Title

Fuels and Fuel Technologies for Powering 21st Century Passenger and Freight Rail: Simulation-Based Case Studies in a U.S. Context

Author

Isaac, Raphael S

Publication Date

2020

Fuels and Fuel Technologies for Powering
21st Century Passenger and Freight Rail:
Simulation-Based Case Studies in a U.S. Context

By

RAPHAEL S. ISAAC
DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Transportation Technology and Policy

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

____
Paul A. Erickson, Chair

____
Joan M. Ogden

____
Andreas Hoffrichter

Committee in Charge

2020

ACKNOWLEDGEMENTS

While this dissertation represents the culmination of many years of hard work on my part, I could not have produced this piece, as it stands, without significant help along the way from many individuals and organizations. First and foremost, there is the significant input and insights provided by my dissertation committee, composed of Dr. Paul Erickson, Dr. Andreas Hoffrichter, and Dr. Joan Ogden. Beyond that, Dr. Andrew McGordon and his team with the Warwick Manufacturing Group, University of Warwick, UK, allowed me to make use of the Single Train Simulator that served as the basis for much of this work, and Dr. McGordon also provided some assistance with its usage.

Particular thanks goes to Athanasios Iraklis, formerly of the Warwick Manufacturing Group, and Orwell Madhovi, a Ph.D. student at Michigan State University, both of whom have a very strong command of MATLAB and Simulink's programming aspects, and whose contributions towards developing and refining the single-train-simulator, and help with troubleshooting, when necessary, were crucial in order for me to successfully produce the simulation results presented in this dissertation. The time freed up by these two individuals allowed me to expand the scope of this project, enabling me to provide an analysis that, rather than focusing only on the technical aspects of vehicle simulation, aims to provide policymakers and members of the rail industry with some insights on cost and environmental impacts, which can be taken into account when deciding how to approach fuel choices for rail applications in the coming years.

Dr. Lewis Fulton, of UC Davis, first brought me onto a project involving rail, which was rather unusual for UC Davis' Institute of Transportation Studies at the time. For his continued support of my pursuit of this topic, and for his having served as a key mentor during my time at UC Davis, particularly on the cost modeling side, I am very much appreciative!

An additional thank you goes to Dave Cook, of Rail Propulsion Systems, whose in-depth knowledge of and experience with locomotives meant that he was a great go-to source when questions came up about a particular locomotive function or characteristic.

Other people who provided invaluable assistance that ultimately improved the quality of this work include various employees, past and present, of both the Class I freight railroads and the local passenger rail agencies, who provided valuable information on actual rail routes along with additional insights into typical rail operations. Additional assistance was provided by representatives from numerous manufacturers of various rail equipment components and sub-components, whose insights helped ensure that the analyses conducted in this study were as realistic as possible.

To these people, and those not specifically mentioned, but who provided academic or emotional support along the way, I owe my many thanks!

ABSTRACT

The last century brought a shift in rail propulsion from the (typically) coal-powered steam engine to a combination of the diesel-electric locomotive and the electrified locomotive running under electrified overhead lines. While, no doubt, an advance over the earlier technology, the two incumbent technologies are not without their shortcomings.

In the current era, rapid technological developments and increased concerns about climate change have also spurred interest away from the internal combustion engine and the use of fossil fuels in various applications. These same technologies hold promise in a rail context, a mode of transportation that relies on a smaller number of more centralized operators.

With the tremendous investment of time, cost, and other resources that can go into a pilot experiment of a fuel technology and, often, related regulatory processes, it makes sense to determine the key candidates for such pilots. A major goal of this work is to help industry and government narrow down the key technologies, in terms of cost, viability, and environmental impacts, and simultaneously identify the challenges that may be encountered by a given technology that otherwise appears to hold significant promise. This study focuses on a U.S. context, and on the period between 2022 and 2038. Passenger and freight rail routes and systems were examined, each with different characteristics, via simulations of a single rail trip, A general environmental analysis was also performed on freight switcher locomotive activity.

The fuels examined included diesel, natural gas, Fischer-Tropsch diesel, hydrogen, and, in a passenger rail and switcher context, diesel and hydrogen powertrains paired with batteries to take in regenerative braking energy. The study finds cost reductions with both natural gas and (natural gas-derived) Fischer-Tropsch diesel, but with limited environmental benefits.

Hydrogen via fuel cell has significant promise to reduce GHG and criteria pollutant emissions. That technology's costs, both fuel and equipment, are highly uncertain; however, the study finds that, with lower bound projected costs, it could be competitive with diesel-electric costs; in the case of passenger rail, hybridization with batteries is also compelling. Hybridized hydrogen also was found to demonstrate a clear environmental benefit in switcher locomotive applications.

Table of Contents

Figures and Photos

Tables

CHAPTER 1. INTRODUCTION

1.1 Recent and Near-term Context: Rail, Energy, and Emissions

The U.S. rail system (transit systems[1] excluded) comprised, in 2016, just under 2% of all U.S. transportation energy consumption (S. Davis & Boundy, 2019)--and a similar percentage of domestic transportation emissions (OTAQ, EPA, 2019) [2]---,with over 98% of this impact from freight rail (S. Davis & Boundy, 2019). (At the global level, rail was responsible, that same year, for just over 1% of all transportation CO2 emissions (International Energy Agency, 2019). However, the contributions towards NOx and PM were higher, at 4% and 5%, respectively (IEA, 2019c).)

While the global data show rail's contribution to "total energy-related emissions" at 0.3%, EPA data suggests that U.S. rail, a sub-sector that is run largely on diesel fuel (S. Davis & Boundy, 2019), accounts for closer to 0.6% of all domestic GHG (i.e. Greenhouse Gas) emissions (OTAQ, EPA, 2019).

While these energy and emissions shares for rail are relatively small, both recent rail passenger data and expert projections suggest that rail is a growing subsector, at both the domestic and global levels.

---

[1] Section 1.4 and footnote 3, below, clarify what is meant by "transit systems," also referred to as "urban rail transit systems."

[2] The latter figure appears to include transit rail; however, in terms of total energy consumed in rail, this contribution is minimal. (ORNL & USDOE, 2019). Transit rail is almost exclusively electricity-based, also (ORNL & USDOE, 2019); according to (OTAQ, EPA, 2019), electric emissions accounted for at most 8.2% of all rail emissions in 2016, but, based on the portion of rail electricity that, in 2016, was consumed in transit rail operations, roughly 5% of the GHG Emissions in the above figure is attributable to transit rail.

In terms of the actual passenger data, it is clear that passenger rail[3], the smaller of the two non-transit rail sub-sectors here in the U.S., has seen growth in the U.S. in the past several years (Amtrak, 2016, 2017, 2018) and even decades. This is particularly the case among the regional intercity routes (Amtrak, 2018) and (metropolitan area) commuter routes. In fact, nine of the commuter rail systems that have been around since at least 1986 have seen growth in passenger boardings and passenger miles of greater than 50% (Nelson & O'Neil, 2018) since that year (up to 2016). Also during that same period, 14 new commuter railroads[4] were established (Nelson & O'Neil, 2018).

The trend towards system and ridership growth extends to the two California passenger routes that are assessed in the present study: the Capitol Corridor intercity line that extends from San Jose, California on the southwest end, to the Greater Sacramento region (north and east of the SF Bay Area), and Caltrain, a commuter route that extends from San Jose, on the south end, up to downtown San Francisco on the north end. Each of these rail systems, which were established in the 1990's (Capitol Corridor, 2019a; San Mateo County Transit District, 2019), have seen large increases in ridership since that period, including up through recent years (Capitol Corridor Joint Powers Authority, 2019; San Mateo County Transit District, 2018). (And substantial growth in ridership inevitably translates into increased service frequency, as Capitol Corridor's own history demonstrates. (Nelson Nygaard, 2014))

[3] The term passenger rail is used, in this study, to refer to both "commuter" and "intercity" rail. While these services have similarities—e.g. both focus on the transport of passengers rather than goods—commuter rail systems tend to focus on connecting suburban areas with a nearby metropolitan center, whereas intercity rail focuses on transporting passengers between different metropolitan regions. Commuter systems tend to have slightly higher service frequency, particularly during typical commute hours. Many passenger services are a bit a hybrid between these two. Not covered in this study are urban transit systems. Such systems typically have among the highest service frequencies, and focus primarily on connecting areas within a dense urban area.

[4] The term, 'railroad' is frequently used to refer to a railroad company or, in the case of passenger rail, a rail agency.

As mentioned above, this growth in passenger rail is evident at the global level, too. In fact, the International Energy Agency has noted an increase in both non-high-speed and high-speed[5] rail travel, from 2.1 trillion passenger-km in 2000 to 3.9 trillion passenger-km in 2016 (IEA, 2019c). The IEA suggests that even in its so-called "Base Scenario," "conventional" (i.e. non-high-speed) rail service would roughly double between 2017 and 2050, to 6.2 trillion passenger-km (IEA, 2019c), while with high-speed rail (HSR) included, it would more than double (IEA, 2019c).

This should not really be a surprise given demographic trends. There is ample indication that people, worldwide, are moving into cities. By 2050, the number of people living in cities is expected to grow from 55% of the world population to 68% (UN, 2018). Assuming this means that surrounding metropolitan areas grow along with the city centers, this density, along with the resulting increased demand for travel alternatives, is exactly what allows for public transportation systems, in this case commuter rail, to thrive.

But it is not only passenger rail that will continue to make an impact. The IEA notes that freight transport activity, across modes, will triple (in its Base Scenario) (IEA, 2019c), hewing closely to global GDP. This kind of scenario, it says, would mean a doubling of freight rail activity to over 20 trillion tonne[6]-km by 2050 (though perhaps, at the same time, a decreased relative share for rail out of all freight activity). In its "High Rail Scenario," with an additional increase of 3 trillion-km by 2050, the contribution of rail freight transport to overall freight transport, not including shipping, would mean the freight share for rail could remain about the

[5] High-speed rail is a form of intercity passenger rail. Serving to connect city centers with each other in faster times than is characteristic of intercity passenger rail, there is not agreement on the exact speed beyond which a system is considered high speed; however, typically, top speeds of 250 km per hour and higher are common for high speed rail systems (UIC, 2018).

[6] This refers to a metric ton, or 1,000 kg.

same, at 27% in 2050. Looking at the U.S., specifically, the U.S. Department of Transportation (DOT) has also projected significant growth for freight rail, with freight rail growth by weight expected to increase by 24% between 2015 and 2045, with an increase in freight rail by value of goods shipped expected to go up by 82% during this same period (BTS, 2017).

Pointing out that already in 2017, diesel freight trains accounted for about half of all rail energy use, the agency suggests that, even in its Base Scenario, by 2050, North American freight trains, the activity of which would account for about 14% of the increase in global freight traffic, would be responsible for greater than half of the world's demand for rail diesel.

The link between freight rail and diesel is strong in North America. While the pattern of diesel propulsion being more prevalent in freight rail than in the passenger rail sub-sector is seen throughout the world (IEA, 2019c), the degree to which diesel currently dominates in the United States is notable, and may stem, in significant part, from the key role that oil and oil production played in U.S. history of the last century and a half (History.com, 2018).[7] Overhead Line Electrification, or OLE, rail propulsion is not unknown to U.S. freight rail, with electric freight trains running as early as 1915 (Clark, 1973), and electric freight service in the busy Northeastern part of the country operating as late as 1982 (J. G. Allen, 2019). (Among the most well-known OLE lines was the Milwaukee Road, which began service in 1915 and operated in this mode for over 50 years! (Clark, 1973)) In the present era, however, freight rail in the U.S. runs almost entirely on diesel operations (S. Davis & Boundy, 2019)[8], with the exception being a very short isolated line in Arizona (Southwest Railfan, n.d.), which will be shutting down shortly (Mitchell IV, 2019).

[7] In fact, according to a reputable source, "Oil production in the United States by 1909 more than equaled that of the rest of the world combined. (History.com, 2018)"
[8] Some reasons for the dominance of diesel-electric propulsion in U.S. freight rail are discussed in Chapter 3.

All of these trends suggest that the energy impacts of rail will continue to increase, at the very least in absolute terms. Moreover, both the automotive and heavy-duty road sectors have begun to transition to fuel technologies and fuel sources that will improve human health and reduce negative impacts on the environment. The rail industry stands to benefit from (as well as contribute to) these same technological developments.

The 21st century has proven, so far, to be an era in which energy technologies (along with many other technologies) are undergoing rapid change. As alluded to above, rail companies, particularly the private Class I[9] (freight) railroads, are always eager to explore fuel alternatives that may reduce fuel costs, a not insignificant component of their annual budget[10] In addition, the potential to reduce price volatility would also be attractive, as this would allow for more budget planning certainty[11]. Passenger rail, meanwhile, is usually run at least in part by a government entity, and that can mean an openness to innovation, especially in order to meet public health and environmental goals. And, along these lines, continued concerns regarding the health effects of mobile-source pollutants and the impacts of greenhouse gases on the earth's climate have come to loom large in the energy picture.

In fact, from the environmental and regulatory standpoint, even by 2016, GE Transportation staff had observed and noted, in comments to the California Air Resources Board (CARB), that developing Tier 4[12] locomotive technology had been very challenging and that, as

[9] Of the 600 freight railroads that operate in the U.S. (AAR, 2018a), the seven "Class I" railroads are the largest. Each has a revenue of at least $450 million and has operations that cross multiple states. Together they comprise 69% of domestic freight rail mileage and 94% of total freight rail revenue. (AAR, 2018a)

[10] Between 2008 and 2017, fuel costs varied, as a percentage of the Class I railroads' total operating expenses, between 11.0% and 25.8%. A significant component of this variation is a direct result of the variation in the cost of diesel fuel over time.

[11] Oil price per barrel has varied by a factor of more than 3 over the last 10 years alone (Macrotrends.net, 2019)! With the resulting variations in diesel price, fuel costs as a proportion of total company costs varied, between 2012 and 2017, from just over 10% to about 22% of Class I annual total costs.

[12] This term is introduced in Section 1.2

standards continue to get tighter, “fewer opportunities exist” to further reduce emissions “solely from modifications to the engine and locomotive.” (Shea & Broome, 2016) In other words, any “Tier 5” emissions standard that is likely to be eventually set[13] is almost certain to require major technological developments over the status quo.

1.2 Research Statement

Given the previously described context, it should be of no surprise that the fuels that have been used to propel rail vehicles during the last century continue to be assessed and evaluated for alternatives. Characteristics on which the evaluation is typically based vary, particularly in importance, between the public agencies that run passenger trains in the United States and the privately run, publicly listed, freight companies that run domestic freight rail operations. The evaluative criteria include (not necessarily in exact order of importance):

- Cost
    - This may include the cost of the fuel (and the stability/predictability of this cost), the cost of the propulsion equipment, the cost of relevant fuel-related infrastructure, and the cost of any overhauls and maintenance necessary for that particular system across a given time period. Freight railroads tend to be particularly sensitive to costs due to the nature of their profit-driven business.
- Fuel Availability
    - Closely linked to cost, the ease with which a given fuel can be produced, or otherwise accessed, in the amounts required would be an essential concern

[13] As noted in more detail in Section 4.7, California, in 2017, suggested to the Federal Government that a Tier 5 be adopted in the near future. It would involve a further reduction in NOx, PM, and HC, along with a GHG limit, which would be a first for a locomotive emissions standard.

- Environmental impacts
    - Passenger rail agencies typically focus significantly on the impact of their operations on both the environment and health, seeking, as government agencies (usually at least in part), to demonstrate to the public their attentiveness to the needs and concerns of the public and, often, publicly showcasing their innovativeness, in the process[14]. The Class I railroads have traditionally focused the public's attention on their efficiency improvements to current operations and on the widely acknowledged environmental benefit of freight rail to the freight trucking alternative (AAR, 2019b). However, in recent years, serious exploration of alternatives, e.g. the use of liquefied natural gas (LNG), and the testing of batteries and even hydrogen fuel cell technology (see Chapter 3 for a discussion of the specific projects in more detail), has begun on the freight side, also.
- Ability to meet (environmentally-oriented) regulatory requirements
    - Amtrak[15], the public agencies, and the Class I railroads must meet all of the requirements and standards issued by the Federal government (see table 1, below, for criteria associated with the latest EPA locomotive standard)
- Safety of the fuel and fuel systems
    - Regulatory requirements often arise in this area, also; e.g. the Federal Railroad Administration—FRA (of the U.S. Department of Transportation) would seek to

[14] Examples of such "showcasing" abound in public bus. systems, also operated by public agencies (and for which there are many examples, in the U.S., of alternative fuels exploration). For example, slogans such as "Go Green" (Arlington Transit, 2019) or "Zero Emission," (CAFCP, 2018) have appeared on the outsides of the vehicles. Meanwhile, in Germany, in a project detailed later on in the present study, the seating fabric of a hydrogen-propelled train is patterned with the "clean" oxygen, hydrogen, and water molecules (Cooper, 2018) that are part of the reactions that occur in a hydrogen "PEM" (described in detail in Section 3.6) fuel cell.

[15] According to (Amtrak, 2019), Amtrak is a "federally chartered corporation, with the federal government as majority stockholder. The Amtrak Board of Directors is appointed by the President of the United States and confirmed by the Senate. Amtrak is operated as a for-profit company, rather than a public authority."(Amtrak, 2019)

set a safety standard for any newly developed equipment that would be required for rail propulsion in a freight rail context[16]

- Amount of new learning required by staff (e.g. locomotive maintenance staff) to accommodate a new technology
  - This may depend partly on the complexity of the fuel system as well as the abilities of technology to adequately manage such complexity
- Amount of disruption to operational processes as currently conducted
- Ease of use (e.g. once operational processes have been adjusted, as necessary)
- Issues that arise from interfacing with the public (e.g. equipment noise, visual effects, etc.)

Table 1: EPA's Tier 4 Standard, Applicable to all Locomotives Built since 2015 [17]

(adapted from (US EPA, Office of Transportation and Air Quality, 2016))

All units in grams/brake horsepower-hour[18]

Year of Original Manufacture	Tier	NOx	PM	HC	CO
2015 or later	4	1.3	0.03	0.14	1.5

Note: Information on previous tiers can be found in the appendix.

With the above factors kept in mind, and given several larger contextual factors, including:

[16] The Federal Transit Administration (FTA) has jurisdiction over many passenger rail systems.
[17] Section 4.7 discusses these pollutants in some detail.
[18] Brake horsepower-hour is an energy value associated with combustion engine output that is typically Used to measure emissions for a given energy output resulting from rail motive power vehicle operation."

1. the rapid pace of recent and ongoing energy technology developments (which has enabled both the automotive and heavy-duty road sectors to begin to transition to non-fossil-based fuel sources);
2. the growing consensus that stopping the man-made impacts on climate change will require drastic measures across sectors;
3. a growing concern about pollution levels in rapidly developing countries across the world (which may be, in part, a contributor to the rapid development in innovative energy technologies);
4. the increasing stringency of regulation that can be seen in countries, such as the U.S., that have been able to minimize the health impacts of potential air pollutants traditionally associated with transportation technologies;
5. the fact that, in general, the operation of rail systems is highly centralized, with a limited number of operators, which means that a shift within the sector should not face quite the level of coordination challenges that face the passenger automobile, or even on-road heavy-duty, sectors; and
6. the fact that by establishing a technology/fuel shift in the rail sector, the above-noted direction of influence between modes can also be established in the opposite direction, with such a shift encouraging and reinforcing the spread of this transition to larger road vehicles, for example through the establishment of regional refueling infrastructure;

the author sought to determine whether a shift away from fossil fuels in the domestic rail sector (with lessons potentially pertinent across the globe) could be a) helpful for human health and for the environment, b) feasible, from both a technical and operational perspective, and c) potentially cost-effective.[19] In order to best assess such questions, the author chose to use detailed case studies of two actual U.S. passenger rail systems (each with different route characteristics), and, on the freight end, a case study of an actual U.S. freight route and of various trip types that are commonly made along that route. In addition, an environmental analysis was also performed on data that the author considered would be typical of daily domestic freight switcher[20] locomotive activity. For the cost assessment portion of the analysis, the near-to-mid-term period between 2022 and 2038 was focused on, with low and high cost ranges set that attempted to take into account a variety of potential developments in the relevant markets and respective technologies.

The topic of alternative fuels in rail is not, in and of itself, a new topic of exploration. However, as described in further detail in Chapter 2, the transparent and detailed nature of the simulations carried out (including an examination of actual routes Using realistic equipment characteristics) and the comprehensiveness of this study (which spans the passenger as well as the freight rail contexts, with an exploration of technical feasibility) combine with a focus on the latest developments in rail propulsion to make this study a crucial contribution to the existing knowledge and literature.

[19] While a reduction in cost might be ideal, the avoidance of any significant increase in cost over the status quo for the public agencies and rail companies on whom the task of carrying out such a transition falls should be adequate, especially given unknown additional costs that may be ascribed to carbon-emitting sources in the future.

[20] Switcher locomotives are locomotives which remain in railyards, where they are assigned the tasks of assembling and disassembling freight trains, generally a few cars a time. Because they remain within a limited area and haul only a few cars at a time, switcher engines exhibit a lower total power capacity, usually under about 2300 horsepower (~1.72 MW) (Norfolk Southern, 2014).

1.3 Additional Historical Context: Rail Propulsion

Transportation services are among the most consumed services by humans (driven by the opportunity to greatly increase the resources obtainable via travel that exceeds the limitations of the human body's own transport mechanism). While, for thousands of years, the wheel remained almost certainly the most significant development in transportation technology (Wolchover, 2012) (and, nonetheless, even this invention was mostly limited by the capacities of various non-human animals), things began to change in the early 19th century. It is around that time that Richard Trevithick, employed as a repairman of steam engines in the Southwest of England (History.com, 2009), sought to contine to build on 18th-century developments into that key technology, particularly those advanced by Thomas Newcomen (Csele, 2019; Palermo, 2014) and, later, James Watt (Kingsford, 2019). While the Newcomen and Watt steam engines operated at low pressures (Csele, 2019), Trevithick brought higher pressure to this application (Cavendish, 2001; History.com, 2009; Sussex Steam Co., 2011). With this adaptation, he was able to demonstrate the first steam-powered "passenger-carrying"(Cavendish, 2001) vehicle, first as a road vehicle and, then in 1804, along a rail track (Cavendish, 2001; History.com, 2009; Sussex Steam Co., 2011).

Figure 1: Steam Engine Train Belonging to the Cumbres & Toltec Scenic Railroad.
Photo courtesy of Roger Hogan, and the Cumbres & Toltec Railroad (with permission granted)

The steam-powered locomotive enjoyed a long and illustrious heyday; however, during the first decades of the 20th century, diesel-electric engine technology started appearing in locomotives and, by mid-century, this technology had largely replaced earlier fleets of steam engine-run locomotives (Wilson, 2017). A variety of factors propelled this change, including advantages with regard to vehicle maintenance (both labor and parts), operational resource efficiency, and availability (Wilson, 2017).

The diesel-electric powertrain---whose prime mover consists of a diesel engine that runs an electric generator (the latter step reducing the necessary complexity of the gearing system, among other advantages)---continues to dominate the U.S. locomotive fleet; however, electric traction, via an external electricity source, has become increasingly common, particularly abroad (IEA, 2019c). This propulsion form offers reduced noise and enables greater capacity on a line (due to higher acceleration rates than diesel equipment is capable of achieving), and it is also the oldest of the technologies that currently serve as a viable alternative for rail traction, having preceded the development of diesel by a full decade (Siemens, n.d.). Propulsion via offboard electricity, hereto referred as OLE, is a significant source of passenger rail energy in the U.S. (S. Davis & Boundy, 2019); however, due to the predominance of freight, which is virtually all fueled, presently, by diesel fuel, in domestic rail energy consumption, the domestic locomotive fleet is overwhelmingly composed of diesel-electric locomotives, with nearly 40,000 of these (Humphrey, 2019) and less than 200 electric OLE locomotives (AAR, 2019c; Comati, 2018; US Department of Transportation, 2017). (There are, in addition, under 100 dual-mode locomotives, too. (US Department of Transportation, 2017) This typically refers to vehicles that can operate Using either diesel-electric or OLE propulsion.)

OLE is, however, not the only alternative that has been on the radar of rail manufacturers and the Class I railroads over the past several decades. When political or regulatory forces have increased, or at least threatened to increase, the costs of diesel fuel, natural gas's potential role as an alternative has been explored by these same railroads (Schultz, 1992). For example, Canadian National, from 2012-2013, tested liquid natural gas (LNG) locomotives along 300 miles of tracks heading north from Edmonton, Alberta (Railway Technology, 2012). On the other hand, when concerns regarding climate change began to take center stage earlier this century, the Federal government, which is not as cost-focused as private industry, began to explore a potential role for biodiesel in rail. (For example, B20---20% biodiesel from beef tallow, 80% diesel---was tested for a year's period along Amtrak's Heartland Flyer, which travels between Oklahoma City and Fort Worth Texas (W. Smith & Shurland, 2013).)

1.4 Overview of the present study

In demonstrating the progression of a technology, the three stages of Pilot, Demonstration, and Commercial, are often used as key categories of technology development (e.g. International Energy Agency---i.e. IEA, in its Biofuels Roadmap, as just one example (Brown & Fulton, 2011)). However, before investing the tremendous time, cost, and other resources that can go into a pilot experiment of a fuel technology (not to mention the resources that go into related regulatory and other decision making processes[21]), it makes sense to determine the key candidates for such pilots. Simulations represent one method that is frequently used for this purpose, and this method was, in part, used in this work, in order to help industry and government narrow down the key technologies and simultaneously identify the challenges that may be encountered by a given technology that otherwise appears to hold significant promise.

The present study aimed, first, to use a single-train-simulator[22], or STS, to produce realistic data on per-trip energy requirements and to assess technical feasibility. Secondly, the

[21] Development of an "industry-standard" LNG fuel tender is something that has been under investigation since at least 2013 (K. Smith, 2013) (Kirkpatrick, Wagner, & Northrup, 2019). This has involved convening a national advisory group consisting of representatives of Amtrak, the Association of American Railroads, and all Class I railroads (K. Smith, 2013).

[22] A Single Train Simulator refers to a program that models the performance of a train over a given route. The

author sought to apply the information gleaned from the STS results towards a high-level, initial evaluation of the potential environmental impacts and financial costs of alternative fuel technology pathways for use in trains, focusing on a U.S. context. This includes both passenger trains as well as freight trains, the latter dominating energy use within the U.S. domestic rail sector. Specifically, this study evaluates (as summarized in Table 2, below) a diesel-electric powertrain, compressed natural gas (i.e. CNG)---Using internal combustion engine (heretofore abbreviated as 'ICE') and, as with diesel, a generator, hydrogen via fuel cell, OLE, a synthetically derived fuel known as Fischer-Tropsch diesel substituted into the diesel-electric powertrain, and, in the case of the passenger trains, diesel-electric and hydrogen powertrains hybridized with batteries.

Table 2: Brief Summary of the Fuels/Fuel Technologies that are Examined and Evaluated in this Study

Prime Mover	Fuel	Rail Service Type(s)
Internal Combustion Engine ("ICE")	Diesel	Passenger, Freight, Switcher
ICE	Natural Gas	Passenger, Freight
ICE	Fischer-Tropsch Diesel	Passenger, Freight
ICE hybridized with batteries	Diesel	Passenger, Switcher
Fuel Cell (FC)	Hydrogen	Passenger, Freight, Switcher
FC hybridized with batteries	Hydrogen	Passenger, Switcher
Overhead Line Electrification (OLE)	Source fuels for electric power (electricity is an "energy carrier")	Passenger

methodology employed to determine impacts of vehicle and powertrain changes. However, it does not account for impacts from other trains on operations, as might occur in a railway network analysis.

High speed trains are not examined in the analysis, in part because true high speed rail doesn't currently exist in the United States, but also because the power and energy requirements of high speed rail pose a challenge for many of the fuel alternatives (at least in the near-to-mid-term), which is why the majority of such lines, where they do exist, already operate using OLE (IEA, 2019c). Similarly, urban rail transit systems are also not included, as these systems also depend largely on electricity, already—though, due to space limitations (since they are typically underground), and the characteristics of tunnels, a third rail (which is located at the track level), rather than overhead line equipment, is typically the source of the electricity. The traditional reliance on electricity by urban systems is also due to the acceleration requirements, but also because, from an early point, municipalities recognized the direct safety hazards of the associated smoke and soot and the less directly visible, but problematic impacts of releasing pollutants in underground areas (Andreas Hoffrichter, 2013). More specifically, in addition to the health hazard of releasing pollutants in confined spaces, there were collisions between trains that resulted from the impaired visibility (J. Allen, 2017; Andreas Hoffrichter, 2013), including one in New York in 1902 (J. Allen, 2017), which directly led to electrification of that system, beginning in 1906 (J. Allen, 2017).

The alternative fuels explored in this dissertation have been chosen based on those which appear to demonstrate feasibility (i.e. no major challenges to their use in such applications, e.g. toxicity of the fuel, as might occur with ammonia), in either the near or mid-term. Excluded were some technologies that, while certainly cleaner than the status quo, would simply not be possible or practicable given physical limitations. For example, with an annual average ranging from 3 to 6 kWh of solar radiation per square meter per day across the continental U.S. (NREL, 2019), the energy required to move a train is at least one order of magnitude above what a train with roofs entirely made of solar panels could ever possibly provide[23]. That said, trains propelled by either OLE or by hydrogen via fuel cell are likely to increasingly rely on renewable electricity, especially in states like California, which have a Renewable Portfolio Standard (DSIRE Insight, 2019). In that way, solar power may increasingly serve to provide power to trains, albeit mediated via the electric grid.

The linear synchronous motor (LSM) is a propulsion technology that could be explored in a study such as this; however, recent research suggests that it may be prohibitively costly, particularly in a freight rail context (UIUC-RailTEC, 2016). Even moreso, there is, at this time, limited information on many of the operational and practical usage aspects of the technology (UIUC-RailTEC, 2016).

The energy analysis portion of this study relies largely on the use of a single train simulator tool that has been developed, over time, by several universities, with staff at the University of Birmingham (UK) developing the Matlab portion, staff at the University of Warwick (UK) developing the Simulink, and staff at Michigan State University adding further refinements to the modelling tool---along with the help of this author, particularly to allow for simulation of trains with more than one locomotive (particularly relevant to freight rail). Use of this tool allows for a fairly accurate representation (model validation is discussed in a later chapter) of the actual energy consumption along the routes being simulated, which include two passenger train routes in California, Capitol Corridor and Caltrain, and routes that very closely emulate an actually existing freight train route in the United States. (All findings rely on the

[23] The author has used the energy consumption analyses performed as part of this study, and presented in Chapter 5, as examples of the energy required to move a train. Train roofs are assumed as reflective of current train design.

accuracy of the available data; to the extent that there are imperfections with or that adjustments were made to the available data, the findings represent an approximation of real-world results for these routes.)

After the simulations determine the energy consumption of the diesel and hydrogen fuel cell alternatives on a few selected key U.S. routes, energy consumption for the natural gas and Fischer-Tropsch diesel alternatives are assessed using post-simulation processing, since, as with the diesel-electric powertrain, the use of an internal combustion engine and generator are common to both. (And Fischer-Tropsch fuel is designed to be essentially identical to naturally processed diesel fuel, as discussed in Chapter 3.) The author then uses existing databases and research literature in order to determine the resulting well-to-wheel[24] outputs in terms of energy, greenhouse gas emissions, and four other commonly regulated pollutants, including CO, NOx, $PM_{2.5}$, and PM_{10}. The one exception to this simulation method is the case of a freight "switcher" locomotive, which, due to the complexity and variability of any given vehicle duty cycle (and difficulty obtaining the right kind of data to assess an actual in-practice duty cycle), is modeled based on average observed data from a relevant study. The resulting well-to-wheel outputs, however, follow the same process as with the other case studies.

[24] Well-to-wheel here refers to the total energy consumed, or emissions generated, during the entire lifecycle of a fuel. It is composed of Well-to-Pump (WTP) energy/emissions and Pump-to-Wheel (PTW) energy/emissions. Well-to-pump (WTP) energy and emissions are consumed (or generated, in the case of emissions) during the process of resource extraction, transportation of the resource to a processing facility/powerplant, fuel refinement/conversion/power generation, and delivery or transmission of the final fuel product to the point of use or vehicle fuel tank(s). Pump-to-Wheel (PTW) energy and emissions include the energy consumed/emissions generated by a fuel while in a tank (such emissions are often called "boil-off" emissions, e.g. in the case of a fuel with a very low liquid condensing temperature) as well as the energy consumed and emissions generated as a result of the energy contained within the fuel in the tank(s) as it is processed through various energetic means by the prime mover and remainder of the powertrain, driving the vehicle (train, in this case) along the track and powering on-board equipment with various functions (including lighting, heating, etc.).

