque and the electric machine takes power from the wheels, and supplying power to the wheels, when both the engine and electric machine produce a net positive torque. The first mode is described by Figure 39.

![Figure 39- Regenerative Braking](image)

The driver requests that the vehicle brakes by applying the brake pedal. The goal of regenerative braking is to recover as much energy as possible, but the vehicle must also be able to provide sufficient stopping power when necessary. On the conventional
vehicle, the drivers brake signal is between 0-1, which represents the fraction of the total braking power the vehicle can produce.

On the hybrid vehicle, for the first 50% of beta, the braking power comes entirely from the electric machine. When the driver commands a beta of 50% or less, the vehicle recovers the maximum possible braking energy. At $\beta = 50\%$, the electric machine commands maximum torque. At $\beta > 50\%$, the conventional brakes are applied to the wheels so that the vehicle can follow the requested drive cycle.

The torque supplied to the wheels is determined linearly through the throttle signal, with 0 corresponding to no torque to the wheels and 1 corresponding to maximum torque to the wheels. Maximum torque to the wheels is defined by the maximum engine torque at the given speed plus the maximum electric machine torque at the given speed, as shown in Equation 29.

$$T_{\max,\text{wheels}} = T_{\max,EM} + T_{\max,\text{Engine}}$$  \[29\]

The engine is the same for the hybrid vehicle as the conventional vehicle, therefore the hybrid vehicle can actually deliver more torque to the wheels than the conventional vehicle. The amount of torque provided by the electric machine is illustrated in Figure 40.
The amount of torque provided by the electric machine is determined by the battery SOC. At 50% SOC, the electric machine provides full torque to the wheels, and at 30% SOC, the electric machine provides zero torque to the wheels. This is done so that the vehicle is self-balancing in terms of SOC. That is, after a sufficient amount of vehicle cycles, the battery will settle at an SOC that allows it to be charge balancing over a given vehicle cycle. The vehicle supervisory controller is described in Figure 41.

Figure 41- Vehicle Supervisory Controller
The electric machine torque is determined using the algorithm described above and the battery SOC. The engine torque is then determined by subtracting the torque provided by the electric machine from the total torque request to the wheels.

4.7 Hybrid Vehicle Results

The hybrid vehicle was simulated over the drive cycle, and the vehicle speed trace is shown in Figure 42.

![Hybrid Vehicle Speed Trace](image)

Figure 42- Hybrid Vehicle Speed Trace

The hybrid and conventional speed traces are very similar. The fuel consumption of the conventional and hybrid vehicles are compared in Table 13.

<table>
<thead>
<tr>
<th>Table 13- Comparison of Conventional and Hybrid Vehicle Fuel Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumption (kg)</td>
</tr>
<tr>
<td>-----------------------</td>
</tr>
<tr>
<td>0.2068</td>
</tr>
</tbody>
</table>
The hybrid vehicle sees a reduction in fuel consumption of 5.8%. The electric machine efficiency map is shown in Figure 43.

![Figure 43- Electric Machine Efficiency Map](image)

The electric machine has a gear ratio of 3:1. This is done in order to move most of the operating points to a region above 90% efficient. The battery SOC is shown in

60
There is very little change in battery SOC over the cycle. Even though Figure 44 shows that the SOC is flat, there are small changes over the cycle. However, they are so small because the cycle time is very short, and doesn’t leave much time to discharge the battery. Also, the battery is very large compared to the demands of the drive cycle. The battery C-Rate over the cycle is shown in Figure 45.
This confirms the assumption that was previously made that the C-Rate never exceeds 4.2 C. This means that even though the amount of energy in the battery doesn’t change much over the cycle, the full battery power capabilities are being utilized under the current supervisory controller.
5.1 Design of Experiments

The goal of this fidelity study is to determine the impact of different model fidelities on a system level simulation. The different combinations of battery models that will be studied are shown in Table 14.

Table 14- Battery Model Combinations

<table>
<thead>
<tr>
<th>Battery Models</th>
<th>Electrical Models</th>
<th>ECM 1st Order</th>
<th>ECM 0th Order</th>
<th>Thermal Model</th>
<th>Lumped</th>
<th>Reduced Order</th>
<th>Lumped</th>
<th>Reduced Order</th>
<th>Aging Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interconnected Model</td>
<td>ECM 1st Order</td>
<td>---------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PHEV</td>
</tr>
</tbody>
</table>

63
There are two models for each subsystem and the interconnected model. Therefore, there are nine different possible combinations of battery models. There aren’t any limitations on battery model interactions, so every electrical model can interact with every thermal and aging model. The different combinations of the electric drive system models are shown in Table 15.

