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Replacing combustion engines with hydrogen fuel cells to power mining haul trucks: challenges and opportunities

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REPLACING COMBUSTION ENGINES WITH HYDROGEN FUEL CELLS TO POWER MINING HAUL TRUCKS: CHALLENGES AND OPPORTUNITIES

by

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ABSTRACT

With the proven advantage of higher energy density in hydrogen fuel cells over batteries, there is potential to apply fuel cells to power mining haul trucks. This study aims to evaluate the technical and economic feasibility of hydrogen fuel cell electric mine trucks as an alternative to current mine haul trucks. Specifically, the project: (1) developed an economic framework for evaluating the integration of renewable energy powered haul trucks into mining; and (2) applied vehicle drivetrain and energy simulation in Matlab/Simulink to elucidate the challenges and opportunities of incorporating hydrogen fuel cell technology into the current form factors of mine haul trucks. First, the study uses an optimization model to characterize the impact of production, market and policy parameters on a mining firm's decision of what types of trucks (with or without renewable technology) to deploy to minimize its overall costs, including costs associated with greenhouse gas emissions. Second, is an investigation of the significant technical challenges and opportunities associated with integrating hydrogen fuel cells in mining haul trucks using the vehicle drivetrain model and simulation experiments. The results show that even with green energy government incentives and levies for greenhouse gas emission, the cost of operating green energy trucks needs to be competitive to ensure they minimize a mining firm's cost. However, to utilize a hydrogen fuel cell truck in the mine, a new vehicle frame is likely required to support the integration of the technology. This would require financial and technical investments by original equipment manufacturers and mining firms to make the transition.

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NOMENCLATURE

Symbol	Description
AIM	American Innovation and Manufacturing.
CFC	Chlorofluorocarbon
CO2	Carbon dioxide
EPA	United States Environmental Protection Agency
GHG	Greenhouse gases
ICMM	International Council on Mining and Metals
HFCT	Hydrogen Fuel Cell Truck
HFC	Hydrofluorocarbons
TC	Total Cost
UN	United Nations
USA	United States of America

1. INTRODUCTION

1.1. BACKGROUND

This section introduces the motivation, scope and objective of the project. It provides background on climate change and GHG emission in mining.

1.1.1. Climate Change. Climate change is mainly due to human activities such as the use of fossil fuel as a source of energy [1]. Greenhouse gases (GHG) are a byproduct of burning fossil fuels, causing the global temperature to rise [2]. Carbon dioxide and methane are prevalent examples of GHG emitted from burning fossil fuels like oil and gas [2]. Energy, transportation, and agriculture are among some of the significant GHG emitters. Some of the activities within these industries that contribute to GHG emissions include using diesel as fuel to power equipment and to generate electricity [1].

In the quest to overcome climate challenges, governments around the world agreed to the Paris Agreement to combat climate change. The Paris Climate Accord, an international treaty that ensures member countries prioritize remedy plans and actions that uphold the goal of limiting global warming to below 2°C, requires member countries to outline remedy plans of climate actions based on the best science available [3]. The United States is a signatory to the Paris Climate Accord.

The United States Environmental Protection Agency (EPA) is taking action across all industries by formulating regulations and standards to reduce GHG emissions to protect the environment. For example, the EPA is providing regulations and standards for vehicles, which will improve the adoption of alternative energy sources in both passenger cars and medium-heavy duty vehicles. This is projected to help avoid 3 billion tons of GHG emissions by 2050 [4].

The effect of the Paris Climate Accord among member states has spread across many industries. However, to meet the 2°C goal, there is a need for a more aggressive transition to sustainable ways of performing our social and industrial activities. Industries worldwide, especially in the top 10 countries with the most emission, are looking to adopt more sustainable means of producing energy and performing activities since they contribute to 68% of the total GHG emission [1].

1.1.2. Mining Effect on Climate Change. Mining is among the industries with climate concerns as it is an energy-intensive industry. The mining industry is responsible for about 4-7% of the global emission of greenhouse gases [5]. Per the sustainability trend across all sectors, mine operators will also face pressure from governments, investors, and the public to decrease emissions. A considerable part of mining GHG emissions comes from the methane emission from coal mines, while the rest comes from CO_2 emission due to mining operations such as haulage, drilling, etc., and energy usage in mines. According to McKinsey Sustainability, the mining industry's methane and CO_2 emissions are 3-6% and 1 % of global emissions, respectively [5]. The remedy will be to reduce methane emissions from coal operations and invest in technologies that will reduce CO2 emissions from energy usage and mining operations. Technologies supporting decarbonization and reducing GHG emissions include wind energy, solar energy, electric vehicles, battery storage, hydrogen fuel cells, and carbon-capturing technology [1].

Diesel is the primary source of energy in mining operations, and haulage is one of the most energy-intensive operations in mining. Mining vehicles alone are responsible for a considerable amount of energy usage and emit over 68 million tonnes of CO_2 every year, responsible for 30-80% of the total emissions of mine operations [7]. The haulage system in mining includes trucks and conveyor systems. Truck haulage is a significant source of greenhouse gas emissions in mine operations because of the flexibility and cost-effectiveness they bring to material handling, which makes them popular. As the evolution of technology advances, mine production and operational hours are expected to increase. Therefore, it is critical to advance alternative energy technologies in the mining industry to restrict greenhouse gas emissions and reduce the likely impacts of climate change.

Additionally, from the global shift to decarbonization and reducing GHG emissions, there will be a need for raw materials and minerals to support the new technology. The mining industry will play a huge part in providing these solutions to reduce GHG emissions by providing the raw materials needed in these new technologies and innovations. Simultaneously, increasing the need for more energy consumption during mining operations eventually emitting more GHG. Therefore, integrating strategies that only reduce GHG emissions, such as improving energy efficiency in vehicles or mining haulage systems, may not be enough to meet the global climate change goal. There is a need to incorporate zero-emission technologies in mine haulage.

1.2. PROBLEM STATEMENT

Truck haulage is one of the leading causes of greenhouse gas emissions in mine operations because of its wide application in the mining industry. Therefore, mining trucks need to transition from diesel to clean energy sources to drastically reduce emissions and decarbonize the industry. The general problem is identifying the right type of technology solution that effectively replaces diesel engines. Alternative solutions such as battery and hydrogen-powered trucks are needed to help reduce greenhouse gas (GHG) emissions while fulfilling the operational mining requirements.

However, the specific problem is that the current commercially available solutions to help reduce emissions, such as battery-powered trucks, cannot fully replace diesel trucks or fulfill the mining operational requirement without some compromise. Battery trucks have limitations on energy density, range, and fast recharging which means haul trucks are forced to implement battery swapping to make up for lost time due to charging [8]. Hydrogen-powered mining trucks on the other hand have the promise of fast-refueling capability and potentially similar energy density to diesel-powered trucks [9]. However, based on initial observations, the critical challenges associated with integrating hydrogen fuel cells into mining haul trucks are (1) hydrogen storage, (2) the size of fuel cell powertrain, and (3) life span, and durability of the fuel cell powertrain. Because of a lower volumetric energy density of hydrogen compared to diesel, the size of the onboard hydrogen tank has the potential to be larger than that of combustion engines. Also, one of the byproducts of the fuel cell is heat which may require additional hardware for the cooling system. These may mean inadequate space or restructuring of the truck "real estate" to accommodate for the changes.

Even if the technological challenges are resolved, mining companies must evaluate whether it is economically beneficial to invest in the new technology to switch hydrogen fuel cell or other green technologies in truck haulage. The literature does not contain an economic framework for evaluating the decision to integrate renewable energy into mine haul trucks under specific conditions.

The entire process of ensuring the replacement of the combustion part of the existing haul trucks with a fuel cell technology without compromising its effectiveness requires further study. The study will be able to provide the possibilities and challenges in incorporating the fuel technology in haul trucks. Additionally, it is worthwhile to develop an economic framework for examining when a mining company should invest in renewable technology for truck haulage. This will provide insight on the possibilities associated of fuel cell truck haulage and will further aid the transition to a zero-emission mining industry.

1.3. OBJECTIVES AND SCOPE OF RESEARCH

The project's overall objective is to evaluate the technical and economic feasibility of hydrogen fuel cell electric mine trucks as an alternative to current mine haul trucks. Specifically, the project will:

1. Develop an economic framework for evaluating the integration of renewable energy powered haul trucks into mining; and
2. Apply vehicle drivetrain and energy simulation in Matlab/Simulink to elucidate the challenges and opportunities of incorporating hydrogen fuel cell technology into the current form factors of mine haul trucks.

The first objective is addressed by developing an economic model that can be used as a decision-making tool for selecting the combination of truck technologies in mining operations that minimizes the cost. The model evaluates three major technologies: (1) hydrogen fuel cell truck, (2) battery powered truck, and (3) diesel powered truck.

The second objective is achieved by building a model of a hydrogen fuel cell electric truck in Matlab/Simulink that takes a drive cycle (with other input) and predicts the hydrogen consumption and power requirements. The technical model provides an in-depth analysis of hydrogen fuel cell integration in a mining truck. Since other technologies such as battery and diesel are established and proven in the industry, the model validates the technical utilization of hydrogen fuel cells in mining trucks.

Ultimately, the project seeks to provide a preliminary evaluation of the feasibility of implementing fuel cells into an existing mining truck's "real estate." The model's approach is to analyze fuel consumption for different duty cycles and compare differences in components with existing combustion engines to make an appropriate recommendation on the size of hydrogen tank and other requirements for fuel cell electric trucks. The hydrogen tank size and the relationship between the power required and the size of the fuel cell powertrain is used to determine the size of the system. This process helps determine the compatibility of the fuel cell system when replacing the combustion components in an existing truck. Validating the technical potential of a fuel cell truck and providing a tool for evaluating renewable technologies provides the opportunity for the mining industry to evaluate renewable technologies (and fuel cells, in particular) in truck haulage to reduce the industry's GHG emissions.

1.4. STRUCTURE OF THESIS

Section 2 is the literature review, an extensive review of battery-powered trucks, hydrogen fuel cell trucks, and a detailed introduction to how optimization is used in the economic framework for evaluating the integration of renewable energy-powered haul trucks into mining. Section 3 presents the economic framework that evaluates the use of three major types of trucks in mining operations. Section 4 presents the technical model, a fuel cell electric truck simulation that helps to analyze the hydrogen storage and fuel cell to replace the combustion components of a mining truck. Section 5 uses the result from the economic and technical model to highlight the challenges and opportunities associated with integrating hydrogen fuel cells in mining trucks. Finally, Section 6 presents the conclusions and recommendations.

2. LITERATURE REVIEW

2.1. BACKGROUND AND MOTIVATION FOR RENEWABLE TECHNOLOGIES IN MINE HAULAGE

Over the past few decades, climate change has remained a global challenge. After more than a century of industrialization and deforestation, greenhouse gases have risen to a record high in the past three million years. As a result, many industries have begun to reevaluate reducing human influence on greenhouse gases. The mining industry's operations are energy-intensive, thus contributing to substantial greenhouse gas emissions because of decreasing ore grades in mines [6], electricity, and fuel consumption [7]. GHG emissions from electricity, transportation, and other activities in mining were approximately 10% of the global energy-related emissions in 2018 [7]. Truck haulage in mining is one of the leading causes of GHG emissions. According to the International Council on Mining and Metals (ICMM), about 28,000 large mine trucks are in operation in a year and contribute more than 68 million tonnes of CO_2 during that period [8].

Truck haulage is a considerable part of the mining process and responsible for 50-80% of total mining emissions, depending on the mine type [8]. As the primary energy source in mining trucks, diesel is the cause of the direct GHG emission, with 87% of the energy consumed by material handling, such as hauling trucks powered by diesel [10]. Many significant factors such as truck characteristics, operators, haul road, mine plan, and fleet management affect the energy consumption during mining operations [11]. These factors may result in more or less diesel consumption by the truck. For example, if the haul road grade within a mine site is steep (high), the higher-grade resistance will result in higher diesel consumption.

Energy efficiency can reduce energy consumption per output or increase the output per energy consumed [12]. So, in the case of the mine site with steep road grades, energy efficiency technologies could have produced the same result of getting up the hill with lower energy (or diesel consumed). Energy efficiency technologies can significantly reduce energy consumption during truck haulage operations by producing the same outputs with lower levels of energy [11]. Energy is measured as diesel consumed to quantify mine haulage performance and fuel efficiency as the payload per fuel consumed [12]. Truck haulage is one of the operations in mining with the most potential for reducing GHG emissions by improving energy efficiency [12]. Technology has improved haulage systems operations and their impact on climate change. Optimal haulage routing, thermal management techniques, and regenerative energy technology reduce fuel consumption [14] and truck travel times [13]. Others have contributed to energy efficiency [15], like electric drive trucks and trolley assist systems to improve speed [16]. Overall, the inclusion of these technologies has reduced GHG emissions from mine operations.

However, due to the inability to incorporate these technologies in certain mines, such as mines with long haul distances and older mines requiring higher energy intensity due to deteriorating ore grades, energy efficient technology alone may not reduce the GHG footprint of mining [17]. Since some of these technologies are only effective in isolated scenarios, it is essential to find solutions to eradicate GHG emission rather than reduce it, especially with the rise in demand for commodities and raw materials as society transitions to green energy. A world bank report projected the continuous increase in demand for resources used in clean energy technology such as graphite, lithium, and cobalt until 2050 [18]. As a result, the operating hours of the mining haul fleet are projected to increase to support the rise in demand, consequently increasing the mining GHG emission.

Many companies, governments, and organizations such as the ICMM have been looking to expedite the adoption of cost-effective alternative energy in mining operations to combat the rise in GHG emissions in mining. For example, ICMM members are working collaboratively through the Innovation for Cleaner, Safer Vehicles to facilitate the replacement of conventional diesel trucks and develop alternative technologies [19]. Rio Tinto also announced in August 2021 a partnership with Komatsu, a truck manufacturer, to fast-track the development of zero-emission trucks [20].

The initiatives for cleaner haulage technology require rigorous research that builds on the existing literature to ensure its success. This section provides an overview of the existing literature for renewable energy integration into mine haulage systems, particularly hydrogen fuel-cell powered trucks. Additionally, the section reviews the literature on economic frameworks and policies that facilitate renewable integration in mining, which is a significant factor to the adaptation of zero-emission haulage systems within the mining industry.

2.2. RENEWABLE ENERGY IN MINE HAULAGE

Energy is a significant input of mining operations, and the demand is expected to increase by 36% by 2035 [21]. Researchers have discussed the integration of renewable energy within mine operations for power generation utilizing both grid and off-grid conditions [21]. With renewable energy's growing influence in mining, such as stationary power supply integration, [23] many opportunities have been reported for incorporating renewable energy into mine operations [22]. However, with each opportunity, challenges are presented that decrease the adaption of these new technologies within the mines. For instance, batteries and fuel cell technologies are a formidable renewable energy replacement for diesel-powered material handling equipment, such as haul trucks. These technologies are good prospects and potential replacements for diesel and internal combustion engines in mining haul trucks because of the proven concepts in passenger vehicles. However, the technologies are not readily available for operation within mines.

Battery-powered technology involves an electric engine powered by a rechargeable battery such as lithium-ion batteries. Electric vehicles are propelled by electric power [24] through electric motors in place of combustion engines [25]. Today, lithium-ion batteries are the most common battery type used as rechargeable batteries for mining trucks [26]. An example is the Minetruck MT42 Battery Truck, one of the largest battery-powered mine trucks on the market [27]. The truck weighs 34,500 kg with a 42-tonne tramming capacity, and its charging time is about 120 minutes [27]. One of the essential advantages of battery-powered trucks, such as the MT42, is their environmental and worker-friendly features compared to diesel engine vehicles. The utilization of battery-powered trucks reduces greenhouse gas emissions and noise pollution, thus adding to the mines' sustainability goals and improving workers' health and working environment in the case of underground mining operations [25].

While battery-powered haulage has a positive impact on the environment and workers' health, the shortcomings lie within the challenges of the technology. The most prominent challenges of the battery technologies in the automotive application are low energy density, high upfront cost, extended charging, short life span, and safety in the case of battery failure [28]. Since mining operations are devoted to safety and rely heavily on haulage for productivity, a battery-powered truck with a long charging time, lower energy, and a short life span is detrimental to the business. In the case of the MT42 truck, 120 minutes is required to recharge its battery, so periodically recharging electric trucks increases downtime and, therefore, decreases the productivity of the mine. In electric vehicles, the amount of energy stored per unit weight of the battery is low [28]. However, the battery weight and size are expected to increase to power the high load of heavy-duty vehicles. Therefore, when maximizing the truck's capacity, the battery's size is compromised, translating to heavier batteries and thus increasing the load of the truck.

Besides the storage size and weight, another limitation is the source of the electricity used to charge the batteries. Most of the current energy sources in mines contribute to GHG emissions because they depend on petroleum products such as coal, natural gas, or diesel (in case of onsite generation) for energy. The same applies to batteries, with the energy source for charging derived from fuel. In the United States, 32% of fuels consumed in the mining industry are due to onsite electricity [29] and are mainly from fossil fuels. Although batteries are renewable technology, the energy source is not, resulting in GHG emissions regardless. While renewable installations have increased from 42 MW annually in 2008 to 3397 MW in 2019 [30], it is still not the dominant energy source utilized for mining operations. Therefore, the entire energy source and storage need to be emission-free for mining to transition to a zero-emission industry.

Other technologies have been considered a substantial energy source for battery-powered vehicles, such as fuel cells which could eliminate the dependence on fossil fuels.

Fuel cells deployed with batteries as a hybrid electric vehicle in passenger vehicles improve energy density, range and reduce charging time [32]. An example is the use of hydrogen fuel cells by Toyota and Hyundai in their passenger and highway truck Toyota Mirai and Hyundai Xcient. One can use this concept as a template to implement a well-performing electric mining truck. Unlike batteries, hydrogen fuel cells do not require frequent recharging because it undergoes a chemical reaction that produces energy from the movement of hydrogen electrons [31]. The process produces an electric current that can drive electric motors while emitting water and heat as waste [32]. Thus, hydrogen fuel cells can power heavier duty trucks as a hybrid with batteries or standalone with a more extended operation duration than lithium-ion battery packs due to their energy density and ability to charge in 5 minutes [32].