A discussion of the potential costs of and any barriers to developing these alternatives (during the period examined, which is roughly 2022-2038) is also presented, with a focus on how these might specifically impact the representative rail corridors that have been chosen, and others with similar characteristics. This includes touching on likely or required future developments for a given technology to demonstrate success, from the environmental or cost standpoint (or perhaps both), and tackling any key challenges that may arise for a given fuel (e.g. any need for fuel tenders, particularly for natural gas or hydrogen). While the cost analysis is detailed, it is not intended to serve as a project plan for a public rail agency or rail company that seeks to consider one of these fuels, but rather to provide some solid context and background for policymakers or employees of rail agencies or Class I railroads, so that they can consider the kinds of alternatives that are worth further exploration along a given rail corridor or in a given rail context.

Finally, the author examines broader contexts to the results, noting where either California or route-specific characteristics mean that the findings cannot necessarily be translated to other regions of the country (i.e. or at least not before various adjustments are made) and, in some cases, where international differences are relevant to costs and benefits of a given propulsion approach. Further discussion is also given to the implications of the research findings for freight rail on passenger (i.e. intercity and commuter) rail, and vice versa, inasmuch as passenger rail is somewhat dependent on freight rail, both due to a reliance, at least currently, on shared corridors as well as due to the predominance of freight locomotives within the locomotive market.

1.5 Contribution

The present study, which focuses on fuel propulsion in both passenger (i.e. intercity and commuter) and freight rail, builds on previous literature that has examined fuel alternatives in rail. While each of these studies contains aspects of what is conducted in this study, this work seeks to be unique in its combined level of transparency of results and consideration of several viable fuel technology options across several different route types. This work's case studies also hone in particularly on U.S. routes, and, from the findings, draw conclusions that can be applied across the national rail system. This study also includes fuel cycle[25] emissions for both GHG's and pollutant emissions, with a look at various operational fuel engine standards for the current diesel-electric powertrain. (Fuel cycle emissions are only marginally, if at all, touched on in the currently existing analyses that simulate emissions levels.[26]) Data from a national database on emissions in transportation was used; however, rather than utilize the data as it is presented in its most straightforward formats for use, the intermediate data was accessed and often Used in a unique manner so as to add precision to the resulting analyses.

Lastly, cost ranges are put forward for each technology, with the author indicating, in certain cases, the kinds of factors that are likely to influence costs for a given technology (e.g. economies of scale, and even so-called "learning effects"). In many cases, projections from key government sources are utilized; however, in other cases, available modeling tools are incorporated.

[25] The term, 'fuel cycle' emissions, is used here synonymously with WTW emissions. It is meant to make clear the distinction between the approach used in this study and a life cycle approach (see glossary for some details), which would also examine emissions related to production of all fuel-related equipment, along with other processes (e.g. recycling or reuse of such equipment following primary usage).

[26] In one case contained within the relevant literature, WTP electricity production emissions are included, but not any non-operational emissions for the other fuels.

While some of the related literature includes rail route simulations, the present study has a high level of precision, relying on specialized component performance input information (e.g. engine efficiency that is not constant) gathered directly from industry manufacturers or, in some cases, government agencies.

Examining the rail fuel comparisons found in the literature, as is discussed further in Chapter 2, many had not considered hydrogen fuel cell (Proton Electron Membrane [PEM] or otherwise) until very recently, and almost none in a U.S. context. This despite this technology having been addressed by the general rail literature, both relatively old and new (e.g. (Andreas Hoffrichter, 2013)), which, in many cases, note significant promise for this fuel propulsion method. Moreover, this rail fuel powertrain (which is an "energy carrier" rather than truly a fuel "source"[27]) has, in the last few years, gone from being mostly conceptual to been put into actual operation, in the form of the first actual passenger train operating on a set of hydrogen fuel cell stacks---in Northern Germany, with compressed gaseous hydrogen (at 350 bar[28]) (Rohée, 2018) (K. Smith, 2018) .

With some of these fuel alternatives (e.g. hydrogen, batteries, etc.), emissions generated along the fuel production and processing pathway (i.e. "WTP" emissions) are very significant when compared to operational (i.e. "PTW") emissions. Additionally, with diesel and other "conventional" fuels, the life cycle GHG emissions picture is not fixed. For example, there is a trend towards more CO_2-intensive sources of conventional petroleum fuels (Martin, 2016), which largely come from changing petroleum sources and extraction techniques (Martin, 2016). The present study provides a range of GHG or pollutant emissions levels (and sometimes both)

[27] Hydrogen is an "energy carrier" because the molecule rarely exists on its own in nature.
[28] Serving as a metric for pressure of a gas, this refers to a pressure of 100,000 Pascals, a value that approximates the average atmospheric pressure at sea level.

in several cases, demonstrating the within-fuel variation that is dependent on choice of fuel production and delivery, as well as such factors as regulation and its impact on fleet composition (particularly of the diesel-electric fleet).

1.6 Summary and Arrangement of Dissertation Document

In this introductory chapter the author has provided both historical and current context to the development of rail propulsion alternatives. A problem statement has been offered, in which the author has noted the key motivations for engaging in this study, which include key reasons for why the present period is both a crucial and opportune time in which to explore the feasible alternatives for various passenger and freight rail contexts.

Chapter 2 will review the literature that has examined similar questions to this study. Chapter 3 will then explore the details of the various fuel and prime movers[29] examined in this study, including the relevance to rail, any relevant rail applications, why certain variants of a given technology have been selected, and insights as to key advantages or disadvantages in a rail context. Chapter 4 reviews the methodologies utilized in this wide-ranging study. Chapter 5 presents the results (which include energy consumption data, data on GHG and pollutant emissions levels, and cost data), largely in graphical format, but also with an accompanying discussion of key findings, a look at how such findings may apply to similar rail corridors, and noting any significant barriers to developing a given alternative in a given rail context. Finally, Chapter 6 summarizes the findings and gives an international context to the results, discusses any implications for freight rail on passenger (i.e. intercity and commuter) rail, and vice versa,

[29] As the name suggests, the prime mover is the primary technology that converts a fuel into motive power.

and presents key topics and questions that will require further research to build on the present study.

CHAPTER 2. LITERATURE REVIEW: FUEL TECHNOLOGY COMPARISONS IN RAIL

2.1 Chapter Introduction

Chapter 1 provided a broad overview of this work, and some context on fuel propulsion and relevant historical transitions in rail. This chapter reviews much of the literature that has sought to compare and assess multiple fuel/fuel technology alternatives in a rail context. At times properties of the various fuels and fuel technologies are noted, especially when such information was a key finding of or purpose of exploration for a particular report. Chapter 3 provides more details on the history of each fuel and powertrain technology, and also explores fuel and fuel technology characteristics in some detail.

The literature on this topic is large and growing. It is beyond the scope of this dissertation to review the entire literature on alternative transportation fuels. Instead, the author focuses on key publications, especially those that are comprehensive or cover recent or upcoming explorations of fuel alternatives in the context of a specific project or location. (Table 3, at the end of the chapter, offers a brief, comparative, summary of the literature that is covered.) Literature focused on practical implementation has become an area of increasing focus, particularly in the last 5-10 years.

2.2 Literature Review

Among the earlier literature sources, in 1982, is the seminal book, “Railroad Engineering,” by William Hay (Hay, 1982). Hay notes the replacement of steam by diesel-electric propulsion, and then mainly focuses on the then-present primary alternatives of OLE electricity and diesel-electricity, including variants such as gas turbine electric (Hay, 1982). He indicates several of electricity's advantages over diesel, including greater availability (due to lower levels of maintenance, thanks to the absence of the diesel engine and its moving parts) (Hay, 1982), lower on-site pollution (Hay, 1982), higher efficiency (Hay, 1982), and greater horsepower per ton of weight (Hay, 1982).

Skipping ahead, on the academic literature end, to 2013, in his Ph.D. "thesis"[30], Dr. Andreas Hoffrichter examines the potential of hydrogen as a rail fuel. Dr. Hoffrichter notes some of hydrogen's advantages over the currently existing dominant fueling solutions, i.e. the diesel-electric powertrain and OLE electric powertrain. These include the fact that, with hydrogen, unlike with diesel fuel, production is not dependent on one source (Andreas Hoffrichter, 2013), and the fuel cell powertrain is also much quieter than a diesel-electric engine-generator (sometimes referred to as a genset). With respect to electricity, he points out that choosing a hydrogen solution along a route means an elimination of the high cost of the physical infrastructure (assuming that it is not already built) as well as reduce the visual impacts that can also often be problematic with OLE rail (Andreas Hoffrichter, 2013).

Hoffrichter's Ph.D. thesis notes his role as part of a university team that designed the first hydrogen locomotive to run in the United Kingdom, in 2012. Known as the Hydrogen Pioneer, the vehicle, which was designed for a trailing load of 600 kg (but which, at one point, successfully hauled 4 metric tonnes), could accelerate at a bit under 1 m/s^2 (Andreas Hoffrichter, 2013). The vehicle utilized a PEM fuel cell that had a power of just under 1 kW, with total energy output, in one trip, of ~ 2.7 kWh (Andreas Hoffrichter, 2013). (This translated into about 1.5 kWh of energy for use at the wheels. (Andreas Hoffrichter, 2013)) Traveling 15 km in 3

[30] The "thesis" is the equivalent of a dissertation in the United Kingdom.

hours (at 5 km per hour), the vehicle required storage of less than 200 kg, which was contained within, in one case, a metal hydride[31] 10 bar tank (Andreas Hoffrichter, 2013) and, in a second case, a compressed gaseous tank at 200 bar (Andreas Hoffrichter, 2013). This small locomotive displayed performance comparable to that of similar diesel-electric locomotives (which were, themselves, smaller vehicles designed as part of an inter-university competition) (Andreas Hoffrichter, 2013).

Dr. Hoffrichter's work includes estimates of the well-to-wheel vehicle efficiencies, based on the LHV and HHV[32], of hydrogen locomotives (both fuel cell and internal combustion engine), compared to diesel and OLE electric locomotives. (For OLE, he includes data points from the UK, the U.S., and, specifically, California, due to the relatively high penetration of renewables in the state's grid.). He concludes that a fuel cell locomotive running on compressed hydrogen has the highest efficiency of the hydrogen vehicles, with an efficiency value that is basically equivalent to the efficiency of the OLE electrical drivetrain (running on non-California grids, in particular) (Andreas Hoffrichter, 2013). This compressed hydrogen locomotive also has the lowest well-to-wheel emissions of the hydrogen locomotives (Andreas Hoffrichter, 2013). These are lower, he finds, than the diesel locomotive emissions and, again, comparable to the non-California OLE electric cases (Andreas Hoffrichter, 2013).

In 2015, in work also described in his Ph.D. thesis, Hoffrichter et al. examined and simulated a multiple-unit[33] rail vehicle on an actual route located in the Midlands of England.

[31] Section 3.7 discusses metal hydrides, a solid-state form of hydrogen storage, in some detail

[32] Lower Heating Value refers to a way to assess the heat of "combustion", i.e. the energy content, and contrasts to HHV, or higher heating value.

[33] A multiple unit vehicle, often referred to as a DMU (diesel), DEMU (diesel-electric), or EMU (electric)---and now also HMU (hydrogen), is an alternative to locomotive-hauled railcars. Frequently used for passenger services, each unit, which consists of either one or more railcars, contains its own propulsion system and space for passengers on the same vehicle(s), so a full train may be made up of any number of multiple units, depending on the needs of a specific route.

The researchers found that, using 700 bar compressed hydrogen, the equipment required would fit in the vehicle, as it is currently constructed (Andreas Hoffrichter, Hillmansen, & Roberts, 2015). Moreover, due to the superior efficiency characteristics of hydrogen and, particularly, compressed hydrogen hybridized with batteries (which capture regenerative braking[34] energy and then supplement the prime mover with that energy), such vehicles consumed less energy to make the same trip in the same amount of time. In the case of the hybridized fuel cell powertrain, 55% less energy was required for the trip, with a corresponding 72% reduction in CO2 emissions (with hydrogen produced via steam methane reformation of natural gas) (Andreas Hoffrichter et al., 2015).

Also in 2015, work by Dick and Fullerton, of the University of Illinois, Urbana-Champaign, suggested that the North American freight system might have to transition towards a more regionally varying freight fleet in order to meet the environmental requirements of particular regions that are considered not in "attainment" of national environmental standards (set by the U.S. EPA) (Fullerton & Dick, 2015). Suggesting a role, or even need, for alternatives to diesel-electric propulsion in such areas, which are known as nonattainment areas (and sometimes abbreviated "NAA" (US EPA, 2019)), the authors note the challenges of regionalizing what is, currently, a national system in which locomotives regularly cross not only regional, but also state boundaries. (And in which the freight railroads regularly exchange equipment. In fact, the railroads have, since the 19th century, abided by a set of common interchange rules which specifically allow this equipment sharing, as well as by rules that allow a

[34] Regenerative braking is a form of "dynamic braking." In dynamic braking, the traction motors (see glossary for definition) act in reverse, as generators, Using the mechanical energy of the train's movement to power electricity. The resistance then created via the motor's magnetic field acts as a brake on the train's forward movement. In regenerative braking, the electricity produced by the traction motors turned generators is either returned to wayside infrastructure (e.g. OLE) or, alternatively, to an on-board storage device.

given railroad to operate on track owned by other railroads.(UIUC-RailTEC, 2016)) However, the authors also suggest that the "…economics of large-scale locomotive replacement suggest a phased transition to new technologies is the only feasible option." (Fullerton & Dick, 2015)

Figure 2: A Capitol Corridor Passenger Train Pulled by a Freight Locomotive, Oakland, CA May, 2019
(Photo from author's collection)

At the time that this photo was taken, this Capitol Corridor passenger train had just been pulled into the Oakland, California Jack London Square station Using a BNSF (freight) locomotive (with the original passenger locomotive directly behind the front locomotive). Such an equipment configuration indicates that the original locomotive was having a mechanical, or other, difficulty.

While starting local may make sense and, in fact, is often how transitions like this begin, the particular approach of setting a geographic-specific area in which to transition rapidly does have its drawbacks, as the authors recognize. For example, the authors state, from the outset, that the "need to exchange locomotives mid-route will introduce delay and disrupt the seamless movement of freight," which will result in higher costs (Fullerton & Dick, 2015). This, in turn, the authors indicate, risks a mode shift from rail to truck, especially for non-bulk commodity shipments (Fullerton & Dick, 2015). Moreover, the authors also note the need to maintain refueling infrastructure for multiple fuels were such locomotive exchanges to actually occur.

Dick and Fullerton's paper includes an analysis of freight movements involving some operational simulations that, while not described in particularly acute detail, appear to take into account many of the characteristics taken into account in the present study (including route characteristics and resistance factors faced by the train while in motion), at least in their application to these NAA's. It seems that gross averages are used to estimate many of the model inputs, including such characteristics as efficiency of a diesel engine, and EPA standard averages[35] are used for the emissions outputs. With three different train types---one for oil, one for ore (presumably some metallic ore), and one for coal---the authors explores such propulsion options as "diesel-electric with after treatment" (while several potential after-treatment approaches are noted, it is implied that SCR[36] was chosen), LNG accompanied by a fuel tender, a diesel-electric drivetrain hybridized with battery tender cars (though the type of battery modeled is not indicated), and electrification via catenary (Fullerton & Dick, 2015) (introduced, earlier, in the present text as OLE).

The analysis "scenarios" cover well-to-wheel emissions for the electricity and battery hybrid options (with the same emissions data used for both battery and electricity/OLE, in this case), but not for the other choices. Moreover, unique to the paper, the authors assume a locomotive exchange point at which conventional equipment is swapped with the alternative equipment.

[35] It's not entirely clear, from the written analysis, exactly which values are averaged.

[36] SCR stands for "selective catalytic reduction." This refers to a technology that injects urea into a diesel engine's exhaust, which, through chemical reactions, lowers levels of NOx (nitrogen oxides).

Fullerton and Dick's analysis, which combines the alternative fuels operating in NAA's with diesel-electric outside of this area, leads to results that are quite variable. It appears that electricity is the best option (again, with an analysis that doesn't in fact even count WTP emissions for either diesel or LNG), with CO2 reductions of 13%-18%[37] depending on the commodity being shipped and the differing assumptions (e.g. weight, distance of trip, number of locomotives, battery/LNG tender #, etc.) (Fullerton & Dick, 2015). Electricity, in their analysis, leads to NOx reductions (25%-81%), and is the only option, according to their analysis, that leads to particulate matter, or PM, reductions (Fullerton & Dick, 2015). (PM increases by orders of magnitude in their LNG scenarios. The results are quite variable for the battery scenarios.). In addition, the authors acknowledge a very high cost for both OLE (a figure of $4.8 million per track mile is assumed, based on (Cambridge Systematics, 2012)) and the battery tender option, the latter assumed to incur a cost of $5 million per battery tender plus $6 million for battery replacement per tender (for a total of $11 million additional cost) over a 15-year period (Fullerton & Dick, 2015). The UIUC researchers did assume that the increased fuel consumption resulting from the addition of an after-treatment system to a base diesel-electric prime mover would be negligible. How justified of an assumption this is is a topic of debate (Simpson, 2018). It is understandable, and one which this author has, at least in part, also used in the analyses presented herein. (While this author didn't specifically attempt to model the diesel-electric vehicle with or without after-treatment, there are varying levels of after-treatment applications currently used among the locomotives that served as models for this analysis.)

In a document closely tied to the Dick and Fullerton piece, the California Air Resources Board produced, in 2016, a report compiled by a research team at the University of Illinois,

[37] The paper does not present the results in terms of percentage reductions; rather this author calculated these values based on the model output values that are presented in the paper.

Urbana-Champaign (UIUC-RailTEC, 2016), in which some of these same alternatives were analyzed in both a i) “North American” context and a ii) South Coast Air Basin[38]-only context. (UIUC-RailTEC, 2016) (The North American analysis in fact did not cover the entire U.S. freight rail system, but rather included all train movements by trains whose routes either begin in, end at, or pass through the South Coast Air Basin.)

The report’s “air basin scenario” considered diesel-electric with after-treatment, LNG with fuel tenders, diesel-electric locomotives hybridized with battery tenders, a solid-oxide fuel cell (SOFC) locomotive that uses LNG and which captures and combusts the residual gases in a gas turbine to generate additional energy, electricity via catenary, and a linear synchronous motor (UIUC-RailTEC, 2016) (e.g. as evident in some maglev train systems seen across the world (Gieras, Piech, & Bronislaw, 2017), as well as in Vancouver’s “Skytrain” urban transit system (Bombardier, 2016)). By contrast, their “nationwide scenario” considered two of these technologies, only: the diesel-electric with both after-treatment and onboard battery storage (since the researchers acknowledge that the after-treatment, alone, may serve to increase total energy consumption), and the SOFC with LNG (as described above).

The ARB report re-emphasizes concerns about the impact on freight market share of delays related to geographical variations in technology implementation, suggesting, in the South Coast Air Basin-only scenarios, a direct cost of approximately $112 million per year resulting from the so-called “exchange points” (UIUC-RailTEC, 2016). In addition, a freight mode shift of greater than 10 million tons per year is also predicted to result in significant freight mode shift to truck, resulting in an additional loss of $1.1 billion in potential revenue per year (UIUC-

[38] This refers to an area of Southern California, and indicates an area where air quality and pollution are closely monitored. Key areas of coastline (and thus ports), are included in this region.

RailTEC, 2016) (and the authors suggest an overall increase in emissions from all freight movements, as a result of this mode shift).

The report involved a simulation (apparently written in Visual Basic, it appears likely that this is the same ‘train performance calculator’ tool used in the Fullerton and Dick study noted above) of train movements in the South Coast Air Basin region, based on data provided by some Class I railroads for that area, and other nationally available data; while it is quite detailed, some input characteristics, such as diesel engine efficiencies, are based on static, set data points. Also, it’s not clear that hybridized alternatives were truly simulated, but it seems, rather, that assumptions were made regarding energy consumption improvements with a hybridized powertrain. (And GE Transportation, in fact, indicated, in comments submitted following paper release, that the ARB cited an erroneous reference and, as a result, may have overstated assumed improvement in energy consumption using near-term battery technology (Shea & Broome, 2016)). Moreover, as with the other UIUC report, well-to-wheel emissions were not accounted for in this report (not even for electricity, in this case); rather, emissions data was based on train operations only. Thus the three propulsion alternatives that derive their power from the grid offer, according to this UIUC analysis and its approach, 100% reduction of emissions over the status quo.

Both the electricity and battery hybrid options are found to be very expensive. From a sheer value standpoint (the authors refer to the “largest emissions benefit per unit of present-value cost” (UIUC-RailTEC, 2016)), the authors indicate that the SOFC-gas turbine, LNG, scenario might be considered most suitable. That said, the authors also acknowledge that there is not yet a ”working prototype” (UIUC-RailTEC, 2016) that would prove the feasibility of such a technology in a rail application. As for the battery hybrid, it is interesting to note that the battery tender modeled, based on a concept put forward earlier in the decade by Transpower (a Southern California-based company), assumes a capacity of approximately 6.2 MWh ("usable" capacity of about 5MWh) (Simon, 2013), whereas a recently begun pilot project involving a battery tender, with BNSF and GE Transportation the key partners (this project is described in more detail in Chapter 3), is working with tender equipment whose total capacity will be limited to 2.4 MWh (Cleveland, 2019).

The UIUC authors conclude that OLE cost would be prohibitive in a nationwide context, a conclusion with which this author would not disagree. (And this topic is discussed in some more detail in Chapter 3.) Hence, again, only two options are examined for that portion of the analysis: SOFC with LNG and diesel-electric with after-treatment and onboard battery storage. The SOFC option costs more than three times the amount of the diesel-electric with both after-treatment and onboard battery storage, though it also appears to reduce the CO2 emissions by roughly half as well as reduce hydrocarbons (HC) and CO by substantial amounts (but with a large increase in NOx) (UIUC-RailTEC, 2016).

While the idea of wide-scale locomotive exchange at geographic boundary points seems highly problematic, the paper offers an interesting insight for a fuels transition. Noting the rate of new locomotive production capacity, as well as the typical lifetime of a locomotive, the idea that there would be a gradual (i.e. years-long) introduction of any alternative technology for U.S. freight rail makes a lot of sense. The authors suggest a rate of 400 new locomotives replacing the same number of conventional locomotives each year, such that after a period of 15 years the only diesel-electric locomotives remaining in the domestic fleet are in either "secondary" or terminal (i.e. yard switcher) service.

“Clean Rail Transportation Options” is a 2015 book by Dincer, Hogerwaard, and Zamfirescu, of the University of Ontario Institute of Technology (Dincer, Hogerwaard, & Zamfirescu, 2015). After offering contextual information on both passenger and freight rail, Dincer et al. perform an analysis of different fuel and prime mover technologies for trains; however, the analysis approach is to provide a (rather intensive) thermodynamic perspective on the technologies and some of their operating characteristics rather than a vehicle route simulation approach.

In addition to covering diesel-electric and electric locomotives, the authors note the potential for biofuels, including synthetic fuels derived from a Fischer-Tropsch process, SOFC based on LNG (and, as with the previously noted research, utilizing a gas turbine to maximize system efficiency), and even a methanol-diesel mixture (via ICE), which was piloted in the U.S. as early as 1980 (Dincer et al., 2015), and which holds the potential for reducing NOx, SOx, and PM (Dincer et al., 2015). (When made from biomass, Dincer et al. point out that the resulting methanol is in fact carbon-free. (Dincer et al., 2015))

Dincer et al. also note the potential for a diesel-electric powertrain hybridized with a battery pack, though, interestingly, do not go into much detail on this alternative.

The use of hydrogen as an energy carrier is also noted, with the authors suggesting that this could be produced from either natural gas (they suggest a role for synthetic natural gas in helping to make the hydrogen more renewable from the wells-to-wheel perspective) or even ammonia.

The authors also analyze ammonia as a fuel for ICE’s. Pointing out that it can be produced entirely from renewable resources (biomass, included), Dincer et al. additionally cite, as ammonia's positive attributes, its high energy density[39] and high octane rating, relative safety due to its high rate of dissipation in the air, its narrow flammability range, and its noticeable odor, and its ability to reduce NOx (Dincer et al., 2015). Moreover, Dincer et al. note the already extensive production and distribution infrastructure set up, both nationally and internationally, around the chemical (which, itself, has led to a cheap price for the fuel) as another aspect in its favor (Dincer et al., 2015).

In addition to the interest among academics and state government, national governments have also expressed interest in exploring fuel options/alternatives for rail. Here in the U.S., Federal government exploration of these concepts can be traced back to at least as early as December, 2002, when, as another recent report indicates, Frank Stodolsky (2002) "provided a roadmap for railroad and locomotive technology research and development as part of a 2001 effort between the U.S. Department of Energy and industry partners to improve rail energy efficiency 25% by 2010 and 50% by 2020" (TranSysResearchLtd, UIUC-RailTEC, CPCS Transcom, & Lawson Economics Research Inc, 2015).

In 2015, a Federally-sponsored document was released that focused on comparing passenger rail energy consumption with its competitor mode (TranSysResearchLtd et al., 2015). Among other goals, the authors were interested in providing information on ways to improve passenger rail's performance vis-à-vis these other modes. While several operational strategies were discussed, the report also includes discussion of "alternative" and hybridized fuel and prime mover technologies, including biodiesel, natural gas, electrification (via catenary), and fuel cell technologies that operate on hydrogen (TranSysResearchLtd et al., 2015). Also discussed were dual-mode (in this case, diesel-electric and OLE electric) locomotives, energy

[39] Energy density refers to the energy capacity (e.g. of a fuel or fuel carrier, e.g. battery) for a given volume

storage, in the form of batteries, ultracapacitors, or even flywheels, and integrating more renewable energy into the electric grid as a means to offset other emissions.

In conjunction with the FRA report, a model known as MMPASSIM (Multi-Modal Passenger Simulation Model) was used to compare across modes for currently operating passenger trips (TranSysResearchLtd et al., 2015). While aspiring to model something similar to some of the other simulation tools discussed in this proposal, MMPASSIM, which is Excel-based, only provides, energy-wise, total energy amounts expended on a given route rather than demonstrating the duty cycle. In addition, the FRA report notes that MMPASSIM aggregates gradient and curvature along a route into a distribution, rather than precisely simulating these characteristics along a given route. Similar to the present study, resulting GHG emissions are calculated based on the Argonne National Laboratory's GREET Model[40]. Pollutant emissions were not addressed in this study (and it is in this area where the author of the present study made specific adjustments that added precision over what the GREET model has assumed for rail applications[41]).

Beyond the U.S., the Norwegian government has also expressed interest in exploring alternative fuels for rail. In 2016, that nation's railway authority contracted with SINTEF, an independent Norwegian research organization, to look more carefully into these options for four major lines (on which varying mixes of passenger and freight trains run) in Norway that are not electrified (trains operate using diesel-electric), an area of over 1000 km (600 miles) (SINTEF, 2016). SINTEF investigated biodiesel, natural gas, hydrogen via fuel cell, electricity (via catenary), batteries, discontinuous catenary with "smaller batteries," and a hydrogen-battery

[40] Discussed further in Chapter 4, the GREET (i.e. Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model includes various emissions databases that have been developed based on extensive research.
[41] At the time of the FRA report, there was in fact no rail module within GREET.

hybrid. This SINTEF study looked closely at costs; however, specific emissions of each technology were not investigated; rather, efficiency differences between technologies were observed and then, combined with some qualitative observations, the fuel options were ranked according to the team's judgment of a given technology's environmental desirability.

On the cost side, with the high taxes that accompany diesel prices in Europe, quite unlike the situation in the U.S., the diesel option was found to be among the more expensive options (Zenith, Moller-Holst, & Thomassen, 2016), both in the near future, and out to 2050 (Zenith et al., 2016). (Analysis findings were gathered for a few different time periods between the present and 2050, with intervals pre-set by the rail authority (F. Zenith, personal communication, July, 2016).) Only the electricity via catenary option was found to be more expensive. The hydrogen options and the battery-based options were found to be both cheapest and cleanest looking out to the longer term (Zenith et al., 2016). (Improvements in battery technology along with drops in costs of both technologies were assumed.)

Building on this earlier work, in (Zenith, Isaac, Hoffrichter, Thomassen, & Møller-Holst, 2019), this author worked with the SINTEF researchers and another U.S. researcher to compare alternatives for freight in the U.S. versus in a European context. The alternatives included diesel-electric, OLE, hydrogen, hydrogen hybridized with batteries, and two all-battery options[42], including one system with fast charging characteristics and estimated costs were assessed for 2020, 2030, and 2050.

Some of the conclusions noted from (Zenith et al., 2016) remained the same for this research. For example, the diesel option performs poorly among the European options, and,

[42] No specific battery type was assumed in this work. Rather, the range of lithium ion batteries was broadly considered.

again, OLE is found to be the most expensive option in that context, mostly due to the low traffic volume along the Norwegian line selected for the study, the Nordland line (Zenith et al., 2019). The two battery only options and the hydrogen and hydrogen hybrid options do not vary a great deal, in terms of cost, between each other, and the costs for all were found to show even greater cost reductions vis-à-vis the diesel or OLE options looking toward 2030 and 2050 (which makes sense given that the latter two are mature technologies, and the alternatives are based on technologies that are at varied, but certainly earlier stages of their maturity). What little gap does exist between the hydrogen options and the all-battery options, in 2020, diminishes even further by 2050. (Zenith et al., 2019) Interestingly, but unsurprisingly, hydrogen has the best "benefit-cost ratio" (i.e vis-à-vis diesel) in 2020 on the Nordland line, with about 13.5M$ lower "equivalent annual costs" than diesel (Zenith et al., 2019). The hydrogen-battery hybrid is always more expensive than the non-hybrid hydrogen option due to the lower energy density of batteries as compared to hydrogen (a topic discussed further in Chapter 5), though this gap closes slightly by 2050, due to assumed (significant) improvements in battery energy density.

For the U.S. portion of this analysis, OLE appears to perform quite well; however, the cost of OLE electrification was based more on European standards[43] (in fact at a price that is below the low cost bound set in the present work). Moreover, the line selected has high traffic; however, to draw conclusions on the viability of OLE across the entire U.S. freight system based on one of the busier main lines is difficult. (OLE costs in freight is a topic discussed further in chapter 3.)

[43] The difference in OLE cost between the U.S. and Europe is discussed in greater detail in Chapter 3.

OLE aside, (Zenith et al., 2019) finds that diesel is, perhaps unsurprisingly, the lowest cost option in 2020 for the U.S. line; however, by 2030, the fast charging all battery option and both hydrogen hybrid options have eclipsed it, in terms of lowest cost options (Zenith et al., 2019). By 2050, (Zenith et al., 2019) finds that all battery and hydrogen options are cheaper than diesel for the U.S. line. In fact, the three that were already cheaper by 2030 are shown to be significantly cheaper by 2050 (Zenith et al., 2019) , and are, at that point, about as low cost as OLE was estimated to be (Zenith et al., 2019) (albeit, again, with a rather low cost assigned to the OLE infrastructure).