**Table 15 - Different Combinations of Electric Drive System Models**

<table>
<thead>
<tr>
<th>Electric Drive Models</th>
<th>EM models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency-Based</td>
<td>DQ-Axis</td>
</tr>
<tr>
<td>Inverter Model</td>
<td>Efficiency-Based</td>
</tr>
</tbody>
</table>

The level of inverter model depends heavily on the level of electric drive model. For an efficiency-based or DQ-Axis electric drive model, only an efficiency-based inverter model can be used. However, once the 3-Phase current through the electric machine is modeled, the inverter switching dynamics can be then modeled. However, if the model includes either the DQ-Axis or the 3-Phase models, the simulation time-step must be reduced because of the fast electrical dynamics in the model. The time-step for the efficiency-based electric machine models is 0.02 seconds, but the time-step for the DQ-Axis and 3-Phase models is 0.00001 seconds, so there are 2000 simulation steps for every simulation step in an efficiency-based model. This greatly increases the time of simulation.
The hybrid simulator will be run with every combination of the different models. This results in 54 total simulations. The results of each simulation will be evaluated in order to determine differences in the system level simulation. The results that will be observed are shown in Table 16.

**Table 16- Results of Simulations to be Compared**

<table>
<thead>
<tr>
<th>Evaluate Difference In:</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumption</td>
<td>kg of fuel consumed</td>
</tr>
<tr>
<td>Simulation Run Time</td>
<td>real time it takes to run simulations (s)</td>
</tr>
<tr>
<td>Ability to Track Duty Cycle</td>
<td>If the vehicle tracks the duty cycle or not</td>
</tr>
<tr>
<td>Battery Aging</td>
<td>Loss in capacity (%)</td>
</tr>
<tr>
<td>Change in Battery SOC</td>
<td>Change in Battery SOC (%)</td>
</tr>
</tbody>
</table>

**5.2 Model Calibration**

The simulations that include different models will be compared against each other. Therefore, each model must be calibrated to the same set of data. This is done so that any difference between outputs is due to the model itself, as opposed to the parameters used in the model.

**Electrical Subsystem**

The battery models for the electrical subsystem were calibrated to the same cell. The model was run given a power request, and the current is shown in Figure 46.
Figure 46- Electrical Subsystem Calibration- Current

The output of the model is the voltage response of the battery pack, shown in Figure 47.

Figure 47- Electrical Subsystem Calibration- Voltage
The differences in battery voltage are due to the 1\textsuperscript{st} order dynamics modeled by the 1\textsuperscript{st} order model. The additional RC circuit models dynamics that aren’t present in the 0\textsuperscript{th} order model. The battery SOC is shown in Figure 48.

![Battery SOC Graph]

Figure 48- Electrical Subsystem Calibration- Battery SOC

The battery SOC is calculated using the current profile, so each model experiences the same SOC over the simulation. The heat generated by the battery is shown in Figure 49.
The heat generated by the battery is calculated in a similar manor as the change in voltage, so the difference in heat generated is expected.

**Thermal Subsystem**

The pack level models of the thermal subsystem are the reduced order and lumped parameter models. The models were calibrated so that both packs had the same thermal capacity and removed the same amount of heat. The battery temperature over the above simulation is shown in Figure 50.
The temperature of each pack are very similar, however, there are slight differences. This is due to the assumptions made in the lumped parameter model, where the thermal properties of the pack were assumed to be homogeneous.

**Aging Subsystem**

The capacity loss of the two aging models is compared in Figure 51.
The difference in the two models can be attributed to the difference in the formulas used to calculate the loss in capacitance. The capacity loss for the HEV model is shown in Equation 14, and contains the SOC and the C-Rate. The capacity loss for the PHEV model doesn’t contain either the SOC or the C-Rate, but relies solely on the temperature and cumulative amp-hours that the battery has seen.

**Electric Drive System**

The models in the electric drive system are difficult to analyze separately, so they were calibrated as six models. Each model was subjected to a step increase in torque, which is shown in Figure 52.
The efficiency-based model doesn’t include dynamics, so this model responded to the torque increase instantaneously. The DQ-Axis model only includes the current dynamics within the electric machine, which are visible during simulation. The models that include the inverter dynamics create oscillations around the steady state torque. These models never truly reach a steady single torque value. The electric machine speeds during the simulations are shown in Figure 53.
Each of the models reaches a slightly different steady state speed. This is dependent on the average torque from the electric machine, meaning that each model produces a slightly different net torque. This is mainly due to the losses in the inverter.