2.3. HYDROGEN FUEL CELL-POWERED TRUCKS

Fuel cells possess the potential to be a primary energy source for haulage systems and replace the conventional combustion engine. A German study concluded that fuel cell vehicles would provide a 33% reduction in GHG emission while battery vehicles would reduce GHG by 25% [33]. Fuel cell-powered trucks have the potential to save more GHG emissions than both battery and diesel operations. Even with the current electricity production resources, hydrogen fuel cells emit a lower GHG than battery and diesel mixed or standalone. The study determined that battery technology would be more favorable if all electricity production were 100% renewable [33]. However, due to fast refueling and zero-GHG emission, hydrogen fuel cell technology can reduce the adverse effects of diesel-powered haul trucks without compromising the effectiveness of the vehicle like battery-powered trucks.

Hydrogen fuel cells possess additional environmental and health benefits. Zhu et al. [34] evaluated the public health benefits of incorporating fuel cells in a port complex. They estimated that a full deployment of fuel cell technologies across the port would achieve up to $7 million per day in health benefits [34]. Also, the technology produces water as a byproduct, which may substantially increase water availability to the environment through evaporation and rainfall. These advantages illustrate the potential of good working conditions for mine operators and encourage implementation.

Thus, using a hydrogen fuel cell-powered truck to replace internal combustion engine powered haul trucks in the mining industry stems from the established design of hydrogen fuel cell-powered passenger and on-road haul truck vehicles [35] [36]. Although hydrogen fuel cell has not yet been widely implemented within the mining industry, the technology has been utilized in passenger vehicles. These cars exhibit features that come with the convenience of using diesel powered vehicles, such as fast refueling and longer availability. An example is the Toyota Mirai, with a range of 402 miles, which competes with a conventional vehicle's average range of 300- 400 miles [36]. These features are critical in the mining business because they minimize downtime, maintain productivity, and reduce greenhouse gases. Since an appropriate tank and engine design that competes with the range and fast refueling qualities of diesel-powered passenger cars exists, one can transfer the technology to heavy-duty haulage applications such as mining.

However, even though the implementation of hydrogen fuel cells in heavy-duty vehicles like mining trucks has the potential for success, researchers have examined some potential concerns or challenges. Some concerns considered are the size of the onboard hydrogen storage, which is critical to the “real estate” dimension of the vehicle, and the integration of hydrogen fuel cells within mining haul trucks. Although hydrogen's mass energy density is greater than most fuels, it has a significantly low volumetric energy density [37]. Meaning that the volume of hydrogen needed to power a vehicle is relatively higher than that of most other fuels, consequently requiring more space for fuel tanks. This study will look at the possibilities of fitting in the hydrogen tank as a replacement for a diesel fuel tank. Some other significant challenges that still require examination are the cost of infrastructure, method of producing the hydrogen, safety, and storage of hydrogen, which all pose concerns when implementing hydrogen fuel cell technology in a heavy-duty industry like mining [38].

Hydrogen is the most abundant element on earth and has the potential to provide energy without GHG emissions [39]. Even though most hydrogen is currently produced from fossil fuels, it can be obtained through renewable energy-powered electrolysis by splitting water into its individual components. It can serve as fuel to the Polymer Electrolyte Membrane (PEM) fuel cell often used in the passenger vehicles' powertrains [39]. Hydrogen is highly flammable with low visibility [40], raising safety concerns. However, with higher ignition temperature and other safety and handling measures, existing literature indicates that hydrogen can be safe [40].

Also, the cost of transitioning to a hydrogen fuel cell economy may pose a challenge. The distribution infrastructure, cost of manufacturing or acquiring the vehicle, and the cost of maintaining the truck can contribute to high capital and operating costs. The cost of manufacturing the fuel cell powertrain may be higher than existing combustion technology. The membrane electrode assembly (MEA) is one of the most expensive components of the fuel cell. Battelle Memorial Institute estimated the cost of one hundred units of a 12 kW Polymer exchange membrane (PEM) fuel cell stack to be $10,143. The MEA for a 12kW fuel cell stack is $6094. For a 1200kW mining truck, this will require at least 100 of these 12kW stack. However, as the quantity produced increases, the prices go down. For example, the cost of fifty thousand units of a 12-kW system is $474 [41]. Therefore, increasing demand for fuel cells will lead to a competitive lower price. To achieve lower costs, governments may need to implement policies that encourage the development of manufacturing infrastructure to support hydrogen fuel cell technology.

2.4. ECONOMICS AND POLICY SETTING FOR RENEWABLE ADOPTION IN TRUCK HAULAGE

Solar power has one of the most extensive renewable energy installations globally, with about 627 Gigawatts capacity in 2019 [42]. Its extensive adoption is due to policies such as carbon taxes used as a direct fee for carbon emission [43], the Feed-in tariff (FIT), which encouraged the deployment of solar [44], and Renewable Portfolio Standards (RPS), which helped to mandate the production of solar [45], and incentives, which are the most favorable energy policies implemented to drive the growth over the years [46]. Policies are the best avenue for governments and policymakers to adhere to climate commitments. Governments can issue policies that incentivize corporations to adopt renewable energy technologies such as fuel cells by providing tax breaks or incentives for operators or manufacturers who meet zero-emission standards. However, governments need to carefully evaluate policies to ensure they are optimal because the disadvantages of ill-conceived policies could outweigh the benefits [47].

Like consumer cars and solar energy, policies are developed to encourage technological growth within the industries by aiding innovation that promotes government and societal goals. However, one may argue that a major reason of the current absence of policy or unwillingness of policy makers to make policy that encourages technologies like hydrogen fuel cells in trucks is that the technology is yet to be widely proven to withstand the actual performance of current diesel mining trucks. However, lack of supporting policies slows technological and economical evolution. Therefore, hydrogen and fuel cell technology are not yet economically feasible, and infrastructure and manufacturing costs are still high [48].

Researchers have studied the economic feasibility of the different methods of producing hydrogen and concluded that fossil fuel (e.g., natural gas) powered production of hydrogen is still the most economical [49]. However, since fossil fuel does not support the zero GHG emission goal, other factors such as good policy frameworks, economies-of-scale implementation, technological improvement in electrolysis, and cost reduction of fuel cells will determine hydrogen's affordability and economic future in energy and transport [48]. According to studies in literature, hydrogen fuel cells in a vehicle is likely to be economically competitive [50]. Many laws and incentives like the Alternative Fuel Infrastructure Tax Credit are currently in place to enable hydrogen fuel cell technology to grow in the market [51]. These policy interventions and others can encourage technological advancement for economically competitive hydrogen fuel cell technology.

This study aims to evaluate the potential for hydrogen fuel cells to replace diesel in powering mine haul trucks. It is imperative then to evaluate the motivations of mining companies that will influence hydrogen fuel cell adoption. While this author did not find any work in the literature examining the motivation of mining firms in adopting renewable technology, there are several studies in the literature that examine the drivers of renewable technology adoption [52]. Some have used empirical and statistical approaches to determine the drivers of renewable energy adoption [53]. Even though the author did not find direct model-based analysis that show companies' motivations to adopt renewable energy that can support policy work, some researchers have shown the effectiveness of renewable energy policy [54] while others have shown positive economic effect of policy that helps expand renewable energy [55]. However, this study will provide a model-based analysis of the policy can affect the decision mining companies' making.

The first part of this study builds a model that helps to understand how factors such as policies that provide incentives to mining renewable energy adoption in the form of introducing emission fees or taxes, production parameters, and demand for metal commodities can influence the cost of operating different types of trucks in mines. The project investigates three major technologies: fuel cell, battery, and diesel. These technologies all have advantages and disadvantages and, therefore, have a role to play in the future of mining. The economic model can be used as a decision-making tool to choose the cost-minimizing combination of truck technologies. The model helps to understand other factors, such as how policy and production parameters can influence the cost of mining haulage and the growth of renewable energy in mining. The literature has not fully explored the cost implication of replacing the conventional diesel-powered trucks with these technologies. It is not enough to technically develop a replacement for a diesel-powered truck without the awareness of the cost and financial implications. Also, mining companies want to know if it is more economically advantageous to adopt these technologies both fully and partially, even with incentives.

Existing literature mainly describes and compares the cost of buying and operating passenger vehicles with different technologies. For example, Gelmanova et al. [56] estimates the cost to own an electric car per month to show the advantages and disadvantages of an electric vehicle [56]. However, few studies have examined the economic feasibility of using renewable-powered vehicles for the commercial sector [57]

3. ECONOMIC FRAMEWORK RENEWABLE ENERGY ADOPTION IN TRUCK HAULAGE

3.1. OVERVIEW

As explained in the introduction, even if all the technological challenges related to integrating renewable energy into mine truck haulage are removed, mining companies need to decide whether to make the investments to transition from fossil fuels. This requires an economic decision framework that accounts for the motivations of mining companies regarding their decision-making on selecting truck haulage technologies. While such a framework may not describe every mining company's decision to invest in truck haulage technology, it allows us to make certain inferences about conditions under which most companies in the industry are likely to make certain decisions.

In other circumstances, researchers have developed economic decision models that are useful for supporting the decision-making process for companies and communities [58], [59]. This section aims to develop a similar economic framework for evaluating the integration of renewable energy-powered haul trucks into mining. The work approaches this problem by evaluating different combinations of haul truck technology that reduce total cost. The cost evaluation includes the operational expenditures and economic reward/penalty for environmental compliance. With the motivation to reduce GHG emissions, the framework assumes potential policies which create a cost implication associated with any haul technology that produces GHG emissions during operation. The evaluation considers haul technologies such as fuel cells, batteries, and diesel. The economic model is divided into two major parts:

1. A base model that presents a minimized mine haulage cost for a homogenous truck fleet. This model assumes the mine's production is known and the trucks used in the mine have the same features and costs, including capacity, cost of operating, maintenance, purchase, etc.
2. A model that assumes the mine's production is known but the features and costs of the trucks are different because the fleet consists of trucks of differing technologies. This is called the heterogeneous model in this work. This model evaluates trucks powered by three different drive technologies: (1) diesel-powered trucks, (2) hydrogen fuel cell-powered trucks; and (3) battery-powered trucks. Figure 3.1 is an overview of the modeling approach.

The generic model presents a variable, M, that represents the total truck mileage (e.g. total milage needed per unit period to deliver a given quantity of mine commodity) required to attain a mine production, q. Since the capacity and size of all the trucks remain constant, it is assumed that mileage M is an accurate measure of when the truck is available and utilized towards the mine's production goal. TC is the total cost of truck haulage in the unit period. The total cost can be divided into three major parts:

1. The cost of greenhouse gas emission, G, measured in dollar per unit of GHG emission, assumes that the government is charging a fee for emissions or the business cost of emitting GHG. G is a non-negative value
2. The cost of a functioning truck per mile, C_o. This includes the trucks' ownership cost, cost of operation (e.g. cost of fuel, cost of maintenance), and cost of infrastructure that enables the truck to function in the mine (e.g. cost of handling fuel safely)

3. The cost accumulated due to the aging life span or depreciation of trucks C_1.

   Figure 3.1 is an overview of the modeling approach.

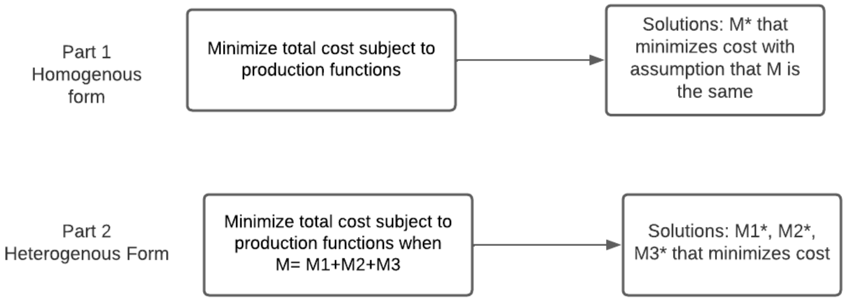


Figure 3.1 Overview of modeling approach in this section

3.2. MINIMIZING TRUCK HAULAGE COST FOR HOMOGENEOUS FLEET

The objective is to minimize the total cost of truck haulage in a mine given that the mine production is known. Both the total cost, *TC*, and the mine production, *q*, are functions of mileage, *M*, and the numeraire input, *n*, (e.g. water). The amount of greenhouse gas emitted per mile (GHG/mile) is *e*.

As a constraint, there exist a production function $q = f(M, n)$. While this work acknowledges that trucks used in mines may have different capacities for different applications, the assumption that all trucks used in a mine have the same capacity helps simplify modeling and facilitates better understanding of the base case. Additionally, there are many mines that use a homogenous fleet of trucks. Figure 3.2 shows a simplified overview of the total cost model.

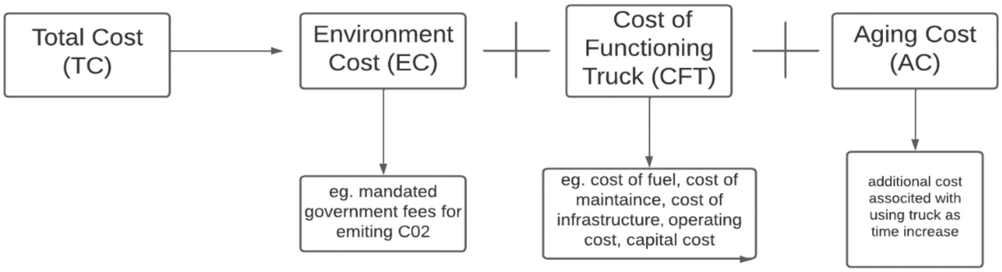


Figure 3.2 A simplified cost model

The production function, $q = f(M,n) = AM^{\alpha}n^{\beta}$, is assumed to be Cobb-Douglas production function which is used to model total productions of a good that is dependent on two or more factors [60]. The parameter A represents the production efficiency, a factor that generally affects the productivity of the whole system [61]. β and α are both constants that indicate the output elasticities of n and M, respectively, which are the ratios of percentage change in output of the mine to the percentage change in input of the mine [61]. Equation 3.1 shows the model in homogeneous form.

$$\min TC(M,n) = n + GMe + C_0M + \frac{C_1M^2}{2} \tag{3.1}$$

subject to:

$$q = f(M,n) = AM^{\alpha}n^{\beta}$$

The first-order conditions will be derived from the Lagrangian equation (Equation 3.2) for the optimization problem in Equation 3.1. λ is the Lagrange multiplier

$$L(M,n,\lambda) = TC(M,n) + \lambda\left(q - AM^{\alpha}n^{\beta}\right) \tag{3.2}$$

The optimal solution of M^* is achieved when the conditions derived from the Lagrangian equation are met. The first order conditions are listed below in Equation 3.3:

$$Ge + C_0 + C_1 M \ + \lambda \, \alpha A M^{\alpha-1} n^{\beta} = 0$$

$$1 - \lambda \, \beta A M^{\alpha} n^{\beta-1} = 0 \tag{3.3}$$

$$q - A M^{\alpha} n^{\beta} = 0$$

Equation 3.4 shows the solution, M^*, n^*, and λ^*, to the optimization problem after solving Equation 3.3.

$$M^* = \frac{q^{\frac{1}{\beta+\alpha}} \ \alpha^{\frac{\beta}{\beta+\alpha}}}{A^{\frac{1}{\beta+\alpha}} \ \beta^{\frac{\beta}{\beta+\alpha}} \ \mathrm{TC}'^{\frac{\beta}{\beta+\alpha}}}$$

$$n^* = \frac{M^* \beta \, \mathrm{TC}'}{\alpha} \tag{3.4}$$

$$\lambda^* = \frac{1}{\beta q n *^{-1}}$$

M^* represents the conditional demand for truck mileage (the demand for trucks that ultimately minimizes the cost of the operating truck mileage in the mine to meet the production demand when considering all types of expenses). TC' now represents marginal cost of operating the truck to meet demand (i.e., the cost of driving the last mile). λ^* represents the change in total cost with respect to production, q. Using the solution for M^* one can predict the impact of cost parameters, demand for mine production, q, and policy parameters on the optimal demand for truck mileage.

When the truck fleet is homogenous, the model allows one to see how the other parameters affect the optimal truck mileage, M^*, regardless of what type of haulage technology utilized. The conclusions derived from Equation 3.4, regarding the optimal truck mileage are consistent with fundamental economic theory. The homogenous model serves as a benchmark model for the heterogeneous case as it validates the relationship between optimal mileage and the mine operation parameters. One can make the following observations from Equation 3.4:

1. The optimal mileage, M^* declines with increasing marginal costs TC'. This relationship is consistent with fundamental economic theory and, thus, shows the homogenous model is a good benchmark for further modeling.
2. When the desired production, q, increases, the optimal mileage, M^*, increases ($\frac{\partial M^*}{\partial q} \geq 0$). This result implies that if management desires to produce more, the optimal mileage will be higher. In other words, assuming the Cobb-Douglas function describes the truck production function, there is no scenario where increasing demand will lead to a lower optimal truck mileage.
3. When mine production efficiency, A, increases, optimal mileage, M^* declines ($\frac{\partial M^*}{\partial A} \leq 0$). That is, if the truck technology used is more efficient, the optimal truck mileage to achieve the desired production, q, will be lower.

3.3. MINIMIZING TRUCK HAULAGE COST FOR HETEROGENOUS FLEET

The model's heterogenous form looks to accommodate the three major energy technologies in the mining haulage system today. The model includes the conventional diesel-powered trucks since they are commonly used among operators. The model also includes hydrogen fuel cells and battery-powered electric trucks because they are emerging technologies in mine haulage [62], [63]. The heterogeneous model provides an understanding of the best combination of technology to minimize the total cost of operating truck haulage in a mine for a given production target per unit period.

Equations 3.5 presents the optimization model to minimize total cost and

$$
\begin{aligned}
&\min TC\left(M_i, n\right) = n + \sum_{i=1}^{3} G_i M_i e_i + \sum_{i=1}^{3} C_{0i} M_i + \frac{\sum_{i=1}^{3} C_{1i} M_i^{2}}{2} \\
&\text{subject to:} \\
&q = f\left(M_i, n\right) = A\left(\sum_{i}^{3} M_i\right)^{\alpha} n^{\beta}
\end{aligned}
\tag{3.5}
$$

Table 3.1 provides the definition of the variables.