Table 3: Review of Key Recent Reports and Studies that have Examined and Sought to Compare Rail Fuel Alternatives

	Hoffrichter et al., 2013/15	**TranSysResearch et al., 2015**	**Dincer et al., 2015**	**UIUC, 2015**	**UIUC-RailTEC, 2016**	**Metrolinx/ Ch2M/E&Y/ CNL, 2018**	**Zenith et al., 2019**	**Shift2Rail, 2019**	**Isaac, 2019**
Passenger	YES	YES	YES	NO	NO	YES	NO	YES	YES
Freight	NO	NO	YES	YES	YES	NO	YES	YES	YES
Single train simulation	YES	YES (Gradient was not specifically simulated)	NO	YES	YES	YES	YES	YES	YES
Geographic Focus	UK (STS), U.S. (no STS), with primary focus on California (CA)	United States	North America, with focus on Canada	U.S., with some focus on CA	U.S., with some analysis specifically focused on a CA port region	Toronto, Canada	U.S. and Norway	Several countries across Europe	U.S., with CA routes serving as passenger case studies
Fuels Examined/ Simulated	DE, Hydrogen ICE (2013), HFC, HFC hybridized w/Batt, Electricity (2013)	DE, OLE, Biodiesel, CNG, LNG (Analysis primarily across transportation modes)	DE, OLE, NG, Biofuels, H2, Ammonia	DE with AT, LNG, DE Hybridized with Batt	**U.S.-wide:** LNG SOFC, DE + AT Hybridized with Batt **South Coast:** Also DE, Diesel-LNG, DE with AT, LSM, Battery Tender	OLE, HFC hybridized with Batt	D-E, OLE, All Battery (with and without fast charging), HFC, HFC hybridized with Batt	Compares HFC to OLE, DE, and, in some cases battery-powered vehicles	DE, CNG, FTD, OLE, DE Hybridized with Batt, HFC Hybridized with Batt

GHGs	YES	YES	YES	YES	YES	YES (General discussion)	NO	YES	YES
Non-GHGs	NO	NO	Discussion	YES	YES	NO	NO	YES (NOx and PM, only)	YES
Cost Analysis	NO formal analysis; some brief, general discussion.	NO	NO formal analysis. Cost range (\$/tonne) provided for ammonia	YES	YES	YES	YES Cost varies by year; one cost value, each, for 2020, 2030, and 2050	YES	YES

AT = After-treatment

Batt = Batteries

CNG = Compressed Natural Gas

DE = Diesel-Electric

FTD = Fischer-Tropsch Diesel

HFC = Hydrogen Fuel Cell

ICE = Internal Combustion Engine

LNG = Liquid Natural Gas

LSM = Linear Synchronous Motor

OLE = Overhead Line Electrification

SOFC = Solid-Oxide Fuel Cell

Also in recent years, in 2018, a report was prepared for Toronto's Metrolinx system by CH2M Hill (now Jacobs Engineering), Ernst and Young, and Canadian National Laboratories that sought to assess the feasibility of hydrogen (via a hydrogen fuel cell hybridized with batteries) powering either a multiple unit vehicle or a locomotive. The initial aim of the report was to explore alternatives to OLE electrification, the latter technology having been of interest to the province of Ontario. (CH2M Hill Canada Limited (now Jacobs Engineering Group, Ernst & Young Orenda Corporate Finance Inc., & Canadian Nuclear Laboratories, 2018)

Among the benefits that the study notes (aside from avoidance of the initial high costs of OLE infrastructure) are the ability to use electricity when the cost is lowest. With OLE, trains typically run more frequently when electric rates are highest. However, hydrogen production, is electricity-intensive. (Electrolysis, which is defined in chapter 4, is significantly more so than steam methane reformation [SMR], also described in further detail in chapter 4.) However, the refueling station typically stores much of what is produced prior to fueling of the vehicle. Thus the actual hydrogen production can be left for overnight and other times of low demand and thereby a low electricity price.

Some of the other benefits, the authors find, would be relevant to any non-OLE solution, e.g. a lack of visual impacts, and also the fact that right of way "clearing" is not "extensive" (CH2M Hill Canada Limited (now Jacobs Engineering Group), Ernst & Young Orenda Corporate Finance Inc., & Canadian Nuclear Laboratories, 2018), as it can be with OLE infrastructure.

The CH2M Hill et al study briefly touches on some comparisons to other propulsion alternatives. The authors suggest a couple of advantages for hydrogen over an all-battery solution, including the fact that batteries shouldn't be operated over their entire nominal capacity if they are to not degrade too quickly. Further, batteries can be quite sensitive to low temperature operation (of particular concern in that study's Canadian context), the study notes, while the study suggests that this may be less of a concern, at this point, for fuel cells (CH2M Hill Canada Limited (now Jacobs Engineering Group) et al., 2018). (This latter point should be verified; however, one fuel cell manufacturer does suggest, from its product data, that the challenges to fuel cells operating at temperatures down to - 40 Celsius have been addressed in recent applications of this technology (Hydrogenics, 2018).)

While this study involves some simulation, it is a system-wide simulation. In one scenario, a mix of fuels is used across the system, while in another a single solution is implemented systemwide. In addition, a few configurations are modeled. These include centralized production with pipeline gas delivery, central production with truck gas delivery, central production with truck liquid delivery, and onsite production as a gas. The final results are presented as a range of low and high values.

The study finds that the total net present value cost is roughly comparable for the hydrogen and OLE cases. Total cost is calculated over 60 years (accounting for the lifetimes of various equipment). A range of cases are examined for hydrogen and OLE, representing high and low cost assumptions., (The low range of hydrogen cost is only 1% higher than the OLE cost.) As one might expect, the fixed infrastructure is more expensive for the OLE solution; however, the initial capital and operating capital costs are higher for the hydrogen scenarios.

Finally, just this past May (2019), Shift2Rail, along with the Fuel Cells and Hydrogen Joint Undertaking, both European public-private partnerships, released a series of related reports examining the potential role for hydrogen applications in the context of European rail (both passenger and freight). Noting that 20 % of European rail traffic is still diesel-based (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, Garrison, et al., 2019), the report indicates that 35 initial case studies were developed for rail lines or yards with the potential to switch to hydrogen propulsion. (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019) Out of these, 10 case studies were selected for further analysis (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019). Four of the routes examined are either currently or are envisioned as relying on multiple units, while there are three case studies, each, representing mainline[44] locomotive and switcher locomotive applications (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019)

For the multiple unit case study analyses, the total cost of ownership "premium" for hydrogen fuel cell technology vis-a-vis diesel technology was determined to range between 4 and 35%, with an average CO2 emissions reduction of 550 metric tons per year per equipment set (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, Garrison, et al., 2019). For the switch locomotive analyses, the total cost of ownership premium for hydrogen fuel cell applications vis-à-vis diesel technology was determined to range between 0% and 28% (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019). (In one case, there is actually a 2% cost savings with the hydrogen solution (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019).) The average CO2 emissions reduction projected is 130 metric tons per year per locomotive (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019). This number is likely on the lower end in part due to the fact that, unlike the case with the remaining nine case studies, in which hydrogen production via electrolysis is assumed, one of the switch locomotive case studies assumes hydrogen via steam methane reformation, since the yard is

[44] Mainline freight rail refers to revenue-based service rather than movements undertaken during the switching of railcars and locomotives across trains.

located alongside an already existing SMR plant (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019). For the mainline freight locomotives, the analyses found a total cost of ownership premium for hydrogen fuel cell technology, over diesel technology, to be between 1% and 30%, with an average CO_2 emissions reduction of 1,620 metric tons per year per locomotive (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, Garrison, et al., 2019).

The computer application used for the analyses just described accounted for specific train type and route characteristics. It also attempted to take in some specific characteristics for each country, e.g. energy and feedstock prices, and the prevailing electricity mix; however, the authors note that neither “specific circumstances” of a country (perhaps the authors are referring to specific government incentives?) nor local business conditions/practices are accounted for in the cost outputs for the case studies (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019).

The overall findings indicate “significant market potential for [hydrogen fuel cell] technology in rail,” with evidence of “attractive use cases” (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, Garrison, et al., 2019) It is noted that hydrogen fuel cell technology seems “especially economical” for non-electrified networks---especially those of 100 km or more (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019)---with “average” traffic levels, especially when a given line also extends into more rural or mountainous regions (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, Garrison, et al., 2019). Routes with low utilization, which it defines as up to 10 trains per day, are also found to be good candidates for such technology (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019, p. 2).

Additional factors that make the use of hydrogen particularly appealing include locations where electricity is less than 5 Euro cents per kWh and cases in which the hydrogen infrastructure is utilized to a high capacity (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019, p. 2). Additionally, the report authors note that, given varying levels of catenary voltage across Europe, use of hydrogen technology circumvents this common barrier (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019) (particularly relevant in comparison to an OLE alternative).

In the case of long distance mainline freight operations, the authors point out that solutions to storing the large amounts of hydrogen necessary to propel the vehicle is an area requiring further research. (And while fuel "tenders" are noted, it seems apparent from the case studies that the authors consider 350 bar hydrogen still a good solution for freight rail applications (Ruf, Zorn, Akcayoz de Neve, Andrae, Erofeeva, & Garrison, 2019, p. 2).)

2.3 Chapter Summary

This chapter has summarized much of the existing literature on alternative fuels in rail, focusing particularly on key reports. Assessing fuel alternatives for rail is not a new topic, with literature dating back to at least the early 1980's; however, the volume of such assessments has increased significantly in recent years, particularly during the last decade (perhaps, in part, due to the growth of alternatives to conventional technologies within the commercial light duty space). Several studies have shown that there is, indeed, significant potential for transitioning away from diesel, but that context matters. For example, such transitions may not necessarily come easily, e.g. in the domestic freight context, where the system is run, in many ways, as a nationwide system, and where time costs may pose a significant challenge.

Beyond context, in the studies that, in particular, assessed cost, assumptions matter, and can matter quite a great deal, in fact. Estimating future prices for technologies (particularly batteries, fuel cell systems, and even hydrogen fuel production) that are in their early stages is not an easy task, but rather one fraught with much uncertainty. (This topic is discussed in more detail in Chapter 4.) Thus the findings of the literature discussed above, as well as of the present study, must not be seen through the lens of providing certain answers, particularly with regard to cost, but as educated attempts at expanding the collective knowledge of those technologies which show promise and which are likely worth future exploration by individual rail agencies and rail companies that are willing to shoulder some risk for the sake of gaining further knowledge for the rail industry as a whole, improving environmental outcomes, improving the customer experience, and even playing a role in speeding up the development of these technologies, which are already or, in some cases are likely to become, more widespread in the current century.

CHAPTER 3.
FUELS BACKGROUND

3.1 Chapter Introduction

The previous chapter examined much of the key relevant literature comparing various fuels in a rail context. Some basic characteristics of the various fuels were briefly noted. This chapter offers a more in-depth examination into these fuels and fuel technologies, including aspects of the technology development, their history specifically pertaining to the rail sector, and the details of why a specific type of the technology may best suited for rail or has been used as a model in these analyses.

As noted in the introductory chapter, the fuels and powertrains that have been examined in this analysis include the following (see Table 3, below, also with this information): a) diesel fuel, as utilized in a diesel-electric powertrain (described further below); b) electricity, distributed to the vehicle via overhead line electrification (OLE); c) hydrogen, utilizing a fuel cell powertrain, which produces electricity through the reaction between hydrogen and oxygen, alongside a catalyst; d) a diesel-electric powertrain (again, diesel as the primary fuel source) hybridized with batteries, which take in the energy produced during the braking procedure (i.e. “regenerative braking”), and; e) a fuel cell powertrain (again, with hydrogen as the primary fuel source) hybridized with batteries in order to recuperate regenerated energy. In addition to these cases, each hybrid powertrain (i.e. ‘d’ and ‘e’) has also been examined with a prime mover that has been reduced in size, since the energy provided via the batteries---which can be used whenever the required power at the vehicle’s DC bus exceeds a given duty cycle’s average power levels---allows for a smaller prime mover. The advantages to this "downsizing" are discussed later on in this chapter.

3.2 Diesel-Electric

As noted in the introductory chapter, the diesel-electric powertrain[45] became dominant, in particular vis-à-vis the previous prevailing technology of the (typically) coal-driven steam engine, through the course of the first half of the 20th century (Wilson, 2017).

Piggybacking off of the success of the automobile (Melosi, 2010; Wilson, 2017), which, increasingly, came to rely on the internal combustion engine (Melosi, 2010), as the diesel and, later, diesel-electric powertrains were increasingly refined for rail applications, it became apparent that this newer technology had other advantages over the incumbent, steam-engine, technology. Notably, the maintenance was simpler---i.e. it required less people, and was required less often (Wilson, 2017)---and this second fact meant, additionally, that fewer vehicles were required for a given amount of service (Wilson, 2017). Moreover, the diesel-electric locomotive demonstrated a design flexibility that steam-engine locomotives, with their more rigid, task-specific designs[46], lacked (Wilson, 2017).

The diesel-electric powertrain includes a diesel engine that drives an electrical generator, which, in turn, distributes the power to traction motors on the vehicle axles, thus turning the wheels. Presently, diesel engine efficiencies (i.e. the amount of energy output as a function of fuel energy input) typically run around 30-40% (depending, in part, on the specific drive cycle) (Smil, 2017; Thiruvengadam et al., 2014). Significant emissions reductions have

---

[45] See figure 27, in Chapter 5, for a diagram of the diesel-electric powertrain.

[46] For example, by changing the gearing system a locomotive model that would otherwise suit one application could be used for yet a different one. (Wilson, 2017)

occurred through technological developments (typically responding to new regulations) over the years, with a new engine technology released as recently as 2018 (Cummins, 2018), which would reduce NOx (already reduced significantly in recent years[47]) and particulate matter (PM) emissions[48] further.

A report from 2014 used simulations of engine technology to determine that, from 2010 efficiency levels (specifically, the benchmark was a heavy-duty engine that had recorded an efficiency of about 39% (Thiruvengadam et al., 2014))), increases of greater than 20% might be achievable---to an efficiency of about 49%---sometime in the next decade (with a large portion of this increase coming from a reduction in exhaust energy, and a more successful harnessing of the remaining exhaust energy), with an additional improvement, to 52% efficiency, possible with waste heat recovery (Thiruvengadam et al., 2014).

Traction motor efficiencies have been estimated to run at about 95% (A. Hoffrichter, S. Hillmansen, & C. Roberts, 2016). This dependence on electrical power to actually drive the wheels is a technological setup that is unlikely to change in the next couple of decades, regardless of the prime mover and original fuel source. That said, the specific traction motor technology utilized can and does vary. In fact, since about 1990, there has been a notable shift away from DC motors to AC induction (and typically 'brushless') motors (Humphrey, 2019; Lustig, 2010)[49]. Within passenger rail, there has, more recently, also been a shift from traditional AC induction motors to a greater reliance on permanent magnetic synchronous motors (PMSMs) (Stuart Hillmansen, Schmid, & Schmid, 2011).

---

[47] EPA's Tier 4 standard, introduced in Chapter 1, required NOx limits that represented a 76% decrease over the previous tier's permitted NOx levels. (See the appendix for EPA tier standards going back to 1973.)
[48] Several pollutant and pollutant categories are regulated in locomotives. More information is provided on each pollutant in Box 2, within Section 4.7.
[49] AC motors rely on an alternating current, while DC motors rely on direct current

The shift from DC to AC motors has led to a very significant improvement in tractive effort[50] (through greater control of adhesion[51]) (Caron & Beal, 2015; Electro-Motive Diesel, 2008), particularly at low speeds (Lustig, 2010). In fact, one expert noted that the tractive effort of recent generations of AC locomotives is double that of DC locomotives (Caron & Beal, 2015). This translates into a reduction in the number of required locomotives needed to pull a given load (Caron & Beal, 2015; Electro-Motive Diesel, 2008, p.). AC motors also have a higher power density (i.e. power for a given volume) (Caron & Beal, 2015), are more reliable (Electro-Motive Diesel, 2008) (Lustig, 2010), and require less maintenance (e.g. no commutator or brushes) (Electro-Motive Diesel, 2008) (Lustig, 2010).

PMSM's display an even higher power density than AC induction motors (Belmonte, 2017) and also exhibit an improved power-to-weight ratio (Stuart Hillmansen et al., 2011). PMSM's display an even further improvement efficiency (beyond AC induction motors (Stuart Hillmansen et al., 2011)), and typically have lower cooling needs than AC induction motors. Disadvantages of PMSM's include, among a few others, a greater sensitivity to operating temperature (Stuart Hillmansen et al., 2011) and a dependence on rare-earth magnets that are rather delicate and lead to a "more complex" rotor construction (Stuart Hillmansen et al., 2011).

Newer technologies notwithstanding, DC traction motors are perhaps unlikely to totally disappear in the near future, but this is mostly due to the slow turnover in the locomotive fleet

[50] Tractive effort, typically expressed in kilonewtons (kN) or pound-force (lbf), refers to the force at the wheel-rail interface used to overcome the resistance to motion, thereby leading to the (typically forward) movement of the vehicle along the track

[51] A characteristic of the interface between the wheel and the rail, adhesion can limit the amount of force that is transmitted between these two. Generally speaking, greater adhesion is preferred, as it translates into higher tractive or braking effort being available; however, there is a trade-off, as the friction created by higher adhesion also increases the resistance faced by the vehicle when in motion, and thus the power required to maintain a given speed.

(Humphrey, 2019). Newer locomotives in North America are, overwhelmingly, manufactured with AC motors (Humphrey, 2019).

3.3 Biodiesel/FT Diesel

Most diesel-electric locomotive tanks have little problem handling biodiesel, a diesel fuel made from plant materials. In fact, blending of biodiesel already occurs to some extent in the U.S., with one international report noting that the U.S. is the country/region with the "highest share of biofuels" in its rail energy sources, at 1.4% of domestic rail energy (IEA & UIC, 2017).

Biodiesel results from a chemical process called transesterification, and is frequently made from animal fats or vegetable oils. A related fuel is renewable diesel. A hybrid of the two, renewable diesel is more similar, chemically, to conventional diesel fuel (i.e. fuel derived from crude oil) (Ernst, 2016), in particular through being hydrogenated (i.e. treated with hydrogen, which, in this case, removes the oxygen (Ernst, 2016)), such that cold weather does not pose any operational challenge (Ernst, 2016). (This is in contrast to biodiesel, which is usually utilized in blends with conventional diesel due to the impact of cold temperatures on its viscosity.)

The North Carolina Department of Transportation (NCDOT) has been experimenting, throughout the last decade, with a variety of blends (pure biodiesel, included)---with the biofuel derived from soybeans (Frey, Graver, & Hu, 2016), and is considering switching over the majority of its current diesel fleet to either B20 or B40 over the next few years (Lynn Harris, personal communication, June 11, 2019).

A report by the Argonne National Laboratory (of the U.S. Department of Energy), in 2008, suggested that use of soybean-based biodiesel could reduce so-called “fossil” energy consumption, per unit of energy output, by somewhere between 52 and 84 percent, depending on the specific method utilized in estimating such consumption (Huo, Wang, Bloyd, & Putsche, 2008). Meanwhile, according to some producers of renewable biodiesel, use of their fuel can result in pollutant and emissions reductions, as compared to conventional diesel, of 15% for NOx, 25% for CO, and 35% for PM (particulate matter)[52] (Propel Fuels, 2018; Renewable Energy Group, 2018). The NCDOT has found, in testing associated with its own biofuels experimentation, up to 60% reduction in emissions of CO, Hydrocarbons (HC), and PM 2.5, with NOx emissions either the same or just a bit higher (Harris, 2019). The Southwest Research Institute, a highly reputable independent applied research facility, has found, in its testing of various locomotive engines, that, while CO and PM were reduced as the amount of biodiesel in a blend increased (up to 20% biodiesel), both total fuel consumption and NOx in fact increased (Shurland, Smith, Fritz, & Frey, 2014). Any increase in NOx, amounts of which generally equate with the temperatures found in the engine during fuel combustion, should not be of much concern, however, as modern locomotives can, if necessary, use NOx reduction techniques that can significantly reduce this pollutant, perhaps by as much as 90%, using Selective Catalytic Reduction (SCR) (Simpson, 2018) technology.[53]

Between 2010 and 2011, B20, which is a blend consisting of 20% biodiesel and 80% conventional diesel (technically speaking, “ultra-low sulfur diesel” or ULSD), was used along Amtrak’s Heartland Flyer route, a passenger route which connects Oklahoma City, Oklahoma

[52] Section 4.7 discusses the different pollutants in more detail.
[53] Due to concerns, on the part of the Class I railroads, about the cost of the related infrastructure, major freight locomotive manufacturers have in fact avoided the use of SCR technology in freight applications while still meeting the latest, Tier 4, standards (Simpson, 2018).

and Fort Worth, Texas (W. Smith & Shurland, 2013). In this case, the biodiesel was derived from beef tallow (W. Smith & Shurland, 2013), and the locomotive engine, which was Tier 0[54], had been manufactured in 1991 (W. Smith & Shurland, 2013). A total of 331 round trips were made, for a total of over 136,000 vehicle miles. In testing of the engine following this trial, there were in fact minimal differences between the B20 and standard conventional diesel (not ULSD in this case, as it was not available for the testing) with regard to CO, PM, and HC, when operating on a simulated line duty (i.e. typical during revenue service of a locomotive) cycle (W. Smith & Shurland, 2013). NOx did increase by about 5%, roughly similar to some of the other findings noted above. (And, again, any increase in NOx should be of little concern (W. Smith & Shurland, 2013).)

More recently, in California, the Capitol Corridor service is planning to test one of its newer, "Charger"[55] locomotives on a renewable diesel (exact type still to be determined (D. Shepherd, personal communication, May 21, 2019)).[56] At the same time, the agency will be collaborating with Caltrans (the California Department of Transportation) to perform some lab testing of an older EMD F59 locomotive (Kutrosky, 2019).

One potential form of renewable diesel (and one selected for the present study) is Fischer-Tropsch diesel, or FTD. FTD refers to various synthetically derived, high quality (Ail & Dasappa, 2016) petroleum alternatives based on a process, discovered in the 1920's (Brecher, Sposato, & Kennedy, 2014)[57], that converts either coal, natural gas, or biomass (often with

---

[54] Locomotive engine tiers are discussed further in Chapter 4. Tier 0 reflects a relatively early technology, in terms of the engine's emissions outputs.
[55] Section 4.6 provides more information on the Siemens "Charger" locomotive
[56] An earlier pilot project that the rail agency had implemented ended up with inconclusive results due to an issue with the purity of the renewable diesel (Kutrosky, 2019).
[57] One source, however, notes that some of the initial technological processes were discovered perhaps by the mid-1910's (Corporan et al., 2007).

syngas[58] as an intermediary fuel, etc.) to the final product[59]. When blended with jet fuel, one FTD derived from natural gas was observed to lower PM and hydrocarbon emissions as compared to JP-8[60] (Corporan et al., 2007), likely a result of FTD fuels' lack of sulfur and the minimal presence of aromatic compounds (Corporan et al., 2007) (Ail & Dasappa, 2016) and due to a higher hydrogen to carbon ratio (Wiryadinata, 2018).

There are four metals that are typically used as catalysts in FTD processes: iron, cobalt, ruthenium, and nickel. The most practical are Iron (Fe) and Cobalt (Co), due to their high availability (Corporan et al., 2007) and low costs (Corporan et al., 2007) (the latter, particularly in comparison to ruthenium) (Corporan et al., 2007).[61] While the earliest experiments frequently relied on Cobalt, Iron has become the most frequently used catalyst (Corporan et al., 2007). Nickel's main downsides are that it produces high levels of methane, and that it degrades (due to chemical reactions) at the temperatures and pressures commonly used in the FT process (Corporan et al., 2007). (Cobalt can also produce high levels of methane, but only at higher temperatures (Ail & Dasappa, 2016), while most FT processes for liquid fuels involve lower temperature processes (Ail & Dasappa, 2016).[62])

(Ail & Dasappa, 2016) found that, based on the use of a cobalt catalyst, the overall fuel efficiency for a biomass-to-FT fuel is 28-40% (Ail & Dasappa, 2016), while (Trippe et al., 2013) suggest a more limited range of about 38-39% (given the same catalyst) (Trippe et al., 2013). (Ail & Dasappa, 2016) also suggest that, with some improvements, including more

---

[58] Syngas is a portmanteau for synthesis gas, which is a mix of various gases, especially hydrogen (H_2), CO, and CO_2.
[59] When derived from a biomass, it can be considered a synthetically derived "biodiesel."
[60] JP-8 is a fuel typically used by the military (Shell, 2019).
[61] (Trippe et al., 2013) note that while a cobalt catalyst has a higher cost than an iron catalyst, this disadvantage is "overcompensated" (Trippe et al., 2013) for by a longer lifetime for the cobalt catalyst.
[62] Lower temperature processes help to ensure the production of as much liquid product as possible (Trippe et al., 2013).

efficient heat transfer, and perhaps even a newer catalyst, this number could go up to 50-55% (Ail & Dasappa, 2016), and a separate team found, in simulations, that the number could approach as high as 59.8% (Tock, Gassner, & Maréchal, 2010).

In terms of energy contained in the fuel relative to the non-renewable energy that goes into the process of extracting, processing, and developing the fuel, FT fuels can demonstrate a similar benefit as is the case with some biodiesels, including those derived from waste vegetables and from palm oil (Ail & Dasappa, 2016). In the case of FTD produced from biomass, this can mean an energy output increase, in some cases of at least 6 times, relative to conventional diesel, for the same amount of fossil fuel inputs (Ail & Dasappa, 2016). Nonetheless, chemically, all FT fuels are similar to petroleum-derived fuels, which means that, for a given volume of fuel, there is more energy than in a traditional biofuel (biodiesel, for example, has an energy density of about 7-8% lower than conventional diesel (Cushman-Roisin & Tanaka Cremonini, 2019)), and no potential negative impact to the engine due to fuel quality.

Due to the near absence of aromatics, as discussed above, FTD fuel, particularly before it has been refined, typically has a higher proportion of alkanes than do conventionally produced diesel fuel products (Wiryadinata, 2018). Using it at this stage results in a slight penalty to its energy density relative to diesel fuel (Wiryadinata, 2018). While additional refining can increase the energy density to the point where it matches conventional diesel levels, this entails additional cost. Also, should further refining not occur (e.g. as may occur when blended with a different fuel (Corporan et al., 2007; Total, 2019)), the low level of aromatics also will affects the fuel's lubricity[63] and may increase leakage risks within the fuel

[63] Lubricity refers to the ability of a lubricant to reduce friction between surfaces, which can thereby increase wear of the relevant equipment.

system (Corporan et al., 2007). While additives are typically added to the fuel to handle the lubricity problem associated with even partially refined FTD fuels, (Wiryadinata, 2018), these additives may, however, result in increased wear to the fuel pump components (Corporan et al., 2007).

3.4 Overhead Line Electrification (OLE)

Even before Rudolf Diesel developed the engine that bears his name, electricity drawn from an external source was being used to power vehicles with wheels. Siemens & Halske (a predecessor of Siemens AG) began operation of the first electric streetcar in the world in a Berlin suburb, in 1881 (Siemens, 2019), and in 1888, the first electric street car operated by above-vehicle electric wire began service in Richmond, VA (Kollatz Jr., 2004). By the time Rudolph Diesel patented his eponymous engine, less than 5 years later—in 1893 (Lemelson, 2019)—over 100 electric railroads were operating or under construction across the globe (Kollatz Jr., 2004). By the early 1930s, many commuter railroads in the U.S. were running on electricity (J. Allen, 2017), in large part due to such concerns as the dangers of diesel within a confined space, such as a tunnel, along with general smoke reduction goals even outside of tunnels (J. G. Allen, 2019).

Overhead Line Electrification (OLE)[64] rail technology, as it currently exists in the U.S., can be divided into roughly three different forms, or generations (J. G. & A. Allen, 2003) (Allen, 2003), based on system voltage (Allen, 2003), from the initial development of the technology during the 1880s to the present day. A significant part of the Amtrak Northeast

[64] Overhead Line Electrification (OLE) refers to a system of support structures, wires (i.e. electric catenary wires), and other equipment (e.g. pantograph, which lies atop the roof of an electric locomotive or coach) that collectively transmit electric power from the grid to a railway vehicle in order to provide propulsion power to the vehicle and to supply other power needs.

Corridor[65], where the vast majority of domestic electric intercity passenger rail exists, operates on a variant of the second generation (constructed between 1905 and 1940 (J. G. & A. Allen, 2003)), using 12 or 12.5 kV at either 25 or 60 Hz, while from about New Haven on Northeastward, a third generation electric rail system, 25 kV at 60 Hz, is now operating (IEEE, 2016; Popov, 2016).

The northeastern part of the U.S. is where most of the overhead line electrification (OLE) in the U.S. can be found. The technology has also become increasingly prevalent abroad, particularly during the last few decades (IEA, 2019c).

In addition to the lack of direct (or "onsite") pollution during operations, (Hay, 1982) noted some other advantages for OLE, including greater availability (due to lower levels of maintenance, thanks to the absence of the diesel engine and its moving parts), higher efficiency, and greater horsepower per ton of weight (Hay, 1982). A train running on electricity can also accelerate more quickly than the equivalent vehicle powered by a diesel-electric engine-generator combination due to the more favorable torque characteristics of an electric motor vs a diesel engine, particularly at higher speeds (due to the lower power limits of the engines as compared to the levels of energy supplied by overhead wire). This offers a particular advantage for busy rail corridors, where it translates into a higher capacity of trains for a given stretch of rail track.

Powering trains with OLE is not without its problems, however. With large amounts of metal materials required, combined with a high cost for the specialized labor involved in constructing the infrastructure, providing electricity to a locomotive in this manner is costly,

[65] The "Northeast Corridor" refers to the rail route that runs from Washington, DC, northeastward, up to Boston, MA.

with reliable estimates ranging from about $2 million per track-mile on the low end (Alstom Communications, 2018) to just under 8.5 million per track-mile on the upper end (calculations based on (Caltrain, 2019)). Costs on the lower end are more often found in Europe, however, where contextual factors are different. The European context includes a significantly shorter load gauge[66] (thus shorter metal poles and, overall, less metal materials), some costs being accounted for by railroads rather than outside project-specific contractors, and minimal design requirements due to many projects being extensions of previously existing electrified lines (Weiss, Hayes, & Shaw, 1983). Moreover, in Europe, the relevant supply chains are also very well established (Weiss et al., 1983).

Steel and copper appear to be the materials that contribute most to the physical cost of building OLE (Kidder, 1982; RSSB, 2007). Moreover, the need for bridges and tunnels can also greatly contribute to high costs (NetworkRail, 2009), particularly in urban areas. One study, produced by Network Rail, which owns the railway network in the UK, has noted that cost may decease with greater space in between support structures (RSSB, 2007); however, this may require reduced speeds during periods of high winds and can't be done around junctions, which require a greater density of these structures (RSSB, 2007).

Where very high levels of traffic exist, (as well as for high speed rail routes, the services for which require very high power and energy levels[67]) the high costs of OLE are often justified (Isaac & Fulton, 2016); however, there are many routes where such high traffic densities are not likely to exist for a very long time (if ever).

---

[66] Load gauge refers to the space envelope that a train can occupy without interfering with wayside infrastructure, such as overhead lines, tunnels, and station platforms.

[67] If one looks at the resistance forces faced by a rail vehicle in motion, a topic described in some detail in Section 4.2 (Box 2), it can be seen that, as the speed of the vehicle increases, the resistance increases exponentially. (Figure 9 provides a graphical representation of this.)

In addition to its overall lower electrification costs, Europe has an overall greater population density[68], and has traditionally focused more on passenger rail services (Vassallo & Fagan, 2007), including a much greater prevalence of high speed rail. Such applications require higher power, and subsequent energy use is much higher, making diesel impractical. These key factors likely explain why OLE has become increasingly prevalent in Europe (IEA, 2019c) as well as in parts of Asia (where many countries also have very high densities, and have invested significantly in high speed rail systems). But even parts of Europe have, in recent years, come to acknowledge the high cost of building electric infrastructure. The UK, for example, has recently faced delays due to concerns over electrification costs (BBC, 2018) and, in fact, this has prompted the exploration of alternatives to OLE in some cases (with the UK one example, as noted in Section 3.6, below).

Beyond the cost concerns, rail powered by OLE incurs other risks, notably that any disruption or damage to this external infrastructure source can wreak havoc on an entire rail system for hours at a time (e.g. see (Aratani, Lori, 2018) (Mcilkenny, 2018)). The visual aesthetics of OLE infrastructure, especially in scenic and urban regions, is, unsurprisingly, often remarked as another factor that argues for an alternative to OLE. In fact, particularly in the heart of cities, it, alone, may be seen as a cause for seeking alternative methods of propulsion.

[68] For example, on average, there are 36 people per square km of land in the U.S.(World Bank, 2019); while France has over 100 (World Bank, 2019), and Germany, the UK, Switzerland, and Italy all have over 200 people per square km! (World Bank, 2019; Worldatlas.com, 2019). Parts of the U.S. are as dense as the densest parts of Europe. New Jersey, at 467 people per sq. km. is almost as dense as the Netherlands (511 people per sq. km), while Rhode Island (395 per sq. km) and Massachusetts (336 per sq. km) have densities comparable to Belgium's (at 377 per sq. km). Thus it is of little surprise that this is where most of the country's OLE infrastructure is found.

Figure 3: OLE Infrastructure at the Princeton Junction Train Station, Princeton, NJ
July, 2018
(Photo from author's collection)

This particular station is not located in the heart of a city; however, when the wires and other OLE equipment such as can be seen in this photo are located in downtown areas, the visual impacts are often seen as problematic by the public.

When a branch line or other portion of additional track is added to previously electrified track, additional track electrification might be expected; however, this means additional investment, in both time and money. Previously the main alternative was the use of bi-modal diesel-electric/OLE equipment (Railway Technology, 2018, 2018), which has been used by a few rail agencies around the world, New Jersey Transit (Frasinelli, 2011) and Montreal (Bombardier, 2019). Such locomotives are heavier than single-mode locomotives (Caltrain, 2014), however, and typically, they have also been more expensive (Caltrain, 2014), too. As noted below, newer hybrid concepts may now offer additional attractive alternatives.

Electricity via induction may eventually become a viable option for heavy duty vehicles (trains, included), particularly for commuter systems whose stop frequency doesn't exceed about 4 or 5 miles. In the meantime, however, the charge capacities (O. van Yperen, personal communication, August 5, 2015) are a bit low for this application, so this technology is likely quite a ways away, still.