5.3 Fidelity Study Results

The notation that will be used to describe the battery models is shown in Table 17.
Table 17- Battery Notation

<table>
<thead>
<tr>
<th>Battery Models</th>
<th>Electrical Models</th>
<th>Model</th>
<th>Aging Models</th>
<th>Model Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ECM 1st Order</td>
<td>Lumped</td>
<td>PHEV</td>
<td>B1</td>
</tr>
<tr>
<td></td>
<td>ECM 0th Order</td>
<td>Reduced</td>
<td>HEV</td>
<td>B2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Order</td>
<td>PHEV</td>
<td>B3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lumped</td>
<td>HEV</td>
<td>B4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reduced</td>
<td>PHEV</td>
<td>B5</td>
</tr>
<tr>
<td></td>
<td>Interconnected</td>
<td>Interconnected</td>
<td>HEV</td>
<td>B6</td>
</tr>
<tr>
<td></td>
<td>ECM 1st Order</td>
<td></td>
<td>PHEV</td>
<td>B7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HEV</td>
<td>B8</td>
</tr>
</tbody>
</table>

The notation that will be used to describe the electric machine models is shown in Table 18.

Table 18- EDS Notation

<table>
<thead>
<tr>
<th>Electric Drive System Models</th>
<th>Electric Machine Models</th>
<th>Inverter Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency-Based</td>
<td>Efficiency-Based</td>
</tr>
<tr>
<td></td>
<td>DQ-Axis</td>
<td>Ideal Switch</td>
</tr>
<tr>
<td></td>
<td>3-Phase</td>
<td>IGBT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MOSFET</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulink</td>
</tr>
<tr>
<td>EM1</td>
<td>EM2</td>
<td>EM3</td>
</tr>
<tr>
<td>EM4</td>
<td>EM5</td>
<td>EM6</td>
</tr>
</tbody>
</table>

Every cycle that was simulated followed the drive cycle correctly. The next metric that was examined is fuel consumption. The fuel consumption of the vehicle over the drive cycle for every model is shown in Table 19.
Table 19- Vehicle Fuel Consumption with Different Model Fidelities

<table>
<thead>
<tr>
<th></th>
<th>EM1</th>
<th>EM2</th>
<th>EM3</th>
<th>EM4</th>
<th>EM5</th>
<th>EM6</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
</tr>
<tr>
<td>B2</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
</tr>
<tr>
<td>B3</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
</tr>
<tr>
<td>B4</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
</tr>
<tr>
<td>B5</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
</tr>
<tr>
<td>B6</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
</tr>
<tr>
<td>B7</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
</tr>
<tr>
<td>B8</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
</tr>
<tr>
<td>B9</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The battery model fidelity has no impact on fuel consumption over the drive cycle. This is due to the fact that the only variable that the battery model fed back into the vehicle model is the SOC, which fed into the supervisory controller. The range of the battery SOC was very small over the 38 second simulation, so the change in the controller output over the cycle was very small. Therefore, the different battery pack models have limited impact over the vehicle fuel consumption. Similar to the results battery models, the model fidelity of the electric drive system did have an impact on the fuel economy. This means that the torque produced by each electric machine is identical, as shown in Figure 54.
The torque request to the DQ-Axis model is almost identical to the torque produced by the model. An additional look at the torque produced by the electric machine is shown in Figure 55.

Figure 54- Electric Machine Torque

Figure 55- Electric Machine Torque
The delivered torque has a very fast first-order response. Therefore, the torque requested isn’t equal to the torque produced during transient periods, however, these dynamics occur on the order of microseconds. This differs from a vehicle, which acts as a low-pass filter to these dynamics. The torque produced by the electric machine with the inverter is shown in Figure 56.

![Figure 56- EM with Inverter Torque](image)

The inverter causes oscillations around the requested torque. However, these oscillations have no impact on the vehicle fuel consumption. An additional look at the oscillations in the torque production is shown in Figure 57.
The inverter allows the model to follow the torque request during transient periods as well. Note that the MOSFET inverter and the Simscape generic inverter that was set to MOSFET produced identical fuel-consumption values. EM6 wasn’t simulated with B9 as a time saving measure. This is because EM6 and EM5 produced identical results for simulations with B1-8. The real-time it took each simulation to run is shown in Table 20.