Table 3.1 Parameters in the heterogeneous model

Parameters	**Definition**
G_i	Environmental cost (\$/GHG) for technology i
M	Total truck mileage (mile)
M_i	Truck mileage of for technology i
e_i	Greenhouse gas emission rate. (GHG/mile) for technology i
C_{oi}	Cost of functioning truck per mile (\$/mile) for technology i
C_{1i}	Cost of Operating due aging truck mile (\$/mile) for technology i
A	Mine production efficiency
n	Numeraire input
α and β	The ratio of percentage change in output of the mine to the percentage change in input of the mine

While the model in Equation (3.5) assumes G_i is different for each technology, under most conditions, policymakers are likely to levy the same cost for GHG emissions because the damage of the emission remains the same regardless of the technology producing it. Which means $G_1 = G_2 = G_3$. However, this work models G_i, to allow for the general case where government charges differential levies for GHG emissions. There is no loss of generality in the model as it works either way.

The first-order conditions equations (3.7) were derived from the Lagrangian equation for the optimization problem in Equation (3.6).

$$L(M_1, M_2, M_3, n, \lambda) = TC(M_1, M_2, M_3, n) + \lambda\,(q - A(M_1, M_2, M_3)^{\alpha} n^{\beta}) \tag{3.6}$$

$$\begin{gathered}
G_1 e_1 + C_{01} + C_{11} M_1 + \lambda\,\alpha A (M_1 + M_2 + M_3)^{\alpha-1} n^{\beta} = 0 \\
G_2 e_2 + C_{02} + C_{12} M_2 + \lambda\,\alpha A (M_1 + M_2 + M_3)^{\alpha-1} n^{\beta} = 0 \\
G_2 e_2 + C_{02} + C_{12} M_2 + \lambda\,\alpha A (M_1 + M_2 + M_3)^{\alpha-1} n^{\beta} = 0 \\
1 - \lambda\,\beta A (M_1 + M_2 + M_3)^{\alpha} n^{\beta-1} = 0 \\
q - A (M_1 + M_2 + M_3)^{\alpha} n^{\beta} = 0
\end{gathered} \tag{3.7}$$

After solving Equation (3.7), the solutions M_1^*, M_2^*, M_3^* n^* and λ^* are illustrated in Equations (3.8).

$$\begin{gathered}
M_i^* = \frac{\left(\alpha\, A^{\frac{\alpha-1}{\alpha}} n^{\frac{2\alpha-1}{\alpha}} q^{-\frac{1}{\alpha}} \beta^{-1}\right) - G_i e_i - C_{0i}}{C_{1i}} \\
\text{Where i = 1,2,3} \\
\lambda^* = \frac{1}{\beta q n^{-1}}
\end{gathered} \tag{3.8}$$

$$n^{*} = \frac{q^{\frac{1}{\beta}}}{(AM^{\alpha})^{\frac{1}{\beta}}}$$

In general, the solution of $M_i{}^*$ resulted in distinctive observations from the base model. The optimal mileage is no longer dependent on the derivative of the total cost, TC', the marginal cost. Also, the environmental cost G_{i} , GHG gas emission e_i and other costs C_{0i} and C_{1i} have a direct impact on the optimal mileage driven by each truck technology, M_i^* . Thus, higher fee ($/GHG) on emission or the rate of emission because of government policy reduces the optimal mileage driven by a given technology $M_i{}^*$. This implies that as government taxes/fees on emissions increase, it will become more expensive to operate trucks that emit GHG, such as diesel trucks. The cost of operating an aging truck also affects the optimal demand for truck mileage. M_i reduces considerably more when C_{1i} increases. Using the solution for M_i one can predict the impact of policy and cost parameters on the optimal demand for each of the truck types. The solutions result in four significant observations:

1. M_i^* is proportional to q, which means as the target production increases the optimal truck mileage of each truck type also increases. This relationship is expected because the mine output drives the number trucks needed at the mine, thus more trucks are needed to achieve an optimal mileage.
2. G_{i} , e_i , and C_{0i} are very important parameters to determining the optimal truck milage. M_i^* linearly decreases when any of G_{i} , e_i , and C_{0i} increase. The $G_{\text{i}}e_i$, and C_{0i} are depicted as cost/mile. Therefore, a mining firm who is seeking to minimize their total cost will need to consider a lower G_{i} , e_i , or

C_{0i}, and as a result will limit their mileage for trucks with higher emissions rate, emissions cost, or operating cost. So, when the cost is too high the company's desire to use the specific technology is low due to the parameter such as environmental fee (G_i) associated with the technology.

3. M_1^* is inversely proportional to C_{1i}. As stated above, costs have a huge impact on the optimal mileage. However, C_{1i} has a greater impact than emissions and operating costs as it is inversely proportional to the optimal mileage of each truck type used. The operating cost due to aging truck mileage makes the truck expensive to operate and if the goal is to minimize the cost, this will have a significant effect on which truck the mine uses. Therefore, a mining firm will limit their use of any truck with a high operating cost, especially due to ageing as the firm cannot rely on that truck.

Given these observations and the goal of this research to evaluate the effect of green energy technology in mining, the main policy implication from this work is that implementing government policies that increase the cost of GHG emissions during operations are likely to motivate mining firms to reduce their reliance on such trucks. Based on the results of this work (Equation 3.8), policies such as implementing GHG emission tax or providing economic incentive (such as access to financial support that may reduce the cost of using renewable technology) will lead to mining firms that seek to minimize their total cost relying less on diesel trucks, for example. However, any effect of rising costs associated with GHG emissions will be mediated by functioning cost (e.g. operating costs) and costs of aging trucks. This implies that, if fuel cell trucks (and other green energy alternatives) do not offer low operating costs, mining firms might still prefer diesel trucks. Thus, any government policy that facilitates reduction in functioning costs, C_{0i}, (e.g., facilitates research and development to bring down the costs of generating and safely handling hydrogen) will leads to mining companies preferring hydrogen fuel cells over diesel trucks.

3.4. SUMMARY

The model presented in this section shows that mining firms that are motivated by a need to reduce their total cost will have a lower preference for trucks that emit high levels of GHG. If government policy continues to enact fees on emission or provide incentives to renewable energy technologies, it will become increasingly more expensive to operate diesel engines. However, efficiency, cost of maintenance, and production q play a key role in the decision-making process for mining firms to consider along with costs associated with GHG emissions. The work in this section shows that, even if government levies taxes and fees for GHG emissions, the cost of operating the green energy trucks must be competitive to ensure that mining firms would want to use them. Further studies may provide insight on the behavior of these solutions under specific scenarios

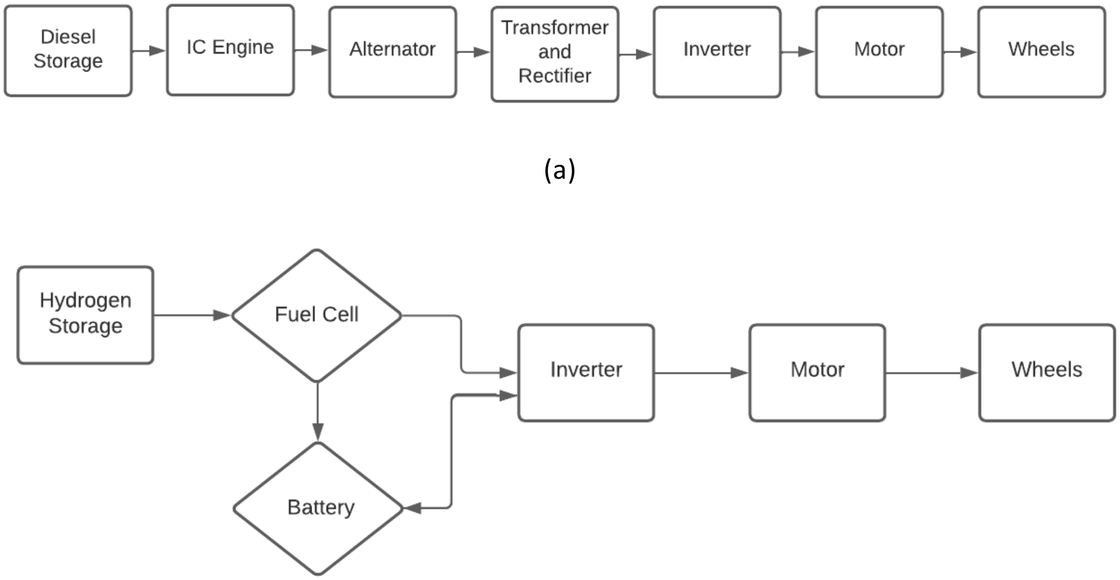
4. HYDROGEN FUEL CELL TRUCK MODEL AND ANALYSIS

4.1. OVERVIEW

This section of the thesis assesses the feasibility of converting a diesel-powered haul truck into a hydrogen fuel cell truck. Since diesel-powered trucks are well established within the mining industry, the goal of this section was to use a hydrogen fuel cell truck model target the challenges of incorporating a hydrogen fuel cell truck into the existing design of the diesel-powered truck. The advantage of building the fuel cell truck model based on existing mining trucks is that one can use existing truck attributes and data to determine what a new hydrogen vehicle would need to perform at the same level. For example, in this study, the author uses the Komatsu 830E-5 truck specifications, shown in Table 4.1, to build the model and experiment based on drive cycle data obtained from the truck during a mine operation. The truck specification and drive cycle serve as a reference for the model and allow one to obtain power demand and corresponding hydrogen fuel consumption during a particular drive cycle. The fuel consumption will enable us to predict the size of the onboard hydrogen storage. Furthermore, it allows us to see if the storage sizes fit the current geometry or "real estate" of the existing mining haul trucks without significant changes to the truck's structure and design. Figures 4.1a and b present an overview of the drive system of the diesel-electric drive truck and the proposed fuel cell electric drive truck.

This section presents the fuel cell truck modeling and validation, as well as simulation experiments to estimate the hydrogen tank requirements. The model is presented in its three main components: the driver, powertrain, and vehicle submodels.

This is followed by verifying the experiment and presenting the results of additional simulation experiments. This analysis uses the result of the simulation experiments to determine the volume of hydrogen consumed, which is used to estimate the size of the onboard hydrogen storage tank. The results are also used to determine an approximate size of the fuel cell stack to meet the power requirements of the haul truck.



(a)

(b)

Figure 4.1 (a) Overview of the proposed fuel cell electric truck (b) Overview of diesel-electric drive truck

4.2. MODELING

This section presents the essential aspects of the simulation model. Table 4.1 shows key specifications of the Komatsu 830E-5 diesel-powered haul truck, which is used to select the basic requirements such as the chassis, torque, and power requirement of the simulated haul truck. The following subsections explain in detail the process of modeling and analysis.

Table 4.1 Major specifications of the 830E-5 Komastsu truck [64]

Gross power	1865 kW @ 1800 rpm
Tire Diameter	3741mm
Nominal Gross Vehicle Weight	408875 kg
Empty Vehicle Weight	182051 kg
Nominal Rated Payload	226800 kg
Calculated Frontal Area.	49.25 m2
Top Speed	64.5 km/h
Ratio	32: 1
Fuel Tank	4542 L

The model was developed in the MATLAB and Simulink environment. The drive cycle (velocity-time, vehicle weight and inclination data) of diesel-electric mine haul trucks, obtained from an actual mine operation, is the input to the model. The velocity-time data passes through a driver subsystem that predicts the required acceleration or braking to achieve the velocity observed in the field data at each time step. The output of the driver submodel is fed to the powertrain submodel, which predicts the required power, torque, and force from the power supply and wheel, respectively. The truck model was designed using fundamental concepts of vehicle motion. Figure 4.2 displays the system level block diagram of the truck simulation.

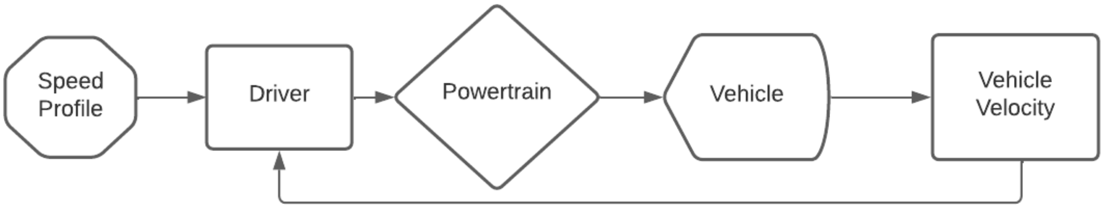


Figure 4.2 Overview of the model at the system level

4.2.1. Driver Model. The driver model takes in the truck speed data as the desired speed and the feedback velocity of the simulated truck as an input. The driver submodel uses a speed-time data of a real truck in the mine with the same capacity and parameters of the simulated truck designed for observation. The submodel uses a feedback mechanism to ensure that the actual velocity of the vehicle follows the desired velocity by providing an acceleration and brake command as an output. The errors are derived when the desired velocity is compared to the simulated truck velocity.

The driver submodel uses a proportional-integral (PI) controller to minimize and control the error between the desired and feedback truck speeds. Equation 4.1 describes the control function of a PI feedback controller. Both the proportional and integral components have a gain that helps manage different errors [65, 66]. The output of the driver is the control variable [66] used to provide the acceleration and brake command. This command acts like an input to the entire system used to trigger other actions and results within other submodels of the truck model. Figure 4.3 illustrates the driver submodel.

$$u(t) = \underbrace{K_p e(t)}_{\text{Proportional component}} + \underbrace{\frac{K_i}{T_i}\int e(t)\,dt}_{\text{Integral component}} + c \tag{4.1}$$

where

K_p: Proportional gain

K_i: integral gain

e(t): Error signal distribution

T_i: integral time step

c: initial value

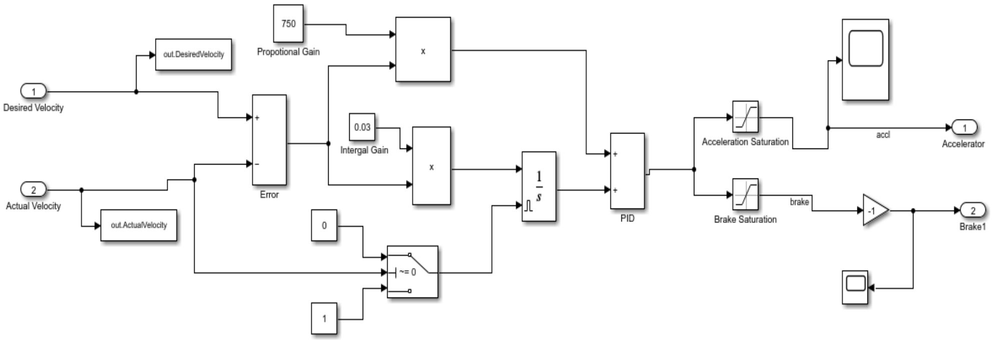


Figure 4.3 Driver submodel

4.2.2. Powertrain Model. The powertrain model provides two major outputs: the traction force and power request. Figure 4.4 shows the overview of the powertrain submodel. The system takes in the acceleration and brake command as inputs. The acceleration and break commands are values between 0 and 1, which shows acceleration or brake the driver demands by pressing the paddle. The subsystem uses the maximum and minimum torque value of the motor and the acceleration and brake commands to derive the maximum torque and minimum torque requested at every given time. The command multiplies the maximum torque when accelerating and minimum torque when braking.

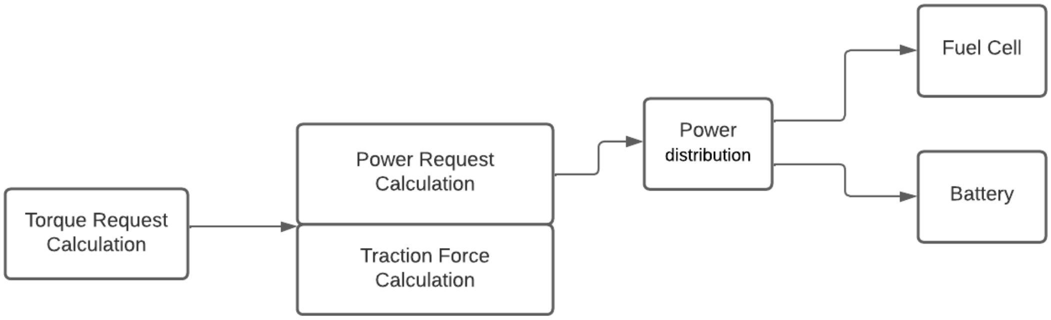


Figure 4.4 Overview of the powertrain

The second part of the submodel represents the power request. Equation 4.2 below shows that the instantaneous power of this truck model [67]. The submodel uses the velocity profile of the vehicle to obtain the angular velocity of the motor. The vehicle angular velocity is derived from the tire radius, *r*, and the vehicle velocity. Then, the model divides the vehicle angular velocity by the gear ratio (GR) to determine the motor angular velocity.

$$P = \omega \tau \qquad (4.\ 2)$$

Where:
P: Power

ω_{em}: Electric motor angular velocity

τ: Torque

The model simulates the product of torque and the motor angular velocity to determine the power request of the truck system. The vehicle model used the traction force, F, and mass, M, to obtain the acceleration, which integrated to obtain the vehicle velocity (Equation 4.3).

$$F = Ma$$
$$V = \int a(t)\, dt \qquad (4.\ 3)$$
$$\omega = \frac{V}{r}$$
$$\omega_{em} = GR * \omega$$

Where:

F: Traction force

ω: Angular velocity at the wheel of the vehicle

τ: Torque

GR: Gear ratio

V: Vehicle velocity

The power request is sent to the respective energy sources. The model in this study uses the fuel cell energy and battery sources that are available in Simulink. Just as the Xcient fuel cell on-highway truck manufactured by Hyundai, the model assumes a fuel cell powered mining truck will have both fuel cell and battery as an energy source. Xcient fuel cell truck has a battery rated at 661V / 73.2 kWh as a support energy source in the vehicle, while the fuel cells can power up to 190 KW [68]. The motor is rated at 350 kW capacity and a hydrogen capacity of 32.09 kg [68]. For the hydrogen fuel cell passenger car Toyota Mirai, the primary energy provider is the fuel cell while the battery helps with energy recovery during regenerative breaking and assists the fuel cell sometimes during acceleration [69], [70]. This study used these existing designs as guidelines during the modeling. However, since the batteries are mainly used as an auxiliary energy source in fuel cell vehicles and for heavier vehicles with significant energy needs, adding more batteries detracts from the effective use of the space, payload, and energy in a moving truck. Therefore, the model tries to keep the energy needed from the batteries as close as possible to that of the Xcient fuel cell road truck.

