HYDROGEN POWER FOR LIGHT RAIL OPERATION: OPERATIONAL FEASIBILITY AND PRACTICAL APPLICABILITY

by

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A thesis submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Master of Science in
Engineering

Charlotte

2014

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ABSTRACT

EDWARD MATTHEW WASHING. Hydrogen power for light rail operation: operational feasibility and practical applicability. (Under the direction of DR. SRINIVAS PULUGURTHA)

As urban areas continue to grow and become denser, transit will be vital in the success and progress of metropolitans. Light rail, particularly in the United States, has become a popular mode of transportation that efficiently and reliably moves people. The need to avoid point-of-use emissions and space-intensive and costly catenary systems of intercity railway is the motivation for the study of hydrogen-power for propulsion. The goal of this thesis is to evaluate the potential for hydrogen-power for light rail operation on a feasibility, energy demand, and emission production basis.

This study is simulation-based, and makes use of the route information, train characteristics, and train resistance equations to determine the movement and energy demand of a train. The line in study is the Blue Line Extension (BLE) in Charlotte, N.C., which is a 9.3-mile long light rail line under construction at the time of this writing (August 2014). The line is operated by the Charlotte Area Transit System (CATS), who has chosen Siemen’s S70 as the rolling stock for the BLE. An initial simulation of the S70 electric train on the BLE sets the basis for the development of concept hydrogen and hydrogen-hybrid trains. The two concept trains are then simulated on the BLE for a comparative study.

The results of the simulations indicate that a hydrogen train and a hydrogen-hybrid train are technically feasible for operation on the BLE. Both concept trains complete a round-trip journey quicker than the electric train and have similar power-to-weight ratios. Due to increased mass and volume requirements, the hydrogen and hydrogen-hybrid trains require additional energy at the wheels for propulsion- 10.1% and 10.7% more, respectively. As the energy is tracked backwards through the energy pathway, the inefficiencies of the hydrogen trains' vehicle efficiency and hydrogen production process are apparent. The electric train, due to improved efficiencies throughout the energy pathway, uses substantially less feedstock energy. The hydrogen and hydrogen-hybrid train require 165% and 87% more energy per year at the pantograph (or in the tank), respectively, than the electric train. The electric train also produces substantially less emissions due to greater energy efficiency. The hydrogen and hydrogen-hybrid train produce 162% and 85% more CO_2 emissions per year, respectively, than the electric train. A hydrogen or hydrogen-hybrid train meets the operation and safety standards set for light rail operation, but does not meet the energy use and emission production standards necessary for adoption of a renewable technology.

ACKNOWLEDGEMENTS

The author would like to acknowledge several key individuals and organizations for support and guidance throughout the undertaking of this thesis. Many thanks to my executive committee, Dr. Srinivas Pulugurtha, Dr. Shen-En Chen, and Dr. Wei Fan, and Dr. Keith Baarson for providing input, support, and motivation for my research. The executive committee was critical in enabling me to research topics of great interest to me: railway engineering, public transportation, and renewable energy technologies.

Many thanks is also due to the Infrastructure, Design, Environmental, and Sustainability (IDEAS) Center at UNC Charlotte for research funding and the opportunity to travel to the University of Birmingham (U.K.) to partake in the 2014 Railway Challenge. Dr. Stuart Hillmansen and Dr. Andreas Hoffrichter of the University of Birmingham were instrumental in preparing me to complete the simulations and providing assistance throughout my research. Their constant involvement during the course of my thesis is very much appreciated.

While at the University of Birmingham, the 2014 Railway Challenge team was gracious to make me a part of the team and allow me to gain invaluable experience in building a hydrogen-hybrid locomotive. Special thanks are due to Robert Ellis and Zhongbei Tian, both Ph.D researchers at the University of Birmingham, for their assistance with the single-train simulator.

Charlotte Area Transit System, or CATS, was very helpful in ensuring that I obtained accurate data for my simulations. Special thanks to Anthony Candarini, Allen Smith, Gary Lee, John Joye, and Ruffner Marshall for their willingness to work with me.

INTRODUCTION

Rail in the United States is in the midst of a revival, for both freight and passenger rail. As a result of the revival and stricter air quality standards, research is beginning to look into the application of renewable energies for railroad traction. Hydrogen fuel cells are becoming more cost-competitive with conventional power sources, and maintain key advantages such as zero-emissions, little wayside infrastructure, and an abundance of hydrogen in the environment. Since rail is composed of many subsets of rail, the application of hydrogen fuel cells requires analysis of applicability for each subset. Freight rail is unlikely to adopt a technology such as hydrogen-powered traction unless strict emission standards are enacted. The freight rail system in the United States is so vast and expansive that electrification may be prohibitively expensive, but hydrogen-powered trains could take advantage of economies-of-scale with optimally placed refueling and hydrogen production sites. Passenger rail, especially intra-city rail, in the United States is largely electrified. Hydrogen fuel cells would enable passenger trains more autonomy and a reduction of wayside infrastructure and maintenance costs. The most suitable application of hydrogen power to rail appears to be for light rail and streetcars, since both rail technologies are small-scale, necessitate zero emissions, and are ideally nimble in an urban environment. Previous research has shown hydrogen to be an appropriate energy carrier for rail traction (Hoffrichter, 2013).

Research Objectives

The research that constitutes this thesis seeks to determine whether hydrogen-power technology is suitable for light rail operation and how a hydrogen-powered train's energy use and emission production compare with a conventional electric light rail train.

Light rail operation is determined to be feasible if current operation schedules are maintained (i.e., the train is reliable), physical characteristics, such as volume and weight, are not overly burdensome, and safety standards are met. The research also seeks to determine the magnitude of difference in energy use and emissions production for both hydrogen and electricity as an energy carrier. The use of an alternative energy carrier, such as hydrogen, is much more logical if energy use and emission production are less than electricity. Finally, the research intent is also to determine the scope of future research and identifying gaps in hydrogen-powered rail research, based on the results of this research.

Organization of the Thesis

The thesis is comprised of five primary sections: 1) Literature Review, 2) Methodology, 3) Results, 4) Discussion, and 5) Conclusions and Recommendations. The literature review sets the framework for the methodology by detailing the scope of hydrogen-power technology and existing methodologies for energy demand and emission production estimation. The methodology details the steps taken to produce data and disseminate the results. The results chapter includes all the simulation results and corresponding variables of interest. The results are subsequently analyzed and further processed to produce energy use and emission production data in the conclusion. Finally, the conclusion and recommendations chapter addresses hydrogen-powered rails future research needs, and what may be the primary determinant in whether hydrogen may be adopted for light rail operation.

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LIST OF ABBREVIATIONS

°C	degrees Celsius
°F	degrees Fahrenheit
$	U.S. dollar
A	ampere
Bar	barometric pressure
BLE	Blue Line Extension
BTU	British thermal unit
CATS	Charlotte Area Transit System
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
e	electron
Ft^2	square feet
ft^3	cubic feet
g/s	grams per second
GJ	gigajoule
H^+	hydrogen cation
H_2	hydrogen molecule
H_2O	water molecule
HP	horsepower
hp:ton	horsepower per ton

IDEAS Center	Infrastructure, Design, Environmental, and Sustainability Center
Kg	kilogram
Km	kilometer
kW	kilowatt
kWh	kilowatt-hour
lb	imperial pound
LHV	lower heating value
m^3	cubic meter
Mm	millimeters
Mph	miles per hour
mphps	miles per hour per second (acceleration)
$mphps^2$	miles per hour per second per second (jerk)
mW	megawatt
mWh	megawatt hour
N.C.	North Carolina
O_2	oxygen molecule
PEM	polymer electrolyte membrane
rpm	revolutions per minute
S70	Siemens Charlotte S70 light rail vehicle
SMR	steam methane reforming
STS	Single Train Simulator
TIGGER	Transit Investments for Greenhouse Gas and Energy Reduction
Ton	short ton (2,200 pounds)

Tonne	metric ton (1000 kilograms)
TriMet	Tri-County Metropolitan Transportation District of Oregon
U.K.	United Kingdom
DOT FTA	Department of Transportation Federal Transit Administration
U.S. or U.S.A.	United States of America
V	voltage
WTW	well-to-wheel

LITERATURE REVIEW

Overview

In 2009, for the first time in history, the urban population of the world exceeded the rural population (United Nations, 2009). Societal challenges in the future will be characterized by a need to create denser population centers, which creates the need for more efficient methods of transporting people and goods. For many metropolitan areas, including Charlotte, North Carolina, light rail has been a preferred mode of public transportation. Light rail benefits include reducing personal vehicle trips and encouraging dense and sustainable development. However, the electrification of light rail lines is often prohibitively expensive, and it does not directly address the urgent need to reduce greenhouse gas emissions, as overall emissions are dependent on the specific electricity mix.

Hydrogen as an energy carrier is more sustainable than conventional carriers (such as coal generated electricity and diesel), reduces negative health impacts on humans, reduces negative environmental impacts, and takes advantage of the abundance of hydrogen in the environment. By combining hydrogen as an energy carrier with light rail, it is possible to take advantage of all these benefits, and perhaps create a synergistic effect where the whole is greater than the sum of the parts.

The United States relies on foreign oil for a sizable portion of its energy needs and, with this reliance, spends considerable resources protecting overseas assets. Furthermore, the American economy is often subject to events out of its control, such as turmoil in the Middle East and growing oil demand. Hydrogen-powered rail, or hydrail, has the potential to invigorate a domestic renewable energy market and reduce foreign oil dependency.

Greenhouse gases that are released during the combustion of fossil fuels have many negative implications for people and the environment. Respiratory diseases and various cancers result from excessive amounts of greenhouse gases (American Lung Association of California, 2004). While the effect of manmade greenhouse gases on climate change is under debate, the potential consequences of climate change due to greenhouse gases are worth noting. Light rail operation powered by hydrogen addresses the health of individuals and the environment in two ways: 1) The energy carrier itself voids harmful point-of-use emissions, such as particulate matter, and can reduce overall greenhouse gas emissions, while 2) encouraging a road to rail modal shift, thus reducing personal vehicle trips and stimulating a change in land use patterns. Suburban sprawl that has occurred has been accompanied by environmental degradation, but urban densification may be a catalyst for environmental reclamation.

Chemical Properties of Hydrogen

Hydrogen, the first element in the periodic table of elements, is a diatomic molecule, meaning two hydrogen atoms make up one hydrogen molecule. As the first element, hydrogen is also the lightest of all elements. While hydrogen shares the same column in the periodic table as the alkali metals, it is not an alkali metal, but rather shares properties with various periodic groups. Hydrogen's ionization energy, or the amount of energy required to remove an electron from the atom, is more than double that of the alkali metals. The ionization energy of hydrogen is more similar to those of the noble gases, which include many diatomic molecules. Due to its high ionization energy, hydrogen typically shares its electron in nature, forming molecular compounds. Hydrogen is unique in that it is able to form compounds with nonmetals and active metals by sharing its electron, while it is also able to form a cation by releasing the electron it so often shares (Brown, 2012).

The chemical property of hydrogen that is of most interest to this study is its highly exothermic reactions with nonmetals. The combustion reaction between hydrogen and oxygen, shown below, is the basis for hydrogen as an energy carrier.

EQUATION 1: $2H_2(g) + O_2(g) \rightarrow 2H_20(l)$

This reaction will receive further discussion in the hydrogen fuel cell section. Another notable characteristic of hydrogen is its ability to form compounds with active metals. Storage of hydrogen as a metal hydride is a potential solution to the hydrogen storage issue. Hydrogen’s proclivity to form compounds in nature means that it is an energy carrier. An energy carrier is unlike an energy source in that it requires an energy source to unlock energy. Hydrogen requires energy feedstock to separate the compound, so that hydrogen may be used to produce energy.

Hydrogen is not only the lightest element, but it also has the highest energy content per unit of mass (Hoffrichter, 2013). When considering hydrogen as a fuel, this characteristic is ideal because it reduces the power required to overcome gravitational pull. At ambient temperatures, hydrogen is a gas and thus requires a large volume. Currently, fossil fuels, gasoline in particular, are ideal fuels because they have a high energy density and are in a liquid state at ambient temperatures. Liquefied hydrogen, which must be stored at super cooled temperatures, is the fuel of choice for space shuttles. Hydrogen's high fuel value, as shown in Table 1, makes it the most logical choice for the space shuttle industry (Dunbar, 2013).

TABLE 1: Fuel values of common fuels (Brown, 2012)

Fuel	Fuel Value (kJ/kg)
Hydrogen	142
Natural gas	49
Gasoline	48
Texas Crude Oil	45
Pennsylvania Bituminous Coal	32
Pennsylvania Anthracite Coal	31

Light Rail

Light rail, as the name suggests, uses equipment that weighs far less than conventional rail. Light rail is purposed specifically for passengers, and thus is more agile and appropriate for intra-city transit. The horsepower-to-ton ratio is higher than nearly all other rail types, at roughly 10 hp:ton (Sproule, 2012). Trains are powered by overhead catenary and occasionally share the right-of-way with vehicular traffic.

The primary drawbacks of overhead electrification of light rail are the capital cost, maintenance expense, and hazards. Catenary systems are notoriously expensive, though they provide a zero-emission system that is ideal for intra-city transit. The catenary systems are also hazardous due to their exposure to the general public and constant high-levels of electricity. A hydrogen-powered light rail provides emission-free operation, the potential for cost-savings, and autonomous traction that requires little wayside infrastructure.

Hydrogen power, in light of successful simulations of hydrogen-powered commuter rail, appears to be sufficient for the power requirements of light rail. A limitation that may exist is whether or not hydrogen storage would be so heavy that operation of the train would be impaired. Regardless, the need for no pollution in urban city centers is paramount and autonomous traction that does not require catenary systems is a very appealing technology. Demonstration of hydrogen-powered light rail is provided in the results chapter, which demonstrates whether the mass and volume requirements of hydrogen storage impair the feasibility of hydrogen-powered light rail.

Streetcars

Streetcars, in many respects, operate in the same manner as light rail, but subtle differences set the two types apart. A streetcar looks vastly different than light rail, but both types serve intra-city transit, operate with overhead catenary, and share the right-of-way at times. The main difference is the frequency of stops. While light rail stops may range from less than a mile to a few miles apart, streetcar stops are much more compact. The distance between streetcar stops can be measured in city blocks, while the distance between light rail stops are measured in miles. Streetcars in a sense are urban circulators, convenient ways to move within dense areas.

Like light rail, streetcars are ideally emission free and autonomous. Hydrogen power fits these requirements. Of the railway applications mentioned, streetcars operate on the smallest scale, and could also be the most logical application of hydrogen power. The use of hydrogen as an energy carrier on a streetcar is comparable to that of hydrogen-powered buses. In December 2013, the first use of hydrogen-powered rail for passenger service commenced in Aruba. Aruba's streetcars are battery-powered, but augmented by hydrogen power (altenergymag.com, 2013).

Hydrogen makes sense for streetcar application because of its small-scale operation, emission-free energy, and autonomous nature. For countries like Aruba, energy dependency is very important due to the expense of importing fossil fuels and the natural abundance of wind energy on the island. The wind energy in Aruba allows for 100% carbon free hydrogen production and energy generation. Aruba has pioneered the use of hydrogen-powered rail for passenger service, but certainly will not be the last. Other countries or cities that are motivated to decrease fossil fuel dependency and use renewable energies are likely to consider hydrogen for streetcar traction.

Hydrogen Power Technology

Hydrogen as an Energy Carrier

The motivation for using hydrogen as an energy carrier is two-fold. There are substantial potential benefits, both environmentally and economically, in using hydrogen as an energy carrier. Hydrogen is an energy carrier, which is a very important distinction when considering hydrogen as a fuel source. In order to use hydrogen for power generation, energy input is required to make hydrogen useful. Various feedstocks, primarily fossil fuels, are responsible for imbuing hydrogen with energy. Use of a renewable feedstock, such as wind or hydroelectric energy, permits hydrogen to be an entirely emission-free energy source. Secondly, hydrogen is a very common element and is not geographically concentrated like fossil fuels. Hydrogen could revolutionize the energy market by shifting the pricing power to consumers, rather than the suppliers.

Conversely, hydrogen as an energy carrier for most applications is redundant. In order for hydrogen to be a worthwhile energy carrier, it should be produced by renewable energy. In this case, the renewable energy is already in the form of an energy carrier, electricity. Further transformation of the renewable energy into stored chemical energy adds complexities that require energy. The energy requirements to produce, package, distribute, store, and transfer hydrogen are not small amounts. Well-to-tank analysis, which evaluates the energy consumption of the entire production pathway, indicates that for every unit of hydrogen energy available approximately 0.35-0.40 units of energy is expended. Alternatively, electricity only requires 0.1 units of energy for each unit of electricity produced (Hoffrichter, 2013) (Bossel & Eliasson, 2003).

For these reasons, hydrogen as an energy carrier in most conventional stationary applications is inappropriate. Electricity is a far more logical and efficient energy carrier in stationary applications. Hydrogen's niche as an energy carrier is limited to roles that require mobility and zero emissions at the point-of-use. In this arena, batteries are much more common and widely available. Batteries, though, suffer from their own drawbacks. They have notoriously poor life cycles, low energy density per unit mass, and lengthy recharge times. Hydrogen offers the advantage of an improved life cycle and a comparable energy density and refill time to liquid fossil fuels.

The primary utility for hydrogen as an energy carrier to-date has been specialty niche markets, while hydrogen is mostly researched for automobile applications in the future. Hydrogen fuel cells are commercially available technologies that provide zero harmful point-of-use emissions and autonomy from the grid. The appeal of such characteristics is particularly strong for industrial vehicles that operate in confined areas, such as indoor forklifts and mining rail cars.

Hydrogen Production

Hydrogen's unique elemental properties require extensive research into hydrogen production. Hydrogen is one of the most abundant elements on Earth, but it is necessary to produce hydrogen because it is rarely present in elemental form, but rather predominantly exists as a compound (Schlapbach & Zuttel, 2011). Since hydrogen is the lightest element and it is a gas at ambient temperatures, any elemental hydrogen will rise to the upper echelons of the atmosphere. Otherwise, due to its high ionization energy, hydrogen will form compounds with other molecules. Thus, hydrogen must be produced, or more accurately, separated from compounds. Compounds containing hydrogen are useful fuels, but pure hydrogen is an efficient energy carrier that produces zero harmful emissions.

Hydrogen may be produced from compounds containing hydrogen in many different manners and with different fuel feedstock. A feedstock is the energy source required to produce hydrogen (Hoffrichter, 2013). The primary methods of hydrogen production are steam reforming of fossil fuels, water electrolysis, partial oxidation, auto-thermal reforming, gasification, pyrolysis, and thermo-chemical water splitting (Hoffrichter, 2013). Of these, the energy required to free hydrogen may be provided by fossil fuel feedstock or renewable feedstock. By separating compounds containing hydrogen, the diatomic hydrogen molecule is free to react with oxygen and thereby produce energy.

Methods to produce hydrogen are numerous and varied, but may be generalized into broad categories: thermal, electrolytic, and photolytic (Office of Energy Efficiency & Renewable Energy, 2014). Thermal production utilizes high temperatures and partial oxidation to separate elemental hydrogen from compounds. Electrolytic methods involve separating water with various feedstocks of electricity. Photolytic production of hydrogen also splits water molecules to produce hydrogen, but relies on sunlight to serve as the catalyst (Office of Energy Efficiency & Renewable Energy, 2014). Of the methods, thermal production, specifically natural gas steam reforming, is the most common method of producing hydrogen.

Hydrogen production may be centralized at a large production plant or decentralized in units that are distributed throughout a network. Currently, centralized production of hydrogen is commercially available technology used in the fertilizer and energy industries. The centralized production of hydrogen is currently the most efficient and economical method to produce hydrogen (IEA, 2007). Distributed production is a primary advantage of using hydrogen as an energy carrier because it allows consumers to produce their own hydrogen and avoids the cost of transporting hydrogen long distances. Current decentralized hydrogen production costs approximately $50/GJ, which is more than double the cost of gasoline ($20/GJ) at $2.50/gasoline gallon equivalent (IEA, 2007). The goal of the hydrogen production research is to lower the hydrogen production costs to a level competitive level with gasoline.