Table 20- Simulation Run Time

<table>
<thead>
<tr>
<th>Simulation Time (s)</th>
<th>EM1</th>
<th>EM2</th>
<th>EM3</th>
<th>EM4</th>
<th>EM5</th>
<th>EM6</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>3.134</td>
<td>10903</td>
<td>11196</td>
<td>11848</td>
<td>10702</td>
<td>11098</td>
</tr>
<tr>
<td>B2</td>
<td>3.213</td>
<td>10525</td>
<td>11159</td>
<td>11828</td>
<td>11199</td>
<td>10811</td>
</tr>
<tr>
<td>B3</td>
<td>3.493</td>
<td>10296</td>
<td>11137</td>
<td>11920</td>
<td>11401</td>
<td>11603</td>
</tr>
<tr>
<td>B4</td>
<td>3.371</td>
<td>10712</td>
<td>11600</td>
<td>12685</td>
<td>11853</td>
<td>11280</td>
</tr>
<tr>
<td>B5</td>
<td>2.934</td>
<td>10275</td>
<td>10846</td>
<td>11719</td>
<td>11320</td>
<td>11963</td>
</tr>
<tr>
<td>B6</td>
<td>3.066</td>
<td>10698</td>
<td>10715</td>
<td>11805</td>
<td>11279</td>
<td>10952</td>
</tr>
<tr>
<td>B7</td>
<td>3.455</td>
<td>10771</td>
<td>10899</td>
<td>12135</td>
<td>11108</td>
<td>11851</td>
</tr>
<tr>
<td>B8</td>
<td>3.378</td>
<td>11570</td>
<td>11361</td>
<td>12075</td>
<td>11435</td>
<td>11570</td>
</tr>
<tr>
<td>B9</td>
<td>18.916</td>
<td>39933</td>
<td>39728</td>
<td>39820</td>
<td>40388</td>
<td>N/A</td>
</tr>
</tbody>
</table>
The efficiency-map electric machine model completes the simulation in less than 20 seconds, even with the interconnected battery model. This is the opposite of the DQ-Axis models, where the fastest simulation was completed in almost three hours and the longest took three and a half hours. There isn’t a trend in simulation time between different simulations with the DQ-Axis or 3-Phase electric machine models.

The interconnected battery model took 19 seconds to simulate, where the median time for the lumped pack models was 3.3 seconds. Simulating the interconnected battery model with the DQ-Axis electric machine model increased simulation time to a maximum of 11 hours and 13 minutes. There isn’t a trend in simulation time, however, for the lumped pack models. This non-trend includes 1st and 0th order equivalent circuit models, even though it was previously assumed that a 0th order model would run much quicker than a 1st order model. A boxplot of Table 20 is shown in Figure 58.

Figure 58- Boxplot of Simulation Time
The interconnected battery models are shown as the outliers in all cases. Therefore, the boxplot is shown again without the interconnected models in Figure 59.

![Boxplot of Simulation Time](image)

**Figure 59- Boxplot of Simulation Time**

Figure 59 shows that EM2 runs faster than EM3, EM4, EM5, and EM6, however, there is no distinction between EM3, EM4, EM5, and EM6.

Only the battery capacity loss will be analyzed when comparing the battery aging models. This is because the HEV model computes the loss in capacity and the severity factor, and the PHEV model computes the loss in capacity and increase in resistance. The difference in battery capacity loss is shown in Table 21.
The difference in battery capacity loss between the electric drive system models is less than 1%. Similarly, the difference in capacity loss between the different electrical and thermal models is below 5%. This is illustrated in Figure 60 and Figure 61, respectively.

![Boxplot of Capacity Loss](image)

**Figure 60- Boxplot of Capacity Loss**
However, the aging models provide significant differences in the capacity loss. The HEV model consistently calculates a greater capacity loss than the PHEV model. This is illustrated in Figure 62.

Figure 61- Boxplot of Capacity Loss

Figure 62- Boxplot of Capacity Loss
This is due to differences in the algorithms that compute battery aging. The HEV model computes the capacity loss using the SOC and C-Rate, as shown in Figure 63.

- **HEV**

\[
Q_{\text{loss},\%} = (\alpha \cdot \text{SOC} + \beta) \exp\left(\frac{E_a + 163.3 \cdot C \cdot R}{R \cdot T}\right) \cdot \text{Ah}^{0.57}
\]

- **PHEV**

\[
S_{\text{loss}} = \alpha_c (\text{SOC}_{\text{init}}, \text{Ratio}) \cdot \exp\left(\frac{-E_{\text{s}}}{R \cdot T}\right) \cdot \text{Ah}
\]

where,

\[
\alpha_c() = \alpha_c + \beta_c \cdot (\text{Ratio})^2 + \gamma_c \cdot (\text{SOC}_{\text{init}} - \text{SOC}_c)
\]

Figure 63- Difference in Capacity Loss Algorithms

The change in SOC over the cycle is shown in Table 22.