In the case of freight rail, the last freight trains that ran on OLE in North America, on a main line, were taken out of service in 2000, while one of the two more recent trains that ran on isolated lines will be retiring shortly (Mitchell IV, 2019). (The Black Mesa & Lake Powell Railroad, which supplied coal to a power generating station in Arizona, will soon cease operation (Mitchell IV, 2019). The remaining line is the Deseret Power Railroad, which is a 35-mile stretch that covers land in both Utah and Colorado, also serving a mine (Mitchell IV, 2019).)

As noted in the introductory chapter, freight railroads are, by far, the dominant fuel consumers in the domestic rail sector. Moreover, network-wide electrification has in fact been seriously considered for this application, perhaps most recently during the 1970's and 1980's (Withuhn, 1999). This was a period that began with very high oil prices, due to oil price embargoes that led to greater concerns about the security of energy resources (Withuhn, 1999), particularly those resources that, at the time, were mostly obtained from abroad. Most of these potential plans ended up being shelved due to several factors. Included among the factors were the high uncertainty regarding the logistics of cooperating with the electric utilities over resource provision (Withuhn, 1999), a concern about high ramp-up rates required for both power generation and electric locomotive stocks in order to offset the high risks (Withuhn, 1999), and the long time periods required to build new power plants (estimated, by one source, as between eight to twelve years (Withuhn, 1999)). Moreover, concerns extended to the delay in getting from a negative ROI to a positive ROI (and the levels of debt required to get from the former point to the latter point (Withuhn, 1999)). (Withuhn, 1999) also noted that diesel prices had come down by the end of this exploratory period and, at the same time, significant fuel efficiency improvements had been made to the diesel-electric locomotive. Combined with fuel conservation efforts on the part of the railroads, these factors raised the attractiveness of the status quo as compared to what was seen as the riskier choice of fuel switching to OLE.

Globally, however, the freight rail sub-sector is no stranger to electrification. In fact, OLE rail accounted for, in 2017, about 10 million tons of oil equivalent on an annual basis, about 1/5 of all energy expended by the rail sector (IEA, 2019c). This proportion represents a greater percentage than was previously the case, at least going back to 2000 (IEA, 2019c). Much of the growth in OLE freight rail during that period came from China, India, and Russia (IEA, 2019c), where the increases are disproportionate to any growth in diesel freight rail (and, in the case of China, at the expense of the latter (IEA, 2019c)). Particularly in the case of China and India, this increase has, though, coincided with larger increases in OLE passenger rail (vis-à-vis diesel passenger rail (IEA, 2019c)).

3.5 Natural Gas

Natural gas production has become a very significant enterprise in the national and international energy systems, with global gas production doubling between 1980 and 2010 (US EIA, 2012), and projected to grow another 10% between 2017 and 2023 (IEA, 2018). The United States' role in this enterprise is extensive. It is currently the world's top producer of natural gas (IEA, 2018) and its production is expected to account for roughly 43% of the global production increase during that 2017-2023 period (IEA, 2018).

It should thus come as little surprise that this energy source has also been of interest to decision makers within the rail industry over the last several decades. Initial exploration of natural gas as a potential fuel for rail started during the 1980's and the first half of the 1990's, when Burlington Northern (BN) worked with Electro-Motive Diesel (EMD) and later, also Energy Conversions, Inc. (ECI), to convert locomotives for use with, first, compressed natural gas (CNG), and then, later, liquid natural gas (LNG) (Ditmeyer, 2014). In fact, in most cases, these early natural gas locomotives, and many that followed, were dual-fuel, diesel-LNG locomotives[69] (Schultz, 1992), apparently since the spark ignition (SI) required of a 100% natural gas engine would have required a significant move away from the current, diesel-oriented, engine technology (W. C. Vantuono, 2013). With the current approach, a "retrofit kit" that can cost up to $400,000 (UIUC-RailTEC, 2016) is already required as part of the locomotive conversion process.

[69] A duel-fuel locomotive is able to run on either one or the other fuel, but does not run on both at the same time.

Continued interest in natural gas as a rail fuel waned a bit following this period, while, during this past decade, a combination of historically high diesel prices and low natural gas prices---likely resulting from the large increase in shale production in the U.S.---reignited this interest.

During 2012 and 2013, Canadian National (CN) essentially replicated the BN experiment of the 20th century (with an up to 90% LNG-10% diesel combination (K. Smith, 2013)), using LNG with retrofitted EMD locomotives along with specialized fuel tenders to carry the fuel (and keep it cold).

EMD, on its own, has also developed two other LNG engine technologies, one of which uses a diesel engine with a mix of diesel fuel and LNG; the other a spark ignition engine running on 100% LNG (William C. Vantuono, 2014).

Following on the earlier pilots, one railroad has now gone ahead and begun to operate on LNG (with an up to 80% LNG-20% diesel mix (W. Vantuono, 2018)). From 2015 onwards, the Florida East Coast Railway, a Class II railroad based in the Southeastern U.S. (FEC, 2019), converted 24 Tier III-compliant locomotives, its entire long-distance fleet, such that they could operate on LNG (Keefe, 2018). As of early 2018, this fleet has used more than 6 million gallons, traveling more than 1.9 million miles (R. Keefe, personal communication, January 4, 2019). On the passenger side, the Napa Wine Train, in Northern California, has been running on CNG since 1999, first at 60% natural gas (Brecher et al., 2014), and, as of 2008, at 100% natural gas (Brecher et al., 2014). While there was previously significant interest from the North Carolina Department of Transportation in Using natural gas in one or more of its (passenger) locomotives, this interest has somewhat waned, being translated over to other diesel alternatives (as is discussed elsewhere) (L. Harris, McDowell Engineers & Associates, Consultant to NCDOT, personal communication, January, 2019).

Experimentation with natural gas in rail is not isolated to the U.S. Looking abroad, India already has some trains running on CNG and has recently demonstrated interest in expanding into LNG for rail, also (Das, 2018; Reuters, 2018). Brazil has, in the last decade, used dual-fuel diesel-LNG locomotives in freight. The vehicles rely on a maximum of 70% LNG (30% diesel), and only begin to use natural gas at powers of 650 horsepower (roughly 485 kW) or higher due to the risk of engine misfires that might occur otherwise (Carvalhaes, 2013). Russia has also experimented with LNG for freight, though through the use of turbine rather than ICE technology (Barrow, 2018b).

Although combusted natural gas contains about 20% fewer GHG emissions per unit energy than diesel fuel combusted (based on (GREET, 2018)), a few factors result in a steep erosion of this advantage in practice. For example, there are efficiency losses from the high pressures required for gaseous storage, while liquefaction, in the case of LNG, is even more energy intensive, estimated at roughly 2.9 MJ per kg of natural gas (Franco & Casarosa, 2014). Also, more often than not there is some methane (the primary component of natural gas) leakage both on board and within the upstream (i.e. WTP) transport of natural gas. The EPA's official estimate of methane (the primary component of natural gas) leakage in the U.S. natural gas system is 1.4% (Cornwall, 2018), though one recent study estimated that the actual leakage rate is likely closer to 2.3% (Alvarez et al., 2018).

At the point of entry into the engine, natural gas is in a gaseous state. Storage on the vehicle can, however, occur utilizing either a cryogenic liquid (i.e. LNG) or a compressed gaseous state (i.e. CNG). Unlike CNG, LNG requires large "cylindrical shaped pressure vessels with a surrounding vacuum space for thermal insulation" (Stewart, Olson, & Cook, 2015), which are both costly and would result in increased space requirements within a locomotive. (CNG is best stored using small diameter tank pairs, often made of either steel or aluminum (Stewart et al., 2015).)

Despite its storage reflecting a simpler system than for LNG, CNG also provides considerably less energy per unit volume. Given traditional approaches to fuel storage, this has often resulted in limits on travel range, and, in fact, until recently, most CNG tests had involved railyard switcher locomotives.

India does run CNG in passenger trains; however, the issue of space has indeed become a challenge (Das, 2018), and led to a greater interest in switching over to LNG. Here in the U.S., meanwhile, Norfolk Southern, a Class I that operates primarily in the eastern half of the country, has a history of demonstrating a strong interest in CNG (Allen Rider, 2014; Barbee, 2015; Rimer, 2014). Back in 2014, one Norfolk Southern engineering executive suggested that eventually compressed natural gas could be a viable fuel for some of the sub-1,000 mile (1,609.3 km) freight routes that it operates (Rider, 2014). And, in fact, Norfolk Southern has continued to press forward towards this goal. Earlier this year, thanks to the development of a tender by a company called CNGMotive (W. C. Vantuono, 2019), Norfolk Southern will soon begin testing a CNG tender for use with its mainline locomotives (G. Trillanes, personal communication, December 2, 2019; W. C. Vantuono, 2019), aiming first for successful completion along a 400-mile stretch (W. C. Vantuono, 2019). The tender, which is pictured in Figure 4, has 28 cylinders (G. Trillanes, personal communication, December 2, 2019), which, in total, will hold 4,600 DGE (W. C. Vantuono, 2019) of CNG, at ~300 bar (G. Trillanes, personal communication, December 2, 2019).

Figure 4: A CNG Tender Recently Developed by CNGmotive
Photo courtesy of William C. Vantuono, and Railway Age (with permission granted)

This fuel tender, which holds 28 cylinders of CNG (G. Trillanes, personal communication, December 2, 2019), will soon be tested by Norfolk Southern along a 400-mile stretch of track (G. Trillanes, personal communication, December 2, 2019; W. C. Vantuono, 2019).

Broadly speaking, there may be a role for natural gas as a bridging fuel on the path towards very low GHG fuels, in rail, over the long term, e.g. by focusing on renewable natural gas (from biomass) or possibly as a step on the way to conversion to hydrogen fuel, which can then be used in fuel cell systems (discussed further, below). Natural gas use is rising within the trucking sector, both in the medium-duty/delivery and heavy-duty sectors (STEPS, UCD, 2017), another plus for natural gas as a rail fuel. Moreover, a sizeable number of micro-liquefaction plants and LNG refueling stations (64 of the latter, according to the U.S. DOE (EERE, US DOE, 2019) already exist throughout the country.(EERE, US DOE, 2019)).

Although LNG is, as noted above, more energy dense (i.e. energy contained in a given unit volume) than CNG and can power trains over longer distances, it faces some major challenges even beyond its higher system cost per unit fuel storage volume and the frequent need for a fuel tender. For example, as noted above, the low temperature at which it must be kept to remain a liquid (– 252.8 C) (US DOE, 2019) is particularly energy intensive. A related concern is the potential for boil-off[70] during storage (whether this is on- or off-board). Moreover, at least at the domestic retail level, CNG costs less than LNG (US DOE, 2018), presumably due to lower costs for compression than for liquefaction. (The cost difference is, however, not particularly large (US DOE, 2018).)

As addressed above, with its lower energy density, CNG would require more frequent refueling. While a CNG tender (e.g. as in Figure 4) could significantly increase storage capacity, when deemed necessary, it would most likely also translate into increased cost.

Refueling rates with natural gas demonstrate significant variation. Assessing CNG, the vehicle used in Napa refuels at a rate of 50 DGE (diesel gallons equivalent) per hour (S. Jensen, personal communication, June 10, 2019). However, CNG Motive, which aims to provide natural gas to North American freight locomotives, claims to have a technology that can refill CNG at 5,000-13,000 DGE per hour (CNG Motive, 2019), a rate that should prove adequate for mainline freight service.

Whether using natural gas is truly an effective way to reduce emissions remains up to debate, and, as with biofuels, depends on the specific assumptions made in any analysis. On the rail operations side, some research has shown that neither NOx nor PM emissions would be reduced by switching from diesel to natural gas (Brecher et al., 2014). In examining the upstream

[70] Boil-off refers to evaporation of a cryogenic liquid gas (i.e. one that is typically a gas at ambient temperatures).

process of extracting the natural gas, one thing that is known is that the production of shale natural gas in the U.S. is closely and “increasingly” tied to increased tight oil[71] production (IEA, 2018). Whether the upstream impacts of tight oil production is worse, from an environmental perspective, than more conventional oil production methods is a subject of debate. While some work has shown that methane leakage associated with tight oil production has typically been underestimated, more recent work has shown that the overall upstream impacts are no worse than with more conventional production methods, at least in the case of the Eagle Ford Shale (Yeh et al., 2017).

3.6 Hydrogen and Fuel Cells

Hydrogen is a fundamental building block of the universe, and the source of the sun’s energy. It is also found in abundance on earth; however, due to certain properties of the element, this is almost always as part of another molecule (e.g. H_2O---water, as one significant example). Overall, though, this means that there is no danger of running out of hydrogen during the earth’s lifetime, which sets it apart from the fossil fuels.

Utilizing hydrogen in a fuel cell to create electricity has origins going back to the middle of the 19th century (Bellis, 2019), with the first mobile application over 100 years later, in 1959 (“Allis-Chalmers Fuel Cell Tractor,” 2015; Bellis, 2019; Kantola, 2008; University of Strathclyde, 2009) (though the latter relied on propane, a hydrogen-containing alkane[72]). Applying the technology to transportation applications regained popularity in recent years, as a way, alongside batteries, to spur the transition away from fossil fuels.

[71] Tight oil is a lighter petroleum product that often requires hydraulic fracturing (i.e. fracking) to be accessed due to its location in impermeable rock deposits

[72] Alkane (also known as a paraffin) is a technical, chemical term for the kinds of molecules that make up various fuels, including diesel fuel and natural gas.

In fact, fuel cells are already being utilized in heavy-duty vehicle applications, notably in several bus systems throughout the country. Fuel cell buses have been in operation in California since 2000, when Sunline Transit began a thirteen-month in-service demonstration of an early generation fuel cell bus (FTA, 2001). By 2006, AC Transit, in the Bay Area, had begun to operate three fuel cell buses in revenue service (Chandler & Eudy, 2010)while Sunline had one fuel cell bus (Chandler & Eudy, 2008; Leslie Eudy & Post, 2018) . Since then, fuel cell bus usage in the state has expanded, with 13 now in service with AC Transit, 8 with Sunline, and a few others scattered about the state and the nation. (Most of these applications are, to some extent, hybridized (Leslie Eudy & Post, 2018), and can also be referred to as fuel-cell-dominant.)

Hydrogen has also begun to emerge as an application for trams. In 2017, a hydrogen-powered tram developed by China Railway Rolling Corporation (CRRC), began commercial operations in China's Hebei Province (ChinaDaily.com.cn, 2017). In the vehicle, a 15-minute fueling session enables the vehicle to travel for 40 km at speeds of up to 70 kilometers/hour (ChinaDaily.com.cn, 2017).

Among the "greener" forms of powering a full-size train, the notion to operating a train with hydrogen, via fuel cells, has, in recent years, gone from being mostly conceptual to, in a few cases, operational.

The first decade of the millenium is when the earliest examples of hydrogen fuel cell in rail applications can be found. For example, in Japan, two early prototypes of fuel cell-battery hybrid multiple unit cars were designed prior to 2010 (Hoffrichter, 2013); while intended to remain tests, the team did learn that issues of equipment size, cost, and fuel cell lifetimes were key areas that would require further development in order for such a technology to move forward (Hoffrichter, 2013). Meanwhile, even before traditional locomotive operation via fuel cell was looked at closely, at the beginning of the millennium, one private firm developed the first fuel cell locomotive (hydrogen-fueled), in the context of a mining vehicle (Barnes, 2005; Arnold R. Miller, 2018). This is a context which the manufacturer aptly noted was particularly ripe for a vehicle that would not emit any pollutants (Barnes, 2005). (Storage for the vehicle was based on a material known as metal hydride, which is discussed in more detail below.) Then, from roughly 2006 through about 2010 (Hess, Miller, Erickson, & Dippo, 2010), that same firm, Vehicle Projects Inc, along with BNSF Railway Company, the U.S. Army Corps of Engineers and various additional partners (Arnold R. Miller, 2018), created and tested a hydrogen fuel cell switcher that was hybridized with lead-acid batteries. With two 150 kW modules, the vehicle had 300 gross kW (with 96 kW the average net power that was required) (Hess et al., 2010). However, in combination with the auxiliary[73] traction battery, the locomotive had a maximum power of 1.5 MW (Arnold R. Miller, 2011, 2011) It was also designed to serve as "power-to-grid back-up" for a military base (Hess et al., 2010).

While a metal hydride (a technology described further in Chapter 3) had been considered as a tank, due to concerns regarding weight (a particular concern due to the presence of the lead-acid batteries (A.R. Miller, Hess, Barnes, & Erickson, 2007), which have a particularly low energy density (Johnson Mathey Battery Systems, 2017)), cost, and a "lack of commercial availability," (A.R. Miller et al., 2007) a decision was made to go instead with compressed H2, stored at 350 bar (A.R. Miller et al., 2007). The storage aboard the vehicle was composed of 14 carbon-fiber composite cylinders, with a total storage of 70 kg, with 63.5 kg of those "usable" (Hess et al., 2010). These were installed at the top of the locomotive, with the authors noting the

[73] See glossary for the definition of auxiliary.

advantages of “roofline” storage, including avoiding or minimizing impacts with potential obstacles that may be encountered in a yard (including, even a derailment) (A.R. Miller et al., 2007), and the resulting “harmless upward dissipation” (A.R. Miller et al., 2007) in the case of any hydrogen leaks rather than more serious effects.

The project originators note that the technology was well received by those tasked with operating it, and the fuel cell demonstrated an average 49% efficiency, LHV (Hess et al., 2010).

One of the prime reasons that the project originators selected a switcher vehicle was due to the large amount of time that these vehicles spend in idle, alongside occasional “sharp” power peaks (Hess et al., 2010). However, in one of their reports (Hess et al., 2010), the authors noted that commuter rail should also be a good candidate for a hybridized hydrogen fuel cell powertrain. They pointed out the suitability of the typical commuter line’s duty cycle, which includes significant variation in power demand between when the vehicle pulls out of stations versus when it reaches cruising speed, between stops, and when it begins to slow again for its next stop (Hess et al., 2010).

And, indeed, following further developments, including the prototype developed at the University of Birmingham (see Chapter 2) (Andreas Hoffrichter, 2013), a leap forward for the rail sector occurred in 2015, when the international train manufacturer, Alstom, and Canada-based Hydrogenics partnered to develop such a vehicle (Hydrogenics, 2015). Following successful testing of the hydrogen fuel cell concept, which concluded in 2018, two hydrogen multiple unit vehicles entered operation in September of that year, along an approximately 100 km regional train track in Lower Saxony, Germany (Alstom, 2018). LNVG, the train operator, expects to receive 14 additional hydrogen trains in 2021 (Alstom, 2018). In Asia, Toyota has recently announced a partnership with the East Japan Railway Company in hopes of also developing a train powered by hydrogen (Kyodo News, 2018). Moreover, interest and even plans for such trains have also been expressed by companies across Europe and even North America (IEA, 2019c; Varney, 2019), including in France, the UK, Austria, and Canada (Varney, 2019). For example, the Rail Standards and Safety Board (RSSB), of the United Kingdom, has been supporting research focused on innovative powertrain designs for trains (Kent, Gunawardana, Chicken, & Ellis, 2016).

The University of Birmingham, along with Hitachi Rail and Fuel Cell Systems, had been among the recipients of funding following their successful 2016 proposal submission (Kent et al., 2016) during the middle of this decade. The team proposed developing a hybrid hydrogen-battery passenger vehicle in which the hydrogen fuel cell meets the baseload power, while the "high-capacity" battery stores braking energy and assists in meeting peak energy demand (Kent et al., 2016). A report on phase 1 of the project demonstrated that close to 70 kg of compressed hydrogen (stored in nine tanks), enough for 500 train-miles (according to the author's analysis), could be stored on an existing or new, but otherwise standard railcar, once the components necessary only for the diesel-electric are removed (or the spaces typically held for them are left vacant) (Kent et al., 2016). More recently, that university has worked with Porterbrook, a leaser of railway stock in the United Kingdom, and various industry partners to develop the "Hydroflex," which involves a retrofit of an electric multiple unit train into an electric-hydrogen hybrid, which could run either on OLE or with hydrogen, via fuel cell (Porterbrook, 2019).

Also in the UK, Alstom and the UK's Rail Safety and Standards Board have announced that rail equipment powered by hydrogen (again, a multiple unit vehicle rather than a locomotive) will be replacing some of that country's diesel-electric equipment within the next few years. (Railway Gazette, 2018a) (Rohée, 2019) UK's transport minister, Jo Johnson, noted that this equipment would be cleaner than diesel-electric equipment while more cost-effective than trying to electrify more tracks (Railway Gazette, 2018a). (Electrification of UK tracks is discussed in a bit more detail in Chapter 4.)

As of this year, hydrogen via fuel cell in a rail context will also soon make an appearance here in the U.S. The San Bernardino County Transportation Authority (SBCTA) is working with Stadler to bring a multiple unit vehicle (with an option for four more vehicles) that will operate on hydrogen via fuel cell (Railway Technology, 2019). Based on Stadler's "FLIRT" model, the fuel cell stacks and tanks will be contained in a module between the two cars of the vehicle (Railway Technology, 2019). Service is expected to begin in 2024 (Railway Technology, 2019).

Hydrogen fuel cells offer two major advantages over combusting diesel in an internal-combustion engine (ICE): they produce zero pollutant or GHG emissions at the "tail pipe" (water is the only emission), and they are more efficient than ICEs, approaching double the efficiency in many rail duty cycles (Andreas Hoffrichter et al., 2015).

Hydrogen, itself, could be combusted, instead. However, due to the presence of nitrogen in the air and the intense heat created during the combustion process, NOx emissions would still result. Moreover, the efficiency of a fuel cell, which involves a transfer of charge rather than of heat (Hassanzadeh & Mansouri, 2005), is significantly higher than that of a combustion engine, due to the irreversibility of the processes involved in the latter (Hassanzadeh & Mansouri, 2005).

Other advantages of relying on a fuel cell rather than an ICE is reliability and generable maintenance requirements. For example, generally speaking, fuel cells are more likely to gradually deteriorate rather than outright fail (CH2M Hill Canada Limited (now Jacobs Engineering Group) et al., 2018). Also, without the moving parts that an engine has, maintenance should be less cumbersome, consisting of determining the state of individual cells (CH2M Hill Canada Limited (now Jacobs Engineering Group) et al., 2018), and only occasionally needing to rebuild a cell and its components (CH2M Hill Canada Limited (now Jacobs Engineering Group) et al., 2018).

Virtually all of the fuel cells applied to rail applications have been and continue to be of the PEM type, as are the fuel cells that have begun to be used in the automotive sector. While there are actually a large number of different fuel cell types (and many don't even require hydrogen as an initial fuel), there are some key advantages of PEM vis-à-vis the other fuel cell types that likely explain its use in these early rail applications, and why PEM is likely to remain the preferred approach in the near future.

Molten Carbonate and Solid Oxide fuel cells (MCFC, SOFC) both allow for internal reforming[74] of a fossil fuel and neither require expensive catalysts; however, the reason for the latter is due to high temperature operation, which, itself, means long start-up times. (One source suggests that "tens of hours" are required for startup of a molten carbonate fuel cell so as to avoid damage (Mench, 2008)). These two fuel cell types are, on the one hand, insensitive to CO (Mench, 2008) (Viswanathan & Scibioh, 2007), something that can "poison"[75] the catalysts that operate within PEM fuel cells, thus greatly reducing PEM efficiency (Mench, 2008) (EERE, n.d.). However, MCFC and SOFC both have low power density (Mench, 2008), which means that a larger size system would be required to generate a given power, a clear disadvantage for a rail application (and most other transportation applications). And an SOFC may also have

[74] Internal reforming refers to conversion of a fossil fuel to hydrogen within the fuel cell, itself (typically at the anode (Sengodan et al., 2018), one of two electrode components of the fuel cell). This can occur through a few different processes. As with external reforming, these processes also result in the production of additional by-products (including carbon products).
[75] Catalyst (platinum, in this case) poisoning refers to a reduction in effectiveness of the catalyst due to chemical disruption of the pathways through which a catalyst typically influences the key reactions.

difficulty withstanding the forces regularly placed upon it in a rail context, particularly, for example, when freight locomotives and cars are being assembled (Martinez, 2011).

Alkaline fuel cells have been applied in the aerospace and naval sectors (Mench, 2008) , and have among the highest operating efficiencies of any fuel cell system (Mench, 2008). However, their main disadvantage as compared to PEM fuel cells is that they are intolerant to CO_2, with perhaps even the CO_2 found in the air greatly impacting fuel cell system performance and durability (EERE, n.d.). As a result, this would require either significant additional equipment or, otherwise, inputs (such as additional gases) which would reduce the energy density.

Phosphoric fuel cells are particularly thermally efficient (Mench, 2008); however, when used only to generate electricity, their efficiency is much closer to that of any combustion-based power plant (EERE, n.d.) (e.g. diesel engine). Phosphoric fuel cells are not sensitive to CO (EERE, n.d.); however, they require higher temperatures than do PEM fuel cells (but lower than is the case with either SOFC or MCFC). They also can be very expensive, likely due to their unusually large size (described by one source as a “bulky, heavy system”) (Mench, 2008), which, itself, stems from such fuel cells’ very low power density.

This brief review, above, of the main alternatives to PEM largely demonstrate the appeal of PEM fuel cells in transportation contexts, including rail. In addition, despite its sensitivities to fuel impurities (Viswanathan & Scibioh, 2007), which means that the hydrogen used in a PEM fuel cell must be highly purified, and the need to prevent water from “flooding” the fuel cell’s electrodes, PEM fuel cells offer a “simple design” (Viswanathan & Scibioh, 2007) that operates at a variety of temperatures, the latter meaning that startup can be very quick (Viswanathan &

Scibioh, 2007). Moreover, the PEM fuel cell offers good power density (Mench, 2008), a significant advantage in a rail equipment application.

In terms of the fuel, itself, hydrogen is already produced in large amounts, mostly for industrial applications. These include applications within the oil industry, as well as in the production of ammonia, methanol, and steel (IEA, 2019b).

While there are many different production methods for hydrogen, most can be placed in, roughly, one of three categories: either reformation/oxidation of a fossil fuel, biomass-based, or water splitting (Holladay, Hu, King, & Wang, 2009), with the latter two categories being mostly derived from renewable energy sources, or at least, in the case of electrolysis based on the electric grid, potentially renewable sources (and, in many cases, presently, partially renewable sources). Out of these many potential methods, this analysis will focus on two of the most common methods currently in use (IEA, 2019b), including for transportation applications, which are water electrolysis and steam methane reformation (SMR).

Electrolysis refers to the production of hydrogen via electricity and water. Electrical charges in an electrolyzer separate H2O (i.e. water) into H_2 and O_2 gases. Of the two methods focused on in this research, this has the potential to be the environmentally superior method of producing hydrogen, but the benefit depends on the specifics of the power grid. In fact, it offers the potential to be completely zero-emission, on a well-to-wheel basis, if only renewable electricity sources are used. Electrolysis is also, however, a more expensive method than SMR due to the amount of electricity, itself an energy carrier derived from primary energy sources, that is required.

Steam Methane Reformation (SMR) is a two-step process which converts natural gas (i.e. predominantly methane) to hydrogen. It is the cheaper of the two on-site production options that are considered in this study, and is also the most common method currently used, accounting for approximately 76% of the world's "dedicated" hydrogen production, or over 50 million metric tonnes[76] (IEA, 2019b)[77].

However, depending on the source of electricity, SMR may not be as environmentally beneficial as electrolysis due to the duplicative processes of producing natural gas (itself a fuel) and then converting that over to hydrogen. (Use of renewable natural gas, e.g. landfill gas, would, however, significantly improve the environmental impacts.) SMR does also require a significant amount of water, perhaps just a bit less than hydrogen produced via water electrolysis (Elgowainy et al., 2016).

In the case that either space or the complexity of onsite production make these options problematic, centralized production and delivery of the hydrogen can be a good option, though the present study finds that liquid delivery (the delivery option examined) is not necessarily a cheaper option. Due, primarily, to the energy required to liquefy the hydrogen (i.e. in a process that brings it down to a very low temperature)[78], and to a much lesser extent, the transportation involved (Yang & Ogden, 2007), this option may lead to high pollutant and especially high GHG emissions (GREET, 2018) (Yang & Ogden, 2007) during the "well-to-pump" phases of fuel production. Exact emissions, would, however, vary depending on the make-up of the electrical grid (Yang & Ogden, 2007)). Moreover, producing the hydrogen via clean

[76] One metric tonne is equivalent to 1,000 kg.

[77] The majority of the remaining hydrogen produced at the global level (regardless of the specific application) is actually derived from coal (via gasification), while a mere 2% is obtained via electrolysis (and still much less than this amount via water electrolysis) (IEA, 2019b).

[78] Even with today's technologies, liquefying hydrogen requires approximately 30-35% of the energy that is contained within the fuel (Andersson & Grönkvist, 2019; Wilhelmsen, Berstad, Aasen, Nekså, & Skaugen, 2018) (Yang & Ogden, 2007), itself, with most of this energy in the form of electricity demand (K. Reddi, Mintz, Elgowainy, & Sutherland, 2016). One study suggests that future technology developments could reduce the energy required for liquefaction to just under 20% of the energy content contained within the fuel (Andersson & Grönkvist, 2019, p.; Cardella, Decker, & Klein, 2017; Ohlig & Decker, 2015).

electrolysis (i.e. with electricity from all or mostly renewable resources), prior to the liquefaction process, would reduce overall emissions, also.

Perhaps the main advantage of hydrogen delivery is that it requires less specialized knowledge on the part of the rail system employees, and it requires less up-front investment of time and money (and, as noted earlier, space). Over time, should hydrogen fuel cell technology prove highly successful in rail applications, the advantages of a centralized liquid delivery approach may erode, in many cases.

As with onsite production, central production of hydrogen and distribution can occur in gaseous form; however, in order to minimize the number of trips necessary for the truck to deliver the fuel to its destination, liquid hydrogen, which packs the same amount of energy in an area much smaller than is the case for gaseous hydrogen, would be the preferred delivery option for most early rail applications. (Use of hydrogen in the fuel cell would be in the gaseous form, however, and, in most cases, hydrogen stored onboard the vehicle, a topic discussed further below, could also be in this state.) Liquid delivery to the station is, in fact, currently the approach in the Northern Germany Alstom project; however, at least a full reliance on this method will be changing in the near future (S. Schrank, personal communication, June, 2019). Liquid hydrogen delivery has also been utilized for the AC Transit bus system previously mentioned. In the case of the former, the liquid hydrogen is primarily delivered from an off-site location about once every two weeks and, in the AC Transit case, approximately once a week (Byrne, D., personal conversation, July, 2014).

Transport of hydrogen via pipeline, while possible, would require a very high and stable (on the scale of years (US DRIVE, 2017)) demand (US DRIVE, 2017) (Reddi, Mintz, Elgowainy, & Sutherland, 2016). One source suggests that demand would need to be of the magnitude of 100 metric tons per day or more (US DRIVE, 2017), while another states that, at the city level, it could be the "lowest cost delivery option for station demand as low as 1,000kg per day, assuming that the city in question has a total demand of at least 150 metric tons per day (Krishna Reddi, Mintz, Elgowainy, & Sutherland, 2016). With demand as the primary driver, this explains why roughly 2,600 (km)/1600 miles miles of hydrogen pipeline that existed, as of 2017 (US DRIVE, 2017)[79] primarily linked hydrogen production facilities with nearby oil refineries and ammonia plants (Krishna Reddi et al., 2016; US DRIVE, 2017). In his Ph.D. dissertation on hydrogen as a fuel for rail, Hoffrichter compares this method of transmission for hydrogen within a rail network to distribution of electrical energy across "short-to-medium" distances (Andreas Hoffrichter, 2013). He notes that, from an aesthetics and overall environmental impact point of view, an underground hydrogen pipeline could be quite advantageous. In the short-term, whether the necessary hydrogen demand exists for such an approach to be cost-effective for a given refueling station would depend on if it were located in a dense, urban area (Krishna Reddi et al., 2016; Yang & Ogden, 2007), how significant the overall hydrogen demand is in the general vicinity (Krishna Reddi et al., 2016; Yang & Ogden, 2007), and how close the station is to any major hydrogen production facilities (Krishna Reddi et al., 2016; Yang & Ogden, 2007). Pipeline might also work well for the freight rail sector, broadly, with its very large fuel demands[80]. However, given how far apart many of the major refueling facilities are, it might make just as much sense to have onsite production at these facilities. In the case of passenger rail, the challenge over the mid-term will be overcoming the

[79] This number of pipeline miles dedicated to hydrogen is only about 1% of the miles of pipeline that exist, onshore, to transport natural gas! (US DRIVE, 2017)

[80] According to one freight railroad employee who is knowledgeable on the matter, a major freight railyard (where much of the refueling occurs) might consume up to 750,000 gallons of diesel fuel per day. Considering the higher efficiencies found for a hydrogen powertrain, as measured in this study (and detailed in Chapter 5), this would translate into a daily hydrogen demand of over 650 metric tons per day.

current limitations of hydrogen storage (discussed in more detail, below) such that hydrogen could be utilized to run the higher speed trains that are prevalent in dense rail networks across the globe (and which would probably play a significant role in the likely case that domestic rail networks expand here in North America). Otherwise, the OLE infrastructure would remain necessary, in any event, and thus OLE would remain as a formidable alternative to hydrogen for slower, but still frequent trains that travel along these same rail networks.