Steam methane reforming and electrolysis are the leaders in distributed hydrogen production. Steam methane reforming hydrogen production utilizes the methane in natural gas. The methane reacts with water and heat to produce carbon monoxide and hydrogen. Such a process is feasible for small-scale distributed production, but would not be as efficient or cost effective as a large-scale operation. Further, the steam methane reforming method of hydrogen production produces carbon dioxide, which requires proper decarbonization (IEA Hydrogen Co-ordination Group, 2006). Fossil fuel feedstock limits the ability of hydrogen to be an environmentally neutral energy source.

Natural gas reforming is currently the most efficient, cost-effective, and common method to produce hydrogen (Alternative Fuels Data Center, 2014). The process reacts natural gas with high temperature steam to form a synthesis gas. The synthesis gas is composed of hydrogen, carbon monoxide, and trace amounts of carbon dioxide. Next, the carbon monoxide can be used in a second reaction involving water, which produces additional hydrogen and carbon dioxide (Alternative Fuels Data Center, 2014). The two reactions that serve as the basis of natural gas steam reforming are shown below (Air Products, 2013).

EQUATION 2: $CH_4 + H_2O \text{ -> } 3H_2 + CO$ (methane reforming)

EQUATION 3: $CO + H_2O \text{ -> } H_2 + CO_2$ (water gas shift)

Natural gas steam reforming, or more specifically, steam methane reforming (SMR), is the method of hydrogen production of greatest practicality for the polymer electrolyte membrane fuel cell application. SMR is unsurpassed in terms of hydrogen production efficiency, and it offers great potential in cost reduction (Chen, 2008). SMR begins by heating the methane gas and water steam mixture to high temperatures in reformer tubes. The reformer tubes are lined with a catalyst, in Air Products' case, a nickel catalyst (Air Products, 2013). The catalyst incites the methane reforming reaction (Equation 2).

The carbon monoxide produced in the methane reforming reaction is further reacted, with the help of an iron-chrome based catalyst, with water steam to complete the water gas shift reaction. Finally, pressure swing absorbers are used to ensure pure hydrogen product without the contamination of the surplus methane, steam, carbon monoxide, and carbon dioxide (Air Products, 2013). A schematic of SMR is provided in FIGURE 1.

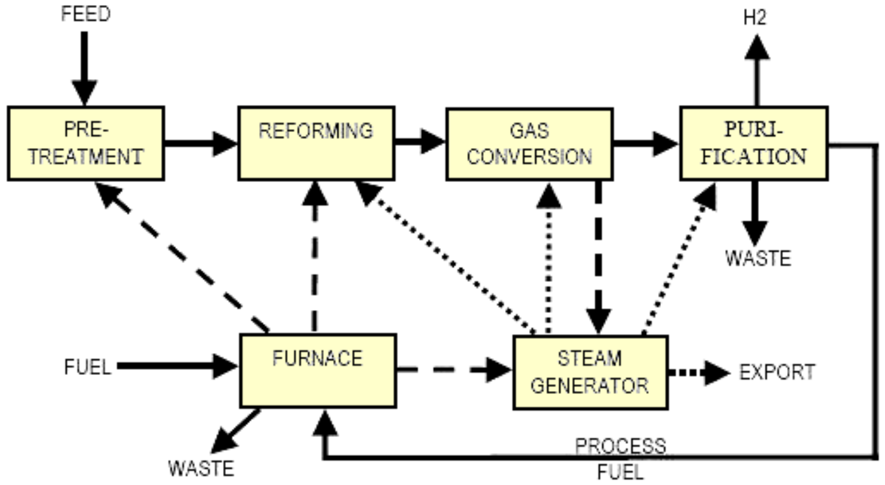

FIGURE 1: Steam methane reforming schematic (Chen, 2010)

The efficiency of the SMR reaction is primarily a function of temperature, pressure, steam/methane ratio, and type of catalyst used. In general, hydrogen production increases as the temperature increases, pressure decreases, and the steam/methane ratio increases (Ali, Zahangir, Badruddoza, & Haque, 2005). Ideal operation of an SMR plant at a high temperature, low pressure, and with a high steam/methane ratio is uneconomical from a cost and space perspective (Molburg & Doctor, 2003). In this instance, fuel costs would be too high and the equipment would be too space-intensive. Research into improving the SMR reaction focuses on the operating temperature, pressure, steam/methane ratio, and catalyst type in order to find the optimum reaction characteristics. Based on leading laboratory technology, the production process efficiency for a distributed steam methane reformer in 2015 was estimated to be 83% (Joseck, 2005).

After SMR, electrolysis is the second most common form of hydrogen production. Electrolysis utilizes electricity as its feedstock to separate water into hydrogen and oxygen molecules. The separated hydrogen and oxygen molecules are then reacted, producing energy. Currently, water electrolysis is well accepted and its feasibility and process have been established (IEA Hydrogen Co-ordination Group, 2006). A major upside for hydrogen energy is the potential for a completely renewable electric feedstock. Water electrolysis, if produced from renewable energy, is a completely carbon and greenhouse gas free method of hydrogen production. Another benefit of water electrolysis is that hydrogen production can be easily distributed without significant infrastructure upgrades. A water electrolysis unit may be powered from existing electricity infrastructure. Compared to the thermal methods of hydrogen production, such as SMR, it is a much simpler process, results in pure hydrogen, and has the potential to be greenhouse gas emission free (Lipman, 2011). The chemical equation that governs electrolysis is below.

$$\text{EQUATION 4: Electricity} + H_2O \text{ -> } H_2 + 1/2\ O_2 \text{ (electrolysis)}$$

The two primary methods of electrolysis are alkaline and polymer electrolyte membrane electrolysis. Alkaline electrolysis utilizes an aqueous, caustic solution as an electrolyte that increases the conductivity of the water (IEA Hydrogen Co-ordination

Group, 2006). This allows the electrical current to dissociate water into hydrogen and oxygen. Polymer electrolyte membrane electrolysis uses an acidic polymer membrane, as opposed to a liquid electrolyte. The design, as compared to alkaline electrolysis, is much simpler, but remains costly and inefficient (IEA Hydrogen Co-ordination Group, 2006). For this reason, alkaline electrolysis is the standard method of electrolysis hydrogen production and is commercially available today (Office of Energy Efficiency & Renewable Energy, n.d.). The primary advantage of electrolysis is the potential for greenhouse gas free hydrogen production.

Beyond SMR and alkaline electrolysis, there are numerous methods of hydrogen production, many recent technological advances, and a few novel and promising production methods. SMR and other thermal methods of hydrogen production break down hydrocarbons, and as a consequence, produce undesirable carbon oxides. The alternatives to such production methods include electrolysis powered by renewable energy, biomass fermentation, and photolytic methods. (NREL, 2014). Photolytic methods include photobiological water splitting and photoelectrochemical water splitting, both of which are in the early stages of development (Energy.gov, n.d.). Both methods utilize solar radiation as the energy source, but differ by mode of water splitting.

The potential for an energy-gain hydrogen production process was announced recently in 2013. Researchers at Virginia Tech demonstrated the ability to produce large quantities of pure hydrogen from xylose, the most common simple plant sugar (Martin del Campo, et al., 2013). The significance in the research is that the method produces three times as much energy as conventional microorganisms, does not require high temperatures or pressure, and utilizes a cheap and abundant biomass (Martin del Campo, et al., 2013).

The production of hydrogen is the first step in realizing hydrogen-fueled transport. The pathways for hydrogen production are illustrated in Figure 2. Hydrogen must be disassociated from the compounds in nature where it is found, which means that energy is required for hydrogen to serve as an energy carrier. The appeal of hydrogen is largely related to its ability to provide autonomous power and zero harmful emissions. Current production methods remain reliant on fossil fuels, namely natural gas, to produce hydrogen and as a result, fail to meet the requirements of an energy carrier of the future. Advancements in technology and research, such as renewable energy electrolysis, photolytic methods, and biomass, will precede the fruition of truly clean hydrogen power.

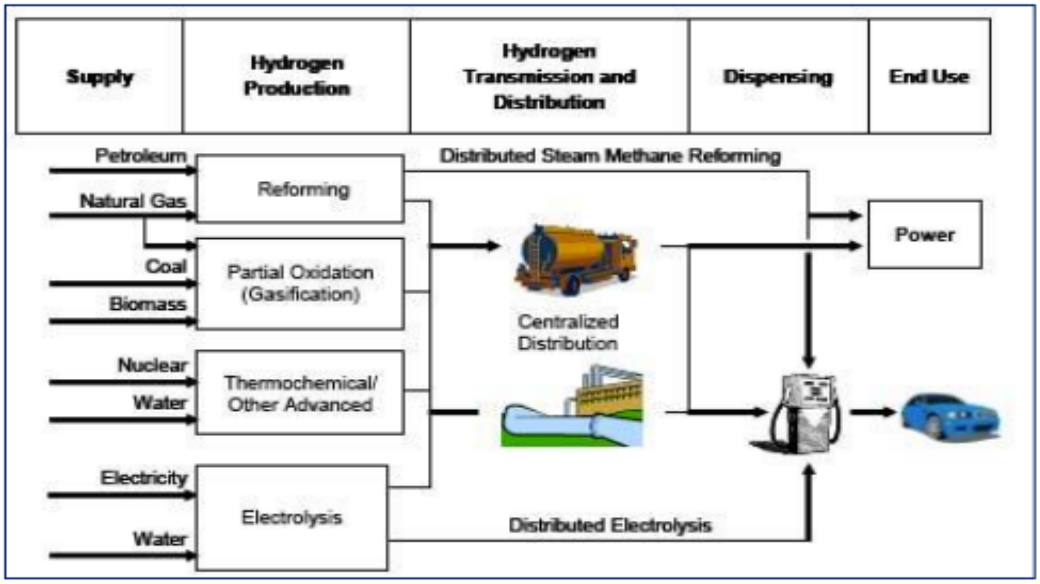

FIGURE 2: Hydrogen production pathways (Lipman, 2011)

Hydrogen Storage

Perhaps the greatest challenge for the hydrogen economy is the need for an improved hydrogen storage system. The difficulty in storing hydrogen is attributable to its state as a gas at ambient temperatures. In order to utilize hydrogen as an energy carrier in the transportation sector, economical and efficient storage of hydrogen is a prerequisite to a practical adoption of hydrogen. Hydrogen's state as a gas at ambient temperatures provides challenges to the adoption of hydrogen as an energy carrier. For this reason, hydrogen storage is being widely researched and solutions are varied.

The primary options for hydrogen storage currently are as a gas in pressurized containers, as a liquid in super-insulated containers, or as a solid in the form of metal hydrides. Storage as a liquid is ideal in that hydrogen's energy content per unit of mass and volume are both maximized, given a fixed pressure. Hydrogen's boiling point is -252.87 °C, which necessitates heavy-duty super-insulated containers. For this reason, liquid hydrogen storage is not ideal for the transport industry, particularly the automotive industry.

According to the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, hydrogen storage is challenged in terms of weight, volume, efficiency, durability, refueling time, and cost. Nearly every facet of hydrogen storage requires advancement. Since hydrogen is primarily researched for personal automobiles, the capabilities of hydrogen storage are compared with conventional gasoline storage, which are very difficult design standards to meet. For railway applications, weight, volume, and refueling time are less of an issue than personal automobile applications.

The challenge involved in storing sufficient on-board hydrogen for mobile applications is highlighted in FIGURE 3. For a light-duty fuel cell vehicle, four kg of hydrogen is necessary for an operating range of approximately 400 km (Schlapbach & Zuttel, 2011). At normal atmospheric pressure, four kilograms of hydrogen would occupy a volume of 45 m^3, but storage at 200 bar drastically reduces the volume requirements to 0.225 m^3 (Schlapbach & Zuttel, 2011). The weight of modern storage vessels is also a concern.

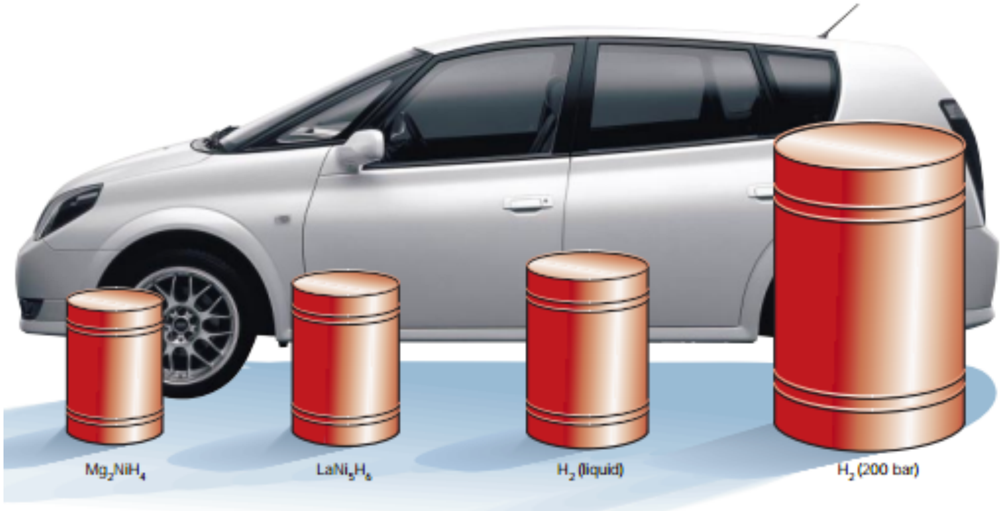

FIGURE 3: Volume requirements for 4 kg of hydrogen in various states (Schlapbach & Zuttel, 2011)

Hydrogen storage as a gas, though less concentrated on a volume basis, is preferred in the transport industry because of minimal weight. For rail, where storage of fuel is not strictly limited by volume, gas storage of hydrogen is acceptable. Commercial storage tanks are currently available to store hydrogen at pressures up to 250 bar, while tanks that can withstand up to 700 bar have been tested (Conte, 2008). Current hydrogen storage options, especially storage as a gas, are inefficient on a density basis, which limits the operating range for hydrogen-powered vehicles (Chalk & Miller, 2006).

Hydrogen storage as a gas is commonly accomplished with American Society of Mechanical Engineers (ASME) certified vessels (Lipman, 2011). The standard vessels today are primarily made of inexpensive steel, though composite vessels hold the most promise for gaseous storage in the future (Schlapbach & Zuttel, 2011). Steel vessels are appropriate for pressures up to 200 bar, while composite vessels have been tested to withstand pressures up to 875 bar (Lipman, 2011) (Winter, 2009). In particular, Type IV vessels are most applicable to the transport application. Type IV vessels are characterized by a polymeric liner fully wrapped with a fiber-resin composite with a port built into the structure of the vessel (Barral & Barthelemy, 2006). Type IV vessels can withstand very high pressures without adding considerable weight.

For a given quantity of hydrogen, composite tanks have the advantage of less volume and less weight. The trend for the automotive industry, the chief promoter of hydrogen storage research, is 700 bar composite tanks (Bakker, 2010). The drawback in pressurizing a gas is the loss of energy content due to the pressurization. As a result, more energy is required to fill a 4 kg 700 bar composite vessel compared to a 4 kg 200 bar standard vessel. Compared to a 350 bar vessel, a 700 bar vessel requires approximately 10-12% additional compression energy (Sirosh, 2013) (Mao, 2010). The volumetric increase, 55%, exceeds the additional compression energy by such an extent that the additional energy loss is worthwhile (Mao, 2010). Gaseous hydrogen storage has the distinct advantage of simplicity and stability compared to other storage mediums (James, 1998). Compressed hydrogen gas is able to remain stored for long periods of time, unlike liquid hydrogen, because it does not suffer from boil-off loss.

Storage of hydrogen as a liquid requires cryogenic temperatures since hydrogen's boiling point is –253°C. In order to liquefy hydrogen, energy that equates to approximately 30% of the hydrogen's heating value is used to condense hydrogen (James, 1998). For this reason, liquid hydrogen storage is costly and is only practical when sufficient scale exists. Liquid hydrogen storage is suited best for bulk storage and industrial production.

Storage as a solid is also possible, given the tendency for hydrogen to form compounds with metals. Metal hydrides offer many benefits of hydrogen storage that liquid and gas storage are currently unable to match. For one, storage as a solid does not require high pressures. In the event of a crash, leakage is minimized. As expected, metal hydride storage is weight intensive and refueling is more time consuming than gas or liquid storage. The characteristics of each type of hydrogen storage are distinct and limit storage options for various transportation applications. Even within rail transportation, various types of rail have different storage options that are most compatible due to specific operating characteristics.

Solid hydrogen storage is the least developed hydrogen storage medium, but has a lot of research momentum. The appeal in storing hydrogen as a solid is the potential to alleviate some of the downfalls of compressed gas and liquid storage, particularly volume, pressure, safety, and hydrogen purity (IEA Hydrogen Co-ordination Group, 2006). The three main groups of solid hydrogen storage, as classified by the U.S. Department of Energy, are metal hydrides, chemical hydrides, and carbon-based materials (Office of Energy Efficiency & Renewable Energy, n.d.). Storing hydrogen as a solid is typically accomplished by way of metal hydrides (James, 1998). To store the hydrogen as a solid in the form of metal hydrides, metal powder is used to absorb hydrogen gas which incorporates the hydrogen into the metal's atomic lattice (Bakker, 2011). Metal hydrides, though, are currently prohibitively too heavy for the transport sector, and storage of hydrogen as a solid is best suited for stationary storage applications (James, 1998). Current research is challenged with the task of making metal hydride storage less weight-intensive, reducing refueling and discharge time, and making operating temperatures more reasonable (Bakker, 2011).

Hydrogen Fuel Cells

Regardless of the production method of hydrogen, the hydrogen may be used in a fuel cell to produce energy. There are other methods of producing energy from hydrogen, such as internal combustion engines, but their energy efficiency is unable to match that of fuel cells (US Department of Energy, Energy Efficiency and Renewable Energy, 2014). Fuel cells today have an operating range exceeding 1,000 hours, which is expected to rise with continued research and development (Chalk & Miller, 2006). Perhaps the most common fuel cell today is the polymer electrolyte membrane (PEM) fuel cell. PEM fuel cells are made up of three distinct parts-the anode, the electrolyte, and the cathode, which create energy from hydrogen and oxygen.

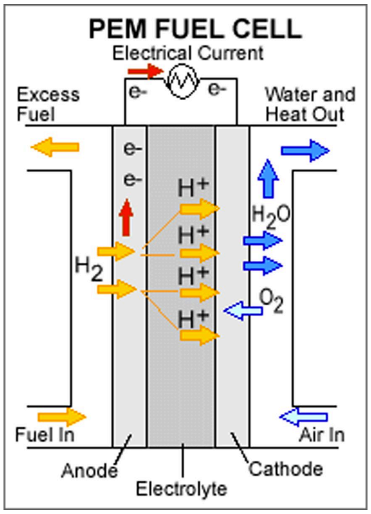

FIGURE 4: Polymer electrolyte membrane fuel cell (National Institute of Standards and Technology, 2014)

As hydrogen enters the fuel cell, on the anode side, the hydrogen molecule is oxidized. The polymer electrolyte membrane that separates the anode from the cathode is permeable for hydrogen cations, but not electrons. The electrons flow to an external circuit, which is how electrical current is produced by the fuel cell.

EQUATION 5: $2H_2(g) \rightarrow 4H^+ + 4e^-$ (Oxidation at the anode)

On the cathode side of the fuel cell, the electrons, hydrogen cations, and oxygen molecules combine to form liquid water and heat. Liquid water and heat are the only emissions from a fuel cell that uses near pure hydrogen, and the heat can often be recycled for different processes. Operating temperature, size, and the pressures of hydrogen and oxygen affect the performance of a fuel cell (National Institute of Standards and Technology, 2014).