In this model, the power distribution determines the energy source based on the amount of power requested. The power system runs on a 630 V nominal voltage, and the battery source is a battery of 100 kWh capacity, which helps with the regenerative braking and power requests of up to 200 kW. At the same time, the fuel cell will provide energy for power requests of more than 200 kW. The algorithm also ensures the system uses fuel cell power as a backup for when the battery is low. Figure 4.5 shows the entire overview of the power distribution in the model. The power request splits into positive and negative at the input of the power distribution submodel. Positive power request means discharging, while negative power request indicate charging. Therefore, all negative power values will go into the battery, provided that the battery's state of charge is less than 90%. The positive power values will go through two magnitude tests to determine which energy source will provide the power. Figure 4.5 shows the logic power source allocation algorithm in the model. Lastly, the powertrain submodel uses the torque and other necessary parameters to derive the traction force of the vehicle. The traction force is adjusted to account for the braking effect by subtracting the product of the vehicle mass, brake command, gravity constant, and vehicle tire radius from the actual torque. These torque values multiply the tire radius to obtain the traction force passed to the vehicle model.

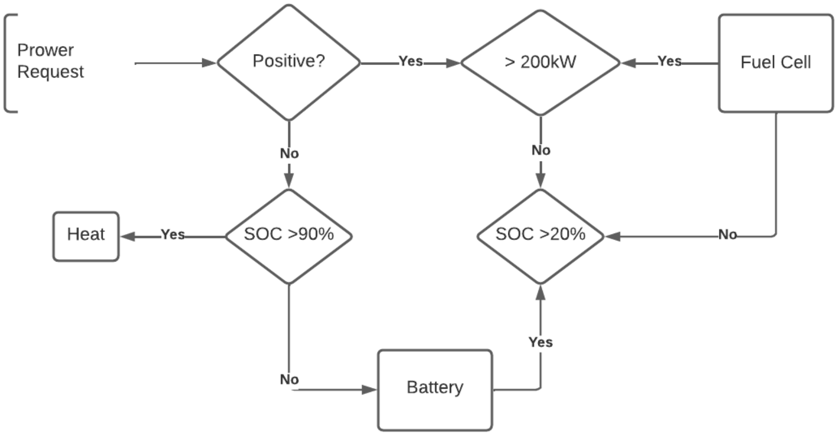


Figure 4.5 Overview of the power distribution algorithm

4.2.3. Vehicle Model. The vehicle model accepts the traction force as an input. However, it needs to overcome some environmental and vehicle resistances. After the traction force overcomes the resistive forces, the resultant force is used to estimate the vehicle's acceleration and velocity. Figure 4.6 shows the vehicle model on Simulink.

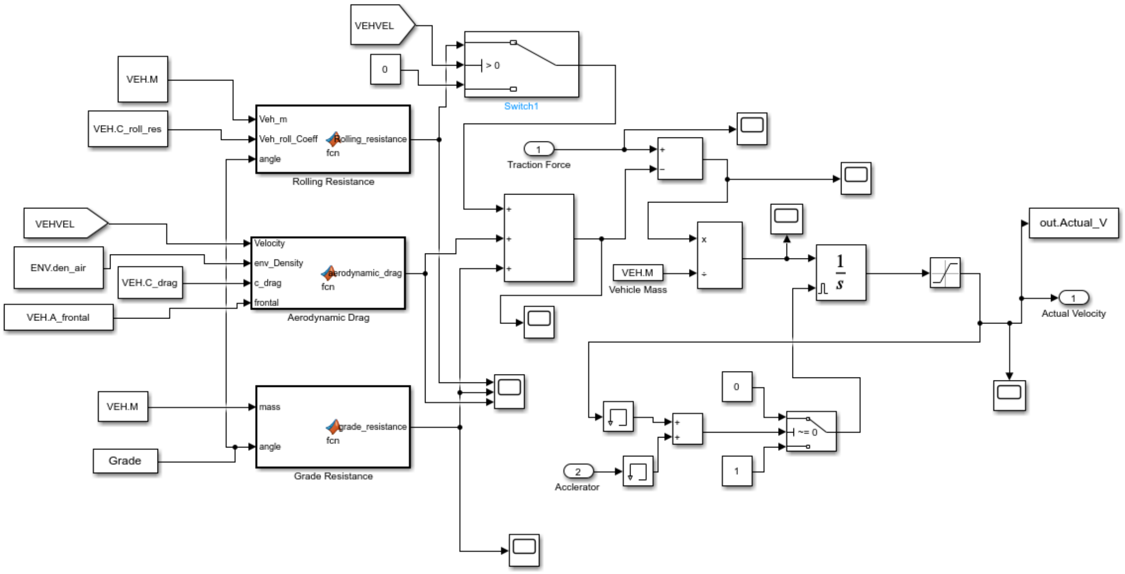


Figure 4.6 Vehicle Model

The model uses fundamental formulas to model and account for the aerodynamic drag, grade resistance, and rolling resistance. The aerodynamic drag is a resistive force in the opposing direction of the moving vehicle due to the air [71]. The airflow from high to low pressure caused by the moving vehicle enacts resistive forces opposite to the vehicle's direction [71],[72]. The model uses the generic aerodynamic drag equation (Equation 4.4) that considers the drag coefficient, air density, velocity, and frontal area of the truck. In the model in this work, this equation is implemented as a Simulink function that takes in the values of the vehicle velocity as a variable, and the constant values (ρ, A, and C_{drag}) and uses these to estimate the aerodynamic drag.

$$\text{Aerodynamic drag} = 0.5V^2 \rho A C_{\text{drag}} \tag{4.4}$$

Where:

V: Vehicle velocity

ρ: Air density

A: Frontal area of the vehicle

C_{drag}: Drag coefficient

The grade resistance affects the truck when moving on an inclined surface. There is resistance on the vehicle when it is moving uphill. The grade resistance depends on the vehicle's mass, gravity, and inclination, as shown in Equation 4.5 [71]. The inclination changes with time during the drive cycle data depending on the haul road profile.

$$Grade\ Resistance = Mgsin\,(\Theta) \tag{4.5}$$

Where:

M: Vehicle mass

g: Acceleration due to gravity

Θ: Angle of the grade

The rolling resistance is due to the constant contact between the tires of the vehicle and the surface of the road. A frictional force between the tires and the road acts as a form of resistance to the forward motion due to the traction force. The mass of the vehicle, gravity, and the angle at which the vehicle is moving all play a role in the rolling resistance. Equation (4.6) shows the rolling resistance of a vehicle [71].

$$Rolling\ Resistance = Mg\mathrm{C}_{\mathrm{rol}}cos\ (\Theta) \tag{4.6}$$

Where:

M: Vehicle mass

g: Acceleration due to gravity

$\mathrm{C}_{\mathrm{rol}}$: Vehicle rolling resistance coefficient

Θ: Angle of the grade

Figure 4.7 is an overview of the forces on a generic vehicle. The model estimates the propelling force from the resistances and the tractive force by subtracting the resistances from the tractive force. Using Equation (4.3), the model estimates the acceleration from the mass of the vehicle M and the propelling force. The model estimates the vehicle velocity by integrating the acceleration.

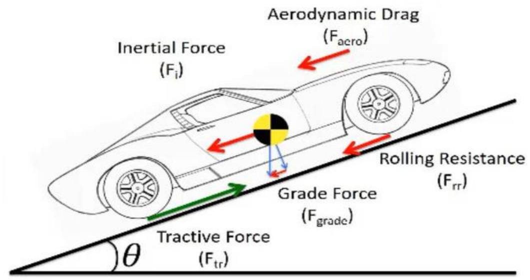


Figure 4.7 Conceptual model of forces on vehicle [72]

4.2.4. Model Verification. Besides the truck specifications, the vehicle model uses parameters from the mine (haul road and drive cycles) and the environment in the simulation. The vehicle model takes input such as the speed profile, grade profile, rolling resistance coefficient, and truck weight depending on the payload. In order to verify the model, this work used data from a real mine running Komatsu 830E-5 trucks for verification. The input data for the verification experiment is based on the data in Table 4.1 for the truck. Additionally, the verification experiment is based on the data in Tables 4.2 - 4.4. The data from the mine (the name of the mine is kept confidential in this thesis as per the non-disclosure agreement between S&T and Komatsu) covered 30 drive cycles over various haul routes and terrain. The author selected a drive cycle that was typical in the data set for verification. The grade (angle of inclination) for the selected drive cycle and the payload are shown in Figures 4.8 and 4.9, respectively. This work used this input data to run the experiment for verification (to ascertain the model works as intended). The entire duration of the simulation is 1,100 secs (18.33 mins).

Table 4.2 Vehicle Parameters

Parameter	Value
Air Density	1.225 kg/m^3
Drag coefficient C_{Drag}	0.65
Gravity g	9.81 m/s^2
Road angle Θ	Varies
Rolling resistance coefficient C_{rol}	0.03

Table 4.3 Fuel cell nominal parameters

Stack Power	900 kW - Nominal 1,500 kW - Maximal
Fuel Call Resistance	0.07224 Ohms
Nerst Voltage of one cell	1.1325
Nominal Utilization	Hydrogen = 99.94% Oxidant = 59.52%
Nominal Consumption	Fuel = 10000 slpm Air = 23810 slpm
Exchange Current [i0]	1.504 A
Exchange coefficient [alpha]	-0.93237

Table 4.4 Fuel cell signal variation parameters

Fuel composition	99.95%
Oxidant composition	21%
Fuel flow rate at nominal hydrogen utilization	10010 lpm - Nominal 20020 lpm - Maximal
Air flow rate at nominal Oxidant utilization	40000 lpm - Nominal 80000 lpm - Maximal
System Temperature	273 K
Fuel Pressure	1 bar
Air Pressure	1 bar

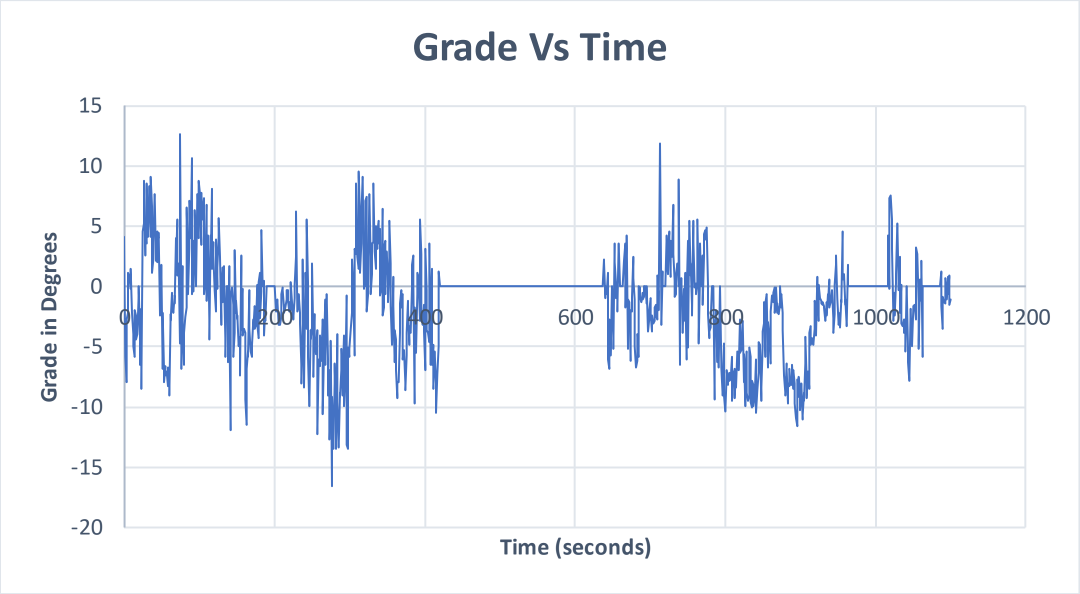


Figure 4.8 Plot of grade over time

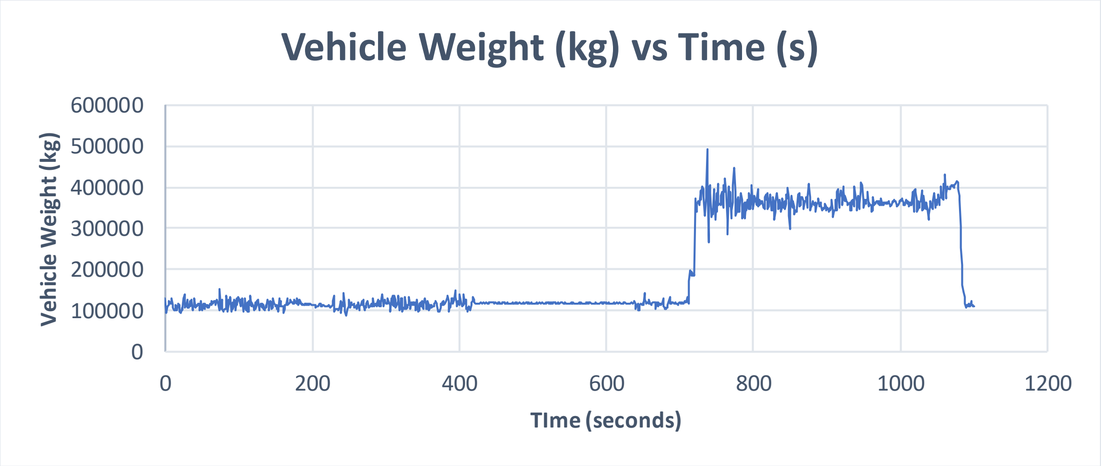


Figure 4.9 Plot of calculated total truck weight over time

Figures 4.10 - 4.17 shows the results of the verification experiments. Figure 4.10 shows the simulated and input truck velocities. As shown by the figure, the simulated velocity matches the input velocities indicating the model's ability to replicate the drive cycle. The truck duty cycles in the data used in this research begin when the truck starts moving towards the shovel to get a load. The idle time shown in the cycle (t = 420-637 seconds) is for when the truck is waiting at the shovel to get a load.

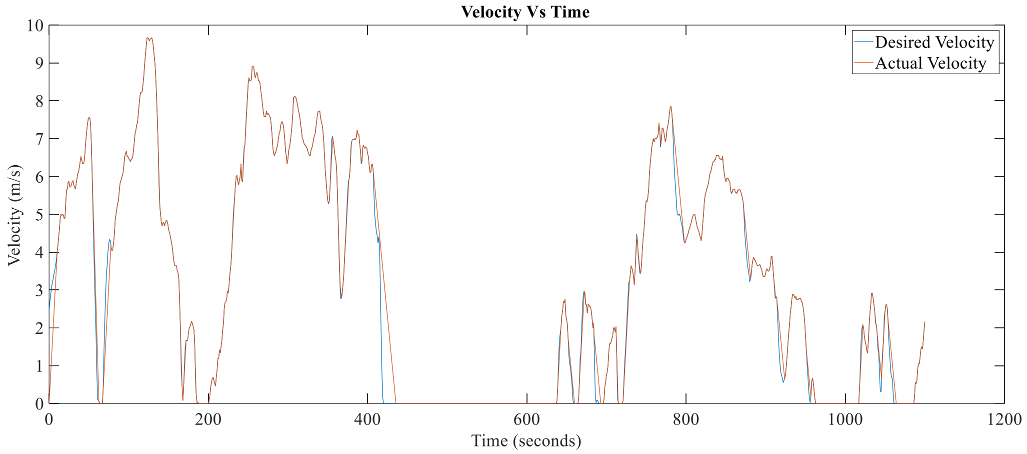


Figure 4.10 Simulated velocity compared to the actual (input) velocity of the vehicle