As with LNG, the colder, liquid form of hydrogen is advantageous from an energy density standpoint vis-à-vis its warmer, gaseous counterpart, perhaps taking approximately half of the space that would be required by gaseous. hydrogen at 700 bar (Grasman, 2013; K. Reddi, Mintz, Elgowainy, & Sutherland, 2016); however, liquefaction is also less efficient a process, with the losses during the liquefaction process that were noted earlier. Despite the technology's overall high capital costs, (Andersson & Grönkvist, 2019; Wilhelmsen, Berstad, Aasen, Nekså, & Skaugen, 2018) research from the Department of Energy suggests that, if an individual station chooses to go with delivery of hydrogen rather than onsite production, liquid hydrogen may be the cheaper option, from a capital cost standpoint, primarily due to the reduced costs of onsite storage relative to compressed (or gaseous) hydrogen (with the data relevant for a station needing to dispense about 4,000 kg of hydrogen per day (Petitpas & Moreno-Blanco, 2018), and the relative advantage for liquid hydrogen increasing with even higher quantities (Petitpas & Moreno-Blanco, 2018; Krishna Reddi, Elgowainy, Rustagi, & Gupta, 2017))[81].

As is the case with LNG, the potential for within-tank boil-off remains a concern (Andreas Hoffrichter, 2013; Krishna Reddi et al., 2016; Schwartz, 2011), though it can be minimized through proper insulation of the storage medium (Linde) and, in many cases, this

[81] Due to the significant electrical energy inputs into the process, the cost of the liquefaction process will also be very sensitive to electricity prices. (Yang & Ogden, 2007) This would likely affect the liquid delivery price, too.

gaseous hydrogen, once vented from the main tank, can be retained for use in the application. (Indeed, the Alstom application in Germany has been able to retain use of liquid hydrogen that has “boiled off” into compressed/gaseous hydrogen [see figure 5, below].)

Figure 5: A Thermally, Vacuum-insulated, Stainless Steel Tank from Air Products
(Photo from author's collection)

Used to refuel the hydrogen rail tank at Bremervörde, Lower Saxony, Germany, this tank is designed to work over a temperature range of 38C to -269C (100F to -452F). It can hold ~2600 kg Liquid Hydrogen, and has a "water capacity" of 10,850 U.S. Gallons (41,071 Liters). A trailer such as this one provides about enough liquid hydrogen for two weeks (S. Schrank, personal conversation, June, 2019) for the two multiple-unit vehicles currently in service along the Buxtehude to Cuxhaven line. A substantial portion of the interior of the tank is, rather than empty area that can hold the fuel, made up of insulating materials that assure that the liquid hydrogen will mostly remain in this state for this relatively long period.

Energy density (i.e. energy per given volume) poses the main challenge for hydrogen fuel vis-à-vis the incumbent diesel technology. Hydrogen is a very light gas, so, even in liquid form, its per gallon energy density is much lower than diesel fuel (less than ¼ of diesel fuel, according to the author's calculations[82]).

There has been considerable progress made in the lifetime of fuel cell stacks. Earlier in the decade, lifetime maxima were close to the 20,000 hour range (Hoffrichter, 2013). Now, however, stack life, in operation, has exceeded 31,000 hours (Leslie Eudy, 2019) so, while this still puts fuel cells at a disadvantage against diesel engines, recent improvement rates and significant technology R&D being fed into this area (e.g. by the U.S. DOE) suggest that fuel cell lifetimes are likely to continue to improve significantly. (Fuel cell lifetime reaching parity with that of the diesel engine may not be likely to happen in the near future; however, measuring true parity is not an easy task. While diesel-electric locomotives have lasted up to 30 years and even longer (CARB, 2016)[83], this includes major refurbishments, including a diesel engine overhaul after each 8 year period[84]—assumed in this study to cost about 1/3 of the original equipment cost, based on anonymous, "ballpark" input from industry members.) Depending on the exact usage pattern, and continued improvements in stack material recyclability (James, Huya-Kouadio, Bach, & Knights, 2019), a lifetime of roughly 40,000 to 50,000 hours might be reflective of a good goal to aim for in order to eliminate this factor as a cause for major concern.

As alluded to earlier, energy density of liquid and gaseous hydrogen may be the primary challenge with hydrogen, particularly in a rail context; this despite the use of fuel cells, which

[82] Based on (K. Reddi et al., 2016).
[83] Engineers familiar with the rail industry suggest, however, that increased complexity among recent tier engines is likely to reduce the lifetime of the diesel-electric locomotive engine (H. Wancura, personal communication, August 26, 2015 & D. Cook, personal communication, August 26, 2015).
[84] The figure of 8 years was estimated based on information provided by or, in some cases, confirmed by multiple people with the relevant knowledge and access to proprietary data on locomotives.

have higher efficiencies than would be achieved through combusting the gas. In the coming decade or two, however, technological solutions may be able to largely solve these issues. One potential approach, known as cryo-compressed hydrogen, involves liquid hydrogen storage at very high pressures. Early research has shown that energy density could be increased significantly with such a technology (Aceves et al., 2010; Satyapal, 2019), thanks, largely, in part to a reduction in evaporative losses during refueling and even onboard of the vehicle (Aceves et al., 2010).[85] Questions, however, do remain about the lifetime of the tank that would contain this high-pressure liquid hydrogen and the durability of its insulative qualities (Aceves et al., 2010). Beyond this approach, there are also various storage mechanisms that fall in neither the liquid nor conventional compressed gaseous categories, and which also could lead to higher densities of hydrogen(Prabhukhot, Wagh, & Gangal, 2016; Taube, Lutz, Bürger, & Jepsen, 2019) (than conventional liquid storage) thanks to the element's ability to bind to surfaces (Murray, Dinca, & Long, 2009). (One source notes a potential volume reduction of two to three times (Taube et al., 2019).) On the metals end, there are metal hydrides and metal organic frameworks (MOF), both of which are often referred to as "solid state hydrogen (Prabhukhot et al., 2016)," and each of which uses a variety of materials that can "reversibly and rapidly store hydrogen" (Murray et al., 2009). The former relies on strong chemical bonding of hydrogen to a solid, known as chemisorption (Murray et al., 2009), and uses only about half of the energy for storage required by gaseous applications (and an even greater reduction as compared to liquid hydrogen (Grasman, 2013)). In these structures, the hydrogen acts as if it were a metal (Prabhukhot et al., 2016) and, due to the fact that energy is actually required to release hydrogen from the hydride

[85] A proof-of-concept prototype of this technology has undergone some testing, during the last decade, by BMW and Linde (Kunze & Kircher, 2012). Some technical findings of the testing are presented in (Petitpas & Moreno-Blanco, 2018)

structure, such a storage mechanism would carry a low risk of leaks (Grasman, 2013). MOF's, meanwhile, work through weaker physical bonding (or "dispersive interactions" (Murray et al., 2009)) of hydrogen gas to a solid (and works best when there is a large surface area (Prabhukhot et al., 2016)), called physisorption. MOFs have demonstrated some of the highest densities, and display a superior rate of hydrogen release (Prabhukhot et al., 2016); however, so far the highest densities were only at very low temperatures (typical of cryogenic liquid (Prabhukhot et al., 2016)). The so-called "rare earth" metals are often utilized in the case of metal hydrides (Prabhukhot et al., 2016), though magnesium-based hydrides have also been experimented with (Prabhukhot et al., 2016). Unlike with MOF's, the major challenge with the metal hydrides is often a very high temperature requirement. Metal hydride materials can also be quite heavy ((Gambini, Manno, & Vellini, 2007; Grasman, 2013))---though there is significant variation across hydrides, especially when considering those identified as "complex" hydrides (Prabhukhot et al., 2016); moreover, the heavy weights may not be a major concern in the case of rail applications (Hoffrichter, 2013). Since neither of the two metallic approaches requires the high pressure required of gaseous hydrogen (Murray et al., 2009), there is a safety benefit vis-à-vis the conventional methods noted above.

Another method of hydrogen storage that may hold promise (particularly in terms of energy density) involves compounds known as liquid organic hydrogen carriers (LOHC). These carrier compounds undergo both hydrogenation and dehydrogenation, processes that involve reactions with a hydrogen compound (Niermann, Drünert, Kaltschmitt, & Bonhoff, 2019). On the one hand, these substances are safe (Niermann et al., 2019), less costly than solid state hydrogen (Niermann et al., 2019), not particularly heavy(Aakko-Saksa, 2017), and they also possess many characteristics similar to conventional liquid fuels (and could thus perhaps utilize much of the existing fuel infrastructure (Niermann et al., 2019)); however, in the case of many LOHC compounds, high temperature requirements may be difficult for PEM fuel cell stacks to achieve, especially during the dehydrogenation phase (Niermann et al., 2019). The latter might be addressed by partial burning of the hydrogen, itself (Niermann et al., 2019), though this reduces the efficiency (Niermann et al., 2019). (Waste heat from a fuel cell can also be valuable; however, this is only a practical possibility for higher temperature fuel cells. (Niermann et al., 2019))

Downsides of this technology include high cost (Aakko-Saksa, 2017; IEA, 2019b), side reactions that mean that the carrier has to be occasionally replenished (Niermann et al., 2019), and a lack of purity of the hydrogen (Aakko-Saksa, 2017). In addition, the carrier molecules need to be transported back to their original location after releasing their hydrogen (IEA, 2019b).

Broadly speaking, one of the main obstacles to practical implementation of fuel cells has been stack cost, and a lot of this cost can be attributed to the use of particular materials. For example, in order to facilitate the redox (i.e. oxidation and reduction) reactions that are integral to the ability of the fuel cell to reliably produce power from a fuel such as hydrogen, catalysts are used. In the case of PEM fuel cells, platinum has been found to be highly suitable (Tang et al., 2018), given that element's stability, activity, and selectivity[86] characteristics (Holton & Stevenson, 2013). Platinum, however, is also very expensive, as a relatively small amount is annually mined (consistently less than 200 metric tons per year (Statista, 2019b)), especially as compared to gold (roughly ten times that amount (Statista, 2019b)) or silver (roughly 100 times (Statista, 2019a)). In fact, as a result, the element has typically been responsible for about 10-

[86] Selectivity has to do with the kinds of products that a catalyst facilitates given a specific set of reactants.

15% of the total stack cost (Colbow, 2018). The oxidation reaction at the cathode has been of the most focus among experimentation with catalyst alternatives (Holton & Stevenson, 2013; Tang et al., 2018) that might allow for the elimination or at least reduction of platinum required. Frequently, the alternatives are not adequate, demonstrating lower stability as well as a lower power density (Kongkanand & Mathias, 2016),; however, some success has been seen with redesign of the catalyst layer, e.g. when using platinum alloys (Ballard, 2017). Further research in this area could lead to considerable breakthroughs, especially as platinum is not without other challenges, including its susceptibility to poisoning[87] (Tang et al., 2018) and durability concerns (Steinbach, 2018; Tang et al., 2018).

More recently, one fuel cell manufacturing company, in association with a team of researchers, has found that moving away from using steel in the so-called “bipolar plates”[88] of the fuel cell stack and instead relying on carbon-based materials reduces stack cost slightly and extends the stack lifetime due to these materials’ superior recyclability (James et al., 2019).

As for sizing of the equipment, a lot of progress has been made with regard to fuel cell technology. (Noted, also, in Section 3.7, the topic of prime mover size is actually quite crucial to technological feasibility, particularly with a hybridized powertrain.) Fuel cell stack size has come down significantly, perhaps even up to 4-fold since 2000, according to one industry representative.

The public has, until very recently, had very limited experience with hydrogen as a fuel and some evidence suggests that the public is, in fact, a bit weary of hydrogen as a

[87] See footnote 63 for a definition of this term.

[88] A bipolar plate has many functions within a fuel cell. Its key roles include primary cooling, distributing hydrogen evenly across cell, and joining the anode of one cell to the cathode of the next one (facilitated by its location between one fuel cell and its neighboring cell in a fuel cell stack).

transportation fuel (Kolodziejczzyk & Ong, 2019). An event that perhaps influences older adults' perceptions significantly more than those of the younger generation, tales of the Hindenburg disaster likely overplayed the role, in the mind of some experts, of hydrogen[89]. It is true that managing hydrogen's risks involves some different approaches than those applied to the liquid fuels that have traditionally fueled our transportation system, but different risks are not necessarily greater risks. (Research attempting to specifically compare the risks, from a benefit-cost perspective, is still in its early stages (Brian Ehrhart, 2019) (B. Ehrhart, personal communication, December 12, 2019).) In most cases, new methods of infrastructure protection need to be employed, which involves technologies that are more complex than has been the case with diesel fuel (for example, pressure sensors and leak detectors, along with related warning systems (CH2M Hill Canada Limited (now Jacobs Engineering Group) et al., 2018), would be necessary since hydrogen is an odorless and colorless fuel), and these technologies likely add some cost.

Some characteristics, for example the fact that hydrogen flames tend to burn straight upwards, lead to pretty clear solutions (e.g. placing storage as high as possible, on the roof of a vehicle in the case of onboard storage) that greatly mitigate hazard risks.

In both production and storage of hydrogen, proper ventilation goes a long way in mitigating hydrogen safety risks. Limiting the rates and amounts of escape would be a priority so as to keep the gaseous mixture nearby below the flammability limits (i.e. the atmospheric

[89] A former Hydrogen Program Manager from NASA conducted extensive research into the disaster and its cause (Bellaby, 2017). Based on the research, he concluded that the coating of the Hindenburg's fabric covering was a poor conductor (Bellaby, 2017). As a result of this material characteristic, combined with characteristics of the approach towards land, an electrical charge led to the ignition of the airship's fabric (Bellaby, 2017). (The possibility of such an event occurring had in fact been noted by the Zeppelin company, itself, based on testing of the fabric material. (Bellaby, 2017)) The hydrogen then did contribute to the progression of the fire, but only once it had already been ignited by the combination of the electrical charge and the flawed material (Bellaby, 2017).

concentration at which a flame can result) (CH2M Hill Canada Limited (now Jacobs Engineering Group) et al., 2018). As with any fuel, periodic inspection and leak testing would also be necessary. As a gas, however, leak testing is a bit more complicated. Moreover, unlike the case with natural gas, for which chemicals known as mercaptans are often added in order to allow for human detection (Ogden, Jaffe, Scheitrum, McDonald, & Miller, 2018) (and which give the gas an unpleasant smell (Independent, 2013)), there is no equivalent chemical that is appropriate for use with hydrogen (Ogden et al., 2018). One key approach, however, is to use UV flame detectors instead (HydrogenTools, 2019).

Hydrogen refueling rates, from a per kg perspective, are not quite as fast as some of the natural gas refueling speeds that have been recently achieved. That said, the fuel has a much higher specific energy (energy per mass) than does natural gas (see Figure 6, below) and this, combined with the efficiency advantages of the fuel cell over the combustion engine, means that much fewer kg need to be loaded onto the vehicle, in any event. Currently available estimates suggest a rate of about 6 to 7.2 kg/minute per fuel connection (Elgowainy, 2018; J. Levin, personal communication, May 2, 2019). However, more than one dispenser at a time could be used for a rail vehicle (assuming that the tank system is designed for such). In fact, in Lower Saxony, two fuel connections are used, in this particular case, one dispenser for each car of the multiple unit vehicle (S. Schrank, personal communication, June, 2019).

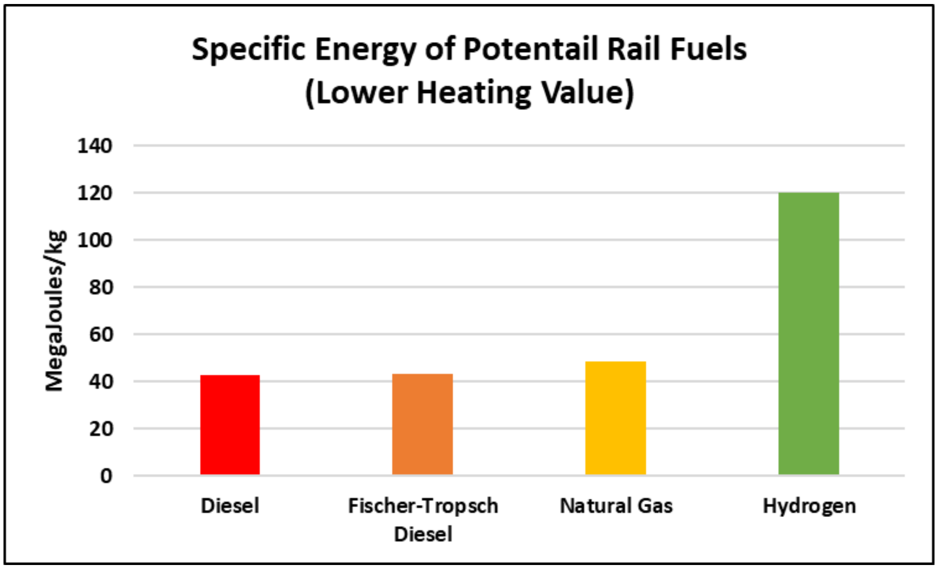


Figure 6: Specific Energy (energy per mass) of Various Rail Fuels Examined in this Study (Numerical values from U.S. DOE, 2008)
Note that these numbers do not include the weight of associated storage equipment, the impacts of which can be significant.

3.7 Batteries and Hybridization

Hybridizing rail powertrains with significant amounts of battery power is not a new idea, but only very recently, as innovations in newer battery technologies have occurred, along with resulting volume and cost reductions in these technologies, has this become a commercially viable approach to pursue. The unique advantage of hybrid powertrains stem in part from the nature of prime movers, which have optimal operating zones. Operating frequently in these zones allows for both the highest possible operating efficiency and a maximal lifetime of the equipment (through minimizing stresses on the equipment). Moreover, especially in cases where there is a lot of starting and stopping or, at least, acceleration and deceleration, hybridizing a system with batteries allows for the ability to re-capture "regenerative" energy, i.e. the energy that would otherwise be released outside of the vehicle system during braking. This energy is currently lost via conversion to heat, both through friction as well as through the use of electrical resistors on rail vehicles. Thus, hybridizing enables the reduction of primary fuel consumption. Meanwhile, it also allows for the reduction of the size (and power capacity) of the prime mover, a feature helpful both when the prime mover is particularly expensive (e.g. due to costly materials) as well as when storage space is limited. (Batteries and their associated cooling equipment can require a significant portion of space, as can either fuel cell stacks or stored hydrogen, with its low energy density, as noted above).

The early part of this century is when batteries as a propulsion method for rail applications first began to get more attention; however, this early history was marked by many challenges. It began in 2002 with the introduction, by RailPower Technologies, of the GG20B, or "Green Goat," as it came to be known (Brecher et al., 2014; Cousineau, 2006). These switcher locomotives relied on 330 lead acid batteries with a capacity of just under 1 MW, which were charged by a small on-board engine (Brecher et al., 2014). Following a lightning-induced fire on one of these switchers, nearly 60 of them were recalled (Brecher et al., 2014). (Among the problems with the equipment may have been an inadequate battery management system, problems with the battery mounting, with batteries going loose, and perhaps some exposed battery terminals (personal communication, M. Cleveland, July 11, 2019).) Some, but not all, were repaired (Brecher et al., 2014).

Despite the shortcomings of this particular equipment design, the Green Goat did demonstrate a fuel savings of 30-80 % (Brecher et al., 2014), a reduction in particulates (Brecher et al., 2014), along with lower operating costs and noise (Brecher et al., 2014).

Later that same decade, Norfolk Southern developed a switcher locomotive identified as NS999. Supported by the U.S. DOE and the FRA, NS999 is a roughly ~1 MW all-battery locomotive (Brecher et al., 2014). Initially consisting of over 1,000 lead-acid batteries (Brecher et al., 2014), the initial design struggled with issues relating to battery management and packaging (Barbee, 2015). In 2013, there was a transition to using advanced lead carbon batteries(Casey, 2013; Duve, 2019) (Brecher et al., 2014). Currently, the project is on hold, waiting for yet a newer battery technology, along with perhaps additional funding (M. Duve, personal communication, June 3, 2019).

Just prior to when NS999 was developed, a battery hybrid application was developed, in Japan, for a passenger rail system (Shiraki, Satou, & Arai, 2010). In 2007, the East Japan Railway Company began operating the battery-diesel hybrid (using a lithium ion battery[90]) multiple unit vehicle (Shiraki et al., 2010), claiming it to be the "world's first hybrid diesel railcar" (Shiraki et al., 2010). Vehicle operations have demonstrated a 10% reduction in fuel consumption and a greater than 50% reduction of "toxic substances" (Shiraki et al., 2010). The company has noted, further, the much quieter operation, particularly during station stops (Shiraki et al., 2010).

That a lithium ion battery was used for the Japanese application is not a small detail. Development of lithium ion battery technology is perhaps the key innovation relevant to batteries for use in transportation propulsion (along with the technology's increasing use in other sectors). With its origins dating back to just before 1980 (Blomgren, 2017), it was in 1991 that Sony came out with the first official lithium ion battery (Blomgren, 2017). This new battery type, which has seen tremendous worldwide growth and price reduction since the

[90] Further discussion of lithium ion batteries can be found later in this section.

beginning of this century (Pillot, 2017, 2018) (see Figure 7), brought with it significant improvements in specific energy (Blomgren, 2017), charge and discharge efficiency (S. Liu, Jiang, Wang, W., & Zhao, 2014), charge retention (Blomgren, 2017), and cycle life (Johnson Mathey Battery Systems, 2017).

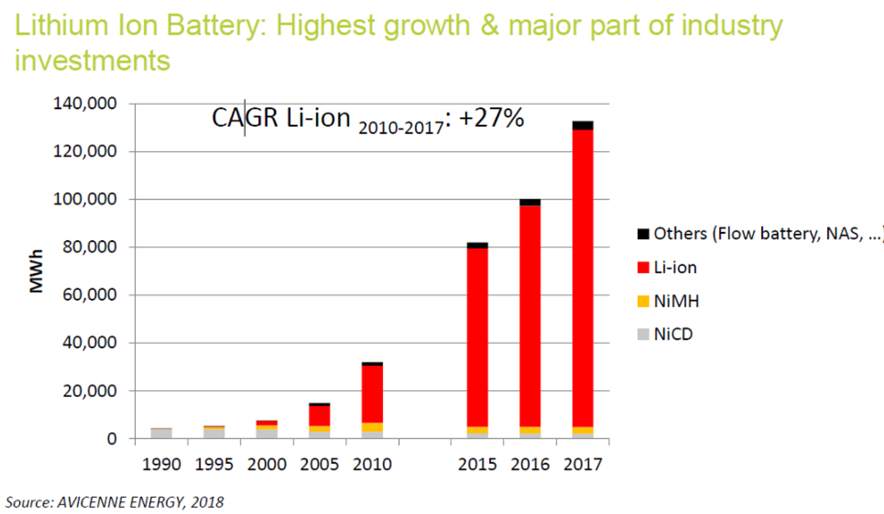


Figure 7: Global Growth of the Lithium Ion Battery

(Note that this graphic does not show the market for all battery types, however, as the lead-acid battery still has the largest market share

Source: (Pillot, 2018)

Lithium ion technology has now entered the rail sector, including here in the U.S., where, following awarding of funding from the California Air Resources Board (CARB), a partnership between BNSF, General Electric, and the San Joaquin Valley Air Pollution Control District began, in 2018, to design and test an all-battery locomotive in Southern California (Railway Gazette, 2018c). With a total capacity of 2.4 MWh, the specialized equipment will use a type of Lithium Ion battery known as NMC (Lithium Nickel Manganese Cobalt Oxide) (personal communication, Michael Cleveland, July 11, 2019), a battery introduced into the market in 2008 (Johnson Mathey Battery Systems, 2017). The equipment is to be tested in the 2020-2021 timeframe (personal communication, Michael Cleveland, July 11, 2019), and is being designed to work alongside conventional diesel-electric powertrains, perhaps reducing the total vehicle energy consumption by up to 10-15% (Railway Gazette, 2018c). The battery-electric locomotive will charge in Stockton, California, and the current expectation is a full charge time of 8 hours (personal communication, Michael Cleveland, July 11, 2019).

The lithium ion battery type selected for these analyses, the Lithium-Titanate (LTO) battery (with lithium titanate used as a cathode material), was chosen specifically for its superior characteristics in terms of safety (Brady, 2017; Cowie, 2015), performance (including a large temperature range of operation (Brady, 2017)), speed of charging (Cowie, 2015), and lifetime (Brady, 2017; Cowie, 2015) . It is likely for these reasons that this battery has in fact been used in several recent hybrid locomotive pilots, including a Turkish hybrid switcher locomotive (Railway Gazette, 2018b; Y. Telci, personal communication, November 7, 2018), a Deutsche Bahn-CRRC hybrid switcher locomotive (Barrow, 2018a) , and, on the passenger side, a Siemens battery hybrid electric multiple-unit (EMU) known as CityJet Eco (based on the Siemens Mireo) (Reidinger, Erwin, 2018). The main downside of the LTO chemistry is that the costs are very high, roughly 25%-50% higher than the NMC chemistry[91], which is increasingly being used within the automotive industry (and variants of which are expected to take even further market share within the EV battery market over the next decade (Curry, 2017)).

[91] This statement is based on comparisons between NMC and LTO from both Argonne National Laboratory's BatPac model (3.1) (ANL, 2019) and from CARB research (California Air Resources Board, 2016)

Increased production of the LTO chemistry could help to reduce the costs, though cost reductions are likely to occur with other lithium ion chemistries, too. (For example, one source suggests a drop of roughly 1/3 in the cost of NMC batteries that are used in EV applications (Pillot, 2018).) More broadly, newer battery technologies may arise and replace, or at least expand, the current stock of technologies (Blomgren, 2017).[92] These may be based on different cathode materials, as this part of the battery plays a crucial role in battery characteristics (Ambrose, 2019; New Scientist, 2017) (as well as cost (Pillot, 2018)). Battery energy density is one key characteristic that could improve, as a result, as shown in Figure 8 (from (Ambrose, 2019), below.

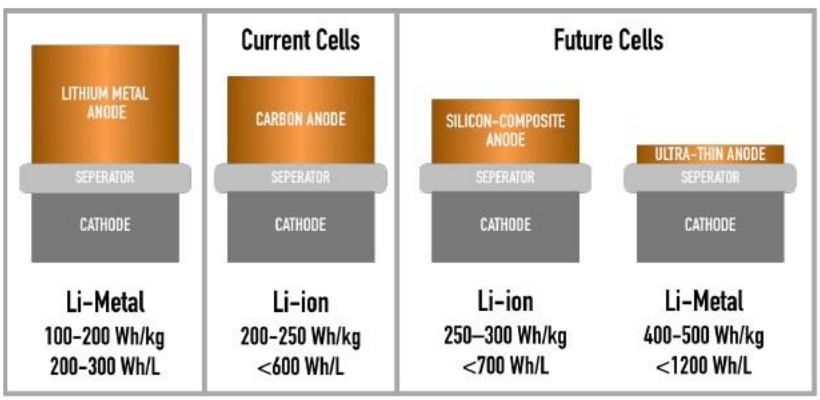


Figure 8: Potential Future Improvements, Energy Density, Lithium Ion Cells.
Source: (Ambrose, 2019)

[92] One source suggests that lithium ion battery technology may be nearing its energy density limits, in fact (Slovick, 2019).

3.8 Chapter Summary

This chapter has gone into significant detail on the fuel and related prime mover technologies that have been addressed in this study and its attendant analyses. Historical progress vis-à-vis the technologies was discussed, both generally as well as within the rail sector. Each technology, either alone or in combination, appears to offer a potential viable way to move forward. Chapter 4 covers the methodology of the present study, aiming to shift the knowledge from what was, in many cases in this chapter, theory-based context towards actual measurements and results based on high-level simulation of actual rail systems and routes, both passenger and freight.

Chapter 4. METHODS

4.1 Introduction

Previous chapters have introduced the reader to the background context in which rail propulsion decisions have historically been and continue to be made, along with an introduction to the technology alternatives being considered in this dissertation. This chapter outlines the methods, including the use of simulations and a few other key models, that the author used to compare the alternatives with regard to emissions, equipment costs[93] (including relevant fuel infrastructure), and energy consumption. The simulations performed by the author focused primarily on the diesel and hydrogen alternatives, and hybridized versions of these two, while post-processing allowed for analysis of some additional alternatives.

4.2 Background on the Simulator Tool Utilized to Assess Energy Consumption

In order to simulate a particular vehicle on one of the routes that was selected for these analyses (and compare that vehicle with its counterparts running on a different fuel), the author utilized an existing set of simulation tools, developed first between the University of Birmingham and the University of Warwick, both in the United Kingdom. More recently, this set of tools has undergone further development, with the assistance of a team of researchers at Michigan State University, along with some contributions from this author.

The tools include a MATLAB®-based tool for the development of rail drive cycles combined with a MATLAB®/Simulink®-based tool, which enables a more detailed analysis of

[93] Costs have been assessed with a focus on the comparative aspects; as such, components common to all technologies have not been considered.

the energy flows through the train's drive system. The combination of these two tools has made possible analysis of a range of route and vehicle system configurations, and it leads to the production of easy-to-interpret simulation output datasets and allows for straightforward sensitivity analyses to be conducted due to such changes (including, e.g., changes in component power or weight, a change in the degree of reliance on a hybrid energy source, such as a battery, etc.). Recent work between the author and MSU staff, noted in the introductory chapter, enhanced the tool so that it could work with the multiple number of locomotives commonly seen in freight applications as opposed to simply one locomotive, for which it was previously designed. Definition of control methods for energy management purposes is also fairly straightforward with this tool, though, in this case, research partners more familiar with the software handled more technical aspects of the simulation such as this.

As described in more detail in Hillmansen and Roberts, 2007, the MATLAB®-based Single Train Simulator (STS), introduced briefly above, uses a combination of forward (for acceleration) and backward (for deceleration) distance-based calculations to produce speed profiles for the routes and vehicle characteristics that have been input (S. Hillmansen & Roberts, 2007). The program relies on train kinematics and Euler's method[94] to develop, first, a duty cycle and, secondly, the power requirements at the wheel for that duty cycle. It does this through the processing of several inputs, including detailed information about the selected route (e.g. elevation changes as indicated through grade calculations across the span of the vehicle trip, station locations and station dwell times[95], and speed limits) as well as information about the

[94] More information is given on this method and its application in the STS in Douglas et al (Douglas, Weston, Kirkwood, Hillmansen, & Roberts, 2016))

[95] Dwell time refers to the period of time during which a train, or other public transportation vehicle, remains open to picking up new passengers while at a station stop.

selected vehicle, e.g. vehicle mass, acceleration and deceleration limits[96] proportion of powered axles to non-powered axles, and the resistance to motion coefficients. The latter are determined by the Davis equation, or a variant of this equation, sometimes referred to as an equation of motion. More information on such equations are provided in the box below.

[96] In the case of passenger rail, the acceleration and deceleration limits were constrained by passenger comfort considerations.

Box 1. Quantifying resistance to motion in trains

The Davis equation, a version of which is presented below, was developed in 1926 by an engineer, W.J. Davis, at General Electric.(AREMA, 2014; W. J. Davis Jr., 1926). The need for such a formula came from the fact that so-called "run-down" tests, in which resistance of motion is estimated by measurements of either deceleration over time during coasting or of the tractive effort required to maintain a constant velocity, at various setpoints (Rochard & Schmid, 2000), can be costly in terms of time, money, and the use of available rail track (Rochard & Schmid, 2000). The formula has since led to various alternative versions(AREMA, 2014; Rochard & Schmid, 2000). In each case, the coefficients developed were taken by applying statistical methods to the curves that resulted from the run-down tests. (Most formulas are very similar, with only the values set for A,B, and C varying(Hay, 1982)). Additionally, the various formulas assume operations under "average operating conditions"(W. J. Davis Jr., 1926) and, in their original forms, do not account for either grade changes or horizontal curvature (Andreas Hoffrichter, 2013).

Each, including the one used by the STS in this study, contain three constant terms and several variables.

Before showing the more complete Davis and Davis-like equations, we can show its origins, derived from the equation for force.