EQUATION 6: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ + heat (Reduction at the cathode)

Hydrogen Power Applications

Hydrogen Powered Highway Vehicles

Modern day roadways are primarily composed of gasoline-thirsty vehicles that utilize internal combustion engines to produce power. More recently, hybrid-electric vehicles and electric vehicles have entered the marketplace, but were a miniscule percent of the total vehicles in the United States in 2011 (0.87% of 253,108,389 vehicles) (U.S. Energy Information Administration, 2013) (Research and Innovative Technology Administration, 2014). In the same year, there were only 527 hydrogen-powered vehicles on American roads (U.S. Energy Information Administration, 2013). Although vastly outnumbered, hydrogen-powered vehicles uniquely combine advantages of both internal combustion engine vehicles and electric vehicles. Hydrogen powered vehicles have an operating range and refill time similar to conventional gasoline vehicles, while also producing zero emissions. The vehicles, though, are limited by cost and existing infrastructure, which are significant challenges for a vehicle to overcome. Given these challenges, and the limits of battery-powered vehicles, such as poor cycle life and lengthy recharge times, tremendous research efforts have been devoted to making hydrogen a mainstay in the U.S. vehicle fleet.

The concept of using hydrogen as an energy carrier for vehicles is not new, with liquid hydrogen being used to power a Datsun back in 1978 (Furuhama, Hiruma, & Enomoto, 1978). In fact, the motivations for the liquid hydrogen-powered Datsun, zero emissions and reduced reliance on fossil fuels, are the primary motivations for hydrogen power today. Furthermore, hydrogen storage was the primary challenge to overcome in 1978, and though more than three decades of research has unlocked gaseous and solid storage options, hydrogen as an energy carrier is still mostly limited by the cost, inefficiencies, and characteristics of storage (Furuhama, Hiruma, & Enomoto, 1978).

For the meantime, hydrogen storage options for the highway vehicle application are limited to gaseous and liquid storage, though solid storage is not out of the picture. The bulk (69%) of prototypes built from 1998 to 2008 used gaseous storage. Daimler, Toyota, Honda, General Motors, Volkswagen, Audi, and Hyundai are just a few of the major automakers that have focused their research efforts on gaseous hydrogen fuel cells. As for liquid hydrogen, BMW is the sole major automaker focusing its efforts on liquid hydrogen (Bakker, 2011).

Initially, internal combustion engines accounted for the majority of hydrogen-powered vehicle prototypes, but since 1998, fuel cells have led the way. The polymer exchange membrane is the preferred in vehicle prototypes due to its ability to be sufficiently efficient at low operating temperatures (Bakker, 2011). More than 80% of fuel cells in production in 2013 were polymer exchange membrane fuel cells (Barbir, 2013). The efficiencies of such systems are far superior to existing fossil fuel-powered internal combustion engines, as exhibited in FIGURE 5.

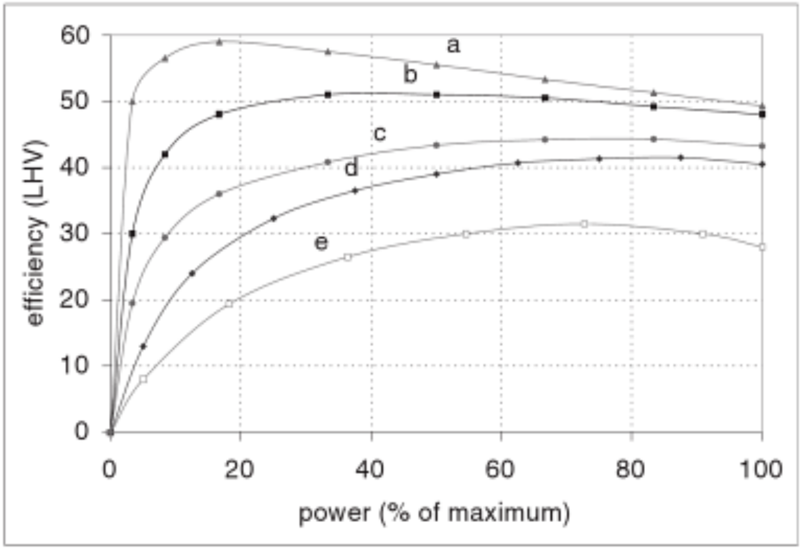

FIGURE 5: Efficiency comparison between a) fuel cell (at low temperature and pressure), b) fuel cell (at high temperature and pressure), c) fuel cell with onboard processor, d) diesel internal combustion engine, and e) gasoline internal combustion engine (Barbir, 2013)

Hydrogen fuel cells remain overly costly, for mass-market acceptance, regardless of application (Hammerschlag & Mazza, 2005). The cost of hydrogen fuel cells is largely a function of the catalyst, which is typically made of a precious metal, and the undeveloped market as a whole (Barbir, 2013). Internal combustion engines have the advantage of more than a century’s worth of research and mass production, resulting in a modestly price power generation of $35-50 per kW (Barbir, 2013). Until the economics of hydrogen fuel cells make sense (in terms of cents), demand for the technology will be less than overwhelming. It is estimated that modern and scaled production techniques could lower the cost of a hydrogen fuel cell to $49 per kW (Barbir, 2013).

Electric vehicles and hybrid electric vehicles that use batteries to store electricity are an opposing technology to hydrogen and are more advanced than hydrogen-powered vehicles. Electric vehicles tout the same environmental benefit and economic benefit (zero emissions at point of use and flexibility in energy production) as hydrogen-powered vehicles. The technology has even proven to operate with impressive power, as exhibited by Tesla’s electric vehicle lineup, and over an acceptable range. Furthermore, the technology has the potential to reduce more greenhouse gas emission compared to hydrogen fuel cells due to greater operating efficiencies (Hammerschlag & Mazza, 2005). If battery technology continues to progress at its current rate and the slow recharging time, low-energy density, range, and maintenance concerns are resolved, then hydrogen fuel cell vehicles would be obsolete.

The drawbacks of battery power remain significant enough that hydrogen fuel cell vehicles are still potential solutions. The technological competition for highway vehicles is between energy carriers, rather than energy sources. In this way, the system that is more efficient and productive with a given amount of energy has a distinct advantage. Current research into hydrogen-powered vehicles is centered on cost-reduction strategies for the fuel cell, improvements in hydrogen storage efficiencies and capabilities, and jump-starting the infrastructure needs. Nearly every major automaker is involved in developing hydrogen-powered vehicles, so solutions to the current problems are not necessarily impractical.

Hydrogen Powered Utility Vehicles

One of most promising applications for fuel cells is the utility vehicle. Utility vehicles include forklifts, golf carts, and mining rail cars. Utility vehicles are distinctly different from highway vehicles because of different performance measures. While the design and marketing of highway vehicles is very much sensitive to cost, utility vehicles are evaluated more on a productivity basis. For instance, a consumer purchasing a car will mostly consider the price tag. On the other hand, a warehouse manager will mostly consider the productivity of the utility vehicle over time. The economics for utility vehicles change the standards set for utility vehicles in the highway vehicle class.

For indoor and closed-space applications, emissions are very undesirable. The use of fossil-fuel utility vehicles indoors is not prohibited in the U.S., but standards are in place to limit carbon monoxide exposure (Whitaker, 2009). Many companies, for the safety and well being of employees, have turned to electric and hydrogen-powered utility vehicles. Though more expensive, the safety benefits of an emission-free utility vehicle are worthwhile.

Similar to the highway vehicle industry, electric utility vehicles are more common than hydrogen-powered utility vehicles. Both vehicles achieve the same goal of avoiding emissions, but the effect on productivity is different. For an electric forklift, the battery may last upwards of seven hours before recharging is required. An electric forklift may take twenty minutes to recharge while a hydrogen-powered forklift could refuel in five minutes. The electric forklift is also subject to loss of voltage as the battery becomes depleted, further hampering work productivity.

A hydrogen-powered utility vehicle has a greater range and faster refill, thereby increasing the productivity of the unit and employees (Ballard Power Systems, Inc., 2010). Electric forklifts vehicles are approximately half the cost of their hydrogen counterparts, but for a large warehouse, the payback for the increased costs of hydrogen fuel cells was found to be less than a year (Ballard Power Systems, Inc., 2010). The lost productivity due to the recharge time, decrease in forklift power through the cycle, and the decreased lifetime of electric forklifts create costs that exceed the upfront capital costs associated with hydrogen. Regardless of forklift class (Class I, II, or III), the annual cost to operate a hydrogen fuel cell forklift is less than that of an electric battery forklift (Kurtz, Ainscough, Simpson, & Caton, 2012). The market for hydrogen fuel cell forklifts exceeds 5,000 units, making it a well-established market (Cella Energy, n.d.).

In addition to forklifts, there are a multitude of additional utility vehicles that operate in indoor and confined spaces. The applicability of hydrogen to the various utility vehicles is akin to their applicability to forklifts, given similar size and extent of operations. Hydrogen fuel cells enable indoor utility vehicles to satisfy indoor air quality requirements, remain autonomous, and be as productive as fossil fueled utility vehicles. They are also superior to electric utility vehicles in terms of labor productivity, range, and total life-cycle costs.

Hydrogen Powered Rail Vehicles

One of the earliest hydrogen-powered rail vehicles was designed as a mining locomotive. The project, under the management of Vehicle Projects, was motivated by the mining industries' need for a zero-emission, safe, powerful, and productive locomotive (Miller & Barnes, 2002). Like indoor utility vehicles, mining locomotives operate in environments that require several safety considerations. Mining locomotives are mostly associated with coal and, as a result, have strict health and safety standards to satisfy. Diesel-electric locomotives are inappropriate for mining applications because of the emissions at the point-of-use and battery-powered locomotives are impractical because of their lack of productivity (Miller & Barnes, 2002). Hydrogen fuel cells were seen as an opportunity to satisfy the mining regulations while allowing mines to operate productively without exorbitant costs. The mining locomotive, shown in Figure 6, used metal hydride storage, with a capacity of three kilograms, and a polymer exchange membrane fuel cell for propulsion power (Miller & Barnes, 2002).

FIGURE 6: Hydrogen fuel cell mining locomotive (Miller & Barnes, 2002)

The locomotive was converted from battery power to hydrogen power, with the hydrogen components fitting into the void left by the removed battery components. The weight of the hydrogen components was less than the weight of the battery components so ballast had to be added to the locomotive to equalize the weights. Evaluation demonstrated the hydrogen locomotive was more powerful, was quicker to recharge, had more storage, had greater gravimetric energy and power density, and had higher volumetric power density than the battery-powered locomotive (Miller & Barnes, 2002).

Beyond utility rail applications, hydrogen has also been tested for use in a variety of other rail applications. Another hydrogen retrofit project involved a Burlington Northern Santa Fe switcher locomotive. Switcher locomotives are used for train assembly, often in rail yards and, as a result, operate a rigorous duty cycle. Vehicle Projects managed the project that converted an existing diesel electric switcher locomotive to a hydrogen hybrid locomotive. The hydrogen hybrid weighs 127 tonnes, is able to produce 250 kW of continuous power, and has transient power greater than one mW. The motivation for this retrofit was the need to reduce rail yard emissions, particularly at seaports, reduce emissions at point-of-use, create a mobile power source for disaster relief and military applications, and reduce foreign energy reliance (Miller, 2007). The duty cycle of a typical switcher locomotive has large peaks of power needs that may exceed 1000 kW, as shown in FIGURE 7.

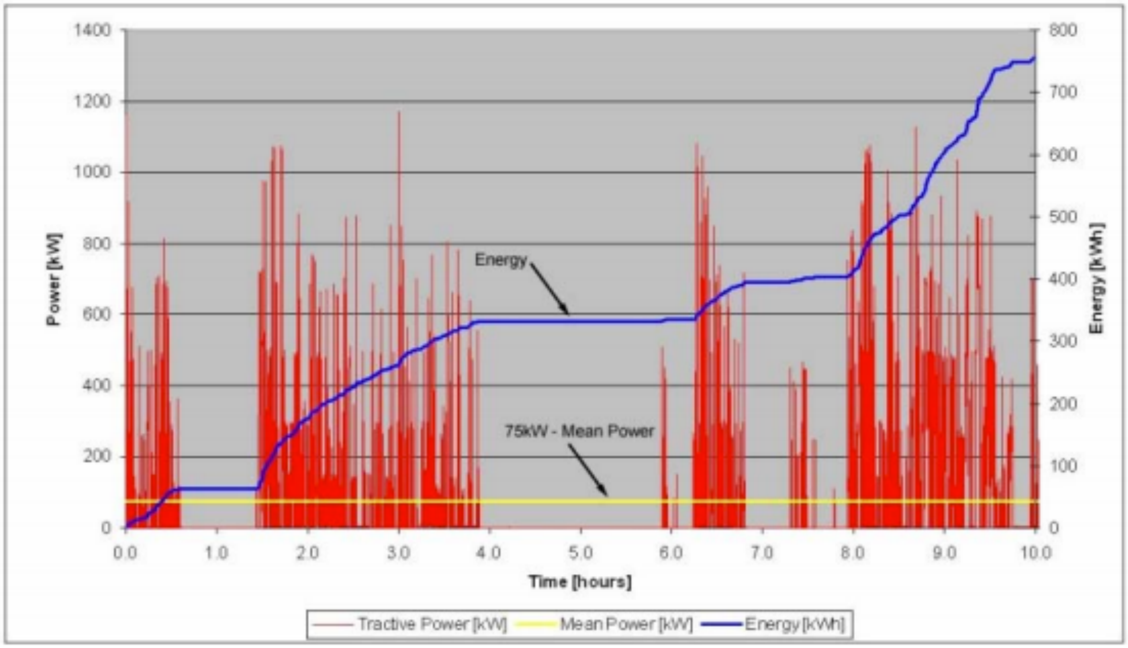

FIGURE 7: Duty cycle of switcher locomotive (Miller, 2007)

In order to sufficiently satisfy the maximum power needs, the hydrogen hybrid utilizes two methods of power generation. The polymer exchange membrane fuel cell supports the mean power output and batteries are used to augment the fuel cells during power demands that exceed the fuel cells' maximum output. For a switcher locomotive, up to 90% of operating time may be spent idle, so emission-free power generation can substantially reduce unnecessary emissions (Miller, 2007).

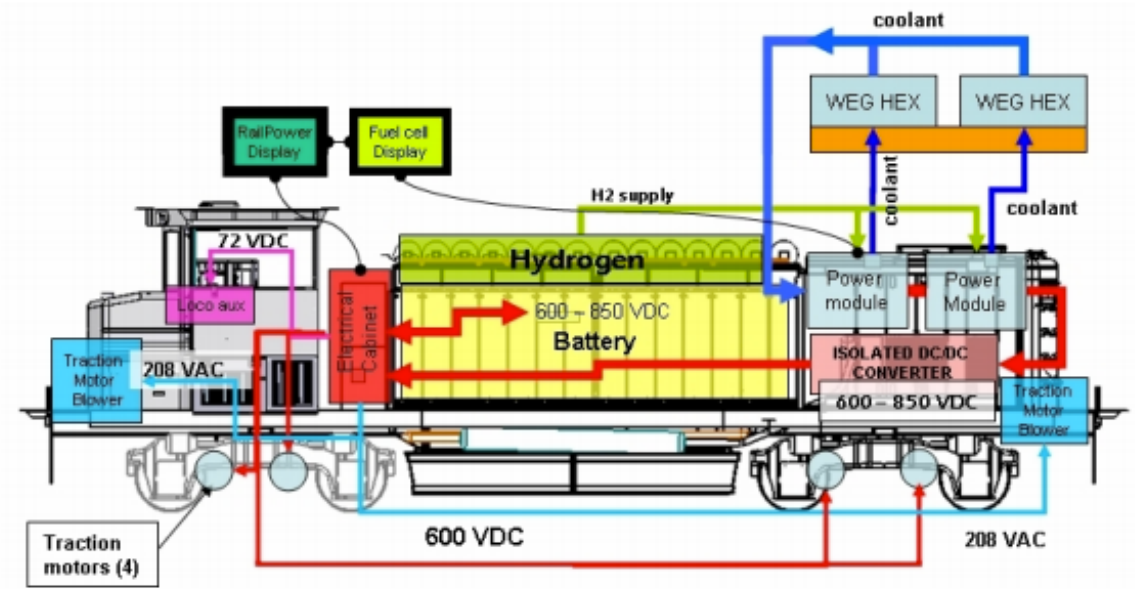

FIGURE 8: Layout of hydrogen hybrid switcher locomotive (Miller, 2007)

In the United States, the EPA has the authority to set emission standards for refurbished and new locomotives. In 2000, emission standards were enacted that limit locomotive idling (Office of Transportation and Air Quality, 2013). Throughout the world, an emphasis is being placed on reducing emissions from locomotives and updating an aging fleet of locomotives. However, the current alternative to diesel-electric traction is electrification, which is prohibitively expensive for many applications. The wayside infrastructure costs associated with electrification can only be justified with sufficient train traffic, so lines with low utilization rates are unlikely to merit the large capital costs associated with electrification. For these scenarios, a hydrogen-powered locomotive provides autonomous traction and zero greenhouse gas emission at the point-of-use, all without the expense of wayside infrastructure.

Simulations of a diesel-electric commuter line in the United Kingdom demonstrated the ability of a hydrogen-powered and hydrogen hybrid train to operate the route with greater efficiency and less greenhouse gas emissions. The increase in volume and weight considered could be accommodated on the train model used for simulation. The author concludes that hydrogen is a technically feasible propulsion system for trains (Hoffrichter, 2013). If steam methane reforming is used to produce hydrogen, there are significant energy savings and carbon emission reductions for hydrogen propulsion systems compared to diesel electric, as seen in TABLE 2.

TABLE 2: Comparison of simulation results for diesel-electric, hydrogen, and hydrogen hybrid train (Hoffrichter, 2013)

Propulsion System	**Overall Vehicle Efficiency**	**Reduction in Energy Consumption**	**Reduction in Carbon Emissions (well-to-wheel)**
Diesel-Electric	25%	0%	0%
Hydrogen	41%	34%	55%[1]
Hydrogen Hybrid[2]	45%	55%	72%[1]

[1] Hydrogen is produced entirely with natural gas via steam methane reforming

[2] Regenerative braking further reduces energy consumption and carbon emissions

Additionally, the University of Birmingham in England has competed in the annual Institution of Mechanical Engineering Railway Challenge with a hydrogen-hybrid small-gauge locomotive. The competition challenges student and industry teams to build a locomotive, which is scored based on traction power, energy storage, ride comfort, noise, and reliability. The author participated in the 2014 edition as a member of the University of Birmingham team, which finished third of five entrants. The hydrogen hybrid locomotive performed impressively, and finished first in the reliability challenge, beating out conventional locomotives with gasoline-fueled internal combustion engines. The reliability of the hydrogen-hybrid locomotive is a tribute to the advancements in the field and the simplicity of the system. Had one of the two electric traction motors not failed, the hydrogen-hybrid would most likely have also won the traction power and energy storage challenge, in the author's opinion.

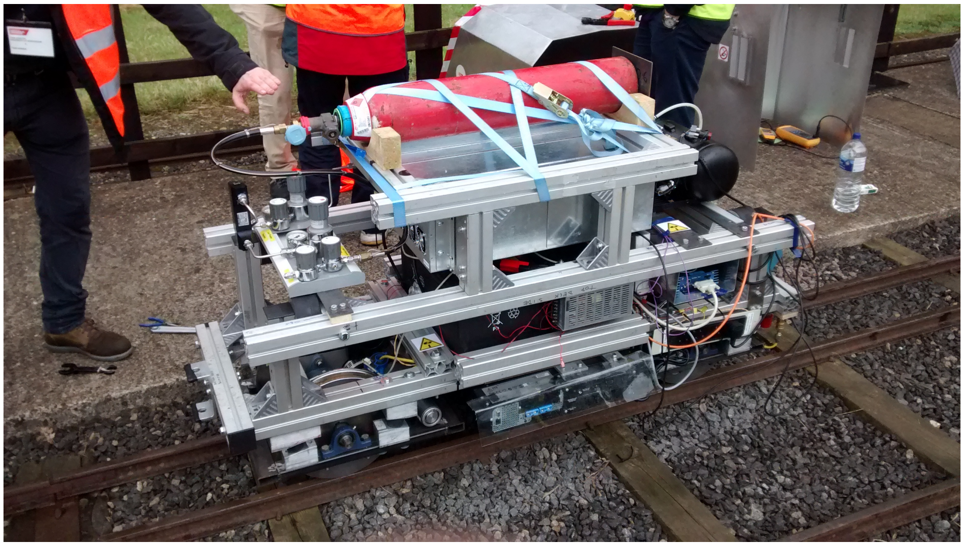

FIGURE 9: 2014 University of Birmingham hydrogen-hybrid locomotive (Author's Collection)

FIGURE 10: 2014 University of Birmingham hydrogen-hybrid locomotive (Author's Collection)

The first hydrogen-hybrid propulsion system for rail transit began operation in the island nation of Aruba in December 2012 (altenergymag.com, 2013). Thanks to abundant and reliable wind energy, the streetcars of Aruba's capital, Oranjestad, are powered by 100% clean and renewable energy. The streetcars use a combination of power generation from on-board batteries and hydrogen fuel cells. The hybrid nature of the streetcars allows the system to improve its energy efficiency through regenerative braking. The fuel cell serves to augment the batteries during high power output and when the battery is close to depletion. In total, the hybrid system is far more efficient than any other fossil fueled propulsion system and retains the autonomous, catenary-free characteristics of diesel-electric trains.