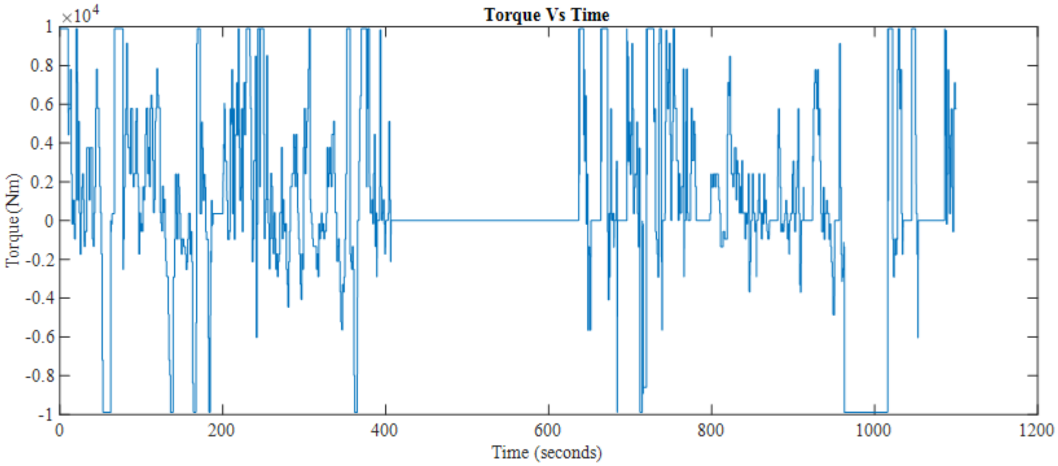


Figure 4.11 Simulated torque of the truck

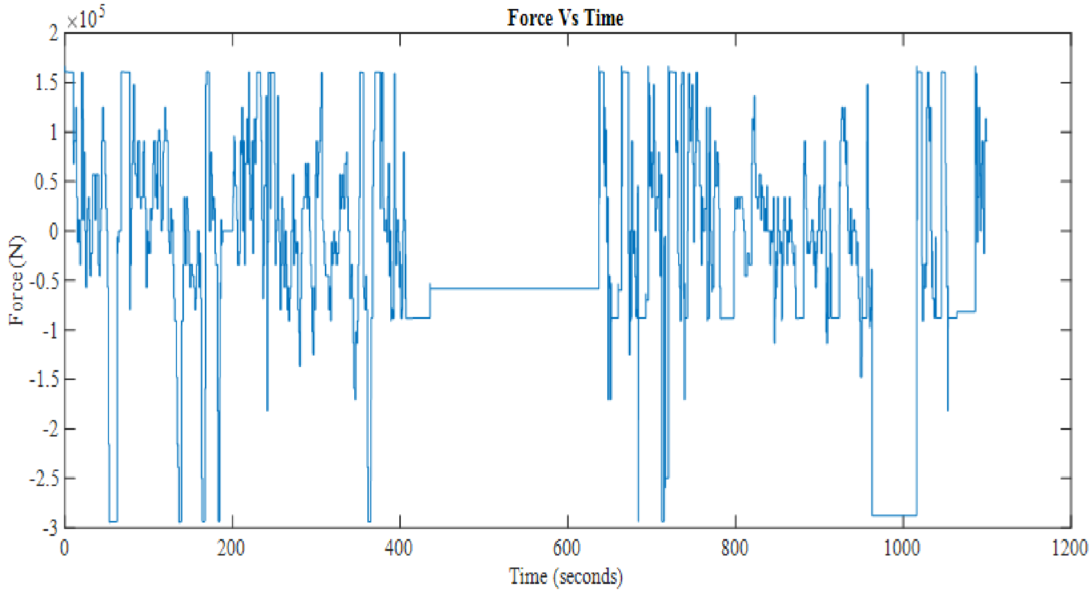


Figure 4.12 Propelling Force

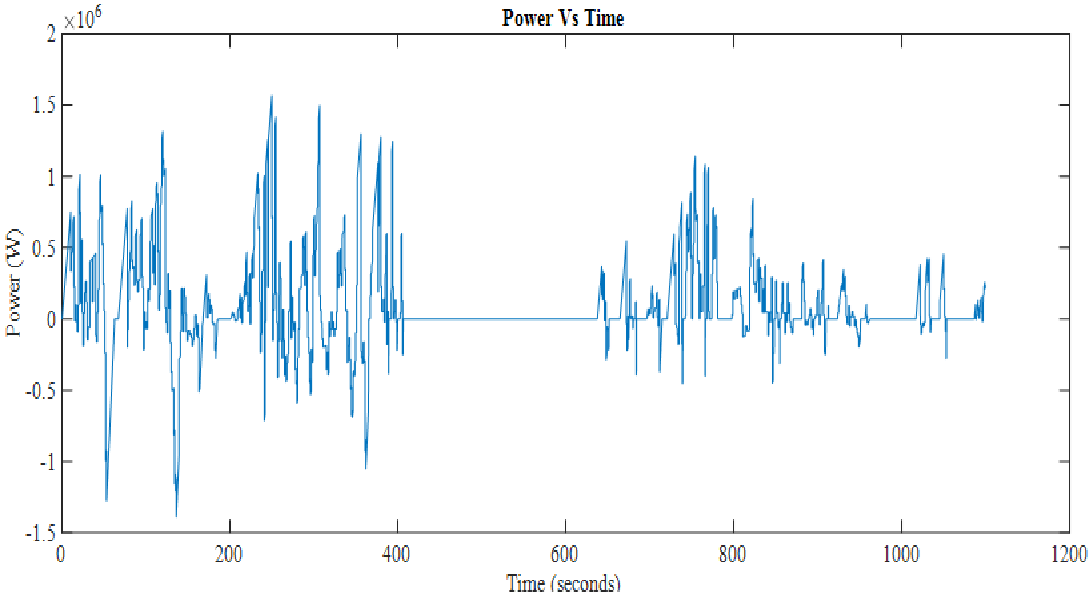


Figure 4.13 Simulated power request from the truck

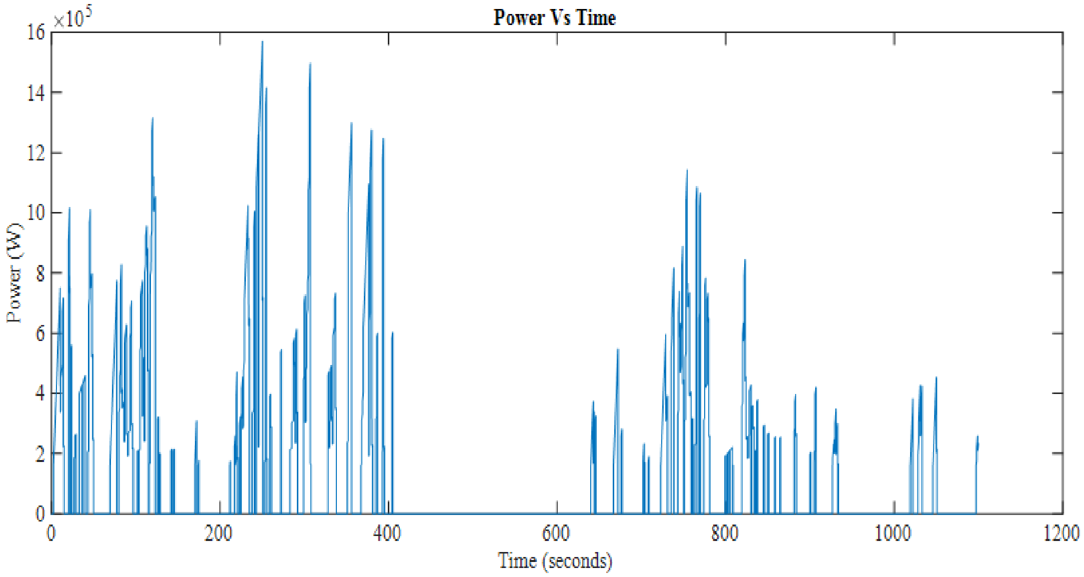


Figure 4.14 Fuel cell power

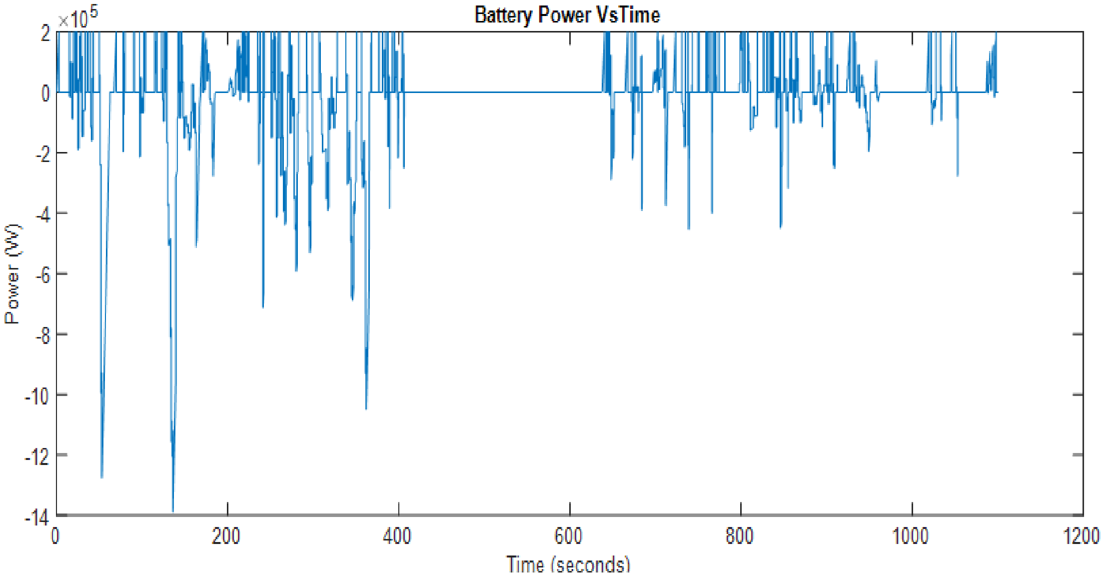


Figure 4.15 Battery power

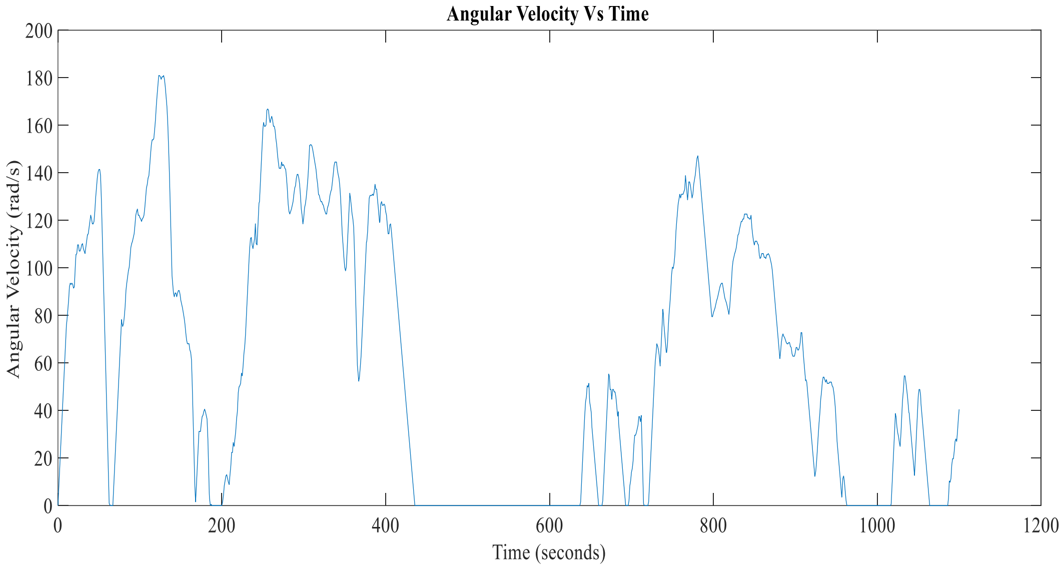


Figure 4.16 Simulated motor angular velocity

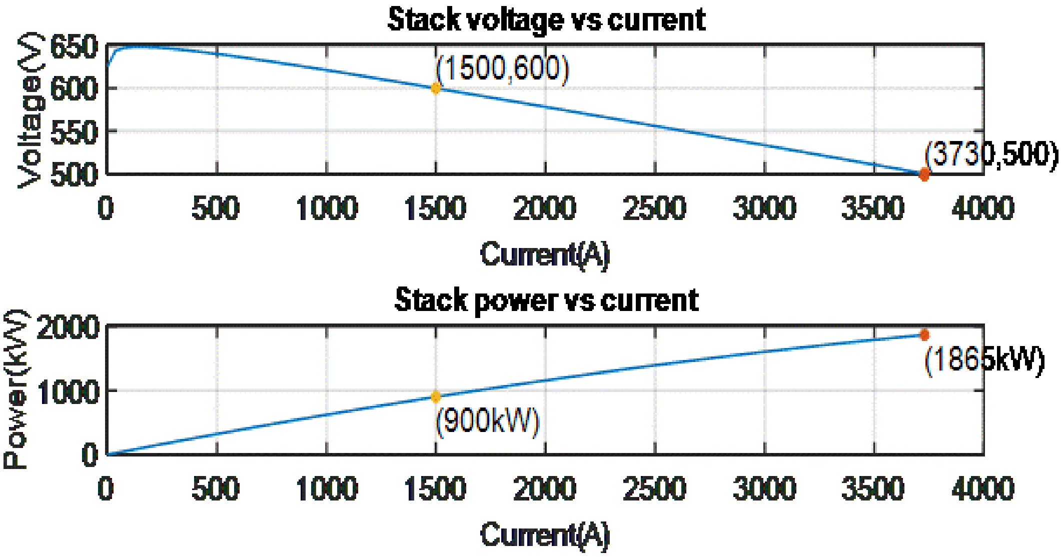


Figure 4.17 Voltage-current characteristics of the Fuel cell stack

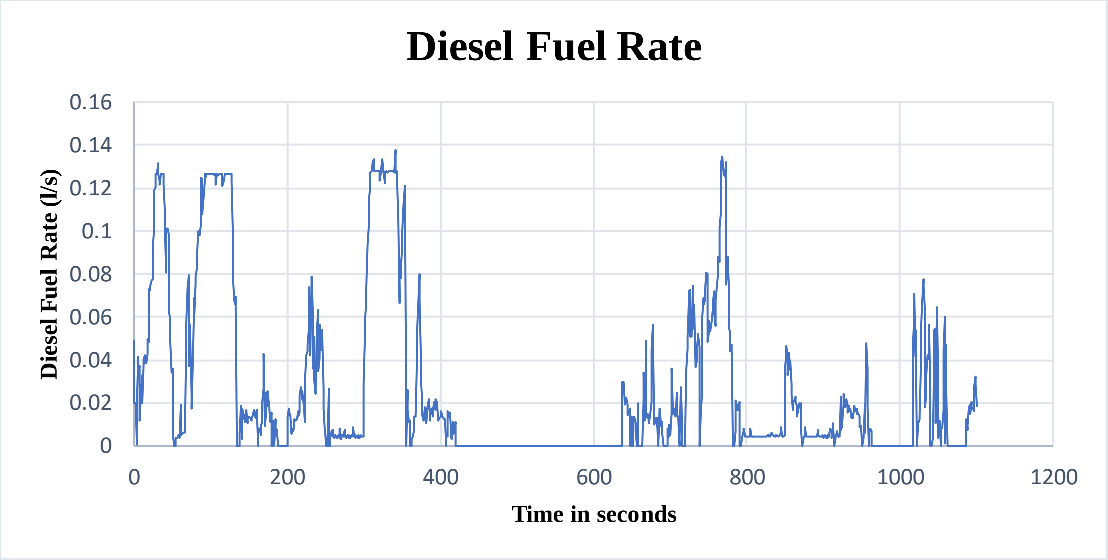


Figure 4.18 Diesel Fuel Rate

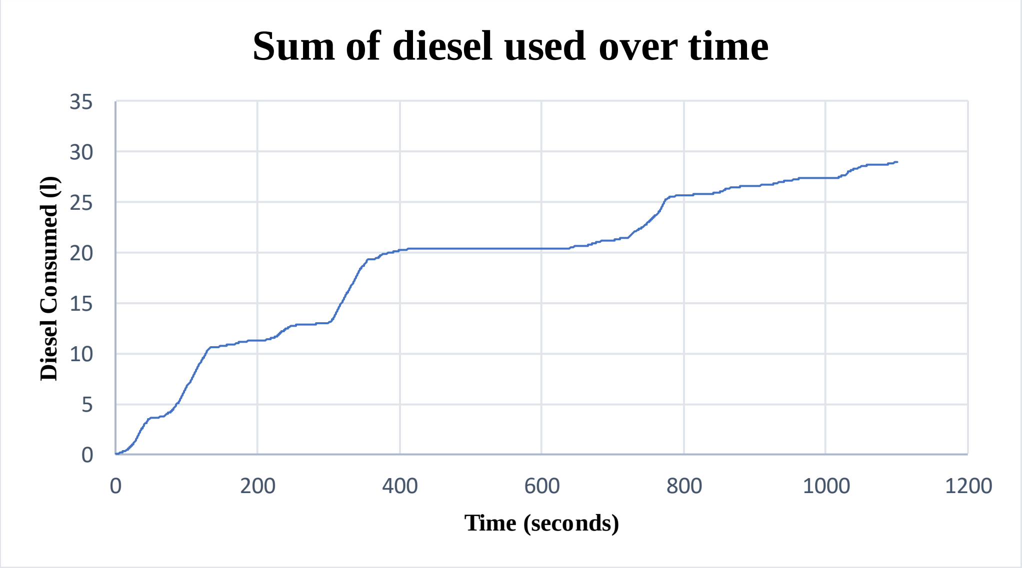


Figure 4.19 Sum of diesel consumed over time

The submodels utilized the fundamental equations shown above to simulate truck paraments such as power, force and speed. Figures 4.11-4.16 show the torque, angular velocity, propelling force, and requested power from the simulation. Based on the simulated power requests, the model predicts the fuel cell and battery power shown in Figure 4.14 and Figure 4.15, respectively. First, it is evident that the input velocity to the driver submodel is similar to the velocity output of the vehicle submodel. The velocity output of the vehicle submodel has a direct relationship with the angular velocity at the wheel based on the gear ratio as provided in Equation 4.3. This relationship can be verified in Figure 4.16 and Figure 4.10.

Power is the product angular velocity and torque as shown in Equation 4.2. A careful examination of Figures 4.11 (torque) and 4.16 (angular velocity) together with Figure 4.13 (power) shows the model is working as intended. Battery power and fuel cell power in Figure 4.14 and Figure 4.15 follow the energy distribution system explained in Figure 4.5, and the entire system is within the rated power of the 830E-5 Komatsu truck, which has a gross operating power of 1,865 kW. Figure 4.17 displays the operating conditions of the fuel cell aligning with the power specifications of the Komatsu truck with the expectation of providing a maximum power of 1,865kW.

On the other hand, the propelling force is positive indicating it overcomes the resistive force. The force provides the correct acceleration, which can be verified by the accurate output velocity from the truck model.

4.3. SIMULATION EXPERIMENTS

The author conducted simulation experiments to estimate fuel consumption under different duty cycles using the data acquired from a mine. The haulage cycle data from the mine contains 30 different drive cycles from the same mine. Each drive cycle consists of six different vehicle states: "empty run," which signifies when the truck moves without any loaded ore or waste; "empty stop," which indicates that the truck is not moving and empty; "loading" which is when the truck is without motion but loading materials; "dumping run", which is when the vehicle is offloading the materials; and "hauling stop," which indicates that the vehicle is loaded but without motion. The drive cycle will be simulated with the grades. In order to reduce computational time from simulating the long waiting times where there is negligible energy consumption (see, e.g., Figure 4.10), some drive cycles for simulation were modified (by removing the idle times) to minimize the simulation time and computational expense. However, all the other data will be kept the same.

It is important to note that in most scenarios, when trucks are stationary in mine operations, power and fuel consumption may not be zero because other activities such as raising the bucket or dumping ore in mining equipment require energy even if there is no motion. In the truck data provided for this model, there is fuel consumption when the trucks are stationary. However, the model in this work only predicts energy and fuel consumption when the truck is in motion since this model uses propelling speed to trigger power and fuel consumption. While this is a limitation of the work, it is not a significant drawback as most of the energy and fuel consumption is attributed to truck motion. Although, scenarios such as dumping may sometimes yield higher fuel consumption than the average no-motion activities, the difference between the fuel consumption associated with these and the motion activities is still high.