It is well known that:

$$F = ma \tag{1}$$

where 'F' stands for Force, 'm' for mass, and 'a' for acceleration.

It has also been established that:

$$P = Fv \tag{2}$$

where 'P' stands for Power, and 'v' for velocity.

Tractive effort, or 'TE', is used to describe the force at the wheel-rail interface which propels the rail vehicle along the track. But there are also forces of resistance, which can be indicated by 'R', faced by the vehicle in its movement.

As a result:

$$TE - R = ma \tag{3a}$$

Flipped around, this equation becomes…

$$ma = TE - R \tag{3b}$$

The Resistance to Motion equation is:

$$R = A + BV + CV^2 \tag{4}$$

(Rochard & Schmid, 2000) where 'V' stands for velocity, and there are three constants, 'A', 'B', and 'C'. The 'A' variable is mostly related to the weight/mass of the vehicle (typically specified as weight per axle in a North American context), and covers some of the track resistance (i.e. how the track reacts to the stress/load of the heavy vehicle), some rolling resistance (AREMA, 2014), and bearing resistance that is encountered (AREMA, 2014). 'A' stands in the formula without any external modification, and thus is static across all vehicle speeds. The 'B' variable is, as can be seen here, multiplied by the speed. Several of its components are, however, also mass-related (Rochard & Schmid, 2000), reflecting "mechanical resistances" (Rochard & Schmid, 2000), including rolling resistance (e.g. friction of the wheel's "flange"[97](AREMA, 2014; W. J. Davis Jr., 1926), and even oscillation of the vehicle along the track (W. J. Davis Jr., 1926)(Andreas Hoffrichter, 2019). Finally, the 'C' variable is, as the formula makes clear, multiplied by the velocity squared. This component of the equation reflects the aerodynamic resistance forces faced by the vehicle, including turbulence between the cars, "skin friction" along the side of the vehicle, and the aerodynamic drag forces against both the front and the back of the vehicle (AREMA, 2014; W. J. Davis Jr., 1926). (The C variable, when broken down into its constituent components, contains within it the frontal area.) Figure 9, below this box, demonstrates some of these relationships in a graphical format.

Below is a more complex equation, developed by a British researcher in the 1990's (Hill, 1994), that seeks to take into account additional factors (e.g. grade) into the equation of motion calculations. In addition to the three constants utilized by the Davis equation, it includes several variables previously discussed. Velocity and velocity squared are, however, shown in their derivative forms, and the left side of the equation shows acceleration in its derivative form. (λ accounts for rotational forces, e.g. such as from wheelsets, traction motors, and gears (AREMA, 2014). In some versions of resistance equations, the impacts of curving forces are also taken into account; however, such forces were assumed as 0 in the present investigation, in part due to the complexity of its measurement, and in part because vertical changes---i.e. in grade---have a more significant impact on the resistance forces (S. Hillmansen & Roberts, 2007).) Otherwise, newly used variables below include g for the acceleration due to gravity (i.e. 9.81 m/s^2), s for vehicle displacement (along the track), t for time, and α for the angle of the gradient (in degrees) [98].

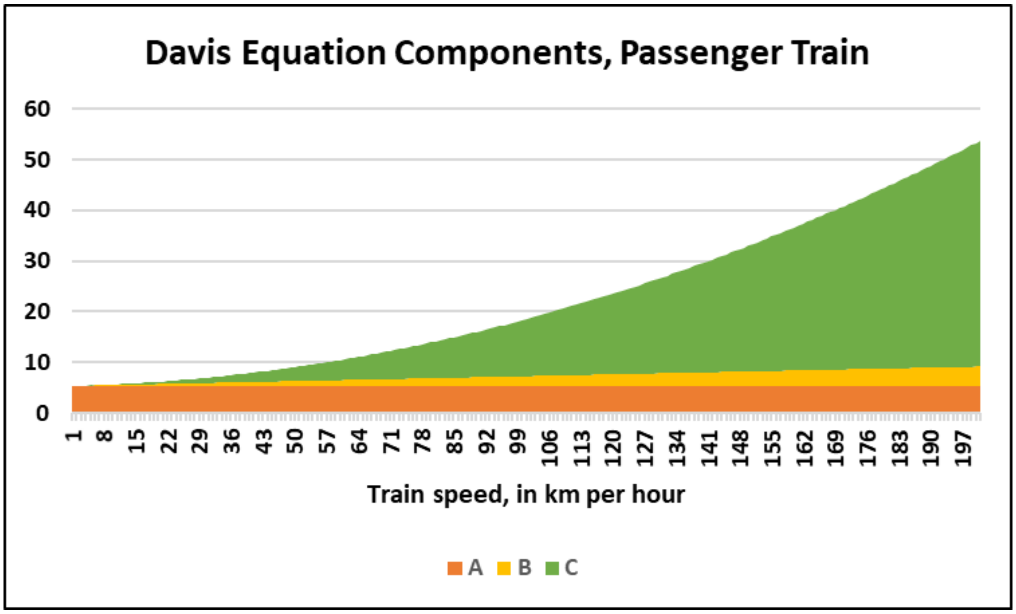
$$(1+\lambda)M\frac{d^2s}{dt^2} = TE - \left[mg\sin(\alpha) + C\left(\frac{ds}{dt}\right)^2 + B\left(\frac{ds}{dt}\right) + A\right] \qquad (5)$$

The $mg\sin(\alpha)$ component of this equation is where elevation changes, i.e. grade, are factored into the calculation. (A graphical depiction of the impact of grade on resistance can be seen in Figure 18.)

The STS utilized Formula 5 to calculate the motion of the railway vehicle(s) along the various routes.

Section 4.5, below, develops the resistance of motion coefficients used for the trains in this study.

[97] The flange, the side of the wheel with the larger diameter of the two sides, helps to keep the wheels on the rail.
[98] a is measured in m/s^2, F in kilonewton (kN), mass in kg, s in meters, t in s, and TE in kN. Finally, α (for the angle of the gradient) is measured in degrees.



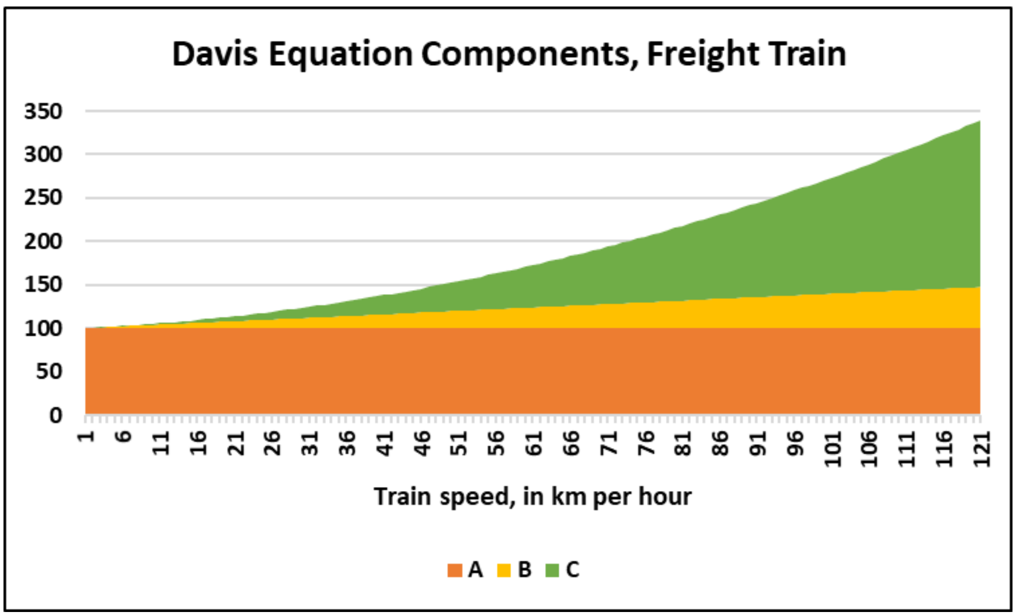


Figure 9: Resistance Forces versus Train Speed
(Passenger example based on Capitol Corridor; freight example based on KC-to-Wellington freight route. Both routes are described in further detail, below.)

The above two charts show the varying impacts of each set of resistance factors (i.e. A, B, and C components, each with their own corresponding coefficient) on the vehicle, as described above, as the vehicle speed changes. While the freight vehicle, with its heavy weight, faces higher resistance forces (and thus typically employs several locomotives), it can also be seen clearly, from these two charts, that the resistance due to aerodynamic drag becomes much more significant at higher speeds. This is due to the structure of the resistance of motion equation, as noted above: $R = A + BV + CV^2$. *(This result is one reason why freight trains typically travel much slower than passenger trains.)*

The “STS” model described above was utilized in several studies, including (Bocharnikov, 2007; S. Lu, 2013; Meegahawatte, 2010), for development of simulated route trajectories and calculation of wheel-level power and energy requirements. Further studies utilizing the tool have been used to assess alternative powertrains, including (A. Hoffrichter, 2013; Andreas Hoffrichter, 2013; Andreas Hoffrichter et al., 2015).

The simulator accommodates different driving “styles,” as the approach to “driving” a rail vehicle will (as with any vehicle) significantly impact energy consumption of the vehicle. In the present investigation, in order to compare the different drive systems’ maximum capability, the ‘’driving as fast as possible’’ style was used. This behavioral setting assumes that all of the available torque is applied at the axles during acceleration and deceleration and that, when a speed limit is reached, the train will cruise—at precisely the maximum allowable speed—as long as the required torque does not exceed the torque actually available to the vehicle.

The second, and related, tool used for the vehicle trip simulations was a Simulink model that was developed based on techniques utilized in the MATLAB®/Simulink®-based Warwick Powertrain Simulation Tool for Architectures, aka “WARPSTAR”. The WARPSTAR tool was developed by the University of Warwick (UK) primarily to explore hybridization potential of conventional automobile powertrains and energy management of hybridized (automobile) powertrains. Examples of WARPSTAR explorations of energy management of automotive powertrains include (Rajan, 2014), (Roy, 2014), and (Roy, 2016), while, in some other studies, wheel-to-wheel CO2 emissions were also calculated through the tool (Muraleedharakurup, 2011; Poxon, 2010)).

A new program was developed, based on WARPSTAR methodology suitable for railway applications, and this allowed for the introduction of several different rail powertrains. This

Simulink model, developed for a rail context (and used for these simulations), has also now been updated by a group at Michigan State University, again with contributions from this author, so that it, too, could work with the multiple number of locomotives commonly used to propel a single train in freight applications. As is the case with WARPSTAR, this Simulink model calculates speed, torque, power, energy, and component-related input values in a ‘backward’ manner, starting at the wheel-level (i.e. the vehicle system output) and sending that first component’s “inputs”, which then become outputs of the component one step up, all the way up to the fuel tank, the overhead line, the energy storage system, or some combination of the above power-providing technologies. (See Figure 10 for a graphical representation of this.)

The STS, as implemented for these rail analyses, required two primary sets of input: a) route information and b) vehicle information. (See Figure 23 for more details.) The Simulink outputs in this analysis included vehicle speed, torque inputs and outputs, traction and braking power outputs, energy storage inputs and outputs, state-of-charge information and electrical outputs (e.g. voltage or current) for energy storage devices, various sub-system duty cycle efficiencies, and energy consumption data from across the entire vehicle trip. The Simulink outputs for this simulation study are calculated in one-second time steps.

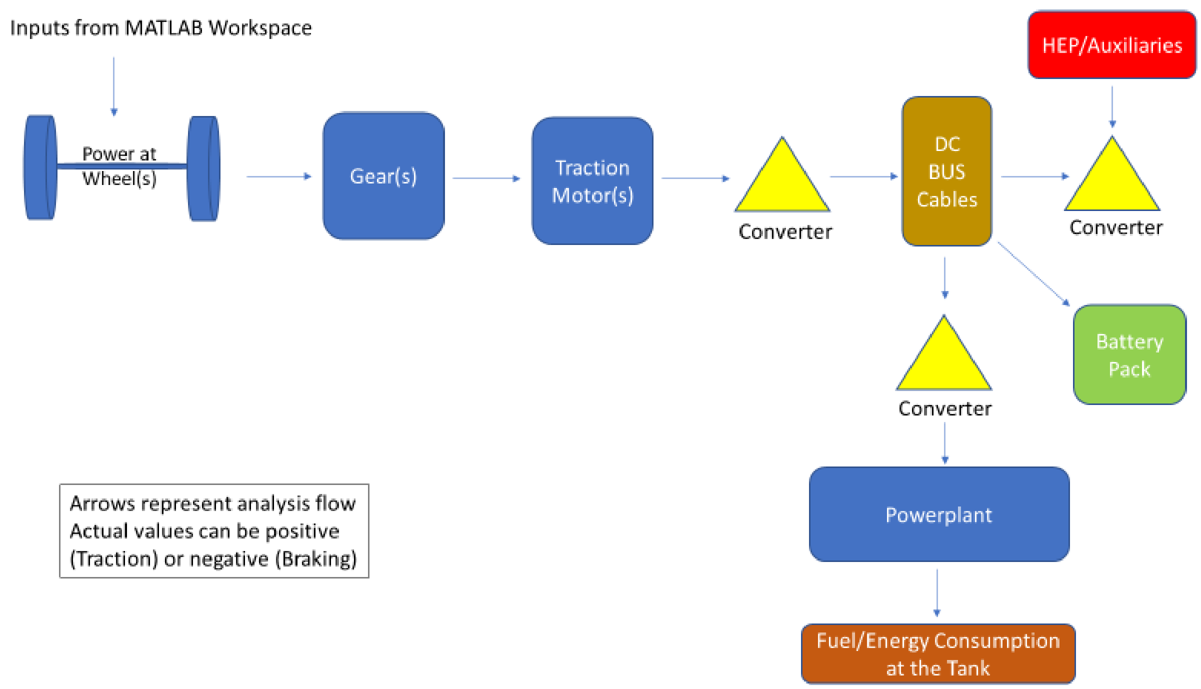


Figure 10: Simulink Structure for the Single Train Simulator (STS)

This graphic represents the Simulink structure for the STS tool that was used for this study. At the top left data inputs can be seen coming in from the MATLAB workspace. This input is continually used to process power requirements at the wheels throughout the course of the trip (based on route and vehicle characteristics). As a wheels-up Simulink model, the data is processed from the upper left corner of this graphic towards the right, with the fuel/energy consumption (whether diesel fuel or hydrogen)—one among a few key data outputs—located at the bottom right.

4.3 Routes Selected for the Simulation-Based Analyses

Northern California's Capitol Corridor route, which spans a corridor from San Jose to the Greater Sacramento region, is the third busiest route in the country (White, 2019), and also one of the routes along which the previously noted locomotive, Siemens' Tier 4 Charger, is also operating.

Figure 11: Siemens "Charger" Locomotive, Pulling a Train Behind It
(Photo from author's collection)

Serving Amtrak's 'Blue Water' Michigan route (though terminating in Chicago, Illinois), this appropriately branded ("Amtrak Midwest") train was stopped at the East Lansing, Michigan rail station. The Charger is now operating in six states.

This route (see Figure 12a, below), with a one-way distance of roughly 150 miles (241.4 km) is a bit of a hybrid commuter-intercity route, with a densely populated north-south span which covers much of the "East Bay" region of the SF Bay Area, followed by a less dense area that takes the train east, from Richmond, to Sacramento and the nearby stops of Auburn and Roseville. (The Auburn and Roseville stops are, at this moment, only one time per day in each direction (CCJPA, 2019); however, for the purpose of these analyses, the author has assumed that the route terminates at the Roseville station, several miles northeast of downtown Sacramento. This was done as future service is likely to terminate more frequently at this location (White, 2019)).

a.

b.

Figure 12 a-b: Passenger Rail Route Maps

a. Capitol Corridor Route Map (through October, 2017); b. Caltrain Route Map

Caltrain spans the west side of the San Francisco Bay (an area often referred to as the ‘Peninsula’), covering a route from San Francisco down through Silicon Valley, terminating most of the time at San Jose, but with a few trains each weekday that head to/from Gilroy, further south. Caltrain is more like a typical commuter-heavy service, especially with its relatively short one-way distance of under 80 miles, from San Francisco to Gilroy (Caltrans, 2015) (and from San

Francisco to San Jose is about 47.5 miles (76.475 km) (Caltrans, 2015)), and the predominance of closely spaced station stops along this route (see Figure 12b, above). Caltrain's daily ridership is well above 60,000 per day (on weekdays) (PCJPB, 2018) (Goodman, 2019). In fact, due to this very high level of ridership, Caltrain is currently in the process of a "modernization" program (PCJPB, 2018), which involves transitioning the system from diesel-electric to running on OLE, which would bring with it environmental and capacity benefits (PCJPB, 2014) (the former would be true, for certain, along the rail corridor itself due to the lack of operational emissions; the agency, according to its literature, suggests an overall emissions benefit on top of this local benefit (PCJPB, 2014)).

While Capitol Corridor has some station stops that are also closely spaced, it also has several stations, especially on its northern and eastern end, that are not so close to each other. Thus the author hypothesized that Caltrain would serve, additionally, as a good example of a rail system that would particularly benefit from hybridization, and this hypothesis seems to be borne out by the results (explained, in further detail, in chapter 5).

While every rail line is unique, these two passenger rail lines were selected---beyond their proximity to the author's institution and the resulting ability to efficiently obtain information---as they offer good examples from which to derive lessons that can be applied across the domestic passenger rail system, particularly outside of the Northeast Corridor, which, as noted earlier in this document, is atypical (for the U.S.) in its reliance on electricity and its rail traffic volumes.

Due to route-to-route and daily variability, the freight simulations were based on freight vehicle configurations and routes that exemplify typical traffic along a major rail freight corridor. In this case, the freight route was based primarily on typical activity on and characteristics of a route between Kansas City and Los Angeles, an approximately 2887-km (~ 1794-mile) route (see

Figure 13, below, for a map of the route in its entirety) that has approximately 35 to 40 trains in each direction each day, at many points along it (B. Smith, personal communication, May 30, 2017; US Federal Railroad Administration, 2017).

Figure 13: Map of the Corridor Selected for the Freight Simulations

The line highlighted in blue marks the simulated route, from Kansas City to Los Angeles.

The STS used in this study focuses on a single train trip. As such, estimates/assumptions of total activity for a given rail system over time, utilized primarily in the cost and emissions results sections, were set during a post-processing phase. In this study, as discussed further below, most of these estimates were based on likely activity between about 2022 and 2038. This time period was selected for a few reasons. While not in the very near future, the author considered this a time period for which both public rail agencies and private railroads are in the process of planning for (and this was confirmed by discussions with various industry representatives) as well as a period during which market and technological development of fuel alternatives to diesel are likely to take place at a fairly rapid pace. Moreover, most passenger rail agencies and freight railroads have likely made commitments for the few years between now and the selected period while, beyond this period, cost projections are subject to much greater uncertainty and, thereby, error, with unpredictable technological changes perhaps throwing new technologies into the mix or rendering current technologies obsolete. Lastly, the median year, 2030, is a key data point that has been used in some significant rail assessments, including (IEA, 2019c), which, in its base scenario, projects significant growth in both passenger and freight rail during the period between 2017 and 2030 (IEA, 2019c).

4.4 Switcher Energy and Emissions Analysis

Beyond the passenger and general freight rail assessments, data from a switcher locomotive was examined to assess the advantages of diesel (and an internal combustion engine) vs. hydrogen (via fuel cell), and how hybridizing a switcher powertrain would impact energy use and emissions in this unique context[99]. The STS was not used for this assessment; rather, results were, in the main case, assessed based on a "standard" switcher duty cycle (as made available to the public(e-CFR, 2019)), and from throttle notch[100] settings (and respective diesel fuel consumption data, by notch) provided from a study on a genset locomotive[101]

[99] Switching's contribution to rail energy and emissions is not insignificant. Even looking just at switching activity within railroad yards, such activity amounts to about 5% to 10% of freight gallons consumed. (AAR, 2019a)

[100] Most locomotives actually operate via power/throttle settings that are known as notches. Beyond the idle setting, there are typically an additional 8 notches (numbered 1 through 8). Each setting is associated with a specific maximum power level (for the prime mover), though the equipment's traction control system can slightly vary the final power output of the prime mover (Simpson, 2018).

[101] Separate from the term, "genset," used elsewhere in this piece as shorthand for an engine attached to a generator, a "genset locomotive" is a locomotive that contains several smaller engines and generators. See Section 5.8 for

(Hedrick, Fritz, & Plunkett, 2012). A second dataset was also used, based on further EPA-based data on typical power per notch (e-CFR, 2019), publicly available fuel consumption data (per notch) and maximum power capacity data for several switcher locomotives (GATX, n.d.-a, n.d.-b), and the previously noted "standard" duty cycle (e-CFR, 2019), itself based on notch[102].

Pollutant emission levels were, rather than assessed by notch, based on overall switcher average emissions rates per fuel energy consumed, based on data (for 2015) from the GREET Model. In addition to showing what the equivalent impacts would be for hybrid switcher vehicles and hydrogen fuel cell switchers (and their respective hybrids), additional sets of pollutant emissions data were presented for a switcher, based on the switcher fleet meeting EPA's Tier 4 as well as California's proposed Tier 5 standards. One adjustment was assumed, however; while the EPA allows, under a slightly modified Tier 4 standard, higher NOx levels for switcher locomotives than for mainline, "line-haul"[103] locomotives (EPA, 2016b), the switcher locomotive fleet, in 2015, had achieved lower CO levels than had the line-haul fleet during that year (based on data from (GREET, 2018)), and both had already exceeded the CO emissions reduction required of Tier 4, for line-haul locomotives (EPA, 2016b). As such, the switcher Tier 4 level assumed in this study is in fact significantly lower than the actual Tier 4 level that has been set by the EPA, particularly the value for switcher locomotives.

4.5 Data Inputs to the Simulator

---

additional information on this equipment.

[102] The "standard" duty cycle information from the EPA (e-CFR, 2019) comes in the form of percentage of rated power by notch; hence, when combined with maximum power information, power by notch can be estimated.

[103] Line-haul is synonymous with mainline, representing locomotives in longer- and long-distances service (in contrast to switching and "road-switching," the latter referring to switchers that can perform aspects of both railyard service and mainline service).

Information on both of the passenger routes that were simulated, described in some detail above, was provided, in confidence, primarily by the respective rail service providers, while some additional, confidential, information came from the California Department of Transportation. Other assumptions were made, based either on the author's judgment (e.g. energy required for hotel and auxiliary power needs[104], station dwell time for the Capitol Corridor route), on data provided in relevant studies (e.g. station dwell time for the Caltrain route came from a study that included actual observed data points (LTK Engineering Services, 2012)), or on available data on components that are commonly used in relevant rail applications. The latter category is discussed in further detail below.

Information that allowed for realistic freight train and route scenarios came from information from the Association of American Railroads (e.g. the commodities most often shipped by rail, the cars most often used to transport a given item, and the typical tonnage of such a car (AAR, 2019c) (AAR, 2017)), as well as from both current and former staff from the Class I railroads. Figures 14 and 15, below, show the 9 freight scenarios (7 manifest trains[105], 2 intermodal trains) that were simulated.

[104] For the purposes of this study, auxiliary power has generally been used to refer to both what is sometime referred to as "hotel power," and what is more technically considered "auxiliary power." The former refers to lighting and heating/cooling needs aboard the train, while the latter includes such equipment as compressors and heat exchangers (e.g. radiators and other cooling equipment) that are required for proper management of the vehicle and its powertrain.

[105] A manifest train is a freight train composed of various car types and cargoes, typically a blend of shipments for multiple customers. A freight train is often constructed this way so as to maximize frequency and business efficiency of movements.

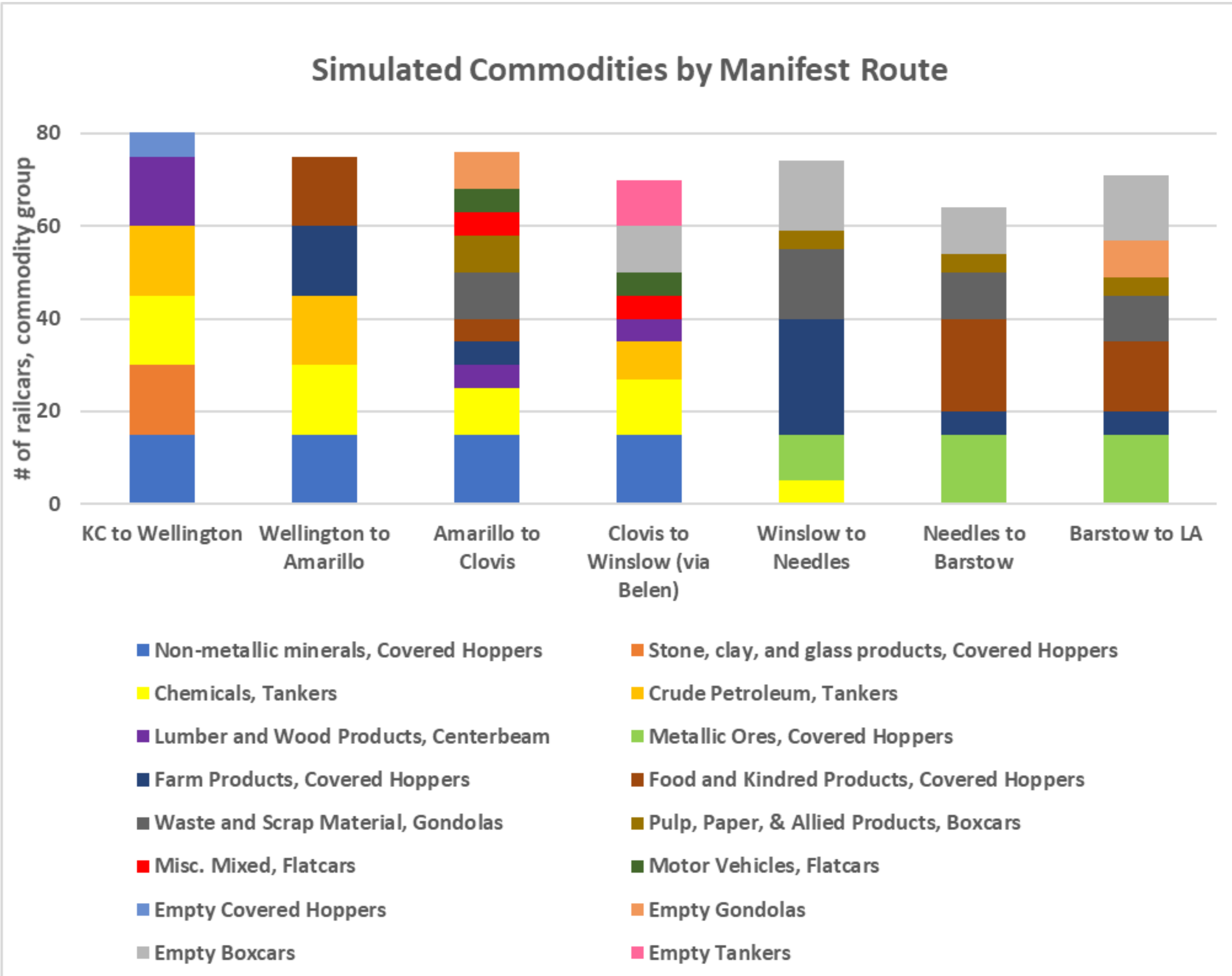


Figure 14: Commodities Shipped, as Modeled (for Weight and Car Type) in the Manifest Train Simulations

(Scenarios developed by author based on (AAR, 2017, 2019c)

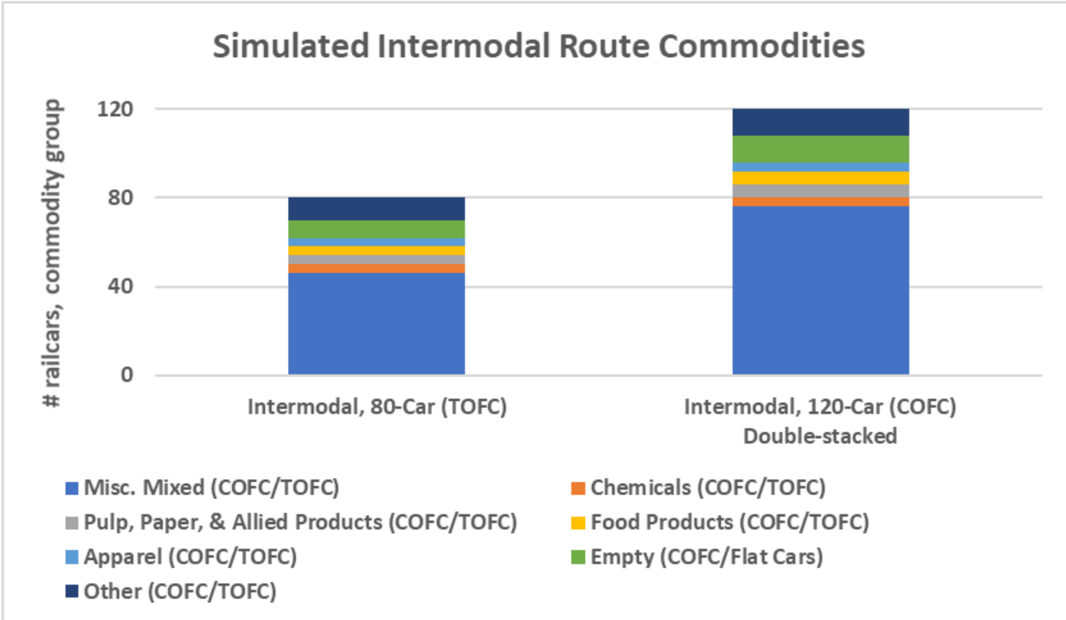


Figure 15: Commodities Shipped, as Modeled (for Weight and Car Type) in the Intermodal Simulations

(Scenarios developed by author based on (AAR, 2017, 2019c))

Figure 16: Wood Being Carried on a Centerbeam Car, Davis, CA

May, 2019

(Photo from author's collection)

This configuration is one of the car-commodity combinations that was modeled.

Table 4, below, shows the Davis equation variables calculated for and utilized in each of the freight simulations. (The equivalent variables used for the passenger simulations in Table A1 of the Appendix, while the weights of each freight train are in Table A2 of the Appendix.) The "Davis equation"/Equation of Resistance variables for this study were calculated based on a formula developed by Canadian National, in 1990 (AREMA, 2014), as this formula, as presented in (AREMA, 2014), included a list of "streamlining," or 'C' coefficient values by freight car type . That formula is

$$Rr = 1.5 + 18\frac{N}{W} + 0.03V + \frac{CaV^2}{10000W} \tag{6}$$

(AREMA, 2014) where Rr = Rolling Resistance of the vehicle, in lb/ton, N = the number of axles for a given locomotive or train car, W = Total weight, in tons, of the locomotive or car, V = train velocity, in mph, C = the "streamlining" (AREMA, 2014) coefficient for use for a given locomotive or car type, and a = cross-sectional area, in square feet, of the locomotive or car. (AREMA, 2014) The first two figures on the right side of formula/equation (5) thereby comprise the 'A' coefficient of the resistance formula that will be input into the simulator (following unit conversion, as described below). The third figure (which is multiplied by velocity) then becomes the 'B' coefficient, with the last figure (the fraction), which is multiplied by velocity squared, becoming the 'C' coefficient. Since the Rr value is defined in lb/ton, each of the values is then multiplied by the weight of that particular car or locomotive. Moreover, because the STS is designed to work with the metric system, the resulting force values are converted into kilonewtons (kN), along with the miles per hour values for velocity converted into meters per second squared.

Following unit conversion, the values produced by this formula for each car and locomotive that comprise a given train are then summed, so that the resulting value becomes:

$$Rr = \sum_{k=1}^{n} 1.5 + 18\frac{N}{W} + 0.03V + \frac{CaV^2}{10000W} \qquad (7)$$

where *n* stands for the total number of rail vehicles (both locomotives and cars), with unit conversions already completed (though not specifically shown in formula (7)).

The particular data used for the C coefficient, which attempts to account for aerodynamic influences of each vehicle within the train (locomotive or car), were based on values provided in Chapter 16 of the American Railway Engineering and Maintenance-of-Way Association (AREMA, 2014) (AREMA) manual (chapter title is “Economics of Railway Engineering and Operations”), values that are specifically for use with the Canadian National Train Resistance Formula. (In the rare case that a coefficient for the specific car type was lacking, the modal value of 5.0 was used for the calculations.)

Table 4: "Davis Equation"/Equation of resistance variables by freight train trip

(Note: Weights for each train are in Table A2 of the Appendix.)