The characteristics of rail vehicles are far different than that of highway vehicles and utility vehicles, and are less sensitive to the constraints of hydrogen technology. For instance, a highway vehicle is limited by the weight and volume of the propulsion system, but for rail vehicles, neither is too restrictive. In the case of the hydrogen hybrid switcher locomotive, ballast was added to bring the weight to a normal operating weight. Further restrictions for the hydrogen technology in automotive sector include infrastructure needs and costs. Utility and rail vehicles benefit from the autonomy of hydrogen, concentrated infrastructure, and emission-free operations. Existing hydrogen power applications have demonstrated that hydrogen fuel cells are efficient and effective in niche applications, such as forklifts and switcher locomotives.

Alternative Fuel Evaluation Methods

Alternative fuels, by nature, are intended to reduce reliance on the current fuel of choice-petroleum. America's reliance on petroleum is a national security risk and environmental hazard. Therefore, alternative fuel must be evaluated on its ability to minimize the economic, safety, and environmental risks associated with petroleum. The parameters of interest are greenhouse gas emissions, resource needs, and resource availability. An alternative fuel that has little resource needs, resource needs that are renewable, and produces little to no greenhouse gas emissions is ideal. The alternative fuel should also perform, on an energy efficiency basis, comparably to existing technology.

The evaluation framework for alternative fuel vehicles, from a consumer's perspective, can be studied through a sustainable development mindset, which focuses on three areas for evaluation: economic, environmental, and social (Hu, Chen, Fan, & Hsu, 2010). The economic aspect considers the monetary costs and benefits associated with an alternative fuel. For the highway vehicle sector, consumers are particularly sensitive to the economic aspect of alternatively fueled vehicles. The environmental aspect of sustainable development evaluates alternative fuels based on their effect on the environment. This evaluation extends beyond tailpipe emissions, and also includes environmental impacts, such as the use of hazardous substances, energy usage, and dematerialization (Hu, Chen, Fan, & Hsu, 2010). Finally, the social aspect encompasses both the ability of alternative fuels to merge into modern-day lifestyles and the impact that the alternative fuel may have on the community. For instance, the social aspect determines the ability of an alternative fuel to integrate into a consumer's lifestyle and the impact that the alternative fuel has on justice, well being, and quality of life (Hu, Chen, Fan, & Hsu, 2010).

For alternatively fueled highway vehicles, the top three evaluation criteria in order from top to bottom were found to be price, user acceptance, and a reduction of hazardous substances (Hu, Chen, Fan, & Hsu, 2010). Each of the top three evaluation criteria represents one of the three components of sustainable development (economic, environmental, and social). The scope of this thesis will focus on the environmental component of hydrogen energy evaluation.

The efficiency of an alternative fuel is a key determinate in the effectiveness of an alternative fuel. Energy usage, in terms of environmental impact, extends beyond energy usage at the point of use. Energy usage is also a function of the procurement of raw materials, fabrication of parts, and assembly of the final product. For a standard highway vehicle, the energy usage and carbon emissions for the entire lifecycle are approximately 34,000 MJ and 2,000 kg, respectively (Sullivan, Burnham, & Wang, 2010). Alternative fuels typically employ new manufacturing techniques and materials, and often require more energy input during the manufacturing phase.

One of the primary cost drivers for the polymer exchange membrane fuel cells is the metal catalyst, which is usually platinum. Platinum is the ideal catalyst for a fuel cell because it catalyzes the reaction more efficiently than any other pure metal (Carter, 2013). Platinum's expensive nature has encouraged much research into methods of reducing the amount of platinum needed as well as alternative catalysts. Platinum, though, is a non-renewable resource and is subject to market fluctuations due to its lack of abundance (Hilliard, 2003). The automotive industry's reliance on platinum is sparking interest in the research field to find alternatives.

A method utilized in previous literature to evaluate the full fuel cell cycle is the well-to-wheel analysis, shown in FIGURE 11, which is separated into a well-to-tank and tank-to-wheel portion (TIAX LLC, 2007). For the railways, this method has been used to compare the energy efficiency and emission production of different propulsion systems (Hoffrichter, 2013). The energy efficiency is a function of the efficiency of the supply chain of energy and of the vehicle's drive train. This analysis determines how much energy from the well, or initial extraction of the fuel from nature, is required to provide one unit of energy at the wheel. The emission analysis determines the amount of greenhouse gas emissions associated with the entire pathway of the energy from the well to the wheel (TIAX LLC, 2007). The emission analysis is very sensitive to the local energy market and production of electricity. In the U.S., 37% of electricity is generated by coal, which reduces the ability of energy carriers to be carbon neutral (U.S. Energy Information Administration, 2014). On the other hand, California relies on coal for just 7.5% of its electricity generation, which enables energy carriers such as electricity and hydrogen, to be less carbon-reliant (The California Energy Commission, 2014).

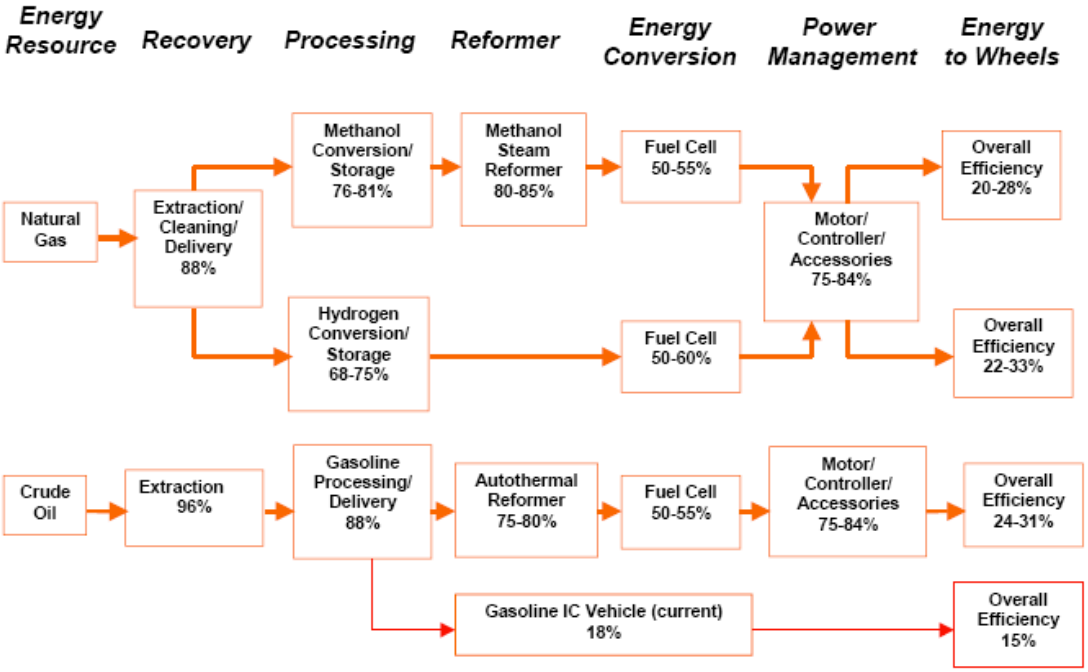

FIGURE 11: Schematic of well-to-wheel analysis (Halacy, n.d.)

The evaluation of alternative fuels should be done on an economical, environmental, and social basis. The environmental evaluation is critical in determining whether alternative fuel ideas are worth further pursuit. The primary criteria of interest, from an environmental perspective, are emissions and energy efficiency. An alternative fuel that demonstrates an ability to reduce emissions and satisfy or exceed current energy efficiency standards should proceed to economic and social evaluation.

Urban Rail Transit Standards and Guidelines

Unlike other forms of rail transit and urban transit, urban rail transit combines the fixed infrastructure of rail with the frequent and dense service of urban transit systems. Unique operational and safety standards and guidelines are in place to ensure effective use of resources and provision of adequate safety. When considering an alternative fuel, such as hydrogen, on-board storage should satisfy existing safety standards and the use of an alternative fuel should not prevent the system from operating at a standard performance level.

Guidelines set by the National Fire Protection Agency specify that potential ignition sources and combustible materials should be isolated (DMJM Harris - AECOM, 2008). For a hydrogen-powered light rail, the satisfaction of this standard is of utmost importance due to the high voltage produced by fuel cell motors (the ignition source) and the high flammability of hydrogen (the combustible material) (The International Consortium for Fire Safety, Health & Environment, 2003). Additionally, the equipment should be located outside of the passenger compartment, leaving few options for the placement of the hydrogen fuel cell equipment (DMJM Harris - AECOM, 2008). Hydrogen storage, particularly in gaseous form, is best suited on the roof of a train so as to take advantage of the properties of gaseous hydrogen and a location outside of the passenger compartment. Gaseous hydrogen, if released, disperses very quickly and would be a minimal hazard to passengers if stored on the roof of the train with ventilation to the environment (The International Consortium for Fire Safety, Health & Environment, 2003). A comparison of the burn characteristics of hydrogen versus gasoline is highlighted in FIGURE 12. The hydrogen flame on the left is noticeable larger, but disperses quickly away from the vehicle while the flame produced by the gasoline consumes the vehicle.

FIGURE 12: Hydrogen flame verses gasoline flame three seconds after ignition (Hoffrichter, 2013)

The voltage produced by the hydrogen fuel cell, along with the conductive components of the electric drivetrain, pose a risk if not properly shielded from the hydrogen. Vehicle design is an important facet of sufficiently isolating the combustible material from the ignition source. The National Fire Protection Agency further set the maximum total combustible content of a light rail vehicle to 90 million BTU and the maximum heat release rate to 45 million BTU/hour (The International Consortium for Fire Safety, Health & Environment, 2003). The combustible content of hydrogen is 142 mJ/kg, so depending on the quantity of hydrogen to be stored on-board, the total combustible content can be calculated as the product of the combustible content of hydrogen and the weight of stored hydrogen (Rodrigue, 2014).

For rail transit, the propulsion system is expected to meet certain standards so that full confidence may be put in the propulsion system in any scenario that arises. The maximum acceleration rate is limited by the mass of the transit unit. Up to 133,800 lbs, the maximum acceleration is 3 mphps with the rate decreasing proportionally to the increase in weight past 133,800 lbs. Vehicles less than 133,800 lbs are also expected to reach 25 mph and 50 mph within 10 seconds and 35 seconds, respectively. The jerk rate, or derivative of the acceleration function, is restricted to a minimum of 2.5 mphps^2 and a maximum of 3.0 mphps^2 (DMJM Harris - AECOM, 2008).

The duty cycle of a locomotive is the daily utilization profile, or percentage of time the locomotive is producing a particular range of power. The design of a propulsion system is completed with the most difficult duty cycle in mind, so that operation can be ensured in all circumstances. For the majority of the time, the transit unit is expected to satisfy the duty cycle of a continuously operating unit that weights 133,800 lbs. The possibility of the mechanical breakdown of a transit unit must also be accommodated so that service on the line is not disturbed. Therefore, the propulsion system should be able to push or tow an inoperable unit, up to 143,000 lbs, from the point furthest from the end of the line (DMJM Harris - AECOM, 2008).

Transit must also be evaluated on a service, efficiency, and demand-responsive basis (Cook & Lawrie, 2010). Demand-responsive service is not completely applicable to rail transit, though wait time deviation is pertinent to rail transit. Service measures include, but are not limited to, availability, on-time performance, travel time, safety, appearance, and communication. The service measures largely attempt to quantify the user's perception of the system. Both the percentage of time that a transit unit is on time and the length of transit travel time are key indicators of the quality of service offered (VTA Transit, 2007).

From an efficiency perspective, transit vehicles are often evaluated in relation to revenue hours, or the number of hours in which revenue is generated for the transit system. Boardings per revenue vehicle hour, which measures the productivity of the transit system, is one of the most useful measures of urban transit systems. The productivity of the stations and route mileage may also be represented by boardings per station and boardings per route mile (VTA Transit, 2007). These measures quantify how efficient the resource inputs are at producing an output, such as ridership.

The goal of understanding urban transit performance measures and standards is intended to ensure that hydrogen fuel cell technology does not restrict the operations of the light rail system. Users have the tendency to become accustomed to the status quo, so a change in propulsion systems should be hardly noticeable. Modern day operating characteristics of hydrogen fuel cells differ from the existing catenary systems used for light rail today, which prompts the question- do hydrogen propulsion systems satisfy existing light rail transit standards?

METHODOLOGY

The scope of this research includes simulations of a prototype hydrogen-powered light rail vehicle as well as a conventional electric vehicle, both operating on the existing electrified Blue Line in Charlotte. The simulations will be used for a comparative analysis of hydrogen traction and electric traction on a 9.3-mile long urban line with eleven stops. Emissions and operational performance of the hydrogen-powered prototype will be benchmarked against the current technology. The simulations will provide the necessary data for an analysis of energy use, emission production, and transit operations.

RailPictures.Net - Image Copyright © Jennifer Leigh McDaniel

FIGURE 13: Light rail in Charlotte, N.C., U.S.A.

For hydrogen to be a worthwhile competitor to electric traction, it should demonstrate the ability to handle the same passenger capacity, offer similar passenger level of service, operate with equal headways, and maintain minimal noise pollution, sufficient speed and acceleration, and no point-of-use emissions. The operational analysis will consider each of these factors, as well as the electricity mix, which is important since hydrogen is an energy carrier, rather than an energy source. Hydrogen-powered light rail does not have the benefit of a continuous flow of energy from wayside infrastructure. Therefore, the simulations will be vital in determining the capabilities of a hydrogen-powered light rail and whether the technology is competitive with electrified light rail on an operational basis. Lastly, consideration of the practical aspects of using hydrogen as an energy carrier for light rail operation is made. These practical aspects include space for hydrogen storage and equipment onboard, safety considerations, and the need for additional infrastructure.

Railway Simulation Software

The software used for the simulations was developed at the University of Birmingham (U.K.) by Stuart Hillmansen, Ph.D. and may be used to simulate a single train or multiple trains (Hoffrichter, 2012). In instances where optimization of a rail line is the desired goal, then a multi-train simulation is appropriate. However, a simulation motivated by questions of capability can simply be answered with a single train simulation. The purpose of this thesis is to investigate the capability of a hydrogen-powered light rail to operate an existing light rail line.

The simulation software, or Single Train Simulator (STS), is comprised of three key components- the infrastructure, the vehicle, and the physics model (Meegahawatte, Hillmansen, Roberts, Falco, McGordon, & Jennings, 2010). In order to run the following simulations, the infrastructure and vehicle model is coded, essentially creating a virtual railway with a virtual train. Finally, the physics model applies the rules of physics to the motion of the train. The primary outputs of the model are travel time, traction energy at the wheels, and regenerative energy at the wheels (Hoffrichter, 2012). The parameters of interest for each of the three models are listed in TABLE 3.

TABLE 3: Parameters used for railway simulation model by model

Infrastructure Model	**Vehicle Model**	**Physics Model**
Speed Restrictions with Spatial Markers	Mass of Train	Mass of Train
Gradient (Magnitude & Length)	Coefficient of Friction	Utilization of Coasting
Spatial Location of Stations	Resistance to Motion (parameters A, B, and C)	Resistance to Motion
	Power	Total Tractive Effort
	Maximum Speed	Gravitational Acceleration
	Number of Powered Axles	Gradient (Magnitude)
	Maximum Acceleration and Deceleration	
	Dwell Time at Station	
	Terminal Time	
	Driving Style	

Physics Model

The parameters used for the railway simulation include the primary forces that affect the motion of a railway vehicle. The vehicle response to the forces is governed by

Lomonossoff's equation, as seen in Equation 7 (Meegahawatte, Hillmansen, Roberts, Falco, McGordon, & Jennings, 2010),

$$\text{EQUATION 7: } M_e \frac{d^2s}{dt^2} = F - R - Mg\, sin\, \alpha \text{ (Railway vehicle response)}$$

where, M_e is the inertial mass of the vehicle; s is the vehicle displacement; t is the time; F is the total tractive effort produced at the wheels; R is the resistance to motion; M is the total mass of the vehicle; g is the gravitational acceleration; and α is the gradient of the track. Tractive effort less the vehicle's resistance to motion is the force available for acceleration. Tractive effort is also known as adhesion force since it is constrained by the friction coefficient, as seen in Equation 8 (Hill, 1994).

$$\text{EQUATION 8: } F = \mu mg \text{ (Adhesion force per axle)}$$

where, μ is the friction coefficient and mg is the axle load. The maximum tractive effort is thus less than μmg, since friction force between the wheel and rail surfaces is present throughout the duty cycle.

The resistance to motion, R, includes four terms (Hill, 1994). The four components, listed in the same order as in Equation 9, are rolling and vehicle track interface resistance, aerodynamic resistance, track resistance, and curvature alignment resistance (Hill, 1994). The total resistance to motion is defined as:

$$\text{EQUATION 9: } R_t = \left(A + B\frac{ds}{dt} \right) * M + C\frac{ds}{dt}^2 + D\frac{Mg}{r} + Mg\alpha \text{ (resistance to motion)}$$

where, A, B, C, and D are constants previously mentioned; M is vehicle mass; s is the vehicle displacement; t is the time; r is the track radius.

The characteristics of a train's journey affect the proportion of tractive effort used to overcome each of the four components of resistance to motion. For example, an urban transit route with stops closely spaced spends a greater percentage of tractive effort in accelerating the train while a high-speed train requires a greater percentage of tractive effort to overcome aerodynamic resistance (Hill, 1994). In general, the tractive effort decreases from its maximum value after reaching a moderate speed, as seen in FIGURE 14 (Lu, Hillmansen, & Roberts, 2011). The total train resistance gradually increases with speed.

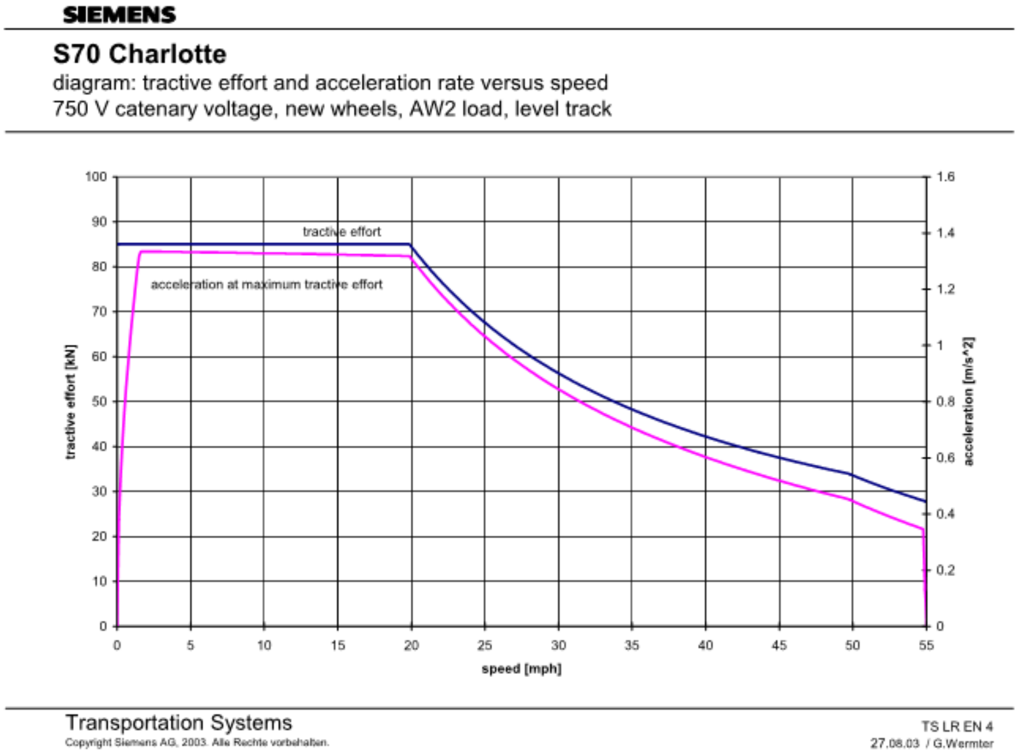

FIGURE 14: Siemens Charlotte S70 tractive effort versus speed (STV/Ralph Whitehead Associates, 2012)

Infrastructure Model

The infrastructure model was developed using data obtained from the Charlotte Area Transit System (CATS) for the BLE, which was under construction during the writing of this thesis. The BLE is a 9.3-mile long, double-track light rail line that connects to the existing Blue Line, which is also 9.3-miles long (Lynx Rapid Transit Services, 2013). CATS made the gradient, speed restriction, and station profiles available for the purpose of this research. The data obtained from CATS was motivated by a goal to build the most realistic simulation model possible. An example of the data obtained for the infrastructure model and input is shown in TABLE 4.