The simulation experiments showcase three different scenarios based on simulations that vary based on cycle time. The first experiment and its associated results are derived from the verification simulation above. It will be regarded as a medium length scenario based on the simulation time. The second experiment is a shorter simulation (cycle time) while the third experiment is from a longer simulation (cycle time) to evaluate the sensitivity of the fuel consumption to differences in haulage cycle times. This section will compare the sum of both fuels used to understand the difference in the amount of fuel used in both technologies for each of the simulations.

For each drive cycle, the analysis estimated the amount of diesel and hydrogen fuel consumed using the simulation results. Each total amount of diesel fuel was derived from the mine data provided by integrating the rate of fuel consumed over the corresponding period. While for each hydrogen fuel, the total fuel rate comes from the model simulation. The obtained hydrogen fuel rate is integrated over the period of each drive cycle to attain the sum of hydrogen used. For example, the drive cycle utilized for the model verification is used as the result for the medium simulation case.

4.3.1. Medium Haul Cycle Case. As seen in Figure 4.18, the plot showcases the rate of diesel fuel consumption. The integration of the rates of fuel consumption overtime allows one to obtain the sum of diesel used over the period. The result of the diesel consumed over the sampled period is 29.025 liters as seen in Figure 4.19. Similarly, to obtain the result of hydrogen consumed, the simulation produces two plots, the rate of hydrogen consumed, and the sum of hydrogen consumed over time. Figure 4.20 and Figure 4.21 show the rate of hydrogen consumption and the sum of the fuel consumed over the sampled period is 24,081 standard liters at standard temperature and pressure (STP), making the pressure around 1 bar.

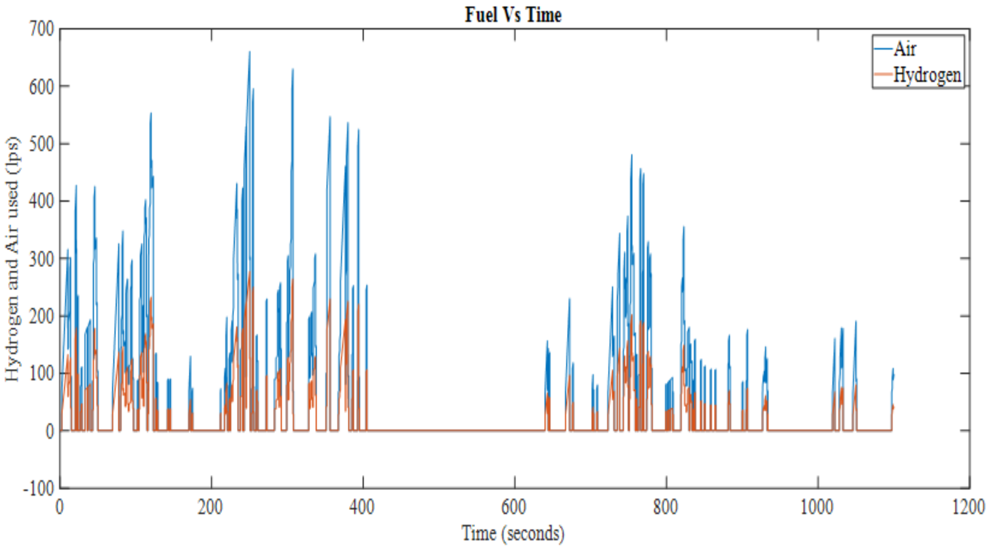


Figure 4.20 Hydrogen and air consumption rate.

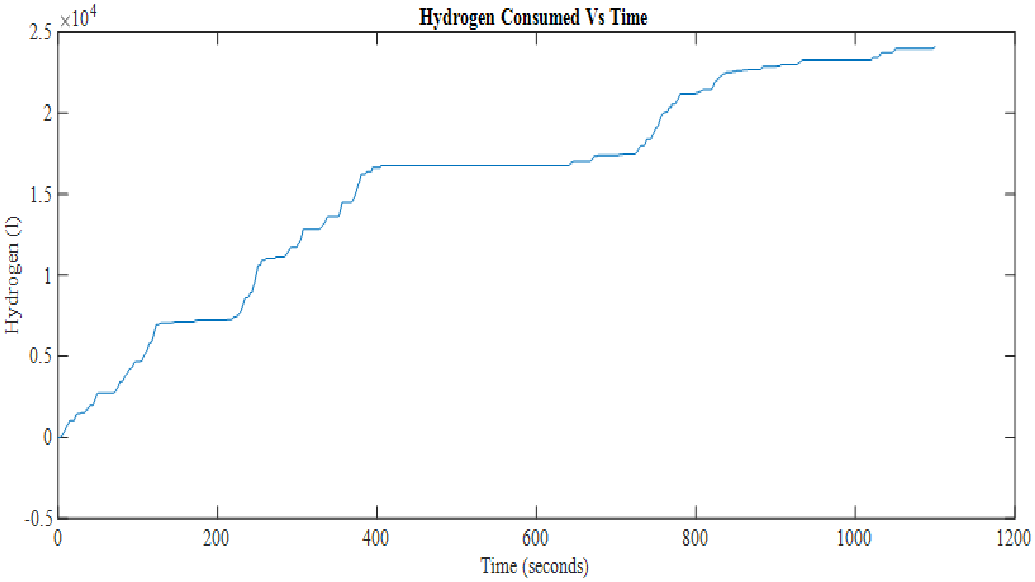


Figure 4.21 Sum of hydrogen consumed over time

4.3.2. Short Haul Cycle Case. The short simulation case is the shortest simulation with a duration of 852 seconds as seen in Figure 4.26. The model took in the drive cycle, which includes varying grade (inclination), mass of the truck, and speed shown in Figure 4.24, Figure 4.25, and Figure 4.26 respectively. This scenario helps to show how the model operates in an environment of consistent high-performance operation within a short period of the time and the swift change in operating states. This was a complete drive cycle without any alteration. The result of the diesel consumed over the sampled period is 23.6 liters as seen in Figure 4.22. Similarly, the sum of the fuel consumed over the sampled period is 17,729 liters after integrating the diesel and hydrogen rates, respectively.

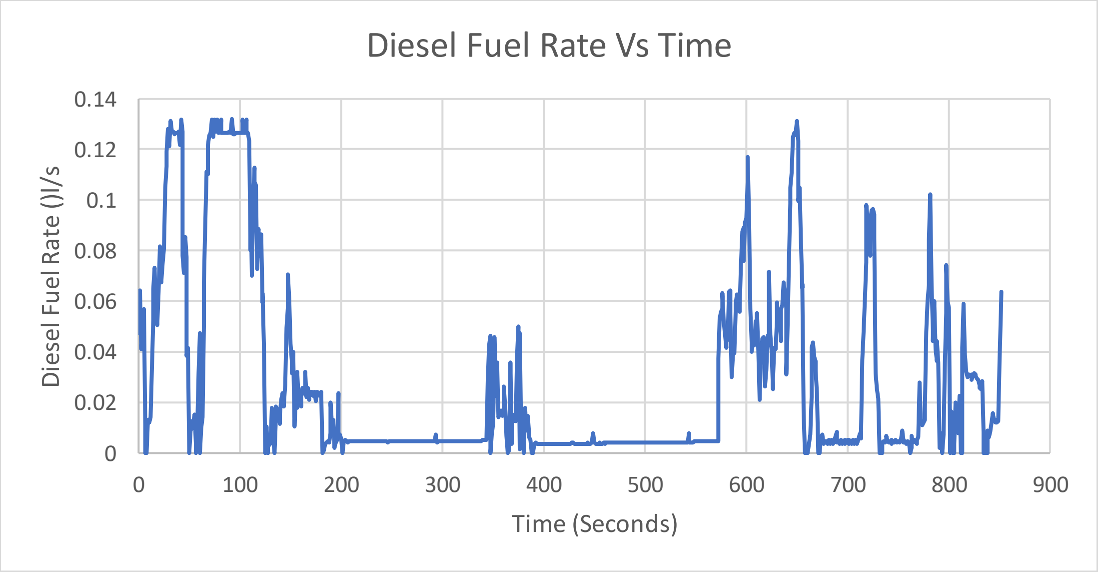


Figure 4.22 Rate of diesel consumption for medium haul cycle case

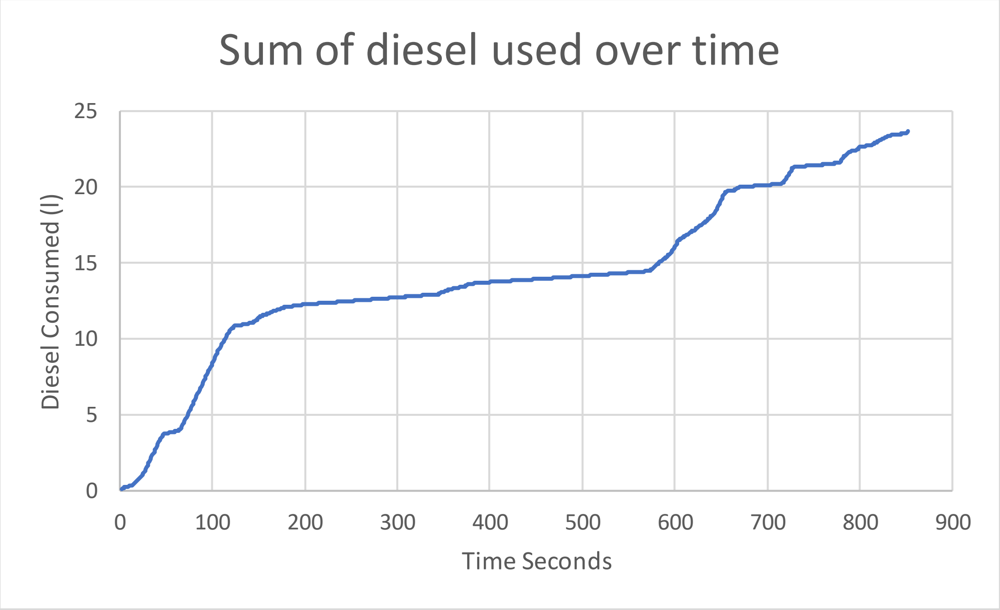


Figure 4.23 Sum of diesel consumed over time for medium haul cycle case

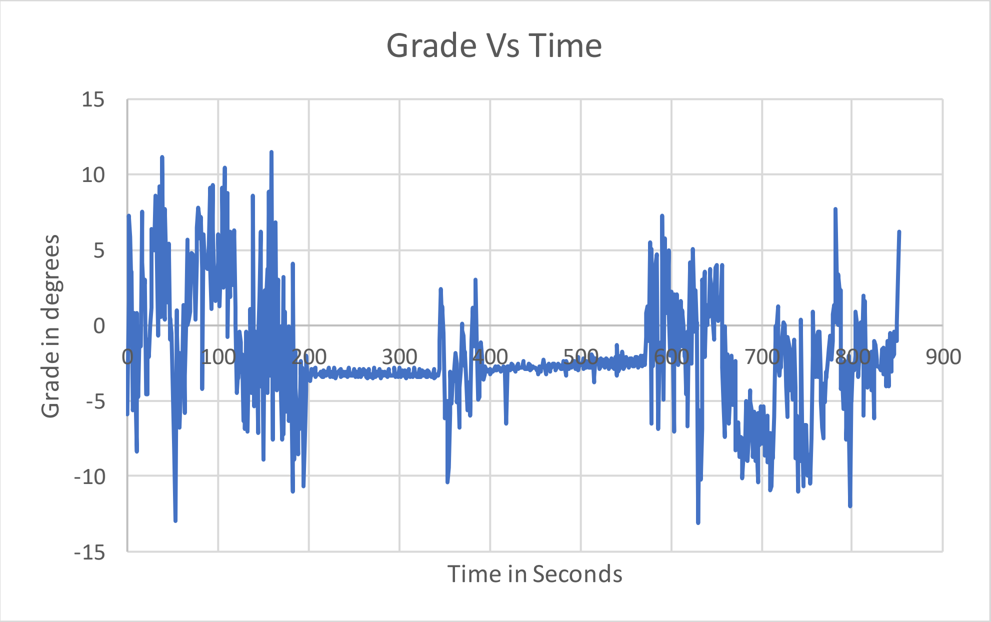


Figure 4.24 Plot of grade over time for medium haul cycle case

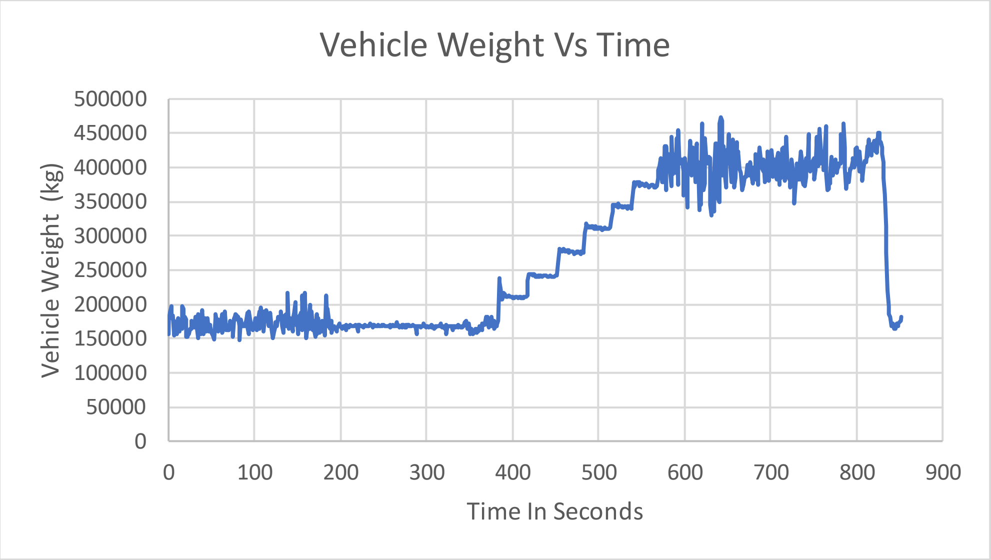


Figure 4.25 Plot of calculated total truck weight over time for medium haul cycle case

Figures 4.26 – 4.28 show the simulation results.

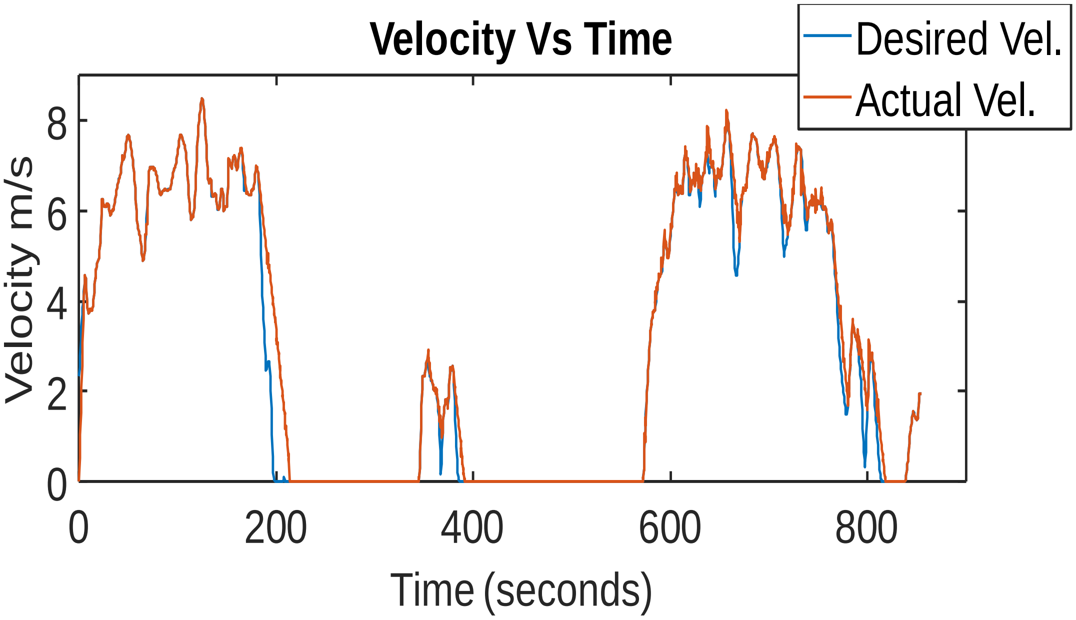


Figure 4.26 Simulated velocity compared to the actual (input) velocity of the vehicle for short haul cycle

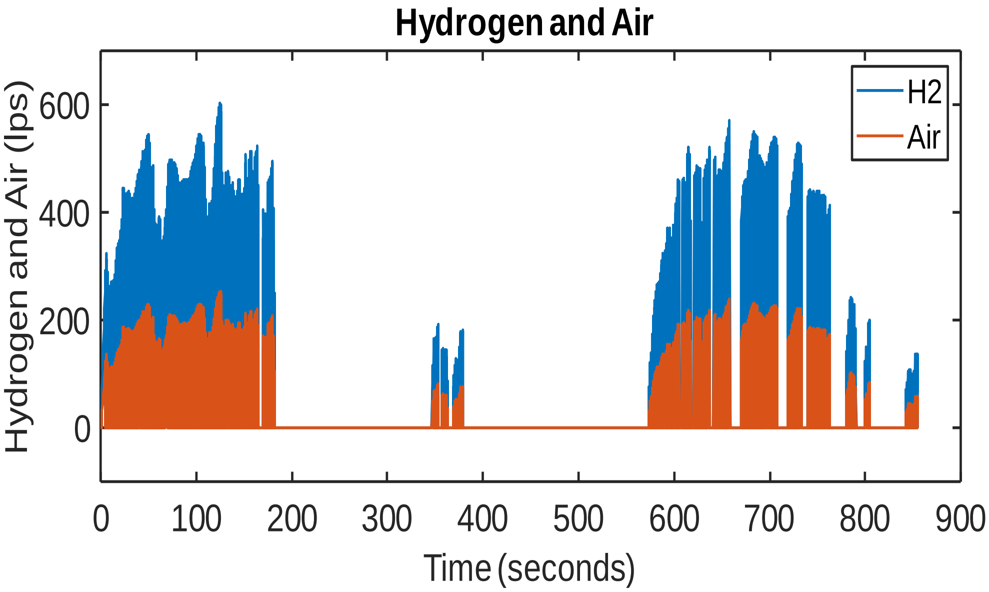


Figure 4.27 Hydrogen and air consumption rate for short haul cycle

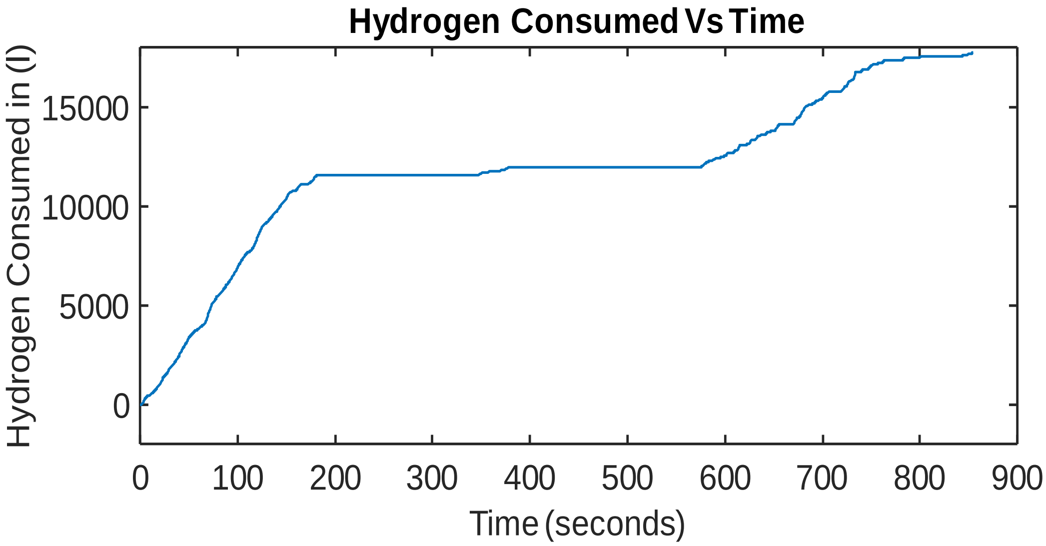


Figure 4.28 Sum of hydrogen consumed over time for short haul cycle case

4.3.3. Long Haul Cycle Case. The third simulation is the longest simulation with a duration of 1,551 seconds as seen in Figure 4.33. It helps to show how the model operates in an environment of consistent high-performance operation within a long duration. Figures 4.29 – 4.32 show the diesel consumption, mine grade and vehicle weight over time, which are the input for the simulation. This also was a complete drive cycle without any alteration and had an overall diesel consumption of 82.94 liters and 25,705 liters of hydrogen.