Route Name	**Davis Equation Factors** **A unit: kN** **B unit: kN/(meter/sec)** **C unit: kN/(meter/sec^2)**	**Route Name**	**Davis Equation Factors** **A unit: kN** **B unit: kN (meter/sec)** **C unit: kN/(meter/sec^2)**
Kansas City to Wellington	A: 99.82646 B: 1.42327 C: 0.16983	Needles to Barstow	A: 65.37559 B: 0.87837 C: 0.15022
Wellington to Amarillo	A: 110.86862 B: 1.60248 C: 0.18475	Barstow to Los Angeles	A: 67.54399 B: 0.87690 C: 0.15185
Amarillo to Clovis	A: 86.76869 B: 1.08419 C: 0.14268	Intermodal 120 cars (Slow) Trailers on Flat Cars (COFC)	A: 60.29086 B: 0.79269 C: 0.14444
Clovis to Winslow (via Belen)	A: 73.57348 B: 0.99429 C: 0.11381	Intermodal 80 cars (Fast) Trailers on Flat Cars (TOFC)	A: 70.04239 B: 0.84400 C: 0.12038
Winslow to Needles	A: 74.89487 B: 0.99510 C: 0.15794		

Among the route data inputs were gradient, typical station stops and layover times, and route speed limits, which can vary significantly along the course of the route[106]. The assumed point of refuelling impacted the simulations to a minor extent; more importantly, it helped the author to determine the kinds of fuel storage options that might make the most sense for freight railroads should they decide to pursue either natural gas or, even more crucially, hydrogen as a fuel.

[106] In addition, for one of the two intermodal trips, all speed limit data points were adjusted upwards---by a constant value that led to limits about 25% higher in that particular scenario. This adjustment was based on information provided by one of the Class I railroads, which noted the higher speeds of certain intermodal trains (particularly those not relying on double-stacking).

Figure 17: A "Trailer-on-Flatcar," or TOFC, Going through the Davis, CA Station

September, 2017;
(Photo from author's collection)

It is these types of car combinations (i.e. a truck trailer carried by a "flatcar") that were modeled for the 80-car intermodal vehicle simulations.

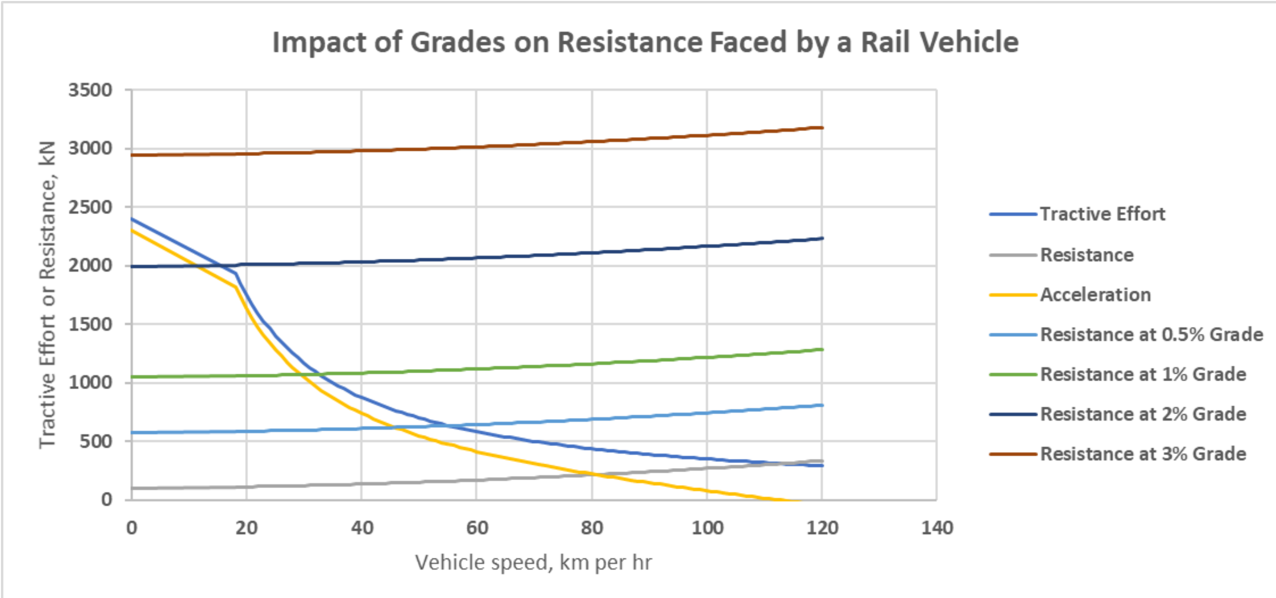


Figure 18: Impact of Grades on Resistance Faced by a Rail Vehicle

The freight routes simulated incorporated various gradients, depending on the actual topography of a given route segment. This chart shows the impacts that different grades can have on a train, and is based on the KC to Wellington route simulation. Where the Resistance line intersects with the Tractive Effort line, this is called the "balancing speed." The balancing speed represents the maximum speed that the vehicle can attain given characteristics of the train and the route, including, particularly, the gradient, in this example. (This particular train would have significant trouble moving at all along a 3% grade, given the power available from its assigned number of locomotives---3, in this case. Even with a 2% grade, the speed that this train could attain would be quite limited.)

Figure 19: Double-stacked Train Traveling through the Davis, CA Station September, 2017.
(Photo from author's collection)

A train similar to this was modeled for the moderate-speed intermodal vehicle, and was assumed to carry 120 cars, in total.

One caveat to note, from the freight data, is that the elevation data used was extracted from maps of the route that were a bit difficult to interpret (e.g. there was no consistent mileage scaling factor), and no access to the underlying data was provided. As a result, the gradient inputs, while generally reflective of this route, and perhaps others that span the area between California and the Midwest, do not reflect the exact elevation changes along the route as closely as the author would have liked. A map of the elevation utilized in the simulations can be seen below, in Figure 20.

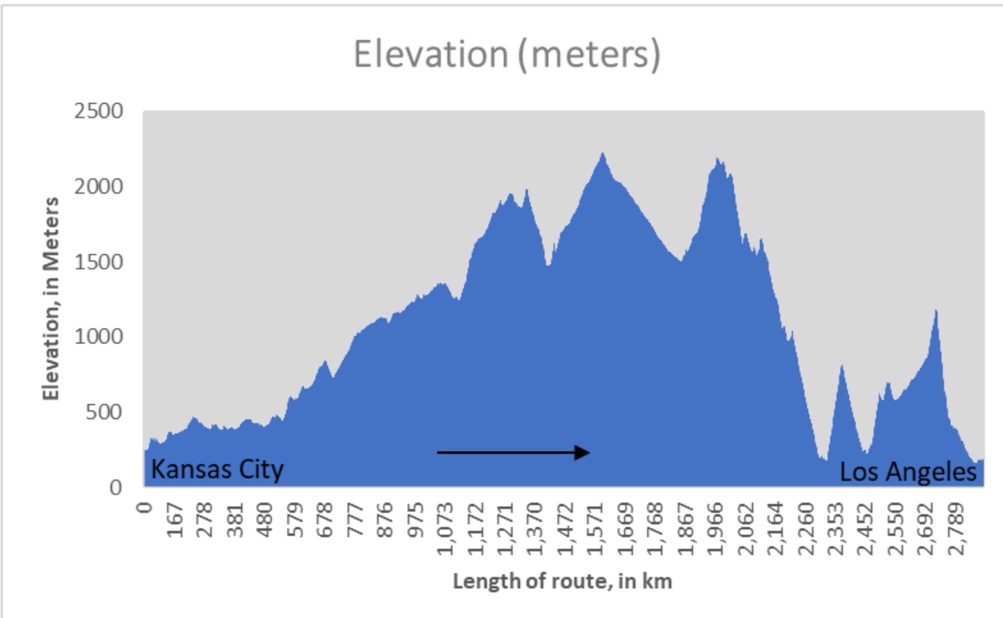


Figure 20. Elevation Map from the Beginning of the Route (Kansas City) to the End (Los Angeles)
This route was estimated at approximately 2,887 km in length, based on interpretations of map data (broken up into several segments of the total line) provided by one of the Class I railroads.

Maximum positive grade was set, for the purposes of the simulation, at 2.5%. 2.2% is generally considered the maximum "ruling" grade[107] in the U.S. (Andreas Hoffrichter, 2019),

[107] The term "ruling grade" refers to the official limiting grade between a given set of rail terminals. This value is important because it can be used by railroads to determine the maximum load that can be transported along the routes subject to that ruling grade, though there are other variables involved, also (C. Pasta, personal communication, December 4, 2019).

while one route, e.g. nearby the Cajon Pass, in California, is in fact closer to 2.8% in grade (C. Pasta, personal communication, December 4, 2019).

4.6 Physical Equipment and Componentry

The overall equipment and components for the rail analyses were modeled around equipment that is typical of the industry. Publicly provided information (e.g. product brochures (GE Transportation, 2016; Siemens, 2016)) was often used; at other times, freight railroad representatives conveyed information directly to the author on typical operational or equipment characteristics; finally, in a couple of cases, industry-provided (but confidential) data for rail equipment was provided and used.

Commonly utilized (domestically) locomotive equipment models were selected for numerous data input characteristics, including maximum horsepower, gear ratio, weight and other physical characteristics that help determine the kinds and levels of resistance forces to model. On the passenger side, the Siemens Charger served as the example locomotive[108]. This vehicle, an EPA Tier 4 locomotive, has served on the Capitol Corridor line since 2017(CCJPA, 2017); however, its service is by no means limited to California. Back in 2014, Illinois, Missouri, Michigan, Washington, and California were all part of a multi-state bulk purchase of the Siemens "Charger" locomotive (Cho, 2014), an EPA Tier 4 locomotive. More recently, All Aboard Florida, a private company, also purchased a nearly identical locomotive from Siemens for its rail service (now branded as Virgin Trains U.S.A (Bond Buyer, 2018; Larsen, 2018)), with only a more aerodynamic nose setting the locomotive apart from the earlier generation locomotive (and

---

[108] While Caltrain does not in fact use the Siemens Charger Locomotive currently, this assumption was made both because of the prevalence of the Charger (as discussed in the current section) as well as in order to minimize the number of variables that were varied across the different passenger scenarios. For the latter reason, the non-locomotive train cars that comprise the remainder of the train were also assumed to be of identical type and configuration in both passenger scenarios.

allowing for speeds of up to 125 mph (Briginshaw, 2016) (Turner, 2018), and Via Rail, of Canada, has also ordered 32 locomotives (alongside passenger cars) from Siemens (Barrow, 2018c), that will also be closely related to this model (Barrow, 2018c).

Five cars were assumed for each passenger train. Modeled primarily on the "California Car," which are the cars most frequently utilized along the route[109] (see Figure 21, below), an average weight (for a couple of different variation of car types, e.g. café car, one of which can typically be found) of 68.765 metric tons per car was assumed based on conversations with a representative who's involved in Capitol Corridor operations (D. Shepherd, personal communication, January 2019).[110]

On the freight end, several characteristics, including weight and gear ratio, were modeled on the ES44AC, a locomotive produced by General Electric. This locomotive is part of the so-called "Evolution Series," of which thousands of such locomotives are in operation across the country (D. Peters, personal communication, August 4, 2019).

Table 5 shows several of the characteristics of each of these locomotives, garnered from publicly available data(GE Transportation, 2016; Siemens, 2016). (At times, the modeled data was slightly different; the table indicates this where applicable.) Meanwhile, Table 6, below that, presents the various fuels and powertrains modeled in this analysis in a form that should be highly accessible to the reader.

---

[109] The exact number of cars can vary by train; however, five seemed to be a good estimate of what is most typical, based on conversations with agency staff (D. Shepherd, personal communication, January 2019).
[110] The weight of any passenger load was not included in the weight assumptions for the vehicle.

Table 5: Characteristics of the "Typical" Locomotives, as Modeled

The table below shows the characteristics of the "typical" locomotives upon which many aspects of each simulation were modeled. Where an estimate signifies that a slightly different value was modeled, the actual value utilized in the simulation is displayed and identified so that the distinction is clear.

***Note that the hydrogen passenger simulations did not always reflect the equivalent amount of hydrogen stored (as compared to the diesel fuel capacity noted below). For one, hydrogen is more efficient than diesel. Secondly, the storage can take up quite a bit of space, so, in attempting to minimize space (where possible) and show potential storage options, differing amounts of hydrogen were stored.**

Locomotive	Siemens Charger	GE ES44AC
Tractive Effort	290 kN	890 kN
Horsepower (gross[111])	Actual: 4400 (~3.281 MW); Modeled as ~3.1-3.2 MW)	Actual: 4500 (3.356 MW) (GE Transportation, 2016); Modeled as ~ 3.2-3.3 MW, depending on the route)
Weight	~123 metric tons	~196 metric tons
Axles	4	6
Fuel Capacity (Diesel Gallons)	2200 (Siemens, 2016)	5,000 (DieselShop, 2006)[112]

[111] Gross horsepower is a measure of the power directly produced by the prime mover, before any deduction due to losses and power that is diverted for auxiliary/hotel power.
[112] Discussions with numerous freight railroad employees (with access to proprietary information) also confirmed that locomotive fuel tank capacities generally range between 4,000 and 6,000 gallons of diesel.

Figure 21 "California Cars," the Railcars Typically Used along the Capitol Corridor Route
Photo courtesy of Rob Edgcumbe, and Caltrans (with permission granted)

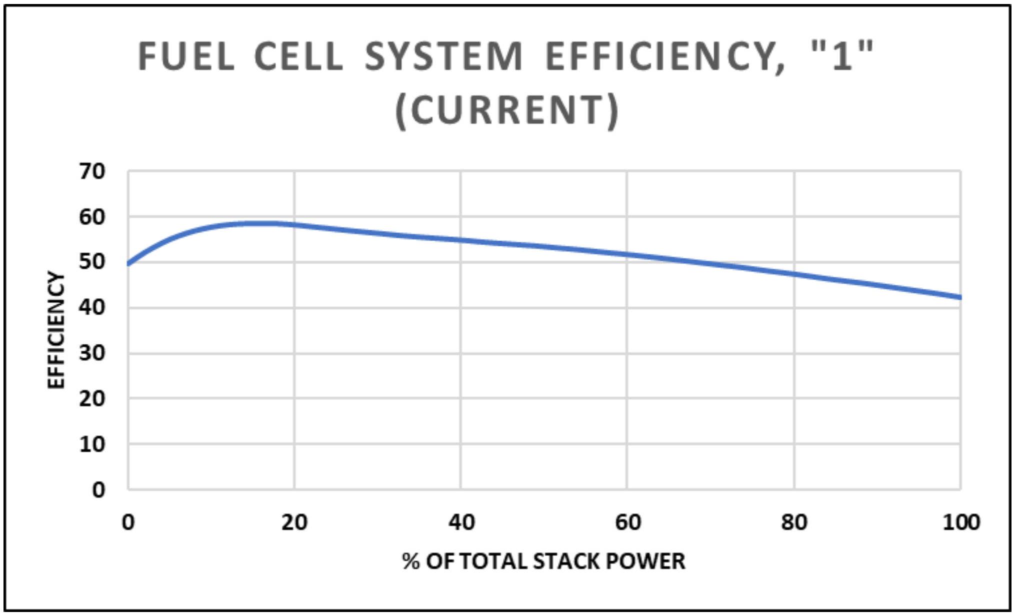
Data from the "bi-level" (i.e. double-decker) "California Cars" such as those pictured here, were used to estimate the weight and aerodynamic characteristics of the train for all of the passenger simulations.

Table 6: Fuels and Prime Mover Technologies Simulated

This table indicates the fuel and prime mover technologies that were simulated in this study, showing which rail service each technology set was applied to.

Prime Mover	Fuel	Rail Service Type(s)	Energy Consumption Results based on… A) Simulation of exact powertrain *or* B) Excel post-processing of simulation results *or* C) Excel Model
Internal Combustion Engine ("ICE")	Diesel	Passenger, Freight, Switcher	Simulation (Excel Model for Switcher Only)
ICE	Natural Gas	Passenger, Freight	Excel Post-Processing
ICE	Fischer-Tropsch Diesel	Passenger, Freight	Excel Post-Processing
ICE hybridized with batteries	Diesel	Passenger, Switcher	Simulation (Excel Model for Switcher only)
Fuel Cell (FC)	Hydrogen	Passenger, Freight, Switcher	Simulation (Excel Model for Switcher only)
FC hybridized with batteries	Hydrogen	Passenger, Switcher	Simulation
Overhead Line Electrification	Source fuels for electric power (electricity is an "energy carrier")	Passenger	Simulation

The size and power levels of the diesel-electric engine and generator were modeled after equipment standard for current day locomotives. In the case of the fuel cell, power levels were assumed the same as for diesel, while weights were based on available industry data (Ballard, 2016). Dynamic operating characteristics for the diesel-electric powertrain simulation were based on actual (proprietary) data from a typical locomotive diesel engine (though not representative of the very latest in diesel technology), along with dynamic efficiency data that would typically be associated with a locomotive generator (again, based on proprietary data). Dynamic operating characteristics were also utilized to model the traction motors, based on the relevant equipment associated with a typical locomotive application (provided, in confidentiality, to the author). For the fuel cell systems, operating characteristics were based on fuel cell efficiency curves developed from data provided in graphical format by the National Renewable Energy Laboratory (NREL) (Wipke et al., 2012) (and digitized). Two different fuel cell efficiency curves are modelled. One represents data that is comparable to non-published values reflective of recent heavy duty fuel cell technology (to which the author has had access), while the other represents a significant improvement (between 5 and 10 percentage points of efficiency improvement on average, across the efficiency curve) in fuel cell technology, with such improvements being a key goal of the U.S. DOE (US DOE, 2017). Graphical versions of the fuel cell curves utilized are presented in Figure 22, below.



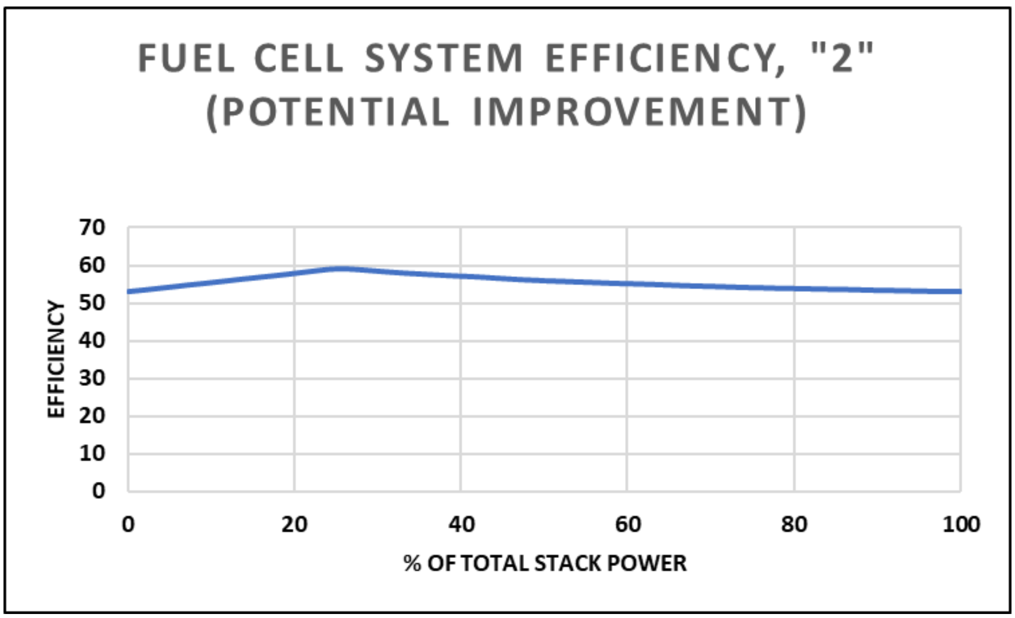


Figure 22: Fuel Cell System Efficiency Curves Utilized for the Simulations.

The above graphics show the fuel cell efficiency curves that were utilized in the present analysis. Based on information provided by the U.S. Department of Energy (Wipke et al., 2012), digitizations were performed, and this information was then entered into the Single Train Simulator. Curve "1" represents a set of values that line up closely with current, non-public efficiency curves, while curve "2" represents a potential future improvement in fuel cell efficiency. Both curves have been used throughout the passenger and freight simulations to show both a "status quo" as well as "best case" scenario for hydrogen fuel consumption (with Hydrogen 1, in Chapter 5, corresponding to the top curve, #1, and Hydrogen 2 corresponding to the top curve, #2).

In each case, modelling of the prime mover by the simulator program was combined with a control strategy implemented on the simulation side, as noted in section 4.2, above. (While locomotive engines are often operated via a notch system of set operating points, as described in Section 4.4, in order to illuminate the potential of a diesel-electric engine-generator setup, this analysis did not seek to emulate the notch system.) For example, each of the hybrid passenger simulations (both those with regularly sized prime movers and those with "downsized" prime movers, described in Section 3.7), assumed that the main prime mover operated close to the average operating point, in terms of power, throughout the operation of the vehicle along a given route; that way the battery system could account for power requirements above and beyond this point, and receive charge when not being utilized (in addition to receiving additional energy due to regenerative braking). In these hybrid scenarios, the final determination of the prime mover's operating point involved iteration of the simulator tool, particularly to a value where the battery state-of-charge stayed within set boundary points---selected as no less than 20% and no more than 92%---and returned to its initial point at the end of the journey---i.e. within about ½ of one percent. The assumed size of the prime mover, in terms of power, efficiency, and cost, was set somewhat higher than this operating point, with the assumption of, roughly, 10-15% buffer power available beyond the set operating point[113].

In the case of the passenger simulations, different weights were used for the diesel vs. for the hydrogen locomotives, based on highly detailed data on the kinds of components that would be necessary in a diesel-electric locomotive (i.e. that work alongside the engine), but not needed in a hydrogen locomotive. In addition, the hydrogen simulations were then iterated in order to

[113] The iteration process involved varying the prime mover's total size, also; however, as indicated by the varying buffer power assumed across scenarios, less precision was sought when setting this value (i.e as compared to when setting the operating point).

incorporate the weight of the accompanying hydrogen tanks, the number of which, due to space constraints and the typical use of multiple smaller tanks, was assumed to vary, depending on fuel needs along the route. In order to accomplish this iteration process, the vehicle was first simulated without any tanks on board, and then, once the fuel needs were determined, the weight of the tanks were incorporated into the simulations, with further adjustments made for any additional fuel required and any accompanying tanks required for that additional fuel. (Tanks were modeled, based on available industry information (Hexagon Composites, 2017), at 101 kg per 7.5 kg of H2 storage). A 20% buffer in additional available fuel storage volume[114] was assumed when determining the number of tanks required for the passenger hydrogen scenarios. In order to help meet the additional space needs required by the hydrogen tanks, the height of the locomotive assumed for the hydrogen rail vehicle was greater[115], by just under 0.5 meters (roughly 1½ feet), based on height of the bi-level "California Cars" described earlier (and as seen in Figure 21).[116] This larger vehicle was also assumed for the passenger hybrid rail simulations.[117]

In the case of the OLE passenger simulations, the weight of the locomotive was, again, adjusted according to the equipment needs of this powertrain.[118]

[114] Typical refuelling procedures for passenger rail, as described in Section 4.10, were used to set the fuel capacity baseline.

[115] While the locomotive height for the Siemens Charger is approximately 4.48 meters (14.7 feet) (Siemens, 2016), an assumed height of 4.91 meters (16.13 feet) was used for the locomotives that required hydrogen storage, based on the height of the "bi-level" (i.e. double-decker) coaches (D. Shepherd, personal communication, January 2019)

[116] There was no weight adjustment for the taller locomotives, as this space was seen as mostly hollow, allowing room for additional hydrogen storage (the tank weights for which were, as noted in the main text, included in the simulations).

[117] Again, no weight adjustment was made for the taller locomotive; however, battery weights were included in all hybrid simulations, with battery weight data based on (Altairnano, 2011).

[118] For the OLE locomotive, as with the hydrogen locomotive, a weight reduction was assumed for removal of the components that would be necessary only in a diesel-electric locomotive. Then the estimated weights of the transformer (~7.99 metric tons) and the pantograph (180 kg) (see glossary for definition) were added back in, based on detailed information provided by Amtrak (A. Otsuka, personal communication, February 27, 2019) and a European company that manufactures pantograph equipment (A. Gruber, personal communication, February 22, 2019).

The natural gas assessment was completed in post-simulation processing, as noted in Table 6, above, so incorporating tank weight into the assessment was not as straightforward. Moreover, despite a lower efficiency than diesel fuel---as modeled here[119], with a spark ignition engine[120], its higher energy density, vis-à-vis compressed hydrogen, means that compressed natural gas should require fewer fuel tanks for a given trip[121]. And, indeed, this finding appeared in the present analysis. (See Section 4.10 for more details on tank number and volumetric densities assumed, both with and without tanks.) Moreover, without relying simply on industry data on currently available tanks, it's been noted that hydrogen tanks require additional materials versus natural gas tanks (Ogden et al., 2018), and so the weight of the hydrogen tanks was deemed more significant of a variable, and thus worth including in the weight of the vehicle.

In the case of the freight analysis, highly precise weight differences were deemed not necessary to include in all simulations as one trial run estimating such differences indicated that the resulting reduction in energy consumption between diesel and hydrogen would fall within a 3% error level of the values found without including such weight differences. (The finding of this sensitivity run is noted in the results chapter.)

Train configurations within the freight industry can vary between locomotives distributed evenly throughout a train vs. locomotives all together (e.g. at the front of the train)---differences which can be traced to various factors, including locomotive availability or the available power distribution technology (UIUC-RailTEC, 2016). This distinction was not captured by this analysis,

---

[119] A 15% reduction penalty for natural gas as compared to diesel was based on (Kargul, 2012)

[120] Natural gas, when combusted alone in an ICE, requires a spark to ignite the engine's air-fuel combination.

[121] This assumes that the same tank size were to be used for either CNG or gaseous hydrogen. Similarly, this assumption should hold regardless of the actual size utilized (again, assuming that it is the same for either gaseous fuel.)

though what is relevant is that each locomotive is assumed to carry an equal proportion of the total power requirements for the vehicle. Each freight train had between two and four locomotives, with most relying on three. The number per train was selected mostly based on formulas used by the freight railroads. These formulas can vary. While one source suggests a "horsepower per ton" ratio of 1.12 for manifest trains, and 2.12 for intermodal (Barkan, 2014), in this analysis, information from one representative of the freight railroad industry who is knowledgeable on the topic suggested a ratio of closer to 1.2 and 2.5 for intermodal routes, and it is these ratios that were used as the primary guidelines. In the case of larger gradients, sometimes an additional locomotive was added just to ensure adequate vehicle speeds.

Before the freight simulations were conducted, a slight calibration was made to the available power at the wheels to ensure that the maximum output power of the prime mover was not greater than the modeled locomotive's power specifications. (As noted above, this is a bottom-up simulation tool, so the wheel power is first assessed based on the route characteristics and other constraints and, from that point, calculations are conducted up through the other parts of the simulated locomotive all the way to the fuel source.)

For the hybrid passenger vehicles, 500 batteries were used in all cases, with characteristics directly based on a commercially available LTO battery (Altairnano, 2011). This number of batteries ensured that the allowable voltage range and current range requirements were met.

Hybridization was not considered for the freight analyses because, in most cases, so-called "mainline" freight rail duty cycles do not offer the ideal case for extensive hybridization. Moreover, the total battery requirements, in size and weight, that would be necessary to optimize the taking in of regenerative braking energy would be extensive and, unlike hydrogen storage tanks, batteries could not safely be stored atop a locomotive vehicle. This topic is further discussed in the results chapter.

Similarly, OLE was not considered, in this analysis, for freight rail for several reasons, some of which were noted in Chapter 3. The upfront cost of electrification is, as was discussed in some detail in Section 3.4, very high and, overall, only cost-effective with high enough traffic levels. While parts of the domestic freight system have high traffic levels, many other areas do not. The domestic freight system operates, as earlier noted, as one large system, with vehicles regularly shared across companies and geographies. Thus, financing of the system, which would require buy-in from all of the freight railroads, might create financial conflicts between companies that would be difficult to resolve. Also, the recent increase in double stacking of cars has led to various sites and projects in which infrastructure (e.g. tunnels) had to be expanded to accommodate these changes. Such infrastructure projects are costly and designed to last for decades so, especially given the other challenges faced by OLE electrification, it is not clear that the system would be able to handle the kinds of additional changes required (nor electric utilities able to handle or easily coordinate the additional power and power infrastructure required). Lastly, with over 138,000 miles of domestic track (BTS, 2015), the time that it would take to convert the entire freight system would be very significant, which would mean that any recouping of initial costs would likely take even longer than usual.

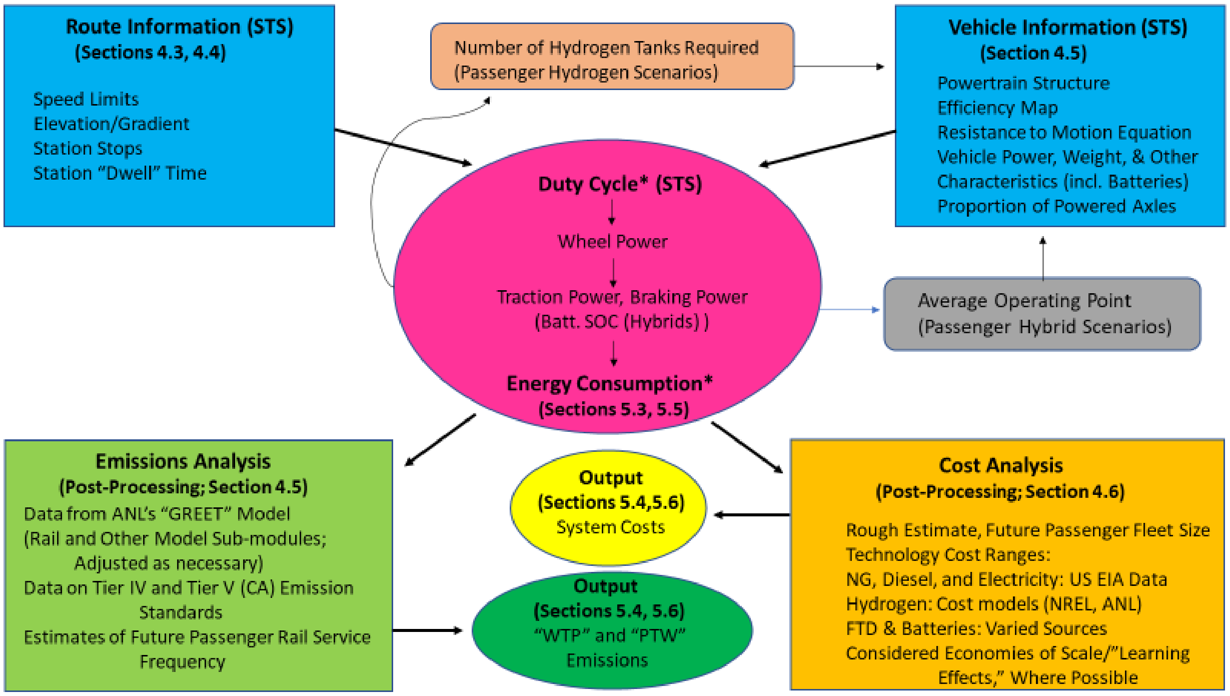


Figure 23: Methodology Overview

This graphical illustration provides an overview of the passenger and freight analyses conducted in this project. (The switcher analysis did not involve any simulations, and focuses on emissions rather than costs.) Information is provided linking each set of data (whether input or output) to the relevant sections where it is reviewed. Circular relationships show where iterations have been performed following initial analysis outputs.

** Note that Duty Cycle & Energy Consumption are both inputs and outputs to the overall study*

4.7 Applying the GREET model to GHG and Pollutant Estimates

In order to assess and compare resulting emissions of the various technologies, both GHG's and several pollutants have been examined, and the examination spans both the "well-to-pump" and the "pump-to-wheel" phases of fuel usage. Combined, these two subsets of emissions that arise in a fuel cycle are often referred to as "well-to-wheel" emissions, the latter referring to emissions at any stage from extraction and later production of the fuel to the emissions that result during combustion or other relevant processing of the fuel aboard a vehicle.

The pollutants that were examined and assessed in this study include Carbon Monoxide (CO), (NOx)---which covers various nitrogen oxides, Particulate Matter---smaller than 10 microns (PM10), and Volatile Organic Compounds (VOC)/Hydrocarbons (HC)[122]. The first three are part of a group known as the “criteria air pollutants” due to their regulation being set by the Clean Air Act (US EPA, 2018). All four were analyzed in this study due to the pollutant standards that locomotives are currently evaluated on. Box 2, below, offers a brief primer on the health and climate impacts of these emissions and pollutants, which are the reason for their regulation.