**Table 22- Change in SOC**

<table>
<thead>
<tr>
<th></th>
<th>EM1</th>
<th>EM2</th>
<th>EM3</th>
<th>EM4</th>
<th>EM5</th>
<th>EM6</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>-0.0264</td>
<td>-0.0263</td>
<td>-0.0261</td>
<td>-0.0260</td>
<td>-0.0260</td>
<td>-0.0260</td>
</tr>
<tr>
<td>B2</td>
<td>-0.0263</td>
<td>-0.0263</td>
<td>-0.0261</td>
<td>-0.0259</td>
<td>-0.0259</td>
<td>-0.0259</td>
</tr>
<tr>
<td>B3</td>
<td>-0.0264</td>
<td>-0.0263</td>
<td>-0.0261</td>
<td>-0.0260</td>
<td>-0.0260</td>
<td>-0.0260</td>
</tr>
<tr>
<td>B4</td>
<td>-0.0263</td>
<td>-0.0262</td>
<td>-0.0261</td>
<td>-0.0259</td>
<td>-0.0259</td>
<td>-0.0259</td>
</tr>
<tr>
<td>B5</td>
<td>-0.0258</td>
<td>-0.0257</td>
<td>-0.0256</td>
<td>-0.0254</td>
<td>-0.0254</td>
<td>-0.0254</td>
</tr>
<tr>
<td>B6</td>
<td>-0.0258</td>
<td>-0.0257</td>
<td>-0.0255</td>
<td>-0.0254</td>
<td>-0.0254</td>
<td>-0.0254</td>
</tr>
<tr>
<td>B7</td>
<td>-0.0258</td>
<td>-0.0257</td>
<td>-0.0256</td>
<td>-0.0254</td>
<td>-0.0254</td>
<td>-0.0254</td>
</tr>
<tr>
<td>B8</td>
<td>-0.0258</td>
<td>-0.0254</td>
<td>-0.0255</td>
<td>-0.0254</td>
<td>-0.0254</td>
<td>-0.0254</td>
</tr>
<tr>
<td>B9</td>
<td>-0.5179</td>
<td>-0.5114</td>
<td>-0.5082</td>
<td>-0.5055</td>
<td>-0.5055</td>
<td>N/A</td>
</tr>
</tbody>
</table>

82
The change in SOC over the cycle doesn’t depend on which lumped pack model is used or which electric drive model is used. However, when using the interconnected battery model, the battery has a lower SOC. This is illustrated in Figure 64.

![Figure 64- Box Plot of Change in SOC](image)

Figure 64 shows that the interconnected models are outliers in each of the simulations. The boxplot without the outliers is shown in
Figure 65- Box Plot of Change in SOC

Figure 65 shows that the means of each simulation are within 0.0005% of the SOC. The interconnected model tracks the SOC of each individual cell instead of the pack, so the pack SOC must be calculated as the sum of the individual cells. This is done by estimating the pack capacity and comparing it to the current delivered by the pack. The capacity of an individual string of cells is the minimum capacity in the string of cells, assuming passive equalization [18]. The capacity of cells in parallel is the number of cells in parallel multiplied by the average of the cell capacities. This means that any cell that is aging faster than other cells negatively impacts the battery capacity.

5.4 Fidelity Study Conclusions

There are some interesting conclusions that can be made from this study that applies to future work. The first is that the level of electric drive system fidelity doesn’t
impact the battery system. Similarly, the level of battery fidelity doesn’t impact the
electric machine system. Therefore, any additional studies that pertain to the battery
system can be performed with the lowest fidelity electric drive system model. This not
only reduces the amount of simulations that need to be performed, but also the time of
those simulations, because the model fidelities can be chosen in a way that minimizes the
overall simulation time.

The second conclusion is that the model fidelity selection has no impact on
vehicle fuel consumption. This is because the lower fidelity models successfully track the
energy flow through the component, and the energy flow is the part of the model that
impacts fuel consumption. The third conclusion is that the selection of model fidelity has
a large impact on simulation time. This is due to the complexity of the selected model as
well as the minimum time-step required by the model.
CHAPTER 6: ADDITIONAL STUDIES

6.1 Time-Step Study

The above fidelity study was performed at two different time-steps. The next study determines the impact of the time-step on a system level analysis. EM1 was simulated with B1-9 at three different time-steps, 0.00001, 0.02, and 0.1. The fuel consumption of the vehicle is shown in Table 23.
Table 23- Time-Step Fuel Consumption

<table>
<thead>
<tr>
<th>Simulation Timestep</th>
<th>EDS- Eff Eff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>B1</td>
<td>0.184</td>
</tr>
<tr>
<td>B2</td>
<td>0.184</td>
</tr>
<tr>
<td>B3</td>
<td>0.184</td>
</tr>
<tr>
<td>B4</td>
<td>0.184</td>
</tr>
<tr>
<td>B5</td>
<td>0.184</td>
</tr>
<tr>
<td>B6</td>
<td>0.184</td>
</tr>
<tr>
<td>B7</td>
<td>0.184</td>
</tr>
<tr>
<td>B8</td>
<td>0.184</td>
</tr>
<tr>
<td>B9</td>
<td>0.184</td>
</tr>
</tbody>
</table>

The smallest time-step caused slightly lower fuel consumption than the finer time-steps. This is due to the resolution of the simulation. The simulation time is shown in Table 24.