TABLE 4: Parameters for the infrastructure model[1]

BLE Infrastructure Marker (miles)	Station Name	Speed Restriction (miles/hour)	Gradient
0.00		17	0.00%
0.07	7th Street		
0.09			-0.74%
0.14			0.00%
0.28			-0.80%
0.30	9th Street	37	

[1] (STV/Ralph Whitehead Associates, 2012)

Vehicle Model

Like the infrastructure model, the vehicle model was completed using parameters obtained from CATS. The vehicle in use on the Blue Line and BLE is a Siemens S70, a popular light rail vehicle in the United States, which is shown in FIGURE 15. The BLE will normally operate a three-car consist upon opening, meaning three of the vehicles in

FIGURE 15 will be attached to form a train. The simulations will be of a three-car consist for operations Monday-Saturday and a two-car consist on Sundays.

FIGURE 15: Drawing of a Siemens S70 car (Vassilakos, n.d.)

The S70 used by CATS is able to regenerate energy while braking, as long as the energy has an outlet (an accelerating vehicle) along the line. The vehicle model incorporates physical characteristics of the train, such as weight and resistances, and performance characteristics, such as motor power and maximum tractive effort. The parameters below were available via a traction power study previously completed, by STV/Ralph Whitehead Associates.

TABLE 5: Parameters for the vehicle model

Siemens S70 Vehicle Parameter	**Value**
Frontal Cross Sectional Area[1]	96 ft^2
Aerodynamic Coefficient (lead)[1]	0.0024 $lbs/ft^2/mph^2$
Aerodynamic Coefficient (trailing)[1]	0.00034 $lbs/ft^2/mph^2$
Flange Coefficient[1]	0.045 lbs/ton/mph
Axles per Car (Powered)[1]	6 (4)
Vehicle Weight with AW3 Loading[1]	74.35 short tons
Normal/Maximum Acceleration/Deceleration[1]	3.0 mphps
Max Operational Speed[2]	66 mph
Motor Power[3]	760 kW
Maximum Tractive Effort[3]	85 kN
Dwell Time[1]	20 seconds
Terminal Time	5 minutes
Driving Style	As fast as possible

[1] (STV/Ralph Whitehead Associates, 2012)
[2] (Vassilakos, n.d.)
[3] Derived from FIGURE 14 and used for simulation of conventional electric light rail locomotive, Charlotte's Siemens S70

Simulation Assumptions

The single-train simulator mimics the actual movement of a train to the greatest extent possible. The assumptions, listed below, are meant to simplify the calculations and decrease the computing power required. The effect of the assumptions in the results is expected to be negligible. Certain assumptions are made due to a lack of empirical data, but remain reasonable.

- Coefficient of friction between the wheels and track = 0.2
- Driving style = As fast as possible (also in accordance with ride-comfort acceleration limits)
- Effect of curving forces on the motion of the vehicle = 0
- Electric train and hydrogen-hybrid train are equipped with regenerative braking
- Regenerative braking for the electric train captures 57.6% of energy available to be regenerated (80% of total is captured due to blended braking, 90% of that is captured due to traction efficiency, and 80% of that is available for use because of receptive catenary) (International Union of Railways, 2002)
- Regenerative braking for the hydrogen-hybrid train captures 72% of energy available to be regenerated (80% of total is captured due to blended braking and 90% of that is captured due to traction efficiency) (International Union of Railways, 2002)
- Auxiliary Load = 35 kW for 3-car consist
- Hydrogen-hybrid concept train carries enough hydrogen to operate autonomously without relying on regenerative energy
- Capacitor in the hydrogen-hybrid concept increases frontal cross section area by 25%
- Hydrogen is produced onsite via distributed SMR
- Weeks are composed of Monday-Saturday

Simulation Output and Use

Following the single train simulation, the following outputs are used for further analysis: energy at the wheels, energy available at the brakes, and journey time. From this data and the operating characteristics of the line, the daily figures can easily be expanded. Finally, from the daily figures, the total hydrogen needed on board is evident. The total hydrogen energy needed will determine the storage type required, volume requirements, and the added mass to the train, which ultimately will help to determine the feasibility and practicality of hydrogen as an energy carrier for light rail operation. The energy and power requirements for the concept hydrogen and hydrogen-hybrid locomotive are demonstrated by the preliminary simulations of the Siemens S70. The subsequent simulations, using the modified resistance, weight, and power parameters, provide the data necessary to compare the performance of the conventional electric, hydrogen, and hydrogen-hybrid light rail locomotive.

Well-to-Wheel Emission Analysis

The well-to-wheel emission analysis is a method used to track energy at the wheel of a vehicle upstream to the well, or source of energy. The well-to-wheel emission analysis is thus dependent on system efficiencies. Throughout the energy chain, or successive steps where energy is converted to alternate forms, there are losses involved that may be accounted for by efficiency factors. Beginning with the energy required at the wheel, the energy is tracked backwards through each part of the chain, such as the drivetrain or generation, and is ultimately used to calculate total emissions.

The well-to-wheel emission analysis is dependent on the energy mix, or the method by which the energy is produced. In the case of hydrogen and electricity, both are an energy carrier, and thus, require a source of energy. The electricity used to power the BLE is supplied by Duke Energy, and the energy mix for North Carolina in shown in TABLE 6. Hydrogen may be produced in a variety of methods, but for the purpose of this thesis, the most successful and scaled method of production was chosen. Steam-methane reforming uses the energy stored in natural gas, specifically methane, to store energy with hydrogen.

TABLE 6: Energy mix by energy carrier

Feedstock	Contribution to N.C. Electricity Generation[1]	Gaseous Hydrogen Production via SMR[2]
Coal	38.5%	3.2%[3]
Nuclear	31.9%	2.7%[3]
Natural Gas	24.5%	93.7%[4]
Hydroelectric	2.5%	0.2%[3]
Other Renewables	2.6%	0.2%

[1] (U.S. Energy Information Administration, 2014)
[2] (Elgowainy, Han, & Zhu, 2013)
[3] Used to generate electricity necessary for SMR
[4] 91.7% (SMR), 2.0% (electricity generation)

The efficiency factors, used to track the energy throughout the entire energy cycle, are based upon a chemical fuel's heating value (U.S. Department of Energy, 2012). Each chemical fuel has two heating values-a lower heating value (LHV) and a higher heating value (HHV). The LHV is also referred to as the net calorific value because it accounts for the heat released during the combustion of the fuel less the latent heat of vaporization of water (U.S. Department of Energy, 2012). The HHV, or gross energy, takes into account the latent heat of vaporization of water. The HHV is a more complete measure of heat because it includes heat stored in the form of water vapor. However, when calculating the energy inputs required based on efficiency factors, the LHV is recommended because it represents the energy available for work (Clarke Energy, 2013). For this reason, efficiency factors in the remainder of the thesis are given in terms of the LHV.

Based on the energy mix for North Carolina electricity, a weighted efficiency factor is calculated that incorporates the LHV efficiency factor for energy generation and the LHV efficiency factor for the recovery and transport of the energy. In calculating a total weighted LHV efficiency for the recover, transport, and generation of N.C. electricity, the well-to-wheel emission analysis is simplified. TABLE 7 shows the formulation of the weighted LHV efficiency factor.

TABLE 7: Total weighted LHV efficiency for N.C. electricity feedstock: recovery, transport, and generation

Feedstock	**N.C. Electricity Mix**[1]	**LHV Generation Efficiency**[2]	**LHV Recovery and Transport Efficiency**[2]	**Weighted Score**
Coal	38.5%	36%	99%	13.7%
Nuclear	31.9%	34%	95%	10.3%
Natural Gas	24.5%	51%	95%	11.9%
Hydroelectric	2.5%	90%	-	2.2%
Other Renewables	2.6%	35%	-	0.9%
Total LHV Efficiency for N.C. Electricity Generation				**39.0%**

[1] (U.S. Energy Information Administration, 2014)
[2] (Hoffrichter, 2013)

The weighted score in TABLE 7 is a function of the electricity mix, generation efficiency, and recovery and transport efficiency. The purpose in calculating a weighted score is to produce a single efficiency value that takes into account the respective efficiencies of each of the energy sources. The method to calculate the weighted score is outlined in Equation 10.

EQUATION 10: $\sum_{i=0}^{n} EM_n * GE_n * RT_n$ (Weighted Score)

where, EM_n is the electricity mix of the n^{th} energy source in percentage, GE_n is the LHV generation efficiency of the n^{th} energy source in percentage, and RT_n is the LHV recovery and transport efficiency of the n^{th} energy source in percentage. The weighted LHV efficiency for the hydrogen feedstock is calculated similarly in TABLE 8.

TABLE 8: Total weighted LHV efficiency for hydrogen feedstock: recovery, transport, and generation

Feedstock	**Hydrogen Feedstock Mix**[1]	**LHV Generation Efficiency**[2]	**LHV Recovery and Transport Efficiency**[2]	**Weighted Score**
Coal	3.2%	36%	99%	1.1%
Nuclear	2.7%	34%	95%	0.9%
Natural Gas	93.7%	51%	95%	45.4%
Hydroelectric	0.2%	90%	-	0.2%
Other Renewables	0.2%	35%	-	0.1%
Total LHV Efficiency for Hydrogen Feedstock				**47.7%**

[1] (Elgowainy, Han, & Zhu, 2013)
[2] (Hoffrichter, 2013)

The remaining efficiency factors consider energy losses through the locomotive drivetrain, power plant, the transmission of electricity for electric trains, and the production of high-pressure gaseous hydrogen for hydrogen trains. The energy chain and the respective efficiency factors for the existing electric S70 and the concept hydrogen train and hydrogen-hybrid train are shown in TABLE 9 and TABLE 10. Neither table includes improved efficiency due to regenerative braking, as that is figured separately.

The LHV efficiency factors are sourced from existing literature and are not specific to the BLE rolling stock or a hydrogen-powered light rail vehicle. Hydrogen production is assumed to be via a distributed SMR, therefore an efficiency factor for pipeline or trucking transportation is omitted in TABLE 10.

TABLE 9: Well-to-wheel efficiency factors using LHV for an electric train

Well-to-Tank (Well-to-Pantograph)	**LHV Efficiency**
Energy at Source	100%
Weighted Efficiency of N.C. Electricity Mix[1]	39.0%
Grid Transmission[2]	94%
Catenary Transmission[3]	92.5%
Total Well-to-Tank (Well-to-Pantograph)	*33.9%*
Tank-to-Wheel (Pantograph-to-Wheel)	**LHV Efficiency**
Feed Cable[3]	95%
Transformer[3]	95%
Control System and Electronics[3]	97.5%
Electric Motors[3]	95%
Transmission[3]	96%
Traction Auxiliaries[4]	93%
Total Tank-to-Wheel (Pantograph-to-Wheel)	74.6%
Total Well-to-Wheel	**25.3%**

[1] Calculated previously in TABLE 7 Total Weighted LHV Efficiency for N.C. Electricity: Recovery, Transport, and Generation

[2] (U.S. Energy Information Administration, 2014)

[3] (Hoffrichter, 2013)

[4] Calculated from assumed auxiliary load of 35 kW, Traction Auxiliaries Efficiency = (1 – (35 kW * .7406 hours)/375 kWh)

TABLE 10: Well-to-wheel efficiency factors using LHV for a hydrogen train

Well-to-Tank	**LHV Efficiency**
Energy at Source	100%
Weighted Efficiency of Feedstock (91.7% Natural Gas and 8.3% Electricity)[1]	47.7%
Steam Methane Reforming (H_2 Production and Compression)[2]	71.4%
Total Well-to-Tank	*34.0%*
Tank-to-Wheel	**LHV Efficiency**
Fuel Cell Power Plant[3]	60%
Electric Motors[4]	92%
Transmission[4]	95%
Motor Auxiliaries[4]	99%
Traction Auxiliaries[5]	93.72%
Total Tank-to-Wheel	48.7%
Total Well-to-Wheel	**16.6%**

[1] Calculated previously in TABLE 8 Total Weighted LHV Efficiency for Hydrogen Feedstock: Recovery, Transport, and Generation
[2] Inclusive of compression efficiency (Elgowainy, Han, & Zhu, 2013)
[3] Efficiency of Ballard FCVelocity-HD6, 60-71% LHV (Ballard Power Systems Inc, 2012)
[4] (Hoffrichter, 2013)
[5] Calculated from assumed auxiliary load of 35 kW, Traction Auxiliaries Efficiency = (1 – (35 kW * .74 hours)/411 kWh). No negligible difference between hydrogen and hydrogen-hybrid.

The final step in the well-to-wheel emission analysis involves estimating total emissions based on emission factors. The emission factors for the feedstocks pertinent to this thesis are presented in TABLE 11. For nuclear energy, radioactive waste is calculated separately since nuclear energy is greenhouse gas free and the two types of waste are not comparable. CO_2 emissions are the direct result of the combustion of fossil fuels, while transport emissions are due to transporting the feedstock from one location to another. The emission factors are based on previous research.

TABLE 11: Emission factors using LHV (Hoffrichter, 2013)

Feedstock	**CO_2 Emissions (kg/kWh)**	**Radioactive Waste (g/kWh)**	**Transport Emissions (kg/kWh)**	**TOTAL**
Coal	0.326	0	0.263	**0.589**
Nuclear	0	0.01	0.263	**0.01 g/kWh, 0.263 kg/kWh**
Natural Gas	0.203	0	0.203	**0.406 kg/kWh**
Hydroelectric	0	0	0	**0 kg/kWh**
Other Renewables	0	0	0	**0 kg/kWh**

Hydrogen and Hydrogen-Hybrid Light Rail Concept Design

The concept designs for the hydrogen and hydrogen-hybrid light rail are guided by current hydrogen production, hydrogen storage, hydrogen fuel cells, and battery systems. Each system is based upon products that are available for consumer purchase at the time of this writing (August 2014).

Hydrogen Production

Steam methane reforming is currently the most advanced and successful method of hydrogen production. SMR may be small-scale or large-scale, which allows hydrogen to be produced on-site or off-site, respectively. If produced off-site at a large industrial

SMR plant, the hydrogen must be transported to the final destination, usually by truck or pipeline. Until hydrogen becomes a widely used energy carrier, distributed SMR plants are the most cost-effective method of hydrogen production (Ogden, 2002). Distributed SMR plants can be located near the point of use and be integrated into the refueling infrastructure. The efficiency factors for a distributed SMR plant are used for the well-to-wheel emission analysis.

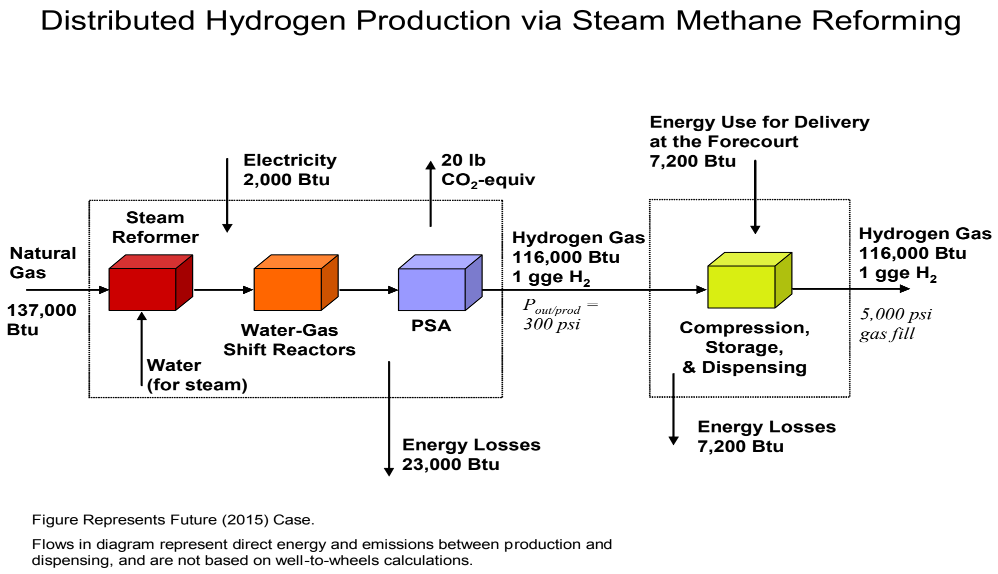
Distributed Hydrogen Production via Steam Methane Reforming

Figure Represents Future (2015) Case.

Flows in diagram represent direct energy and emissions between production and dispensing, and are not based on well-to-wheels calculations.

FIGURE 16: Distributed hydrogen production via steam methane reforming (Joseck, 2005)

Hydrogen Storage

For transport applications, gaseous hydrogen storage is usually 350 or 700 bar, with the preference being 700 bar vessels. Since hydrogen's energy content per unit volume is a fraction of conventional liquid fossil fuels, such high pressures are required to minimize the volume requirements of the storage system and maximize the range of the vehicle. The characteristics of a modern 700 bar vessel for hydrogen are listed in TABLE 12. These characteristics are the basis for the hydrogen storage component design.

TABLE 12: Parameters of a Type IV 700 bar hydrogen vessel (Argonne National Laboratory, 2010)

Parameter	Value
Useable Storage Capacity	5.6 kg H_2
Gravimetric Capacity	4.2%
Gravimetric Density[1]	33.3 kWh/kg
Vessel Weight with 5.6 kg H_2	112 kg
Volumetric Capacity	26.3 kg H_2 / m^3
Vessel Volume	0.22 m^3 (7.77 ft^3)
Storage Cost	$18.7/kWh

[1] (SUSY, 2012)

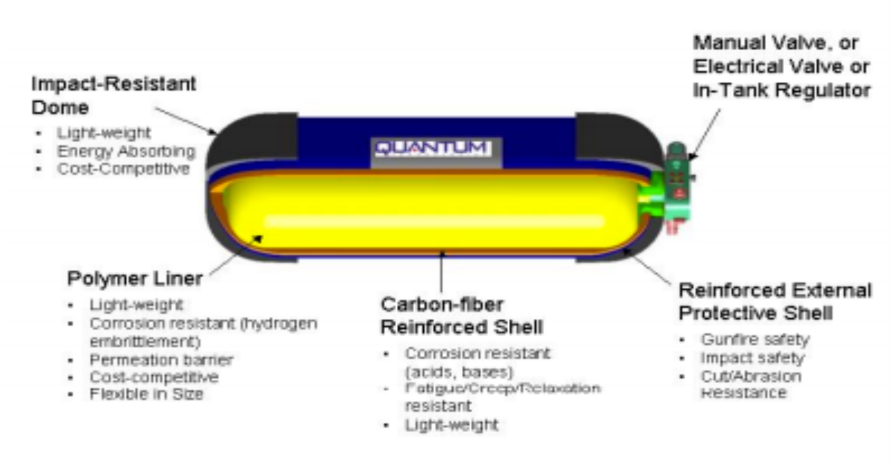

FIGURE 17: Type IV composite vessel for hydrogen storage (Sirosh, 2002)

Hydrogen Fuel Cell System

The hydrogen fuel cell system design is based on currently available commercial technology. Ballard Power Systems, Inc. is a leading fuel cell manufacturer that produces fuel cells for a variety of applications. The Ballard FCVelocity-HD6 fuel cell, which is designed for bus applications, was chosen as the model for the concept design of the fuel cell system. The Ballard FCVelocity-HD6 was chosen for concept design because it is a leading commercial technology for bus applications, which provides the necessary output for a light rail application. The operating and physical characteristics are listed in TABLE 13.