Figures 4.33 – 4.35 show the simulation results showing the velocity and hydrogen consumption.

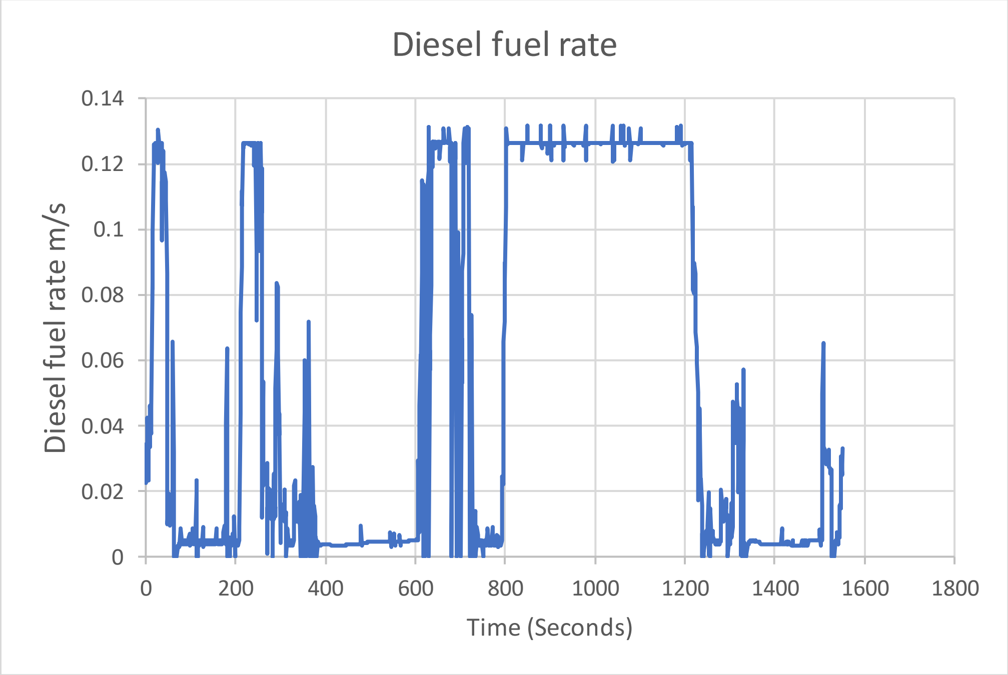


Figure 4.29 Rate of diesel for long haul cycle case

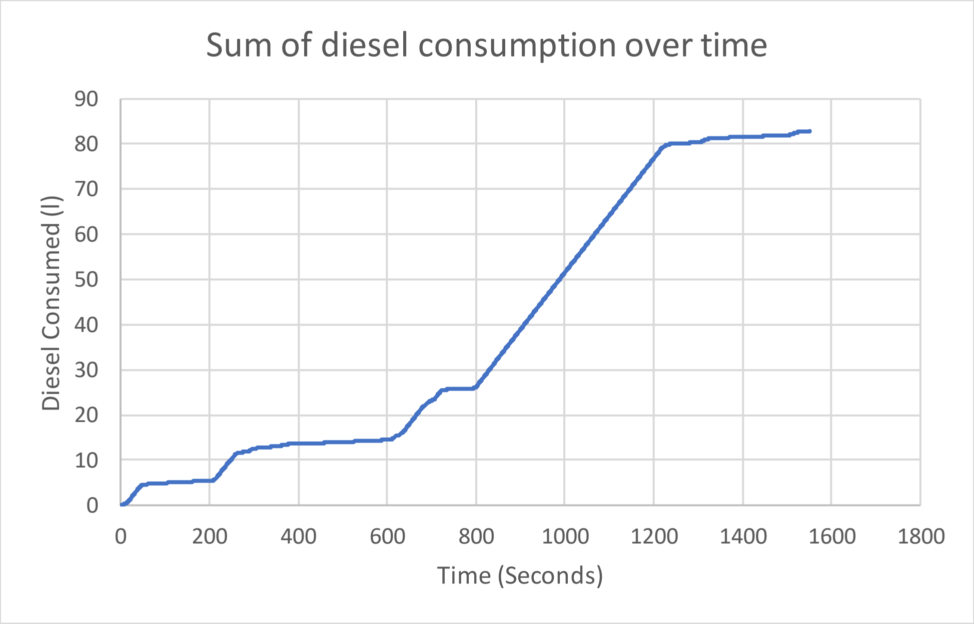


Figure 4.30 Sum of diesel consumed over time for long haul cycle case

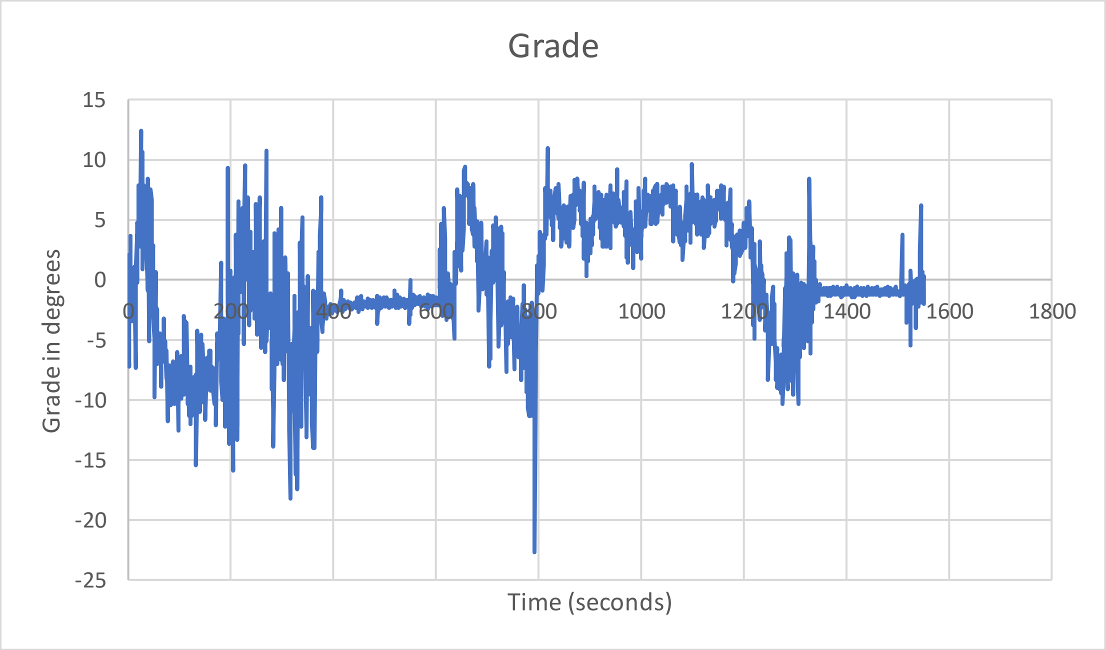


Figure 4.31 Plot of grade over time for long haul cycle case

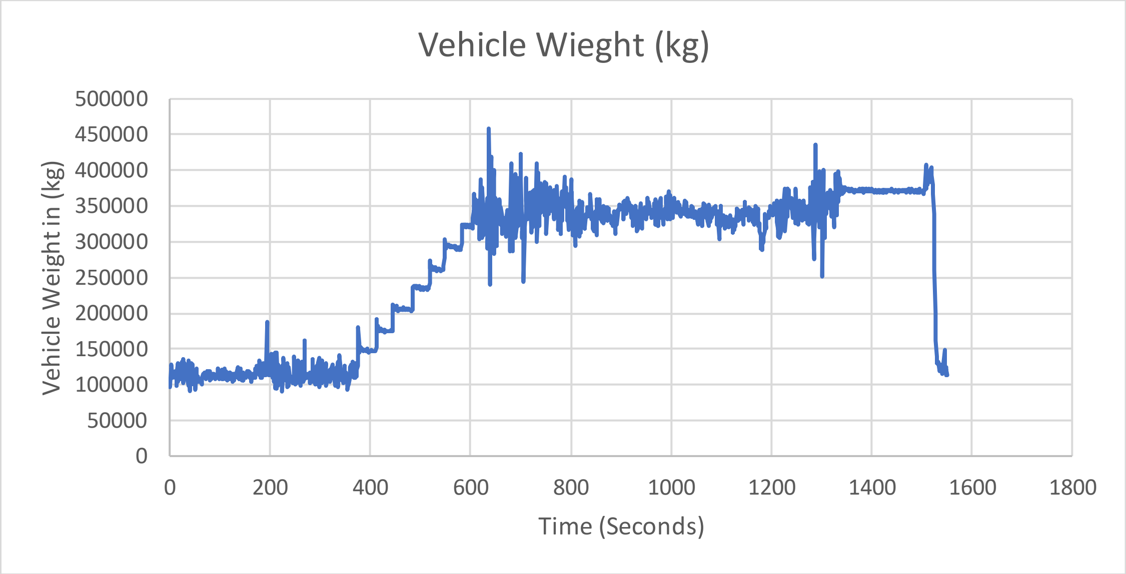


Figure 4.32 Plot of calculated total truck weight over time for long haul cycle case

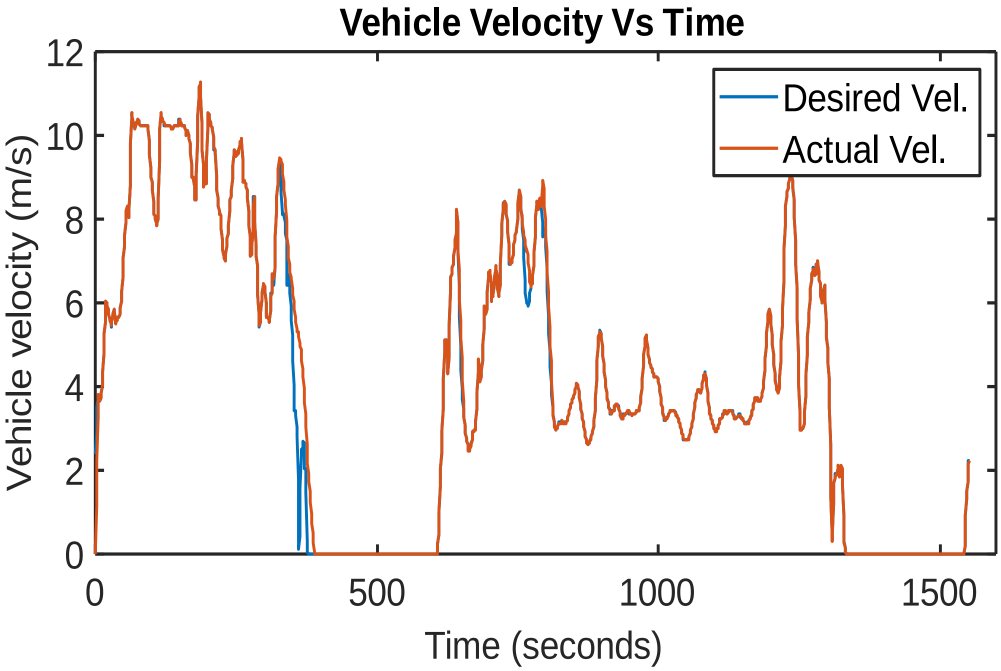


Figure 4.33 Simulated velocity compared to the actual (input) velocity of the vehicle for long haul cycle case

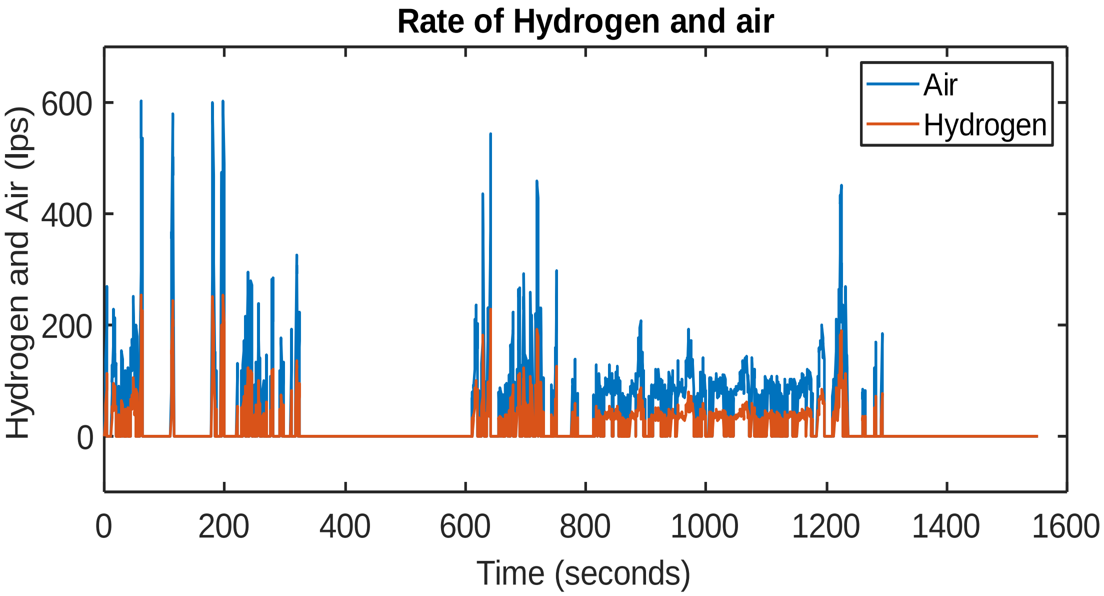


Figure 4.34 Hydrogen and air consumption rate for long haul cycle case

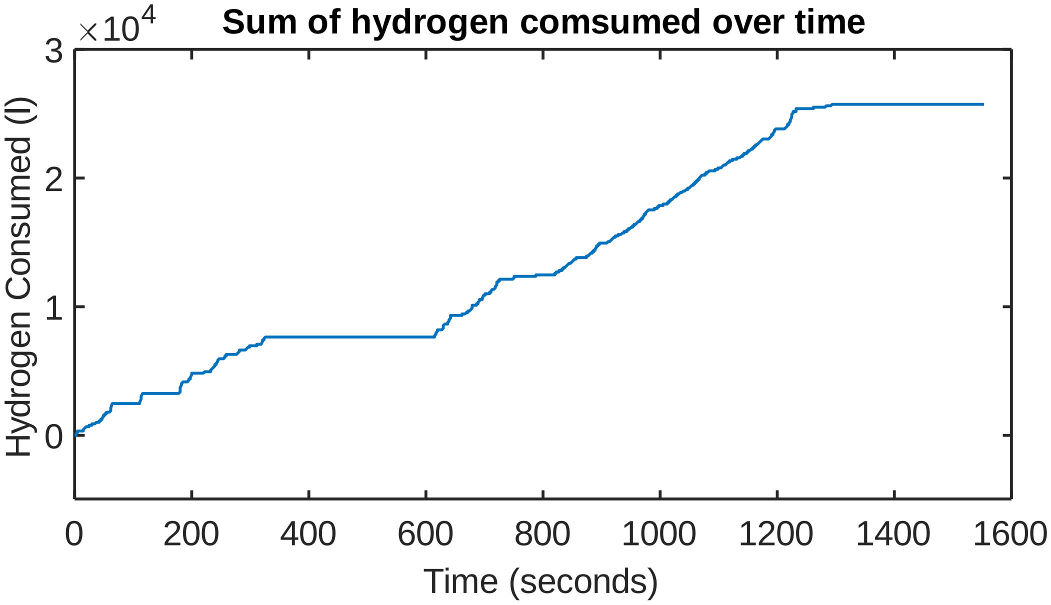


Figure 4.35 Sum of hydrogen consumed over time for long haul cycle case

4.3.4. Hydrogen Storage and Fuel Cell Volume Estimation. The diesel consumed for the short, medium, and long-haul cycles were calculated using the field data as shown above. The diesel consumption increased with increasing length of the drive cycle, as expected. Therefore, longest drive cycle produced the highest fuel consumption of 82.94L. To determine the hydrogen fuel, the fuel consumption was obtained from the simulation results at 1 bar. However, the hydrogen volume at 350 bar and 700 bar was calculated for each drive cycle because most fuel cell vehicles have hydrogen pressurized to 350 bar or 700 bar as an industry standard. Table 4.5 displays the results for the three drive cycle cases. At 1 bar, hydrogen is approximately 0.09kg/m^3. This means for the medium case, hydrogen that powers the entire drive cycle weighs 2.167kg. With increased pressure, the hydrogen density increases, allowing for volume to reduce. At 350 bar and 700 bar, the density is approximately 21kg/m^3 and 42 kg/m^3 respectively. This means that even at the higher pressure of 700 bar, the volume of hydrogen required to power the drive cycle is 51.4 liters greater than 29.025 liters of diesel. As a result, the size of the hydrogen tank is numerically larger and occupies more space.