Table 24- Time-Step Simulation Time

<table>
<thead>
<tr>
<th>Simulation Timestep</th>
<th>EDS- Eff Eff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>B1</td>
<td>1.87</td>
</tr>
<tr>
<td>B2</td>
<td>1.88</td>
</tr>
<tr>
<td>B3</td>
<td>3.59</td>
</tr>
<tr>
<td>B4</td>
<td>1.91</td>
</tr>
<tr>
<td>B5</td>
<td>1.84</td>
</tr>
<tr>
<td>B6</td>
<td>1.85</td>
</tr>
<tr>
<td>B7</td>
<td>1.90</td>
</tr>
<tr>
<td>B8</td>
<td>1.91</td>
</tr>
<tr>
<td>B9</td>
<td>4.86</td>
</tr>
</tbody>
</table>

The time-step has a large impact on simulation time. Decreasing the time-step increases the simulation time. This is illustrated in Figure 66.
This shows how much larger simulation time is with a much smaller time-step. The larger two time-steps are shown in Figure 67.
This shows that the 0.02 time-step simulates slightly slower than the 0.1 time-step. The battery capacity loss is shown in Table 25.

<table>
<thead>
<tr>
<th>Simulation Timestep</th>
<th>EDS- Eff Eff</th>
<th>EDS- Eff</th>
<th>EDS- Eff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.02</td>
<td>0.00001</td>
</tr>
<tr>
<td>B1</td>
<td>2.80E-05</td>
<td>2.70E-05</td>
<td>2.70E-05</td>
</tr>
<tr>
<td>B2</td>
<td>5.95E-05</td>
<td>5.96E-05</td>
<td>5.99E-05</td>
</tr>
<tr>
<td>B3</td>
<td>2.80E-05</td>
<td>2.80E-05</td>
<td>2.80E-05</td>
</tr>
<tr>
<td>B4</td>
<td>5.99E-05</td>
<td>6.00E-05</td>
<td>6.02E-05</td>
</tr>
<tr>
<td>B5</td>
<td>2.60E-05</td>
<td>2.60E-05</td>
<td>2.60E-05</td>
</tr>
<tr>
<td>B6</td>
<td>5.72E-05</td>
<td>5.73E-05</td>
<td>5.75E-05</td>
</tr>
<tr>
<td>B7</td>
<td>2.60E-05</td>
<td>2.60E-05</td>
<td>2.60E-05</td>
</tr>
<tr>
<td>B8</td>
<td>5.75E-05</td>
<td>5.76E-05</td>
<td>5.79E-05</td>
</tr>
<tr>
<td>B9</td>
<td>2.54E-05</td>
<td>1.63E-05</td>
<td>2.51E-05</td>
</tr>
</tbody>
</table>

The only difference in capacity loss occurs in B9. The simulation at a time-step of 0.02 seconds produces a different capacity loss than the other two simulations. This is illustrated in Figure 68.
Multiple conclusions can be drawn from this simulation. First, the time-step has the largest impact on simulation time in the simulator. Second, the time-step has an impact on the capacity loss in the interconnected battery model. Third, the time-step has an impact on the fuel consumption if the time-step is too large.

6.2 Battery Aging Study

The next study that was performed focuses on the battery aging model, specifically the HEV aging model. The study determines the impact of temperature and initial capacity loss on the battery capacity loss. The B1 and EM1 model was simulated throughout the valid ranges of temperatures and initial capacity losses for the aging model. The fuel consumption is shown in Table 26.
The vehicle fuel consumption isn’t effected by the temperature or the initial capacity loss. This is due to the fact that the energy capabilities of the battery aren’t utilized, but the full power capabilities of the battery are utilized. Additionally, the HEV aging model only calculates the loss in capacity and neglects the increase in resistance of the battery while it ages. The capacity loss over the cycle is shown in Table 27.