TABLE 13: Parameters of Ballard FCVelocity-HD6 fuel cell (Ballard Power Systems Inc, 2012)

Parameter	Value
Power Rating	150 kW
DC Voltage	230-800V
Maximum Current	320A
Weight	404 kg
Volume	23.3 ft^3
Fuel Consumption	1.3-2.5 g/s
Fuel Cell Efficiency	60-71% LHV
Lifetime	12,000 hours

FIGURE 18: Ballard FCVelocity HD-6 hydrogen fuel cell (Ballard Power Systems Inc, 2011)

Energy Storage System

The hydrogen-hybrid concept train will be similar to the hydrogen concept in all facets, but with the addition of an energy storage system. The primary purpose of an energy storage system is to enable the train to regenerate energy while braking. The hydrogen train concept is unable to regenerate energy because it operates autonomously and does not have the capability to store energy on-board. An appropriate on-board storage system is necessary to maximize the range of speeds that allow regenerative braking. For catenary-supplied systems without on-board storage systems, some regenerative energy may be lost in an effort to not disrupt the current throughout the system. On-board storage, though, may be useful in absorbing current that exceeds the capacity of the system, therefore extending the range of speed at which energy may be regenerated (Shimada, Miyaji, Kaneko, & Suzuki, 2012). This highlights the need for an appropriate storage system so that maximum energy may be regenerated.

For local direct current (DC) lines, it is suggested that flywheels and capacitors are the best option for energy storage (Wurtenberger & Nolte, 2003). Flywheels store energy in a rotating mass that spins at speeds exceeding 16,000 rpms in a vacuum container (Beacon Power, 2014). Flywheels are most often installed as wayside infrastructure, which prohibits the autonomous nature of a hydrogen-powered train. Therefore, the energy storage system is based on capacitor technology. Capacitors are familiar technology for railways, and recently, a 100% capacitor-powered train had been developed for a tramline in China (Railway Gazette, 2014).

A recent TIGGER Grant, provided by the U.S. DOT FTA, retrofitted the TriMet light rail vehicle fleet with on-board capacitors for energy storage. The goal was to improve the efficiency of the system in capturing regenerated energy since up to 30% of the regenerated energy was lost due to non-receptive catenary (U.S. DOT FTA, 2012). The capacitor stack is roof-mounted, and may be seen in FIGURE 19.

Courtesy of Jason Grohs, TriMet

Clockwise from top left: The double layer capacitor enclosure, the power control unit, and the double layer capacitor modules.

FIGURE 19: Roof-mounted capacitor stack, TriMet light rail fleet (U.S. DOT FTA, 2012)

The characteristics of the TriMet roof-mounted capacitor stack serve as the basis for the design of the energy storage system for the hydrogen-hybrid concept. The TriMet system has demonstrated high performance in a light rail application, making it an ideal fit for this thesis. The characteristics of importance for the energy storage system are listed in TABLE 14.

TABLE 14: Parameters of roof-mounted capacitor energy storage (Grohs & Heilig, 2013)

Parameter	**Value**
Power Rating	120 kW
DC Voltage	525-925V
Current Rating	240A
Useable Energy	0.814 kWh
Weight	550 kg

RESULTS

Conventional Electric Train Concept

The initial simulation, based on the Siemens S70 and infrastructure data, is representative of the expected operation of the BLE Monday thru Saturday. Each train simulated is a 3-car consist. The results for the simulation are found in TABLE 15. The operation and performance of the electric train can be seen graphically in FIGURE 20 to 25.

TABLE 15: Electric train on BLE: results

Output	**Northbound Journey**	**Southbound Journey**	**Round Trip**
Journey Time	19 minutes 59 seconds	19 minutes 38 seconds	44 minutes 26 seconds
Energy to the Wheels (Propulsion)	182 kWh	193 kWh	375 kWh
Energy from the Wheels (Braking)	165 kWh	150 kWh	315 kWh
Net Energy Consumption[1]	149 kWh	172 kWh	321 kWh
Average Traction Power[2]	547 kW	590 kW	507 kW

[1] Net Energy Consumption = (Energy to the Wheels / 74.6% Vehicle Efficiency) – (Energy from the Wheels * 57.6% Regenerative Braking Efficiency)

[2] Average Traction Power = Energy to the Wheels / Journey Time

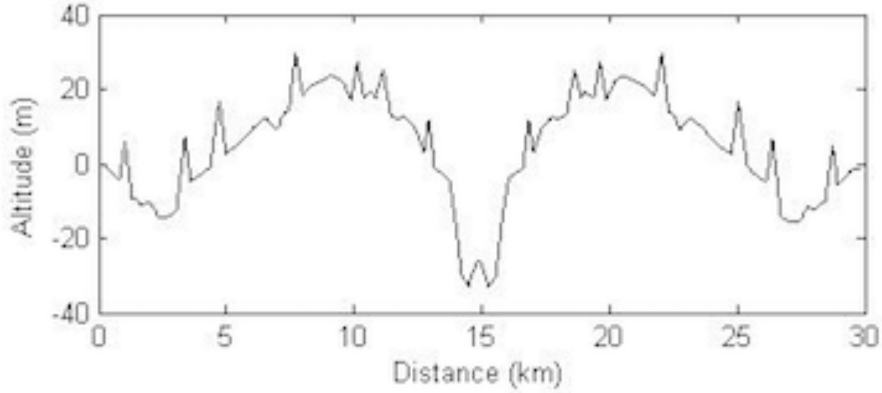

FIGURE 20: BLE round trip gradient profile

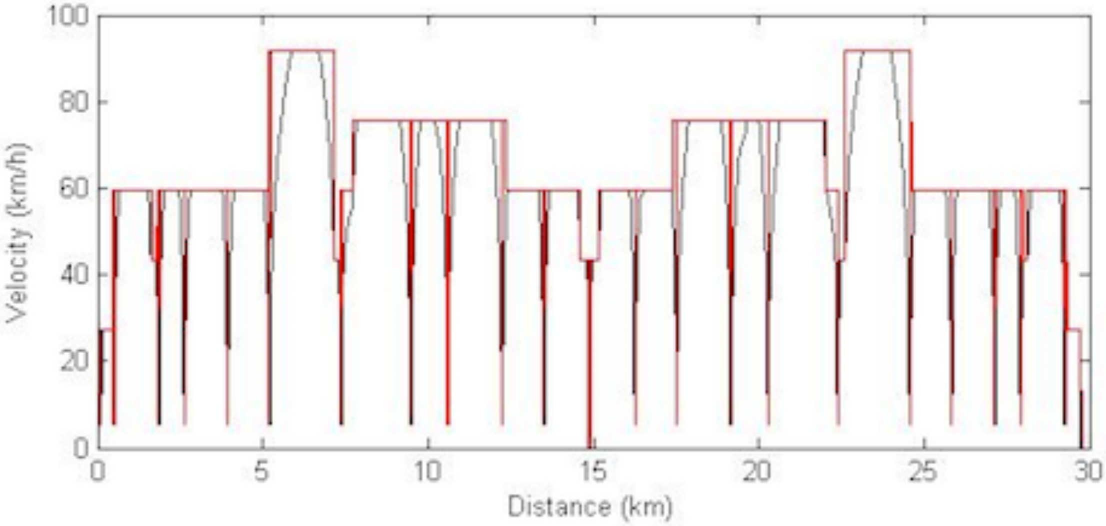

FIGURE 21: BLE round trip speed and speed limit profile

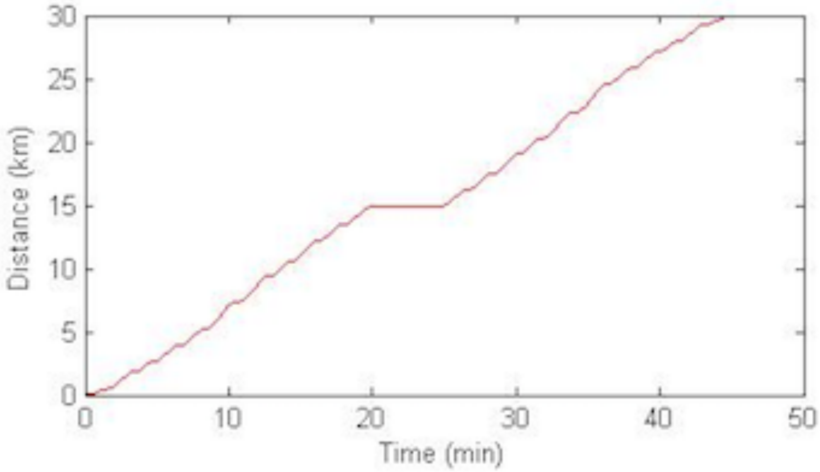

FIGURE 22: BLE round trip running diagram

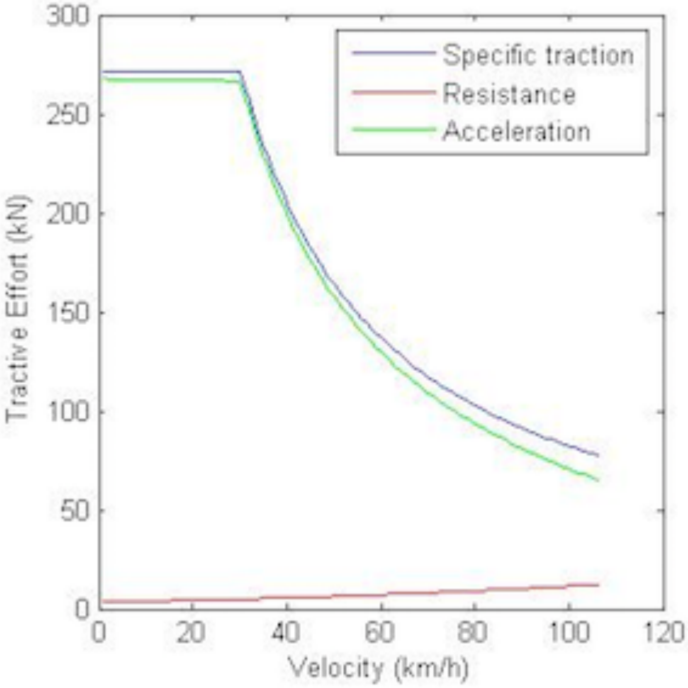

FIGURE 23: Electric train tractive effort versus speed

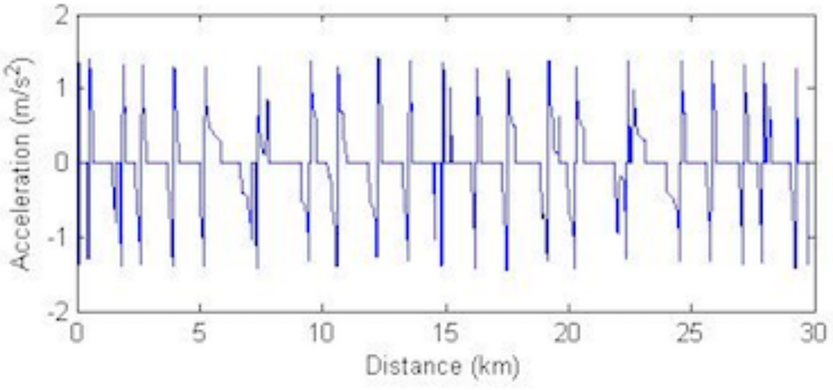

FIGURE 24: Electric train round trip acceleration profile

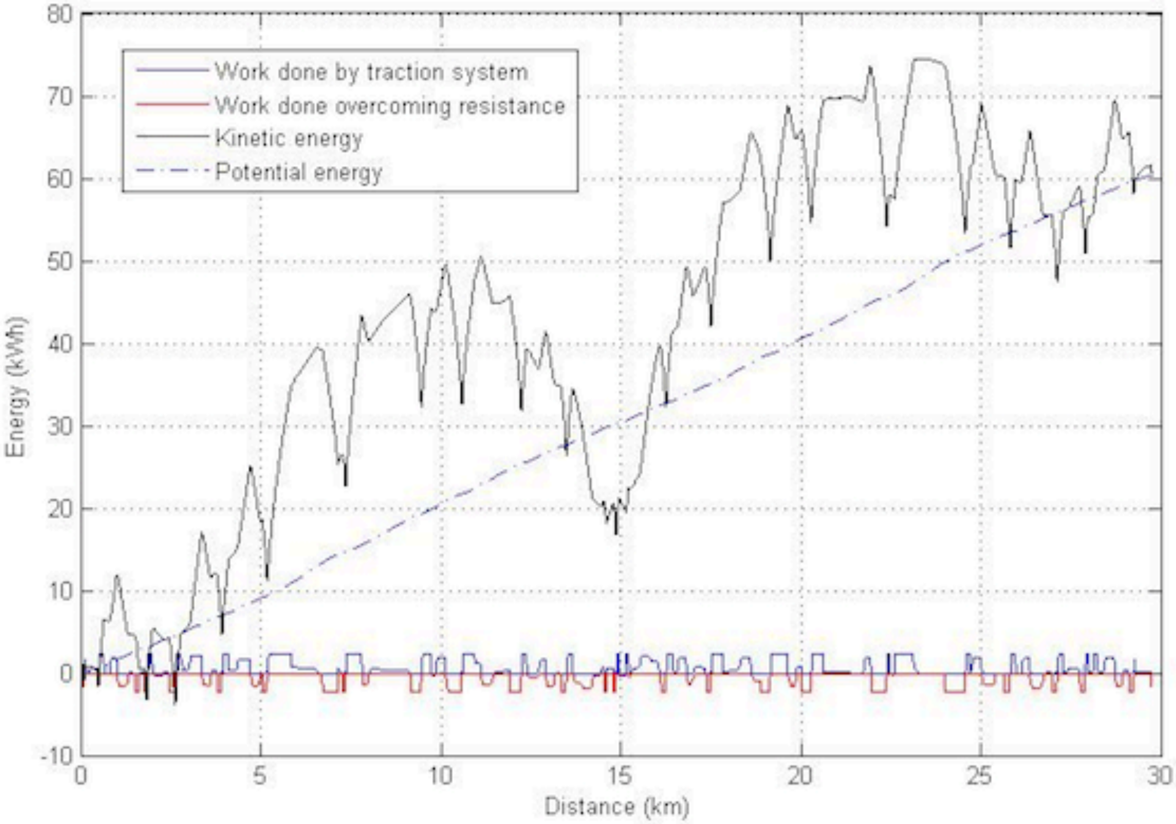

FIGURE 25: Electric train energy and power profile

The outputs above serve as the basis for the development of a hydrogen and hydrogen-hybrid locomotive that resembles the Siemens S70 in all respects but the traction power system. The outputs from a single round trip journey are expanded to daily figures in TABLE 16. Service is assumed to be available from 5:15 A.M. to 1:30 A.M., which are the current operating hours of the Lynx Blue Line (Charlotte Area Transit System, 2014). The headway is assumed to be 7.5 minutes and the auxiliary load is 35 kW, for a 3-car consist, as shown in a previous traction power study (STV/Ralph Whitehead Associates, 2012).

Daily operation requires 6 trains (44.43 minute journey time / 7.5 minute headway) to operate the round trip with 7.5-minute headways. Each train completes 27.3 round trips per day (20.25 operating hours / 0.7406 hour journey), which includes 20 seconds station dwell time and a terminal time of 5 minutes. Total daily energy figures for a single Siemens S70 electric train are shown in TABLE 16.

TABLE 16: Electric train on BLE: daily, weekly, and yearly energy totals

Parameter	**Daily Total**	**Weekly Total[1]**	**Yearly Total[1]**
Energy at the Wheels	10,255 kWh	61,525 kWh	3,199,287 kWh
Energy from the Wheels	8,613 kWh	51,678 kWh	2,687,256 kWh
Net Energy Consumption[2]	8,786 kWh	52,707 kWh	2,740,729 kWh

[1] Does not include Sunday operations

[2] Net Energy Consumption = (Energy to the Wheels / 74.6% Vehicle Efficiency) – (Energy from the Wheels * 57.6% Regenerative Braking Efficiency)

Hydrogen Train Concept

Using the energy consumption data from the initial simulation of the standard electric S70 on the BLE, a concept hydrogen train is designed to meet the operating standards. The key design parameter is energy at the wheels for propulsion, from TABLE 16. The energy at the wheels for propulsion is divided by the hydrogen train vehicle efficiency factor to determine the necessary amount of hydrogen. The on-board hydrogen storage is designed to have an operation range of a single day of operation before refueling. The power plant, or fuel cell stack, is designed based on the maximum power output of the electric train. The addition of on-board hydrogen storage and hydrogen fuel cells adds weight and volume to the locomotive, thereby influencing the resistance of the locomotive. The hydrogen train is autonomous and without energy storage, which voids the opportunity to regenerate energy during braking.

TABLE 17: Preliminary hydrogen train storage and fuel cell requirements

Parameter	**Hydrogen Concept Train**
Stored Energy Requirement[1]	21,057 kWh
Hydrogen Storage Vessels Required[2]	113 vessels
Hydrogen Fuel Cells	18 fuel cells
Hydrogen Storage Weight[3]	27,837 lbs
Hydrogen Fuel Cell Weight[4]	16,032 lbs
Hydrogen Storage Volume[3]	876 ft^3
Hydrogen Fuel Cell Volume[4]	419 ft^3
Total Weight Added	43,869 lbs
Total Volume Added	1,295 ft^3

[1] Stored Energy Requirement = Daily Energy at the Wheels / 48.7% Hydrogen Vehicle Efficiency
[2] 5.6 kg H_2 Vessel, Gravimetric Density = 33.3 kWh/kg
[3] 246.9 lbs/vessel & 7.77 ft^3/vessel, TABLE 12 Parameters of a Type IV 700 Bar Hydrogen Vessel (Argonne National Laboratory, 2010)
[4] 890.7 lbs/fuel cell & 23.3 ft^3/vessel, TABLE 13 Parameters of Ballard FCVelocity-HD6 Fuel Cell (Ballard Power Systems Inc, 2012)

The preliminary hydrogen train requires 113 700-bar vessels to store enough energy for a full day of operation on the BLE. 18 hydrogen fuel cells, detailed in TABLE 13, are required to meet the existing power of the Siemens S70. The Siemens S70 is powered with 760 kW of total power per car, while the hydrogen and hydrogen hybrid trains have six fuel cells per car for a total of 900 kW. In TABLE 17, the additional weight and volume attributable to the hydrogen vessels and fuel cells is listed. TABLE 18 summarizes the changes in parameter values, which are the result of the additional weight and volume.

TABLE 18: Preliminary hydrogen train parameter changes compared to electric train[a]

Parameter	Electric 3-car Consist	Hydrogen Concept 3-car Consist
Total Weight Added[a]	-	21.9 tons
Total Frontal Cross Section Area Added [a,b]	-	4.64 ft^2
Davis A	812 lbs	841 lbs
Davis B	10.04 lbs/mph	11.02 lbs/mph
Davis C	0.30 lbs/mph^2	0.31 lbs/mph^2
Max Power Output	2,280 kW	2,700 kW

[a] TABLE 17 Preliminary Hydrogen Train Storage and Fuel Cell Requirements
[b] Total Frontal Cross Section Area Added = Total Volume Added / 280.8 foot train (Vassilakos, n.d.)

TABLE 19: Preliminary hydrogen train on BLE: results

Output	Northbound Journey	Southbound Journey	Round Trip
Journey Time	19 minutes 54 seconds	19 minutes 33 seconds	44 minutes 16 seconds
Energy to the Wheels (Propulsion)	200 kWh	211 kWh	411 kWh
Net Energy Consumption[1]	411 kWh	433 kWh	844 kWh
Average Traction Power[2]	603 kW	648 kW	557 kW

[1] Net Energy Consumption = Energy to the Wheels / 48.7% Vehicle Efficiency
[2] Average Traction Power = Energy to the Wheels / Journey Time

The process in developing the hydrogen train concept is iterative in nature. First, the energy requirements of the electric train are used to develop a first draft concept train. The energy requirements of the electric train, though, are expected to be less than that of hydrogen concept train due to the lesser mass and frontal cross section area. After a preliminary simulation of the hydrogen concept train, the necessary amount of hydrogen is recalculated based on the electric train energy data.