Similarly, one can also compare the smallest possible volume from hydrogen with diesel volume for the other drive cycles (short and long cases) as displayed in Table 4.5. When looking at the hydrogen fuel consumption at 1bar, the short and long drive cycle are 17,729 liters and 25,705 liters, respectively. However, as stated earlier since most hydrogen tanks are pressurized at 350 to 700 bar, the appropriate measure for comparison between the hydrogen and diesel would be the amount of hydrogen pressurized at 350 to 700 bars. The results in Table 4.5 shows that, for hydrogen tanks to provide similar range and storage, the hydrogen in mining trucks should be pressurized at 700 bars as the difference in volume at 350 bars will be too high. Therefore, for the short drive cycle, with a pressure of 700 bar, the volume of hydrogen required to power the drive cycle would be 37.99 liters. Respectively, for a long drive cycle at 700 bar pressurized tank, the hydrogen needed to power the long drive cycle would be 55.08 liters.

Table 4.5 Showing the volume of hydrogen by pressure for all drive cylces

Hydrogen Pressure & Density		**Drive Cycle: Base Case**	**Drive Cycle: Short**	**Drive Cycle: Long**
		Diesel Fuel Consumed: 29.025 L	**Diesel Fuel Consumed:** 23.6 L	**Diesel Fuel Consumed:** 82.923 L
Pressure (bar)	Density (kg/m^3)	Volume (Liters)	Volume (Liters)	Volume (Liters)
1	0.09	24,081	17,729	25,705
350	21	103.19	75.98	110.16
700	42	51.4	37.99	55.08

Based on the results, it appears that the fuel cell consumes less hydrogen volume at 700 bars than diesel with the long drive cycle case (this is not the case if the hydrogen tank is pressurized at 350 bars). However, the volume of hydrogen required to power the short and medium drive cycle were higher than the diesel fuel determined for the drive cycles. This result shows that as the drive cycle increase, the volume of hydrogen required does not always proportionally increase. Thus, depending on the potential use of the truck (i.e. the length of haulage, the terrain of the mine, and potential payload) the amount of hydrogen used will differ. The appropriateness of the hydrogen fuel cell as a truck powertrain is unique to each specific case. Even then, it is important to note that the required hydrogen tank to provide the 4,542 L of storage (the capacity of the Komatsu 830-E truck) [55] will be bulkier than the current diesel tank because of need to pressurize the hydrogen to 700 bars. Also, other factors such as the fuel cell stack size, the capacity of the auxiliary power source and power distribution strategy between the fuel cell and the other power source play a significant role when designing the fuel cell truck.

The prediction of fuel cell stack size is highly dependent on the maximum power and voltage requirements [73]. In this case, it is 1,865kW power, 625V voltage, and 2,800A current. A CAT diesel engine (C175-16) is used as an estimate for the size of the powertrain in comparing engine sizes because there was no access to the dimension of the Komastu engine. and they both have similar power rating. The cells have an assumed current density of 0.6A/cm^2 [73]. The 2800A current will equate to 4666A/cm^2 of the total active cell area. As shown in the fuel cell stack characteristics in Figure 4.17 above, there are 957 cells in the stack. This means the area of each cell is 4.87 cm^2. The fuel cell stack will be a 4,666 cm^2 compared to an approximately 1.3×10^5 cm^2 area of a diesel engine [74]. Also, Nuvera Fuel Cell produces 67kW fuel cell engines with a 3.0×10^5 cm^3 volume of space [75]. For a 1,865kW power requirement, the system may need up to 8.4×10^6 cm^3 for fuel cell powertrain compared to 28.6×10^6 cm^3 at the minimum for a diesel engine [74].

4.4. SUMMARY

This section presents a MATLAB/Simulink model of a fuel cell haul truck. The model is verified with data from an actual mine using a Komatsu 830-E truck. The verified model is used in simulation experiments to estimate the volume of hydrogen required for short, medium and long-haul cycles. The hydrogen volume at 700 bar is compared with diesel consumption to estimate the required fuel tank requirements while the maximum power, voltage, and current is used to estimate the fuel cell stack size. The model presented in this section highlights the potential possibilities of a hydrogen fuel cell haul truck if we are going to replace the combustion components of a diesel truck with hydrogen storage and fuel cell system. The model results provided the potential hydrogen storage and fuel cell size and compared with the diesel equivalent. The model results show that hydrogen storage for mine trucks should likely be at 700 bars or more to ensure comparable driving range and storage volume to diesel haul trucks. Even then, the results show that it is feasible to replace diesel with hydrogen storage even though the range of a hydrogen fuel cell truck will likely be shorter than the diesel truck. However, depending on the application, such as a specific case of long-range drive cycle, it is possible to achieve better range with hydrogen than with diesel. A new vehicle frame may need to be created to support the design potential of incorporating the fuel cell, and hydrogen storage, because current frame of the existing diesel truck may be too restrictive to accommodate the fuel cell system and the hydrogen and will limit the driving range in many applications as seen in the medium and short drive cycle case of this work. The model presented in this section did not analyze other factors such as the effect of operating conditions on power fluctuation that may influence the power production, durability, and performance of the fuel cell stack. Thus, further work may need to be done to include these parameters.

5. CHALLENGES AND OPPORTUNITIES FOR FUEL CELL INTEGRATION

5.1. OVERVIEW

As shown in Section 4, fuel cell electric vehicles powered by hydrogen can have similar performance characteristics to the internal combustion engine but with no direct GHG emission. Already, Anglo American is testing hydrogen fuel cell trucks at the Mogalakwena platinum mine in Limpopo, South Africa [76]. Even though the integration of fuel cells into a truck will reduce GHG emissions in mining, there are many challenges to overcome to make hydrogen powered fuel cell trucks a reality, which make other OEMs and mining firms skeptical. As deduced from earlier analysis and review, this section highlights the important opportunities and challenges accompanied with incorporating hydrogen fuel cells in mining trucks. Most of the challenges involve the truck's real estate management during redesigning, cost of parts and infrastructure and fuel cell performance. The main opportunities include the fact that the hydrogen powered fuel cell truck is feasible and it can help reduce GHG emission and the potential for similar refueling time to that of internal combustion engines.

5.2. VEHICLE REAL ESTATE

As noted in Section 4, it is technically possible to power a truck with hydrogen fuel cell powertrain. This poses an opportunity for hydrogen fuel cells because the process of providing energy does not directly produce GHG. However, the challenge is in the complete feasibility of directly replacing an internal combustion powertrain and fuel storage with a hydrogen fuel cell system engine. Section 4 discusses the differences in the amount of hydrogen to power the truck. This means the truck may need more space for the volumetric size of hydrogen fuel storage (i.e., even in the long-haul case, because of the additional material required to keep the hydrogen pressurized, the space required for the same amount of driving range is likely to be higher).

The internal real estate available for the diesel tank and the diesel engine cannot be directly replaced with hydrogen storage and fuel cell stack. There is a need to redesign or add component like batteries, electric motors, inverters [77] to support the hydrogen fuel cell system to achieve desired output and ensure a safe and efficient system. For example, Anglo American’s test truck uses a 1.2 MWh lithium-ion battery pack and multiple fuel cells to deliver up to 800kW of power [78] for a Komatsu 930E truck (rated capacity of 290 tonnes).

Additionally, because of the sensitivity and the importance of on-board hydrogen storage in the integration of hydrogen fuel cell technology in vehicles (trucks), researchers continue to propose better and safer ways for onboarding hydrogen. The proposed solutions seek to improve methods of on-boarding and containing hydrogen, as well as techniques that help reduce the volume of hydrogen, which may require additional components. For example, the cryocompression technique uses liquid nitrogen to cool the tank to provide three times the volumetric capacity than a non-cooled hydrogen tank [79]. Another common method of increasing capacity is utilizing mechanical compression at high pressures such as 350 bar or 700 bar, because it is a reliable, efficient and simple approach to the design of hydrogen storage tanks [80]. Mechanical compression helps to increase the volumetric and gravimetric capacity of hydrogen [81], however, the approach poses safety concerns. The system under high pressure, can damage the tank walls as a result of Joule-Thomson effect that increase the temperature during refueling [81]. Also storing hydrogen even at high pressure (700bar) in most cases require more storage space than diesel. Therefore, when implementing hydrogen fuel cell into haulage real estate, the safe on-board of hydrogen storage and the size are crucial to the feasibility of the entire hydrogen economy, especially given by hydrogen’s colorless and highly flammable characteristics. It is important that the entire system provides a safe and reliable solution to store hydrogen on-board at pressures of 700 bar to compete with diesel-powered technology.

This design challenge may call for an entire remodel of the existing trucks because the internal real estate may not allow occupancy for every component. In this case original equipment manufacturers (OEMs) may have to try to manufacture an entirely new truck. A process that means mine operators trust and accept the new products and OEMs will have to change their production line and invest in the materials that will help make the components of these new trucks. One challenge will be that, while this new system has no proven results to ensure durability and effectiveness in the mining sector, it will be challenging the economic and technical structure of diesel trucks that have proven to be durable and effective over many years. This challenge may result in success, but it will take time. A similar type of change is occurring in the passenger vehicle industry dominated by fossil fuel powered vehicles. The past 15 years have been the most successful period of battery electric vehicles [82] and this has resulted in only about 7.2 million battery electric vehicles [83] compared to an estimated 1.3 billion vehicles in use today globally [84]. These changes may occur; however, it may take time.

5.3. INFRASTRUCTURE AND MANUFACTURING

The process of changing production lines and factories may take time and can be expensive. General Motors is expected to spend about $7 billion on a single battery plant to help in the transition to electric vehicles [85]. For OEMs to make this level of investment, they must believe the return on investment is good and the risks are low. Similarly, the material used in manufacturing the components for the fuel cell system is currently more expensive than that of diesel trucks. Because of the higher material costs the hydrogen fuel cell system and proposed trucks are likely to be more expensive than the conventional diesel trucks. For example, the starting price of the Toyota Mirai is $49,500 while a Toyota Camry is $25,395. Both are vehicles of similar features and abilities.

This cost gap stems from the cost components such as the hydrogen tank and fuel cell membrane. Part of the reason for this high gap is the lack of mass production. Therefore, without government policy incentives or significant market demand (i.e., from mine operators), OEMs are unlikely to make the required investments. Some diesel-powered electric drive trucks may already have some of the components needed to fulfil the technical requirement of the fuel cell vehicle, however, the additional real estate needed from hydrogen storage and coolants may still require a completely new truck, retaining the need for more investment.

Besides the investment required by OEMs, for successful integration of hydrogen fuel cells into the mining industry, the mine operators will also have to make significant investments in hydrogen production and distribution infrastructure within the mining industry. Hydrogen production cost is a significant hurdle, especially when obtaining hydrogen without GHG emission. The cleaner processes of hydrogen production are more expensive than the conventional ways that involve fossil fuel. For example, electrolysis and steam reforming-based hydrogen production costs are two and three times the cost of producing hydrogen from natural gas, respectively [86]. Also, the distribution for hydrogen may require a new platform. Some experts propose transporting or distributing hydrogen by blending with natural gas and using the existing natural gas pipeline infrastructure [87]. However, with zero GHG emission goal, this medium may not be the most appropriate as it can only reduce GHG emission and not eradicate it.

5.4. SUMMARY

This section describes the challenges and opportunities for fuel cell integration in mine haulage. The section presents challenges related to the vehicle real-estate and the infrastructure. While this work acknowledges the opportunities to integrate hydrogen fuel cells into mine haulage, there are significant challenges related to incorporating fuel cell engines and required accessories into the existing mine truck form factor. The alternative to using the existing truck real-estate requires significant investment from OEMs to retrofit their manufacturing systems. In addition to these investments, mining firms will be required to make significant investments in the infrastructure required for hydrogen manufacturing and distribution.

6. CONCLUSION, RECOMMENDATIONS & FUTURE WORK

6.1. OVERVIEW

The Mining industry is among the list of industries with climate concerns due to its energy intensive activities. With the industry being responsible for 4-7% of the GHG emissions in the world [5], there is a desire to explore how to reduce the contribution as the transition to green energy becomes paramount. As the industry analyzes the cause of emissions, it has identified that a significant portion of mining GHG is from operations such as haulage. With technologies such as wind, solar, battery storage and fuel cell already contributing to reductions in GHG emissions in energy production, there is the desire to implement these renewable energy technologies to reduce emissions from mine operations. This initiative has had limited impact on mobile equipment used for haulage because of the challenges of mobile energy generation.

The goal of this research is to explore how one of these renewable energy technologies (fuel cell) can be implemented to reduce emissions in mine haulage. The study focuses on two major models to analyze challenges and possibilities of incorporating fuel cell technology into mining haulage systems to reduce the GHG emission is daily operations. The models provide an economic and technical analysis of the possibilities of integrating renewable energy technologies in mine operations. The specific objective for the models were to:

- Investigate the characteristics that may affect the economic decision of mining companies to invest in truck haulage technology based on mine production, market, and policy.

- Explore the technical possibility of a direct replacement of the diesel component with hydrogen storage and fuel cell system in trucks.

These economic and technical models were built to allow inferences on the implementation of fuel cell technologies in the current mine haulage trucks. The models in this study evaluated the prospect of seamlessly integrating fuel cell technology into mine operations. For the economic model, the decision-making framework was utilized to discover the effect of factors such as mine production, government policy regarding levies on GHG emissions, and using different haulage technology (fuel cell, battery and diesel) when trying to maintain an optimal total cost for mining firms. The technical model was to evaluate technical feasibility of implementing hydrogen fuel cell technology into the current haulage systems without manipulating the current truck's frame or real estate and energy output.

6.2. CONCLUSIONS

The study concludes the following from the outcome of the economic and technical models:

- With the increase in policy to reduce GHG emissions, the economic model revealed it will become less economical to implement diesel trucks within the mines. However, even with today's government incentives, it is not always economical to utilize only renewable energy trucks. Diesel trucks should still be considered in the decision-making process, since the model also reveals that other factors such as efficiency, cost of maintenance and production play a key role in minimizing costs. Therefore, although using only renewable technology is not yet the most cost-optimal solution to operators, factors such as government that reduces cost of acquisition and dependence on diesel trucks.

- The verified technical model revealed that on-board hydrogen storage can only be considered over diesel when a pressure of 700 bar is achieved. In the comparison between hydrogen storage (at 700 bar) and diesel fuel storage for short, medium and long drive cycles, the results displayed that even with the hydrogen storage being a promising fit for some cases, as seen with the longer cycle, the frame of an existing diesel truck may not fully accommodate the fuel cell system and hydrogen storage. The study revealed that a redesign of the internal real estate is required to support all the applications analyzed since the current frame is too restrictive to accommodate hydrogen fuel cell system for the various applications as presented for medium and short cycle.
- Hydrogen fuel cell has the potential to eradicate the direct GHG emission from trucks. However, the significant challenges of integrating fuel cell system in mine trucks requires accessories to the truck real estate and the mine. To accommodate fuel cell and hydrogen storage system, the truck frame not only needs to change but the infrastructure required to support the implementation also needs to change. To integrate hydrogen fuel cells in mine haulage, original equipment manufacturers (OEMs) and mining firms have to make significant investments in infrastructure such as the restructuring of the manufacturing process to accommodate hydrogen storage, and the manufacturing and distribution of hydrogen itself.

6.3. RECOMMENDATION FOR FUTURE WORK

The following recommendations are made for future work to improve on the present work:

- The scope of this study did not cover the consideration of other factors such as operating conditions that cause power fluctuations on the truck. It is essential to note that these may cause some technical challenges as they influence the power production, durability, and performance of the fuel cell stack. Therefore, future work should revise the fuel cell model to account for variations in operating conditions to achieve more accurate results.
- This study's estimates of the volume required for hydrogen storage and fuel cell engine was limited by the availability of large storage and engines of the size required for mining haul trucks. Future work should undertake more rigorous design supported by more data by haulage system and fuel cell OEMs to support an accurate estimation.
- The work in the economic model shows that, even if government levies taxes and fees for GHG emissions, the cost of operating the renewable energy trucks ought to be competitive to provide incentive for mining firms to utilize them. Further studies may provide insight on the behavior of these solutions under specific scenarios.
- Future work should conduct cost and technical analysis of the various infrastructure and processes required for OEMs to retrofit their systems for a new vehicle frame specific for hydrogen fuel cell trucks. Additionally, such analyses should evaluate the cost and technical feasibility for hydrogen

manufacturing and distribution for use at mine sites. This will also allow for the cost and technical understanding of hydrogen safety and handling for mining activities and trucks.

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VITA

Ayorinde Akinrinlola graduated with a Bachelor of Science in Electrical Engineering from Northeastern University in May, 2019 where he balanced a rigorous course-load, internships, projects that have allowed him to enhance the skills relevant to energy and power sector. During his undergrad, he worked in three different companies as an intern. His first internship was at Eversource Energy under the strategy and performance group in Westwood, MA. For six months, he worked on several projects, acquired knowledge about power distribution and learned so much about power stability and reliability. He then proceeded to work at the electrical department in Hegenscheidt MFD, Germany for his second internship where he worked on machine power and controls for four months. His third internship was at Racepoint Energy where he directly worked with relays and switches that helped manage energy usage in households. After his undergradute degree, he proceeded to work as an Application Engineer at Reflex Lighting where he worked with lighting controls to enable efficient energy usage in construction buildings.

His research focused on finding key technical inventions and analyzing economic implications that enables the integration of hydrogen fuel cell to power mining operations.

Ayorinde received the Master of Science in Mining Engineering from Missouri University of Science Technology in July, 2022.