Table 27- Battery Aging- Capacity Loss

<table>
<thead>
<tr>
<th>Battery Temperature [°C]</th>
<th>Battery Aging</th>
<th>Initial Capacity Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%</td>
<td>5%</td>
</tr>
<tr>
<td>15</td>
<td>3.87E-05</td>
<td>3.91E-05</td>
</tr>
<tr>
<td>30</td>
<td>7.40E-05</td>
<td>7.46E-05</td>
</tr>
<tr>
<td>45</td>
<td>1.34E-04</td>
<td>1.35E-04</td>
</tr>
<tr>
<td>60</td>
<td>2.27E-04</td>
<td>2.29E-04</td>
</tr>
</tbody>
</table>

As the temperature increases, the capacity loss increases. Similarly, as the initial capacity loss increases, the capacity loss decreases. This is illustrated in Figure 69.
The main driver in capacity loss is temperature. Battery initial capacity loss has an impact, however, this impact is much smaller than that of the temperature. The change in SOC over the cycle is shown in Table 28.

Table 28- Change in SOC

<table>
<thead>
<tr>
<th>Battery Aging</th>
<th>Initial Capacity Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>Battery Temperature</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
</tbody>
</table>

The temperature doesn’t impact the change in SOC over the cycle. However, as the initial capacity loss increases, the change in SOC over the cycle increases. This is because the...
battery has a smaller capacity, so when it delivers the same energy over the cycle with a smaller capacity, the decrease in SOC is larger. This is illustrated in Figure 70.

![Figure 70- Change in SOC](image)

The highest initial capacity loss has the largest change in SOC. However, the temperature has little to no impact on the change in SOC over the cycle.

In this application, the temperature and initial capacity loss don’t have an impact on fuel consumption. This is due to the nature of the aging models as well as the vehicle structure and the short drive cycle. Second, the temperature has a large impact on battery capacity loss. Initial capacity loss also has an impact on battery capacity loss. Third, the initial capacity loss has a large impact on the change in SOC over the cycle.
6.3 Parameterization Study

This study determined the impact of parameter variation on the system. B1 and EM1 were simulated, and the rolling resistant coefficient, mass duty cycle, accessory duty cycle, and hydraulic shovel duty cycle were all simulated at +/-25%. The three shovel torque profiles are shown in Figure 71.

![Shovel Torque Profiles](image)

Figure 71- Shovel Torque Profiles

The three vehicle mass profiles are shown in Figure 72.
The fuel consumption results are shown in Table 29.

### Table 29- Parameterization Study- Fuel Consumption [kg]

<table>
<thead>
<tr>
<th></th>
<th>75%</th>
<th>100%</th>
<th>125%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>0.163</td>
<td>0.187</td>
<td>0.213</td>
</tr>
<tr>
<td>Mass</td>
<td>0.183</td>
<td>0.187</td>
<td>0.190</td>
</tr>
<tr>
<td>Accessories</td>
<td>0.184</td>
<td>0.187</td>
<td>0.189</td>
</tr>
<tr>
<td>Hydraulic Torque</td>
<td>0.178</td>
<td>0.187</td>
<td>0.195</td>
</tr>
</tbody>
</table>

This is illustrated in Figure 73.
The largest variation in fuel consumption is due to the rolling resistance coefficient. This is because the largest source of losses in this application is rolling resistance. Mass has a smaller impact on fuel consumption, due to the presence of regenerative braking. The variation in torque demand on the engine from the accessories is small, so the resultant change in fuel consumption is also small. The variation in hydraulic torque produces the second highest variation in fuel economy.

The loss in battery capacity is shown in Table 30.
Table 30- Parameterization Study- Loss in Battery Capacity [-]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>75.00%</th>
<th>100%</th>
<th>125%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>5.65E-05</td>
<td>6.00E-05</td>
<td>6.35E-05</td>
</tr>
<tr>
<td>Mass</td>
<td>5.95E-05</td>
<td>6.00E-05</td>
<td>6.05E-05</td>
</tr>
<tr>
<td>Accessories</td>
<td>6.01E-05</td>
<td>6.00E-05</td>
<td>5.98E-05</td>
</tr>
<tr>
<td>Hydraulic Torque</td>
<td>6.07E-05</td>
<td>6.00E-05</td>
<td>5.93E-05</td>
</tr>
</tbody>
</table>

This is illustrated in Figure 74.

Figure 74- Boxplot of Battery Capacity Loss

Rolling resistance is the only parameter that impacts the loss in battery capacity. This is because there is an additional current demand from the battery, which is due to the losses caused by the rolling resistance.
The vehicle was also simulated over two additional drive cycles. The first drive cycle simulated low speed operation, as shown in Figure 75.