A preliminary round trip journey time of 44 minutes and 36 seconds equates to 27.45 journeys per day of operation. The daily stored energy requirement is thus the product of the net energy consumption (TABLE 19) and 27.45 journeys per day of operation, as shown in TABLE 20. This iterative approach ensures that enough hydrogen is on-board the train to sustain operation for an entire day. The final hydrogen train concept parameters and results are below in TABLES 20, 21, 22, and 23.

TABLE 20: Final hydrogen train storage and fuel cell requirements

Parameter	**Hydrogen Concept Train**
Stored Energy Requirement[1]	23,165 kWh
Hydrogen Storage Vessels Required[2]	125 vessels
Hydrogen Fuel Cells	18 fuel cells
Hydrogen Storage Weight[3]	30,865 lbs
Hydrogen Fuel Cell Weight[4]	16,032 lbs
Hydrogen Storage Volume[3]	972 ft^3
Hydrogen Fuel Cell Volume[4]	419 ft^3
Total Weight Added	46,897 lbs
Total Volume Added	1,391 ft^3

[1] Stored Energy Requirement = Net Energy Consumption per Round Trip * 27.4 Round Trips/Day

[2] 5.6 kg H_2 Vessel, Gravimetric Density = 33.3 kWh/kg

[3] 246.9 lbs/vessel & 7.77 ft^3/vessel, TABLE 12 Parameters of a Type IV 700 Bar Hydrogen Vessel (Argonne National Laboratory, 2010)

[4] 890.7 lbs/fuel cell & 23.3 ft^3/vessel, TABLE 13 Parameters of Ballard FCVelocity-HD6 Fuel Cell (Ballard Power Systems Inc, 2012)

TABLE 21: Final hydrogen train parameter changes compared to electric train[a]

Parameter	Electric 3-car Consist	Hydrogen Concept 3-car Consist
Total Weight Added[a]	-	23.5 tons
Total Frontal Cross Section Area Added [a,b]	-	5 ft^2
Davis A	812 lbs	843 lbs
Davis B	10.04 lbs/mph	11.09 lbs/mph
Davis C	0.30 lbs/mph^2	0.31 lbs/mph^2
Max Power Output	2,280 kW	2,700 kW

[a] TABLE 20 Final Hydrogen Train Storage and Fuel Cell Requirements

[b] Total Frontal Cross Section Area Added = Total Volume Added / 280.8 foot train length (Vassilakos, n.d.)

TABLE 22: Final hydrogen train on BLE: results

Output	Northbound Journey	Southbound Journey	Round Trip
Journey Time	19 minutes 54 seconds	19 minutes 34 seconds	44 minutes 17 seconds
Energy to the Wheels (Propulsion)	201 kWh	212 kWh	413 kWh
Net Energy Consumption[1]	413 kWh	435 kWh	848 kWh
Average Traction Power[2]	606 kW	650 kW	560 kW

[1] Net Energy Consumption = Energy to the Wheels / 48.7% Vehicle Efficiency

[2] Average Traction Power = Energy to the Wheels / Journey Time

TABLE 23: Final hydrogen train on BLE: daily, weekly, and yearly energy totals

Parameter	**Daily Total**	**Weekly Total**	**Yearly Total**
Energy at the Wheels	11,331 kWh	67,989 kWh	3,543,417 kWh
Net Energy Consumption[1]	23,267 kWh	139,608 kWh	7,276,010 kWh

[1] Net Energy Consumption = Energy to the Wheels / 48.7% Vehicle Efficiency

The final hydrogen train concept weighs 23.5 tons more than the electric train and has a frontal cross section area 5 ft^2 larger than the electric train. The increase in frontal cross section area is based on the assumption that additional volume requirements are placed along the entire length of the train. Overall, the hydrogen train completes a single round trip in 44 minutes and 17 seconds, 9 seconds quicker than the electric train, and consumes 23,267 kWh per day.

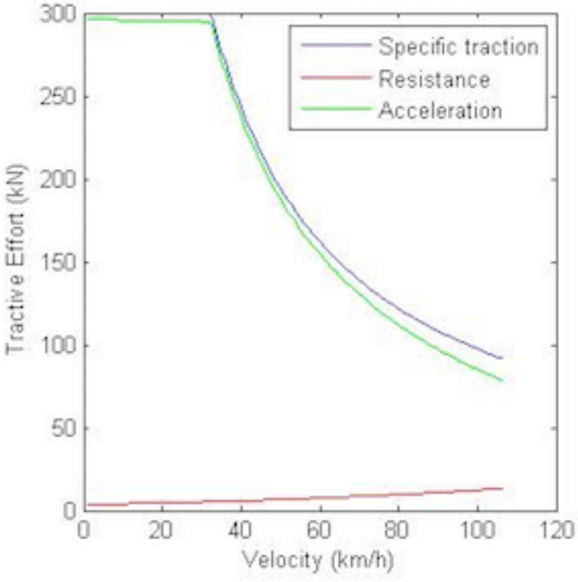

FIGURE 26: Hydrogen train tractive effort versus speed

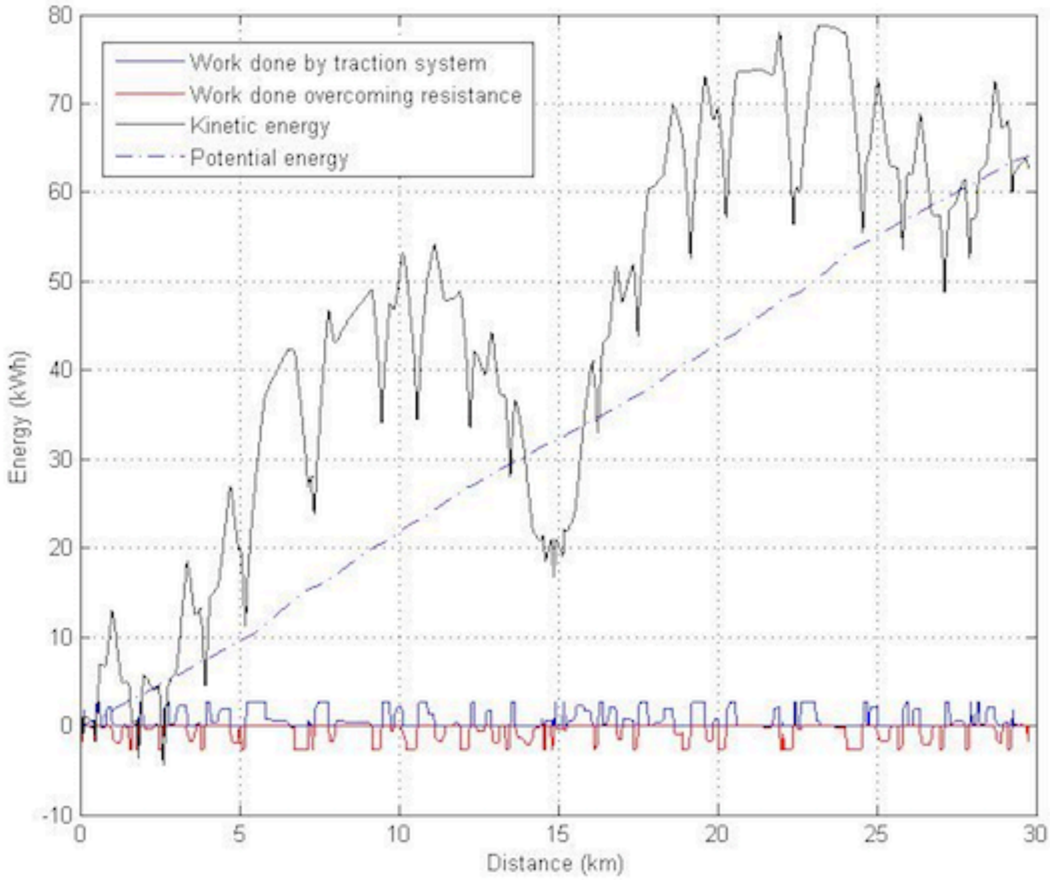

FIGURE 27: Hydrogen train energy and power profile

Hydrogen-Hybrid Train Concept

The concept hydrogen-hybrid uses hydrogen fuel cells as the prime mover, like the hydrogen concept train. Its characterization as a hybrid is due to the presence of a capacitor energy storage system, which allows the train to regenerate energy, store the energy, and use the energy. The parameters and results that directed the concept design of the final hydrogen-hybrid train are shown in TABLES 14 and 16. The hydrogen-hybrid concept design is also an iterative process, as previously detailed in the Hydrogen Train Concept section.

TABLE 24: Preliminary hydrogen-hybrid train storage and fuel cell requirements

Parameter	**Hydrogen Concept 3-Car Consist**[1]
Stored Energy Requirement[1]	21,057 kWh
Hydrogen Storage Vessels Required[2]	113 vessels
Hydrogen Fuel Cells	18 fuel cells
Hydrogen System Weight[3]	43,869 lbs
Capacitor System Weight	1,819 lbs
Hydrogen System Volume[4]	1,295 ft^3
Total Weight Added	45,688 lbs
Total Volume Added	1,295 ft^3

[1] Stored Energy Requirement = Energy at the Wheels / 48.7% Hydrogen Vehicle Efficiency

[2] 5.6 kg H_2 Vessel, Gravimetric Density = 33.3 kWh/kg

[3] 246.9 lbs/vessel & 890.7 lbs/fuel cell, TABLE 12 Parameters of a Type IV 700 Bar Hydrogen Vessel (Argonne National Laboratory, 2010)

[4] 23.3 ft^3/fuel cell & 7.77 ft^3/vessel, TABLE 13 Parameters of Ballard FCVelocity-HD6 Fuel Cell (Ballard Power Systems Inc, 2012)

TABLE 25: Preliminary hydrogen-hybrid train parameter changes compared to electric train[a]

Parameter	Electric Train	Hydrogen-Hybrid Concept Train
Total Weight Added[a]	-	23 tons
Total Frontal Cross Section Area Added [b]	-	5.8 ft^2
Davis A	812 lbs	842 lbs
Davis B	10.04 lbs/mph	11.07 lbs/mph
Davis C	0.30 lbs/mph^2	0.314 lbs/mph^2
Max Power Output	2,280 kW	2,700 kW

[a] TABLE 24 Hydrogen-Hybrid Train Storage and Fuel Cell Requirements
[b] Assumed to be 25% greater than respective hydrogen train value (4.64 ft^2) due to capacitors

TABLE 26: Preliminary hydrogen-hybrid train on BLE: results

Output	Northbound Journey	Southbound Journey	Round Trip
Journey Time	19 minutes 54 seconds	19 minutes 34 seconds	44 minutes 17 seconds
Energy to the Wheels (Propulsion)	201 kWh	212 kWh	412 kWh
Energy from the Wheels (Braking)	184 kWh	166 kWh	350 kWh
Net Energy Consumption[1]	280 kWh	316 kWh	594 kWh
Average Traction Power	606 kW	650 kW	558 kW

[1] Net Energy Consumption = (Energy to the Wheels / 48.7% Vehicle Efficiency) – (Energy from the Wheels * 72% Regenerative Braking Efficiency)

Based on the preliminary hydrogen-hybrid journey time of 44 minutes and 17 seconds, 27.4 journeys may be completed per operating day. The stored energy requirement for the final hydrogen-hybrid train and the resulting parameter changes are shown in TABLES 27 and 28. The final results of the hydrogen-hybrid train are shown in TABLES 29 and 30.

TABLE 27: Final hydrogen-hybrid train storage and fuel cell requirements

Parameter	**Hydrogen-Hybrid Concept Train**
Stored Energy Requirement[1]	23,181 kWh
Hydrogen Storage Vessels Required[2]	125 vessels
Hydrogen Fuel Cells	18 fuel cells
Hydrogen System Weight[3]	46,897 lbs
Capacitor System Weight[4]	1,819 lbs
Hydrogen System Volume[3]	1,391 ft^3
Total Weight Added	48,716 lbs
Total Volume Added	1,391 ft^3

[1] Stored Energy Requirement = Energy at the Wheels * 27.4 journeys / 48.7% Hydrogen Vehicle Efficiency

[2] 5.6 kg H_2 Vessel, Gravimetric Density = 33.3 kWh/kg

[3] 246.9 lbs/vessel & 7.77 ft^3/vessel, TABLE 12 Parameters of a Type IV 700 Bar Hydrogen Vessel (Argonne National Laboratory, 2010)

[4] 890.7 lbs/fuel cell & 23.3 ft^3/vessel, TABLE 13 Parameters of Ballard FCVelocity-HD6 Fuel Cell (Ballard Power Systems Inc, 2012)

TABLE 28: Final hydrogen-hybrid train parameter changes compared to electric train[a]

Parameter	Electric 3-car Consist	Hydrogen-Hybrid Concept Train
Total Weight Added[a]	-	24.4 tons
Total Frontal Cross Section Area Added [b]	-	6.2 ft^2
Davis A	812 lbs	844 lbs
Davis B	10.04 lbs/mph	11.13 lbs/mph
Davis C	0.30 lbs/mph^2	0.315 lbs/mph^2
Max Power Output	2,280 kW	2,700 kW

[a] TABLE 27 Final Hydrogen-Hybrid Train Storage and Fuel Cell Requirements

[b] Assumed to be 25% greater than calculated value (5 ft^2) due to capacitors

TABLE 29: Final hydrogen-hybrid train on BLE: results

Output	Northbound Journey	Southbound Journey	Round Trip
Journey Time	19 minutes 54 seconds	19 minutes 34 seconds	44 minutes 18 seconds
Energy to the Wheels (Propulsion)	202 kWh	213 kWh	415 kWh
Energy from the Wheels (Braking)	185 kWh	167 kWh	352 kWh
Net Energy Consumption[1]	282 kWh	317 kWh	599 kWh
Average Traction Power[2]	609 kW	653 kW	562 kW

[1] Net Energy Consumption = (Energy to the Wheels / 48.7% Vehicle Efficiency) – (Energy from the Wheels * 72% Regenerative Braking Efficiency)

[2] Average Traction Power = Energy to the Wheels / Journey Time

TABLE 30: Final hydrogen-hybrid train on ble: daily, weekly, and yearly energy totals

Parameter	Daily Total	Weekly Total	Yearly Total
Energy at the Wheels	11,382 kWh	68,292 kWh	3,551,184 kWh
Energy from the Wheels (Braking)	9,654 kWh	57,924 kWh	3,012,048 kWh
Net Energy Consumption	16,421 kWh	98,525 kWh	5,123,284 kWh

[1] Net Energy Consumption = (Energy to the Wheels / 48.7% Vehicle Efficiency) – (Energy from the Wheels * 72% Regenerative Braking Efficiency)

The final hydrogen-hybrid train concept weighs 24.4 tons more than the electric train and has a frontal cross section area 6.2 ft^2 larger than the electric train. The increase in frontal cross section area is based on the assumption that additional volume requirements are placed along the entire length of the train. Overall, the hydrogen-hybrid train completes a single round trip in 44 minutes and 18 seconds, 8 seconds quicker than the electric train, and consumes 16,421 kWh per day. Like the hydrogen train concept, the hydrogen-hybrid train carries 125 vessels of hydrogen, even though it consumes 6,846 kWh less energy than the hydrogen concept. The hydrogen-hybrid was designed to carry enough hydrogen to sustain daily operation, should the energy storage system fail.

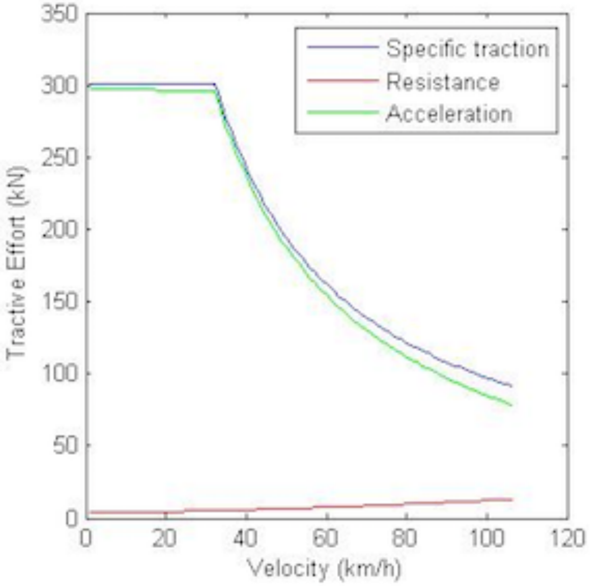

FIGURE 28: Hydrogen-hybrid train tractive effort versus speed

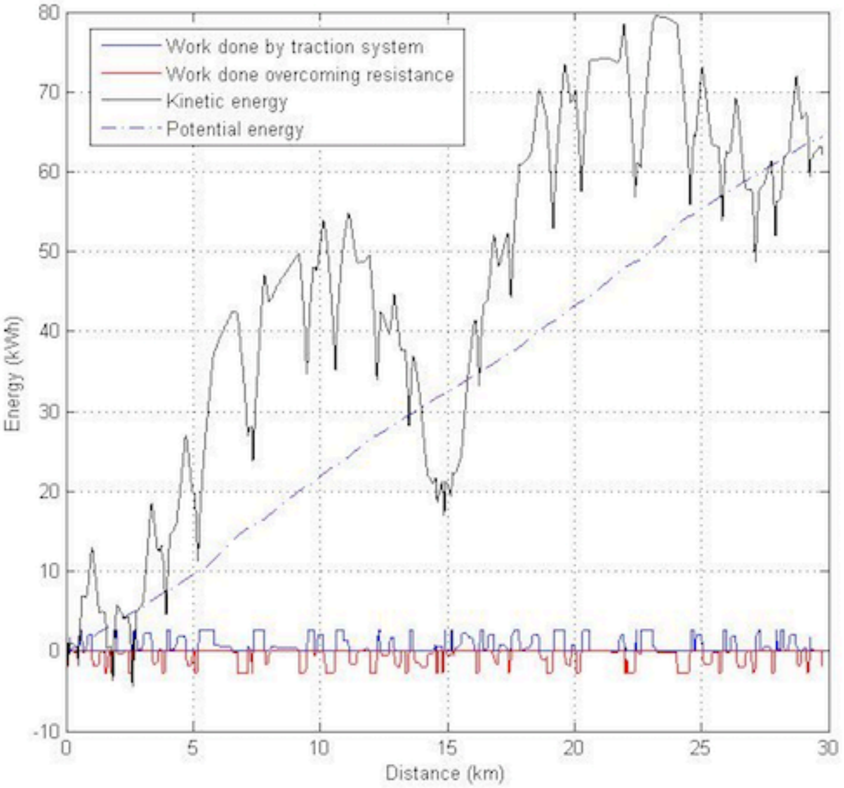

FIGURE 29: Hydrogen-hybrid train energy and power profile

DISCUSSION

Operational Feasibility

A key consideration for the potential application of hydrogen-power to light rail is the ability to maintain operations status quo. The ability of a local commuter to know when and where a train will be at any given time is a primary benefit of light rail. The service is predictable and dependable. The electric train simulation results are nearly identical to the hydrogen and hydrogen-hybrid concept trains. As seen in TABLE 31, the hydrogen trains complete each journey type in less time, which is a positive result. The use of hydrogen as the prime mover is shown to not be a hindrance to the operation of the schedule or dependability of the line.

The maximum average power is a characteristic of the train's duty cycle. For the electric, hydrogen, and hydrogen-hybrid trains, the maximum average powers are 24.6%, 24.1%, and 24.2% of the maximum power output, respectively. Likewise, the horsepower to ton ratios are 13.7 hp:ton, 14.7 hp:ton, and 14.6 hp:ton for the electric, hydrogen, and hydrogen-hybrid trains, respectively. The hydrogen trains have similar duty cycles and power ratings per ton, which indicates that the hydrogen fuel cell system is not overly powerful and is appropriate for the light rail duty cycle on the BLE.