Figure 75- Low Speed Drive Cycle

This drive cycle has the equivalent velocity profile, however all of the speeds are half of the original speeds. The second drive cycle is a high speed drive cycle, as shown in Figure 76.
This drive cycle simulates an acceleration cycle that a car would perform. The cycle shows that the maximum velocity of the wheel loader is 3.7 m/s. The fuel economy results for the different drive cycles are shown in Table 31.

Table 31- Vehicle Drive Cycle- Fuel Economy

<table>
<thead>
<tr>
<th></th>
<th>Fuel Economy [mpg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Speed</td>
<td>0.6816</td>
</tr>
<tr>
<td>Standard</td>
<td>0.6284</td>
</tr>
<tr>
<td>High Speed</td>
<td>0.568</td>
</tr>
</tbody>
</table>

Fuel economy was used for comparison purposes instead of fuel consumption because the drive cycles don’t cover the same distance. Predictably, the low speed drive cycle achieves the highest fuel economy. Similarly, the high speed drive cycle achieved the
lowest fuel economy. The loss in battery capacity over the drive cycle is shown in Table 32.

Table 32- Vehicle Drive Cycle- Battery Capacity Loss

<table>
<thead>
<tr>
<th>Battery Capacity Loss [-]</th>
<th>Low Speed</th>
<th>Standard</th>
<th>High Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.47E-05</td>
<td>6.00E-05</td>
<td>7.21E-05</td>
</tr>
</tbody>
</table>

Similar to the fuel economy results, the loss in battery capacity is predictable. The low speed drive cycle has the lowest capacity loss, and the high speed cycle has the highest. This is due to the more aggressive usage of the powertrain, and in turn, the battery. The change in SOC over the drive cycle is shown in Table 33.

Table 33- Vehicle Drive Cycle- Change in SOC

<table>
<thead>
<tr>
<th>Change in SOC [%]</th>
<th>Low Speed</th>
<th>Standard</th>
<th>High Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.0039</td>
<td>-0.0263</td>
<td>-0.0338</td>
</tr>
</tbody>
</table>

The low speed drive cycle has the lowest change in SOC over the cycle, and the high speed cycle has the highest change in SOC. Again, this is due to the more aggressive usage of the powertrain.
CHAPTER 7: CONCLUSION

7.1 Significance of Work

The purpose of this research was to explore the development of a tool to use a hierarchy of simulation tools, focusing on different levels of fidelity. The battery and electric drive system were evaluated to determine subsystems of interest. The battery was comprised of three subsystems, electrical, thermal, and aging. The electric drive system was comprised of two subsystems, the inverter and the electric machine. Within each subsystem, common modeling techniques were analyzed and evaluated. These models were implemented into a vehicle model, specifically a wheel loader. The impact of the models on the vehicle level analysis was then studied.

How a vehicle simulator reacts to different fidelity models of batteries and electric machines was systematically and objectively determined. Then, the root causes of these differences were analyzed. The most noticeable result of the study was that the vehicle
fuel consumption was unaffected by the model fidelity. The electric drive system fidelity was also shown to have no impact on the battery system, and vice versa. This means that higher model fidelities should only be used when analyzing that particular system.

This study was then used as a basis for more studies done on the models and vehicle simulator. These studies analyzed the impact of various parameters on the simulator. The first study determined the impact of the time-step for the solver on the vehicle simulator. The second study analyzed the impact of different temperatures and initial battery capacity losses on how the battery ages. The third study then analyzed the impact of varying the parameters and drive cycles associated with the wheel loader.

7.2 Future Work

The next step of this project is to include additional models and features to the fidelity study. For instance, peak/continuous limits in could be included in the electric machine models. This differs from the electric machine in this thesis, which was assumed to always be operating in the continuous region. Also, thermal torque derating can be analyzed. This highlights how the inductance, resistance, and flux change when the temperature of the electric machine changes. Similarly, an electrochemical battery model could be included in this analysis. This also has the addition of an aging model that is developed using a first principles approach, as opposed to the semi-empirical approaches described above. Battery aging was analyzed in this project, however, the focus was on short term aging. Long term aging could be added, where the vehicle could
be simulated over repeating drive cycles to determine the true life of the battery, and if different models predict different lengths of battery life.

In this project, the impact of different model fidelities was determined on a vehicle level analysis. The differences in the model output was noted, however, it couldn’t be determined which model was more accurate. This is because there was never a physical vehicle to test and compare to. Therefore, the next step in this project lies in determining the accuracy of the different fidelity models. This requires obtaining a vehicle to test and calibrating all models to the vehicle. This would provide a baseline to compare the accuracy of the simulations.
BIBLIOGRAPHY