TABLE 31: Train comparisons: journey time and max average power

Journey	Electric Concept Train	Hydrogen Concept Train	Hydrogen-Hybrid Concept Train
Northbound Journey	19 minutes 59 seconds	19 minutes 54 seconds	19 minutes 54 seconds
Southbound Journey	19 minutes 38 seconds	19 minutes 34 seconds	19 minutes 34 seconds
Round Trip	44 minutes 26 seconds	44 minutes 17 seconds	44 minutes 18 seconds
Max Average Power[1]	590 kW	650 kW	653 kW

[1] Max average power is observed on southbound journeys

Energy Demand

The hydrogen fuel cell used in the scope of this research touts an impressive 60% fuel cell efficiency, which only a few years ago would be a great feat. However, without any additional losses accounted for such as traction auxiliaries, the overall vehicle efficiency of a hydrogen train is already less than that of an electric train. Until improvements are made in hydrogen fuel cells, namely in efficiency, hydrogen power must compete in feedstock generation. Feedstock generation and hydrogen generation gives hydrogen-power flexibility to reduce overall energy demand and energy emissions.

From an energy demand perspective, the energy at the wheels of the hydrogen and hydrogen-hybrid trains balloons by 503% and 324%, respectively, to the required feedstock energy. These values far exceed the 152% increase in energy demand from the wheels to the well for an electric train as shown in TABLE 32 and FIGURE 30.

TABLE 32: Energy pathway required to satisfy daily operation

Energy Requirements	Electric Concept Train	Hydrogen Fuel Cell Propulsion System	Hydrogen-Hybrid Fuel Cell Propulsion System
Feedstock Energy[1]	25,849 kWh	68,362 kWh	48,248 kWh
Energy for Transmission[2]	10,089 kWh	-	-
Energy for Production and Compression[3]	-	32,587 kWh	22,999 kWh
Energy at Pantograph/in Tank[4,5]	8,772 kWh	23,267 kWh	16,421 kWh
Energy at the Wheels[6]	10,238 kWh	11,331 kWh	11,382 kWh

[1] LHV: 34.0%, and 47.7% from TABLE 9 and TABLE 10, respectively
[2] LHV: 86.95% from TABLE 9
[3] LHV: 71.40% from TABLE 10
[4] LHV Vehicle Efficiency: 74.6%, and 48.7% from TABLE 9 and TABLE 10, respectively
[5] Includes Regenerative Braking Efficiency (Electric Train Regenerative Braking Efficiency = 57.6%, Hydrogen-Hybrid Regenerative Braking Efficiency = 72%)
[6] TABLE 16, TABLE 23, and TABLE 30

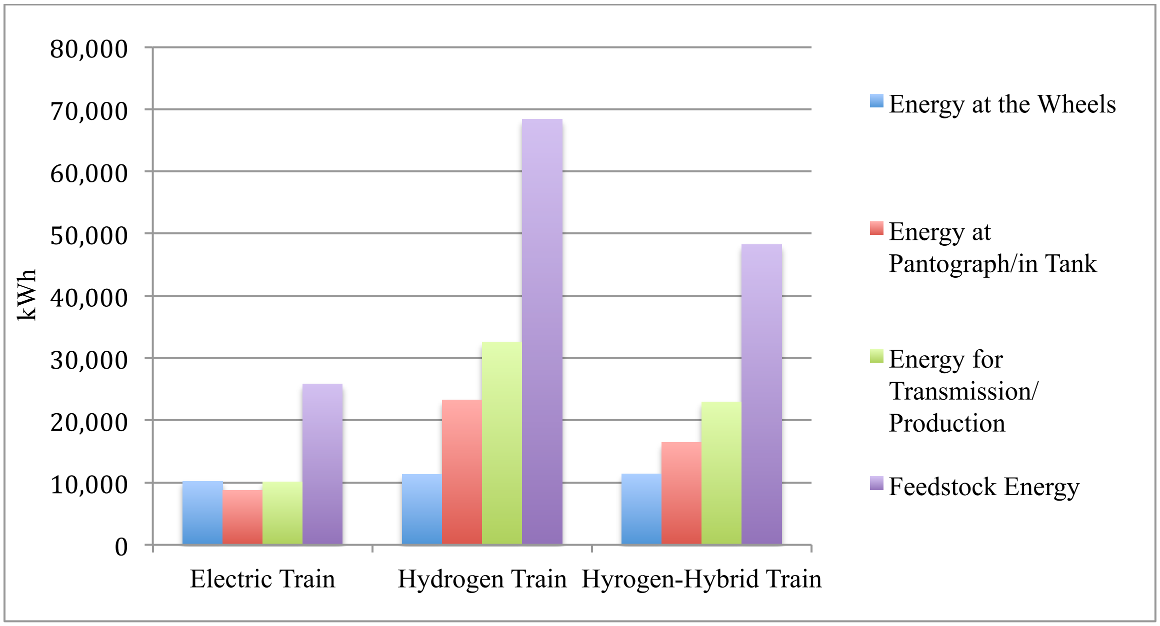

FIGURE 30: Energy pathway required to satisfy daily operation

In total, the hydrogen and hydrogen-hybrid trains require 164% and 87% more feedstock energy, respectively, compared to the electric train. Neither a hydrogen or hydrogen-hybrid train will reduce energy consumption of train operations on the BLE. Two processes restrict the hydrogen train energy pathways- the production and compression of hydrogen and the production of current in the fuel cell. As previously mentioned, improvement in the efficiency of the fuel cell power plant can reduce energy demand and emission production. Additionally, replacing SMR with electrolysis that is powered by renewable energy removes the efficiency factor and emission production. The total well-to-wheel efficiency could improve from 16.6% to a value comparable to the electric train's 25.3% well-to-wheel efficiency. The annual energy demand by train is seen in TABLE 33, and is primarily a function of a train's well-to-wheel efficiency.

TABLE 33: Energy demand by train per annum

Feedstock	**Electric Train Energy Demand[1]**	**Hydrogen Train Energy Demand[1]**	**Hydrogen-Hybrid Train Energy Demand[1]**
Coal	18,626.3 mWh	4,088.6 mWh	2,885.6 mWh
Nuclear	15,453.4 mWh	3,392.1 mWh	2,394.0 mWh
Natural Gas	11,857.5 mWh	119,955.0 mWh	84,660.9 mWh
Hydroelectric	1,187.8 mWh	260.7 mWh	184.0 mWh
Other Renewables	1,265.1 mWh	277.7 mWh	196.0 mWh
TOTAL PER ANNUM	**48,390.1 mWh**	**127,974.1 mWh**	**90,320.6 mWh**

[1] Total energy demand is product of Feedstock Energy (TABLE 31), energy production mixes (TABLE 6), 6 trains, 6 days, and 52 weeks

Emission Production

In comparing the electric, hydrogen, and hydrogen-hybrid trains, the influence of vehicle efficiency and feedstock source is apparent. Electric trains benefit from high efficiencies throughout the energy pathway for a total well-to-wheel efficiency of 25.3%, compared to 16.6% for a hydrogen-powered train. Electric trains also benefit from a large share of low-CO_2 feedstock energy sources, namely nuclear energy. In North Carolina, fossil fuels account for 63% of the production of electricity, of which only 38.5% is coal-generated. Alternatively, the hydrogen trains are limited by the 60% fuel cell efficiency and a fossil fuel based method of hydrogen production (SMR).

For every kWh of N.C. electricity produced, 0.410 kg of CO_2 emissions and 0.0032 g of radioactive waste are produced, compared to 0.406 kg of CO_2 emissions and 0.0003 g of radioactive waste for hydrogen produced from SMR. Below, in TABLE 34, is the emission production by energy carrier over the course of an entire year, excluding Sunday operation. Compared to emissions from the electric train, total annual CO_2 emissions increase 162% and 85% for the hydrogen and hydrogen-hybrid trains, respectively. However, the nuclear waste emissions decrease by 78% and 85% for the hydrogen and hydrogen-hybrid trains, respectively, in relation to the electric train. While both CO_2 emissions and nuclear waste are problems yet to be resolved, reducing CO_2 emissions is perhaps more urgent due to the present day effect on the general population. From an emissions perspective, neither the hydrogen nor hydrogen-hybrid trains exceeds the performance of the electric train. Until fuel cell efficiency improves or the hydrogen production process becomes cleaner and more efficient, an electric light rail is expected to have an advantage in energy demand and emission production.

TABLE 34: Emissions by energy carrier per annum

Feedstock	**Electric Train Emissions[1]**	**Hydrogen Train Emissions[1]**	**Hydrogen-Hybrid Train Emissions[1]**
Coal	12,093 tons	2,655 tons	1,873 tons
Nuclear	4,480 tons (CO_2) 376 lbs (radioactive)	983 tons (CO_2) 82.4 lbs (radioactive)	694 tons (CO_2) 58.2 lbs (radioactive)
Natural Gas	5,307 tons	53,684 tons	37,889 tons
Hydroelectric	-	-	-
Other Renewables	-	-	-
TOTAL PER ANNUM	**376 lbs (radioactive) 21,880 tons (CO_2)**	**82.4 lbs (radioactive) 57,322 tons (CO_2)**	**58.2 lbs (radioactive) 40,457 tons (CO_2)**

[1] Product of emissions factors by feedstock (TABLE 11) and total energy demand (TABLE 33)

For hydrogen production, an alternative is electrolysis, which would produce fewer emissions than steam-methane reforming. Electrolysis would equalize the emission production per unit of energy between hydrogen and electricity. The downside of electrolysis is decreased efficiency, so a decrease in total emissions would be accompanied by an increase in total energy demand. For electricity mixes with a high coal share, SMR may be worthwhile since it effectively switches energy generation from a dirtier fossil fuel to a cleaner fossil fuel. The use of hydrogen as an energy carrier becomes more appealing as more renewable energy is incorporated into the hydrogen production process.

Practicality

The practicality of hydrogen-power for light rail operation is a qualitative measure, and is primarily based on the author's opinion. Technically speaking, hydrogen is capable of serving as an energy carrier for rail vehicles, as demonstrated in this thesis and previous studies. The use of hydrogen as an energy carrier differs from conventional electric trains in several keys ways: 1) hydrogen as an energy carrier increases the weight and volume of a train; 2) fuel cells also add weight and volume; 3) catenary infrastructure is no longer necessary; and 4) hydrogen-related infrastructure is needed. Each of these differences poses barriers or improvements to the existing electric technology, and help determine the practicality of hydrogen as an energy carrier for light rail operation.

The weights of the hydrogen and hydrogen-hybrid trains increase 10.5% and 10.9%, respectively, compared to the electric train. The increases in weight and frontal area cross section correspond to an increase in demands of energy at the wheels of 10.7% and 11.2% for the hydrogen and hydrogen-hybrid trains, respectively. The increase in weight in volume is typically overcome by fuel cells that provide more power output than conventional electric trains. The increase in power allows hydrogen trains to overcome any weight or volume barriers and operate normally.

In switching catenary infrastructure for hydrogen fuel cells, the vehicle efficiency is lessened by at least 15-20%. In order to make the switch worthwhile, it must be demonstrated that electrification is prohibitively expensive or space-intensive, and that hydrogen may be produced in a manner that produces fewer emissions than electricity generation. Conventional light rail schemes require expensive catenary systems, which in an economical sense may be unjustified. Furthermore, the maintenance of the catenary system must be considered. Hydrogen and hydrogen-hybrid trains have minimal mechanical parts, which reduces maintenance and makes parts more standard. Fuel cells are easily interchangeable and require very little maintenance. The fuel cell used for concept design in this thesis has a lifetime of 12,000 hours, which is sufficient for two years of operation.

The addition of the capacitors to the hydrogen train is vital in making hydrogen-power competitive. For moderately traveled local DC lines, such as the BLE, regenerative energy is lost due to unreceptive catenary, or the absence of an accelerating vehicle nearby. Hydrogen-powered trains are autonomous by nature, which forces the design of an on-board storage system. The on-board storage design reduces the energy that must travel through hydrogen's inefficiency energy pathway and improves regenerative energy efficiency because energy is not lost to unreceptive catenary. A hybrid system is key since hydrogen vehicles are impaired by low vehicle and energy pathway efficiencies. In comparing the hydrogen train with the hydrogen-hybrid train, the hydrogen-hybrid train is clearly more appropriate for light rail operation because of the ability to regenerate energy.

A primary concern when dealing with hydrogen, or any combustible fuel, is the safety concerns relating to potential ignition. Hydrogen-powered trains, particularly trains with gaseous storage, have combustible content (hydrogen) and an ignition source (fuel cell output current) in close quarters. Standards set by the National Fire Protection Association list the maximum combustible content of fixed guideway transit and passenger rail systems as 90 million BTU per car. Both the hydrogen and hydrogen-hybrid meet this standard, as seen in TABLE 35.

TABLE 35: Maximum combustible content per hydrogen-powered train

Hydrogen/Hydrogen-Hybrid Train	
Total H_2 Vessels per Train	125 vessels
Total H_2 Mass per Train	700 kg
Total H_2 Fuel per Car[1]	233.3 kg
Total Combustible Content per Car[2]	33,133.3 mJ (31,404,341 BTU)
Maximum Allowed Combustible Content[3]	90,000,000 BTU
Safety Standard Met	**Yes**

[1] Total H_2 Fuel per Car = Total Fuel per Train / 3 cars

[2] Combustible Content of Hydrogen = 142 mJ/kg (Rodrigue, 2014)

[3] (DMJM Harris - AECOM, 2008)

The Role of the Energy Production

Electricity mix plays a very important role in determining well-to-tank efficiency and emission production. Therefore, a sensitivity analysis was completed to understand the extent to which electricity mix affects the results. The energy demand and emission production analysis was repeated for two additional states in the U.S.. Vermont and North Dakota were chosen because they have electricity mixes that are one of the cleanest and one of the dirtiest in the nation, respectively. TABLE 36 and TABLE 37 summarize the electricity mix for North Dakota, North Carolina, and Vermont, the annual energy demand, the annual emission production, and the arc elasticity function. Arc elasticity is the relationship between the changes in two variables (i.e. a 1% increase in *x* results in a 3% increase in *y*).

TABLE 36: Energy demand sensitivity to energy production

State	Electric Train		Hydrogen-Hybrid Train	
	Energy Demand	Δ Energy Demand / Δ Generation Efficiency	Energy Demand	Δ Energy Demand / Δ Generation Efficiency
North Dakota	46,692.8 mWh	-1.0	90,098.0 mWh	-0.1
North Carolina	48,390.1 mWh	-	90,320.6 mWh	-
Vermont	45,676.3 mWh	-0.9	89,957.3 mWh	-0.1

The arc elasticities for energy demand and energy generation efficiency demonstrate the sensitivity of the electric train to the electricity mix. For North Dakota and Vermont electricity, a 1% increase in energy generation efficiency results in a 1.0% and 0.9% decrease in energy demand, respectively. Alternatively, the hydrogen-hybrid train's energy demand is almost entirely inelastic to electricity mix. The inelasticity is due to the assumed method of hydrogen production: steam methane reforming. More than 90% of hydrogen production is sourced from natural gas, regardless of the electricity mix, which is why the hydrogen-hybrid train's energy demand is inelastic with respect to electricity mix.

TABLE 37: Emission production sensitivity to energy production

State	Electric Train		Hydrogen-Hybrid Train	
	Emission Production	Δ Emission Production / Δ Weighted CO_2 (Radioactive) Production Coefficients	Emission Production	Δ Emission Production / Δ Weighted CO_2 (Radioactive) Production Coefficients
North Dakota	23,969 tons	0.7	40,814 tons	0.1
North Carolina	21,880 tons (CO_2) 376 lbs (radioactive)	-	40,457 tons (CO_2) 58.2 lbs (radioactive)	-
Vermont	10,010 tons (CO_2) 839 lbs (radioactive)	1.0 (2.1)	38,554 tons (CO_2) 137.2 lbs (radioactive)	0.1 (2.4)

The arc elasticities for emission production and weighted emission production coefficients are nearly unit elasticity. CO_2 emission production is 0.7 for North Dakota and 1.0 for Vermont. A 1% increase in weighted CO_2 emission production coefficient corresponds to a 1% increase in CO_2 emissions. However, the hydrogen-hybrid train's emission production is nearly inelastic to the weighted emission production coefficient, while the electric train is unit elastic (1.0), with respect to Vermont. Both sensitivity tests demonstrate the effect that electricity mix has on the results of the electric train. Hydrogen produced from electrolysis would be just as sensitive to electricity mix as the electric train. As a result, the final results of this thesis are largely dependent on the use of the North Carolina electricity mix and SMR-produced hydrogen.

Study Limitations

The simulation of the electric, hydrogen, and hydrogen-hybrid vehicle models, as well as the subsequent analysis are subject to particular limitations. First, the simulations themselves are not intended to be perfect representations of reality, but are intended to be a model that outputs the approximate energy demand and energy recovery at the wheel. A famous statistician, George Box, once said, “All models are wrong, but some are useful.” The models used for the research that composes this thesis are useful in performing energy demand and emission production analysis.

The study is also limited by the input data and assumptions. Any assumptions and data used throughout the research were intended to be as realistic as possible, and without bias. A conservative approach was taken in designing the hydrogen and hydrogen-hybrid vehicle models because emerging technologies in the transportation sector are often slow to be adopted. In the public transportation sector, new technologies are often viewed with skepticism and require a substantial amount of evidence that proves their value and reliability.

The primary results of the research, energy demand and emission production, are a function of input data that was sourced from existing literature and commercially available technology. The goal of the study was to understand the ability of hydrogen to compete with electricity as an energy carrier for light rail operation at the time of the writing of this thesis (2014), so there remains opportunity for technologic improvements and new analysis of hydrogen for light rail operation in the future.

The data used to construct the well-to-wheel energy pathway efficiencies and the emission production coefficients are the primary drivers in the total energy demand and emission production results. The data is assumed to be reasonable and within range of reality, but some variation may exist. As a result, the conclusions of this thesis are very much dependent on the many assumptions and input data. Nevertheless, the simulation model and analysis remain useful and demonstrate an approximate representation of reality.

CONCLUSIONS AND RECOMMENDATIONS

Before making conclusions about the results, it is important to note that the simulations are an approximation of the energy use of a train and are specific to the made assumptions. Furthermore, the results are a function of the electricity mix, which is based on the electricity mix in North Carolina. Nevertheless, the results highlight the performance of various propulsion systems along the BLE for a meaningful comparison.

As exhibited in TABLE 33 and 34, the annual energy demand and emission production of a hydrogen and a hydrogen-hybrid train exceed that of a conventional electric train substantially. In North Carolina, the current hydrogen energy pathway is far more inefficient and pollutive than electricity generation. Therefore, efforts to reduce energy demand or emission production of a light rail in North Carolina using hydrogen fuel cell power are unlikely.

From a practical perspective, the volume and mass of hydrogen and hydrogen power-related components, is not overly burdensome to the operation of the light rail on the BLE. The additional weight and air resistance is overcome by the greater output of the hydrogen and hydrogen-hybrid train. Furthermore, the storage of 233.3 kg of hydrogen per car is not in violation of maximum combustible content standards set by the National Fire Protection Association.

The scope of this thesis serves as a starting point for the evaluation of hydrogen as an energy carrier for light rail operation. The simulations have demonstrated a theoretical application of hydrogen to light rail operation, but further studies are needed to demonstrate empirical and economic evidence. In railways, empirical evidence is important since theory typically involves assumptions or implications regarding the complex physics of the movement of a railway vehicle. Empirical studies would help to clarify and detail the results of simulation.

Finally, a detailed cost analysis of hydrogen as an energy carrier versus electrification is needed. The cost analysis is a key component in the evaluation of hydrogen for light rail operations since the expense of catenary systems can be burdensome and may be avoidable. The cost of railway electrification is becoming an issue for governments and organizations with limited funds and tightening emission standards, a further motivation for making better use of available resources. Despite being shown to be uncompetitive on an energy demand and emission production basis, economic superiority occasionally supersedes such inefficiencies.

DISCLOSURE

The views and opinions expressed in the thesis are those of the author, and do not necessarily reflect the views and opinions of Charlotte Area Transit System (CATS). Data received by CATS is open to the public, and any assumptions and calculations made by the author using said data are not necessarily CATS views and opinion. Likewise, the results of the work are the sole opinion of the author.

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