[122] The VOC outputs of the GREET model were assumed to model hydrocarbons. (University of Calgary, 2015)

Box. 2 Brief primer on the impacts of GHG's and Pollutants Analyzed in this Report

Greenhouse Gases (GHGs)

CO_2, the levels of which, in the transportation sector, correlate almost directly with fossil fuel consumption levels, represents the baseline GHG, with a global warming potential (GWP) of 1. (The GWP is a metric used to demonstrate the relative impact of a GHG on climate, and is based on CO_2 as its baseline, with a GWP of 1 (US EPA, 2017)).

CH_4, or methane, is the primary component in natural gas. Its GWP is 28 to 36 (US EPA, 2017). Methane's warming impacts dissipate relatively quickly, lasting about a decade (US EPA, 2017), but this fact is taken into account in its GWP score. Methane is also a precursor to ozone, another GHG (and this factor is also taken into account in its GWP score (US EPA, 2017)).

N_2O is one of many by-products of fossil fuel combustion. Its GWP is close to 300 times that of CO_2 (US EPA, 2017) (and thus roughly ten times that of methane). This high score likely reflects its longer lifetime than methane, at roughly a century (US EPA, 2017).

Pollutant Emissions

Carbon Monoxide (CO), which commonly results from incomplete combustion, can interfere with and thereby limit the oxygen reaching the bodily organs and tissues(Gouvernement du Québec, 2019). It can also impact mental alertness and vision (Townsend & Maynard, 2002). It is believed that people with cardiovascular ailments are especially prone to its negative impacts, even at levels commonly associated with air pollution (Reboul et al., 2017).

NO2, which is just one variant of so-called "NOx," can irritate one's airways, and is particularly harmful to those who suffer from asthma (EPA, 2016a). In the short term, coughing and wheezing may result, while longer term exposure can actually lead to the development of asthma or respiratory infections (EPA, 2016a).

In addition, NO2 can chemically react in the environment in a way that leads to increased amounts of particulate matter and ozone, themselves harmful pollutants (EPA, 2016a) (one of which is discussed below).

Particulate matter refers to a variety of "extremely small particles and liquid droplets containing acids, organic chemicals, metals, and soil or dust particles" (Anderson, Thundiyil, & Stolbach, 2012) and, according to some research, accounts for "the fraction of air pollution that is most reliably associated with human disease" (Anderson et al., 2012). Through promoting "systemic inflammation," particulate matter can lead to cardiovascular and cerebrovascular disease. (Anderson et al., 2012) Evidence exists to implicate PM in increased mortality rates from cardiovascular disease in both the short-term and long-term (Anderson et al., 2012). Moreover, the inflammation that results from PM has also been linked to increased symptoms among those with respiratory ailments (Anderson et al., 2012).

Like CO, Hydrocarbons (HC), which largely overlap with a group known as the Volatile Organic Compounds (VOC) (University of Calgary, 2015), also result from the inevitably incomplete nature of fuel combustion. Diesel-linked hydrocarbons have been implicated in disrupting hormonal pathways in the body, which may increase the risks from cancer (Organization of Frontier Science and Innovation, Kanazawa University, 2014). Total Petroleum Hydrocarbons (TPH), more generally, may impact the nervous. system, especially at prolonged or high doses (CDC, n.d.). While such doses may be limited primarily to people whose work relates to the petroleum industry (including fuel dispensing), it is recognized that some exposure to TPH's is virtually impossible to avoid, currently, as even the inhaling of vapors at a gasoline station allow for TPH to enter one's bloodstream (CDC, n.d.).

Not a part of the simulation outputs, the emissions/pollutants portion of the analysis involved post-processing, with the author relying primarily on the framework set forth in the "GREET" (i.e. Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) Model. (Figure 23, above, provides a visual perspective on the various analyses conducted as part of this study.) A government-run, Excel-based model managed by Argonne National Laboratory, GREET is updated annually and has two components, GREET 1 and GREET 2. GREET 1 is regularly utilized by researchers seeking to assess the energy and environmental impacts of transportation fuels, covering all stages from the upstream production phases (i.e. Well-to-pump) down to the in-use consumption phases (i.e. Pump-to-wheel), and it is data from this sub-component that was used for this analysis.

In the last several years, the GREET Argonne team has added in a rail sub-component to the GREET 1 model. This component does include pre-set emissions assumptions and resulting estimates by train type; however, for these analyses, those particular pre-set assumptions were not useful, since the author was attempting to assess variation between fuel types and between train trips with specific characteristics. Instead, this study relied specifically on fuel pathway inputs and assumptions (both well-to-pump and pump-to-wheel) that the GREET rail module utilizes within its processes. Moreover, in several cases, adjustments were made. For example, in-use emissions data was found to be based on 2015 data, and on a fleetwide mix of diesel-electric locomotives from various tiers. Moreover, data for switch locomotives was combined with data for locomotives in revenue service. Hence these values were adjusted, within the GREET analysis framework and, in addition, per-unit-consumption values[123] that line up with

[123] For example, (GREET, 2018) provides much of its emissions data in the form of grams/mmbtu (i.e million btu) of fuel input. (Such data can then be converted to grams per MJ or kWh, as necessary.)

the latest tier standards and with a potential Tier 5 standard that has been proposed by the state of California (see Table 7, below) were also evaluated (outside of the GREET model).

The per-consumption values utilized in this study for the different tiers are presented in Table A3 of the appendix. Where a given standard had already been achieved by the 2015 fleet, for example in the case of CO (based on data from(GREET, 2018)), the assumed Tier 4 level has been adjusted to reflect the lower emissions level that has already been achieved.

Table 7: California's Proposed Tier 5

Year of Original Manufacture	Tier	NOx	PM	HC
2025 or later	5	1.3	0.03	0.14

Note: The proposed new tier would include updated standards for the above three pollutant categories, and a new standard, to be determined, that would apply also to Greenhouse Gas emissions. Adapted from (Nichols, 2017)

In addition, the GREET model relies, in the case of some fuels, on blanket emissions adjustments vis-à-vis the diesel status quo. In the case of natural gas and CO in-use emissions, the author concluded that this estimate was a bit too optimistic and so assumed an unadjusted (from the diesel benchmark) value for CO for natural gas. On the other hand, in many cases, NOx reductions were found to be, in the author's opinion, too pessimistic. For example, NOx reduction for natural gas could achieve the same low levels achieved in diesel-electric operations relying on SCR systems through their own use of three-way catalytic converters. On the other hand, CO emissions levels resulting from diesel operations were, in some of the standards, set higher than levels that are already being seen in the current rail fleet. In this case, the assumption based on the standard was revised downward, based on the actual fleet data. Looking to upstream emissions, in the cases of natural gas and hydrogen, the upstream components in GREET's rail module assume production and delivery of the liquid forms of the fuels. As a result, the author relied on data from other components of the GREET model in order to most accurately assess the upstream impacts of the gaseous forms of these fuels, which were the focus of the study. Also, WTP emissions results for OLE operations were adjusted to include emissions resulting from energy losses during transmission and distribution (i.e. between the powerplants and where the grid meets the OLE), based on (US EIA, 2019f).

4.8 Cost Methodology: Context

A study such as this one is incomplete without addressing the issue of technology cost. Emissions and pollutant reductions are to be lauded, but, in the "real world," where decisions must be made to switch technologies (or to put off any such transition), either by a government agency or by a publicly owned freight railroad, cost is a fundamental area of concern. Hence cost analyses were performed for the passenger and freight routes noted above in order to provide a rough comparison of potential expenditures for fuel technologies for the particular technology scenarios and routes described above (with results provided in the Chapter 5).

Estimating future costs is an inherently difficult process, as it involves projecting developments in research and development processes, in markets, and even in policy changes. Moreover, significant breakthroughs that were not expected, and may have come from an industry that is only peripherally related to the one of interest, can have significant impacts on cost[124]. Likewise, unpredicted obstacles (e.g. a physical limitation that proves harder to circumvent than had been expected) may arise that may limit potential cost reductions.

[124] For example, the proliferation of lithium ion battery technology across the smartphone and laptop markets, in recent decades, very likely played a role in the significant cost drop in lithium batteries that has now impacted the cost (and even viability) of battery technology for use in transportation. Among other contextual factors, this drop in cost of such batteries for electric vehicles (Pillot, 2018) impact can be seen in the growth of electric cars (IEA, 2019a). Now, in turn, the rail sector has begun to see increased attention towards applications of this technology (as touched on in Section 3.7) in this sector.

Yet attempts to estimate future technology cost, as accurately as possible, are crucial, not only due to the primary reason noted above, but because, in many cases, projected costs are both impacted by research and development (with this impact tending to occur a bit more in the early stages of technology development (Nemet, 2012)) and, in turn, likely to shape the direction of research and development. Technologies that are seen as too costly are not (or are hardly) invested in, while those that seem to demonstrate economic viability are disproportionately focused on.

Cost projections developed by various sources, both private and public, for the relevant technological components, for the period from about 2022-2030 (with fuel costs focused on the year 2030, as fuel is purchased annually and thus subject to change through the period of analysis) play a large role in the low to high cost ranges set in this study. But, in a few cases, information on a specific technology was hard to come by (e.g. cost of LTO batteries) or the sources are disparate and note the high uncertainty involved (e.g. cost of fuel cell stacks and of hydrogen as a fuel)[125]. For fuel cell stacks, best estimates were made by the author given the available literature (see Section 4.10, below, for more details) combined with some of the context described above. In the case of hydrogen, on the other hand, general future projections are not yet broadly disseminated. It is a fuel that, with regard to the transportation sector, is in a rapidly developing and early stage. However, there are extensively developed modelling tools

[125] To use fuel cells as an example, fuel cell stack design and method of and materials used for hydrogen storage are likely to change, which may enhance the viability of this technology. (And this, in turn, will shape market trends, which are already inherently uncertain for this rapidly evolving technology.) Just one example of a potential change is, as alluded to in Chapter 3, a transition away from platinum-based catalysts, which are typically rather expensive, to materials that are cheaper.

with which near-to-midterm cost estimates can be modeled with a fair amount of granularity. A combination of two of these modelling tools was used, as explained in Section 4.9, below.

In certain cases, technology and cost assumptions were constrained by current practices due to highly uncertain developments and limited information on the potential cost of technologies currently in the research and development stages. For example, in the case of hydrogen storage, the cost estimates assume the use of compressed hydrogen storage (at 350 bar) as opposed to taking into account any move towards storage via either liquid organic hydrogen carriers or metal organic hydrides (both described in Chapter 3).

In order to deal with the inherent uncertainty involved in estimating costs, particularly given a timeline that covers a period of about a decade, most costs have been estimated with both a low and high value. In some cases, low and high values are taken directly from a single source (e.g. oil, natural gas, and electricity "fuel" costs, which were obtained from EIA data[126]), in which case these numbers already take into account a variety of potential market or policy changes (or perhaps both) that might occur around 2030. In other cases, where the author has selected the values from different sources (or, in a couple of cases, calculated them based on available data), the range also attempts to account for potential differences in market penetration and technological developments (during the relevant period). The tables that comprise much of Section 4.10, below, summarize the key cost assumptions utilized in this study. (And the resulting values for an entire train service type are presented in Chapter 5.)

---

[126] For more detail, see tables 9 through 13, in Section 4.10

4.9 Hydrogen Cost Methodology and Calculations

While hydrogen production, broadly, is not a new technology and, in fact, in 2017, in its application broadly to industry was described by the IEA as "a big global business with strong fundamentals," the production and consumption of hydrogen specifically for transportation applications is still in its early stages.

There is an active hydrogen cost analysis effort among the U.S. DOE national laboratories, particularly focused on near and mid-term costs. Two government laboratory-developed models that help assess the cost of hydrogen infrastructure given different contexts (e.g. taking into account daily production levels, specific station equipment characteristics, and overall station/equipment volumes) were adapted for use in this rail analysis.

The first model that has been used in this study for the purpose of estimating likely hydrogen fuel costs was the National Renewable Energy Laboratory's H2A "Hydrogen Production Analysis Model (NREL, 2018b)," which includes "transparent reporting of process design assumptions (NREL, 2018b)." H2A "case studies" (NREL, 2018a) were used and adapted for the station sizes of interest, with most of the default financing assumptions maintained. (For more detail, see Tables 8a-d, below.). The second model utilized was Argonne National Laboratory's Heavy-Duty Refueling Station Analysis, or "HDRSAM" (ANL, 2017) model. As its name indicates, this model attempts to model costs for refueling stations, specifically in a heavy-duty context. Input variables that can be set including refueling rate, number of vehicles, total kg output per day, and gaseous or liquid storage.

For this study, three combinations of production and station storage were assumed, each, for both passenger and freight rail. These combinations include a) hydrogen production via (onsite) electrolysis, with gaseous storage at the station, b) hydrogen production via (onsite) SMR, also with gaseous storage at the station, and c) liquid hydrogen delivery to the station from an offsite location. (For part c, the exact method of production may vary, at least from the standpoint of the cost modeling. From an emissions standpoint, the last option assumes hydrogen production via SMR [with natural gas] prior to liquefaction and transportation.) The cost basis for the costs in option a was 2012, and for the costs in option b was 2005 (with all costs adjusted to 2016 values---the most recent year allowable). Option c was based on delivered costs from (Leslie Eudy, 2019), for hydrogen delivered in 2018. For both options a and b, plant life, from the H2A model, was assumed as 20 years.

Table 8 a-d, below, reviews the varied hydrogen cost figures that were utilized in this study, and breaks them down into their key constituent components (with rounding used to emphasize the ballpark nature of all costs.) Among the adjustments that were made in the calculations (beyond what is apparent from Tables 8a-d), gaseous station information, in HDRSAM, was limited to a maximum of 20,000 kg/day, so this value was used for the freight analysis. (In HDRSAM, industry production volumes, which impacts component costs, were assumed as “HIGH” for all scenarios.)

Table 8 (a-d): Station Hydrogen Supply Cost Analysis

8a. Passenger Trains (LOW energy cost)

Based on a usable capacity of 13,000 kg/day

	Case 1: Onsite Electrolysis	Case 2: Onsite SMR	Case 3: Liquid Hydrogen Truck Delivery
STATION DESCRIPTION			
Design capacity per station, kg/day	13,400 (97% Electr Cap. Factor)	14,450 (90% SMR Cap. Factor)	13,000 (100% Stn Cap. Factor)
Gaseous H2 dispensing pressure (bar) and method	350 Cascade	350 Cascade	350 bar via LH2 Pump/Vaporization
Dispenser rate (kg H2/min)	7.2		
Refills per day	Capitol Corridor:15, Caltrain: 25		
Station Capital Specific Cost $/(kg/day)	2077	2792	315 *
Station Capital cost ($, million)	27.0	36.3	4.1 *
Station lifetime, years	20	20	20
Discount rate	10%	10%	10% (Station only)
Cost Recovery Factor	0.1278		
Station capacity factor	100%	100%	100%
VARIABLE OPERATING COSTS			
Electricity Consumption kWh/kg H2	53.08	3.48	2.06 *
Electricity Price ($/kWh)	0.06		
Natural gas consumption MMBTU/kg	-	0.156	-
Natural gas Price ($/MMBTU)	-	$9.51	-
Natural gas cost $/kg	-	1.53 SMR	-
Truck delivered LH2 cost $/kg	-	-	5
Annual Fixed Op. Cost as % of capital cost	5%	5%	5%
Fixed operating cost, $ million/year	1.35	1.82	0.21
LEVELIZED H2 COST $/kg H2	Electrolyzer + station	SMR + Station	Delivery Cost + Station
Capital Cost	.71	.92	.14
Fixed Operating Cost	.54	.34	.10
Electricity	3.18	.21	.13
Other Utilities	0.01	0.05	-
Natural Gas	-	1.53	-
Liquid H2 (Delivered)[127]	-	-	5.00
Total	4.44	3.05	5.37

* No production costs included; Refueling costs only

[127] Based on (Leslie Eudy, 2019)

8b. Passenger Trains (HIGH energy cost)

Based on a usable capacity of 13,000 kg/day

	Case 1: Onsite Electrolysis	Case 2: Onsite SMR	Case 3: Liquid Hydrogen Truck Delivery
STATION DESCRIPTION			
Design capacity per station, kg/day	13,400 (97% Electr Cap. Factor)	14,450 (90% SMR Cap. Factor)	13,000 (100% Stn Cap. Factor)
Gaseous H2 dispensing pressure (bar) and method	350 Cascade	350 Cascade	350 bar via LH2 Pump/Vaporization
Dispenser rate (kg H2/min)	7.2		
Refills per day	Capitol Corridor:15, Caltrain: 25		
Station Capital Specific Cost $/(kg/day)	2077	2792	315 *
Station Capital cost ($, million)	27.0	36.3	4.1 *
Station lifetime, years	20	20	20
Discount rate	10%	10%	10% (Station only)
Cost Recovery Factor	0.1278		
Station capacity factor	100%	100%	100%
VARIABLE OPERATING COSTS			
Electricity Consumption kWh/kg H2	53.08	3.48	2.06 *
Electricity Price ($/kWh)	0.14		
Natural gas consumption MMBTU/kg	-	0.156	-
Natural gas Price ($/MMBTU)	-	$12.45	-
Natural gas cost $/kg	-	1.53 SMR	-
Truck delivered LH2 cost $/kg	-	-	5
Annual Fixed Op. Cost as % of capital cost	5%	5%	5%
Fixed operating cost, $ million/year	1.35	1.82	0.21
LEVELIZED H2 COST $/kg H2	Electrolyzer + station	SMR + Station	Delivery Cost + Station
Capital Cost	.73	.92	.14
Fixed Operating Cost	.57	.34	.10
Electricity	7.44	.49	.29
Other Utilities	0.01	0.06	-
Natural Gas	-	2.00	-
Liquid H2 (Delivered)[128]	-	-	5.88
Total	8.75	3.81	6.41

* No production costs included; Refueling costs only

128 Based on (Leslie Eudy, 2019)

8c. Freight Trains (LOW energy cost)

Based on a usable capacity of 68,000 kg/day

	Case 1: Onsite Electrolysis	**Case 2: Onsite SMR**	**Case 3: Liquid Hydrogen Truck Delivery**
	STATION DESCRIPTION		
Design capacity per station, kg/day	70,000 (97% Electr Cap. Factor)	76,000 (90% SMR Cap. Factor)	68,000 (100% Stn Cap. Factor)
Gaseous H2 dispensing pressure (bar) and method	350 Cascade	350 Cascade	350 bar via LH2 Pump/Vaporization
Dispenser rate (kg H2/min)	7.2		
Refills per day	Capitol Corridor:15, Caltrain: 25		
Station Capital Specific Cost $/(kg/day)	1537	1240	349
Station Capital cost ($, million)	104.5	84.3	23.7 *
Station lifetime, years	20	20	20
Discount rate	10%	10%	10% (Station only)
Cost Recovery Factor	0.1278		
Station capacity factor	100%	100%	100%
	VARIABLE OPERATING COSTS		
Electricity Consumption kWh/kg H2	53.08	3.48	15.33 *
Electricity Price ($/kWh)	0.06		
Natural gas consumption MMBTU/kg	-	0.156	-
Natural gas Price ($/MMBTU)	-	$9.51	-
Natural gas cost $/kg	-	1.53 SMR	-
Truck delivered LH2 cost $/kg	-	-	5
Annual Fixed Op. Cost as % of capital cost	5%	5%	5%
Fixed operating cost, $ million/year	5.23	4.22	1.19
LEVELIZED H2 COST $/kg H2	Electrolyzer + station	SMR + Station	Delivery Cost + Station
Capital Cost	.80	.76	.20
Fixed Operating Cost	.34	.26	.10
Electricity	3.18	.21	.93
Other Utilities	0.01	0.05	-
Natural Gas	-	1.53	-
Liquid H2 (Delivered)[129]	-	-	5.00
Total	4.33	2.81	6.23

* No production costs included; Refueling costs only

Higher number of dispensers assumed for freight due to high fuel volumes.

[129] Based on (Leslie Eudy, 2019)

8d. Freight Trains (HIGH energy cost)

Based on a usable capacity of 68,000 kg/day

	Case 1: Onsite Electrolysis	**Case 2: Onsite SMR**	**Case 3: Liquid Hydrogen Truck Delivery**
	STATION DESCRIPTION		
Design capacity per station, kg/day	13,400 (97% Electr Cap. Factor)	14,450 (90% SMR Cap. Factor)	68,000 (100% Stn Cap. Factor)
Gaseous H2 dispensing pressure (bar) and method	350 Cascade	350 Cascade	350 bar via LH2 Pump/Vaporization
Dispenser rate (kg H2/min)	7.2		
Refills per day	Capitol Corridor:15, Caltrain: 25		
Station Capital Specific Cost $/(kg/day)	2077	2792	$315 *
Station Capital cost ($, million)	104.5	84.3	23.7 *
Station lifetime, years	20	20	20
Discount rate	10%	10%	10% (Station only)
Cost Recovery Factor	0.1278		
Station capacity factor	100%	100%	100%
	VARIABLE OPERATING COSTS		
Electricity Consumption kWh/kg H2	53.08	3.48	2.06 *
Electricity Price ($/kWh)	0.14		
Natural gas consumption MMBTU/kg	-	0.156	-
Natural gas Price ($/MMBTU)	-	$12.45	-
Natural gas cost $/kg	-	2.00 SMR	-
Truck delivered LH2 cost $/kg	-	-	5
Annual Fixed Op. Cost as % of capital cost	5%	5%	5%
Fixed operating cost, $ million/year	5.23	4.22	1.19
LEVELIZED H2 COST $/kg H2	Electrolyzer + station	SMR + Station	Delivery Cost + Station
Capital Cost	.83	.76	.20
Fixed Operating Cost	.31	.23	.08
Electricity	7.20	.25	2.16
Other Utilities	0.01	0.06	-
Natural Gas	-	2.00	-
Liquid H2 (Delivered)[130]	-	-	5.00
Total	8.35	3.30	7.44

* No production costs included; Refueling costs only

Higher number of dispensers assumed for freight due to high fuel capacities.

[130] Based on (Leslie Eudy, 2019); Due to high delivery capacities, low delivery cost data point used.

For the four SMR production sub-scenarios, due to difficulty adjusting the pre-set H2a case studies to the selected volumes used (i.e. Usable capacities of 13,000 and 68,000 kg per day), all capital costs were individually calculated (separately from the model) assuming a scaling factor of 0.6.

In order to calculate the adjusted capital cost value per kg, equation (8), below, was used (calculations were broken down into both (a) capital and (b) fixed o&m costs, in order to record each value separately, as in the tables above), while, in order to calculate the total capital cost, which included a variety of additional costs, equation (9) was used to determine the total capital cost:

$$c_0 * \left(\left(\frac{S_0}{S} \right)^{1-z} \right) = cost\ per\ kg \tag{8}$$

$$C_0 * \left(\left(\frac{S}{S_0} \right)^{z} \right) = Total\ capital\ cost \tag{9}$$

where z is the scaling factor of 0.6, c_0 is the pre-set capital (or fixed o&m) cost (for the reference capacity), S is the actual capacity set for this study, S_0 is the pre-set reference capacity in the model, and C_0 is the pre-set Total capital cost. The reference capacity was rounded to a value of 387,000 kg/day.

4.10 Cost Assumptions for the Analysis

Tables 9 through 13 note many of the cost assumptions assumed for the present study (with footnotes offering some more details on how such figures were obtained).

Table 9: Input Cost Assumptions and Sources: Diesel/FTD
(Diesel tank/fuel storage cost considered negligible, so excluded)

All non-fuel costs added together comprise the cost of one locomotive. Overhaul costs assumed at 1/3 cost of initial prime mover cost.

Route/Vehicle Type	Locomotive Glider Cost	Engine-Generator Cost	Fuel Cost	Notes
Capitol Corridor	$6,100,000[131]	$900,000[132]	***Diesel*** LOW: $2.00[133] HIGH: $5.56[134] ***FTD*** LOW: $1.66[135] HIGH: $3.90[136]	Taxes are not included in fuel price.
Caltrain	$6,100,000	$900,000		
Freight	$1,800,000[137]	$700,000[138]		

131 Passenger locomotives cost about $7 million. (Cho, 2014). The cost of the engine-generator was removed from this cost to obtain cost of the "glider" (see glossary).

132 Cost for the passenger engine-generator has been assessed based on discussions with various representative of industry

133 Low and High values have been obtained from the lowest and highest 2030 cost value projections for diesel across a variety of different available scenarios from the 2019 Annual Energy Outlook, EIA, U.S. DOE

134 Ibid.

135 Derived from production cost of $9/GJ (Tijmensen et al., 2002). Retail cost adjustment based on (US EIA, 2019d)

136 This is based on a cost of production of $26.4 $/GJ from (G. Liu, Larson, Williams, Kreutz, & Guo, 2011), for a biomass-to-liquid FT diesel; also assumes a recycling of unconverted syngas and that "output coproduct CO_2 is "vented to the atmosphere"(G. Liu et al., 2011). Cost value reduced by 20% due to data being from 2011; Retail cost adjustment based on (US EIA, 2019d)

137 Freight locomotives cost about $2.5 million. (Black & Clough, 2014; Tita & Hagerty, 2014) The cost of the engine-generator was removed from this cost to obtain cost of the freight "glider."

138 Freight engine-generator cost was adjusted down from the passenger engine-generator cost due to a) increased economies of scale for freight equipment and b) overall difference in cost between passenger and freight diesel locomotives. (The latter is a result, in part, of the increased economies of scale, and also likely due to differences in crash-worthiness standards (Simpson, 2018) and other aspects of the acquisition process that differ between the two types of locomotives (Simpson, 2018)

Table 10: Input Cost Assumptions and Sources: Natural Gas

All non-fuel costs added together comprise the cost of one locomotive. Overhaul costs assumed at 1/3 cost of initial prime mover cost. Storage per volume figures for natural gas adjusted downward by 15% to account for space required by storage vessels.

(Compressed natural gas, 300 bar; Volumetric assumption is only roughly estimated, expected to lie somewhere between the fuel-only value of 3.38 kWh/liter (Simmons, Betts, Roan, & Erickson, 2002) and a 2.35 kWh/liter value determined based on information from an industry representative about the size of a specific Type III[139] tank that is currently sold.)

Route/Vehicle Type	Locomotive Glider Cost	Engine-Generator Cost	Fuel Storage Costs	Fuel Cost (Natural Gas) $/kg	Notes
Capitol Corridor	$6,100,000	$900,000	$3,500 per tank[140]; 62 (gaseous) tanks required	LOW: 0.42[141] HIGH: 0.56[142]	Gaseous pressure assumed as 350 bar. Engine-generator costs assumed as same as for diesel.[143] Taxes are not included in the fuel price[144].
Caltrain	$6,100,000	$900,000	34 (gaseous) tanks required (tank cost same as above)		
Freight	$2,800,000	$700,000	125 (gaseous) tanks required (tank cost same as above)		

---

[139] There are four different types of pressure vessels. Type III tanks have metal as their liner, with a surrounding composite wrap typically composed of aluminum and carbon fiber.
[140] This is the cost for each 275 Liter (~71 kg) tank. This value was estimated based on industry information provided (anonymously), and lines up closely with available literature, e.g. (James, Houchins, Huya-Kouadio, & DeSantis, 2016) A single cost value has been applied here (rather than a low-to-high range) due to the fact that CNG storage is viewed, by the author, as a mature technology.
[141] Low and High values for have been obtained from the lowest and highest 2030 cost value projections for compressed natural gas across a variety of different available scenarios from the 2019 Annual Energy Outlook, EIA, U.S. DOE
[142] Ibid.
[143] While an SI engine might be expected to be slightly cheaper than a diesel engine, there are also additional components involved in bringing the fuel from the tanks to the engine.
[144] In the case of natural gas, taxes had to be removed from the available data based on information available in some of the accompanying documentation on price assumptions (US EIA, 2019a).

Table 11: Input Cost Assumptions and Sources: Hydrogen

All non-fuel costs added together comprise the cost of one locomotive.

(Compressed Hydrogen, 350 bar, volumetric assumption is only roughly estimated, expected to lie somewhere between the fuel-only value of 23 kg/m3 (Sheffield, Martin, & Folkson, 2014) and a lower value of 16.9 kg/m3. representative of one specific tank size from one manufacturer (Hexagon Composites, 2017).)

Route/Vehicle Type	Locomotive Glider Cost	Fuel Cell Stacks (and BoP/BoS) Cost[145]	Fuel Storage Costs	Fuel Cost (Hydrogen), $/kg	Notes
Capitol Corridor	$6,100,000	LOW: $80/kW[146] HIGH: $900/kW[147]	LOW: $13/kWh[148] HIGH: $18/kWh[149]; 138 tanks required	LOW and HIGH refer to feedstock (i.e. natural gas, electricity) price assumptions. See Tables 8a-d for cost development. **SMR:** LOW: $3.05(P) HIGH: $3.81(P) LOW: $2.81 (F) HIGH: $3.3 (F) **Electrolysis:** LOW: $4.44(P) HIGH: $8.75(P) LOW: $4.33 (F) HIGH: $8.35 (F) **Liquid Delivery:** LOW: $5.37 (P) HIGH: $6.41 (P)	**See Section 4.9, above, for comprehensive fuel cost development.** Fuel costs assumed as pre-tax, at fuel purchaser level. P = Passenger Rail Scenario F = Freight Rail Scenario Tender necessary for some, but not all, freight movements. (See Chap. 5
Caltrain	$6,100,000		80 tanks required (tank cost same as above)		
Freight	$2,800,000		239 Tanks (tank cost same as above)		

[145] This includes virtually all costs associated with the physical fuel cell stack system, including what is referred to as "balance of plant" (or BoP—see glossary) and what is sometimes referred to as "balance of systems," or BoS (also defined in the glossary).

[146] This value is double the 2025 target for fuel cell stacks for light duty vehicles (which are likely to have much higher volumes of production) set by the U.S. DOE (Satyapal, 2019). It was also informed by the work of Strategic Analysis, Inc. (James, 2018) , which suggests a price of $79.61 per kW in 2025 for medium duty vehicle stacks, given production of 100,000 systems per year. (Heavy duty vehicle should have lower production levels, but costs should further reduce by 2030.)

[147] This number has been informed by conversations with an (anonymous) industry representative, who stated that, assuming a relatively low level of mass production (roughly 5 MW) of heavy duty fuel cells for a given project, a cost of $1,000 per kW is expected before 2025.

[148] Both the low and high hydrogen storage cost values are derived from the work of Strategic Analysis, Inc. (James et al., 2016). These numbers also line up with industry-provided input (from sources with access to proprietary data).

[149] Ibid.

			LOW: $6.23 (F) HIGH: $7.44 (F)	for details and related costs.)

Table 12: Input Cost Assumptions and Sources: OLE

Glider and transformer/pantograph costs added together comprise the costs of one locomotive.

Route/ Vehicle Type	Locomotive Glider Cost	Transformer and Pantograph Cost	OLE Construction and Maintenance Costs	Electricity Cost	Notes
Capitol Corridor	$6,100,000	$900,000[150]	**Construction:** LOW: $4 Million per track-mile[151] HIGH: $7.5 Million per track-mile[152] **Maintenance:** $1.32 per train mile[153]	LOW: 6.47 ₵ per kWh[154] HIGH: 14.30 ₵ per kWh[155]	
Caltrain	$6,100,000	$900,000[156]			

[150] This number is based on input from an (anonymous) industry representative.
[151] OLE cost varies widely depending on the density of a given region, labor costs, amount of traffic along a (previously existing) route, etc. The low and high values for electric (OLE) infrastructure cost were selected by the author given the available data on recent projects, both in the U.S. and abroad, but with the intention of setting the price range in line with the (somewhat higher) costs of U.S. OLE infrastructure construction. (These differences were discussed in Chapter 3.)
[152] Ibid.
[153] This number is based on annual maintenance cost data provided by an operator that operates trains along a domestic OLE corridor.
[154] This low value has been obtained from the lowest available cost valued observed for electricity in the nation in the most recent (as of the time of writing) Electric Power Monthly report (IEA), covering July, 2019 (US EIA, 2019b). This particular electric price was observed in the state of Georgia.
[155] This high value has been obtained from the highest 2030 cost value projected for electricity, for the transportation sector, across a variety of different available scenarios from the 2019 Annual Energy Outlook, EIA, U.S. DOE
[156] See footnote for 137.

Table 13: Input Cost Assumptions and Sources: Hybrid Vehicle

All non-fuel costs added together comprise the cost of one locomotive. Diesel engine-generator overhaul and fuel cell stack replacement assumed to occur at the same points of time as with non-hybrid systems. All notes from above diesel and hydrogen tables apply to the relevant hybrid powertrain, unless specifically indicated otherwise.

Route/Vehicle Type	Locomotive Glider Cost	Prime Mover Cost Reduction (Downsized only)	Fuel Storage Costs (Hydrogen only)[157]	Battery Cost	Notes
Capitol Corridor	6,100,000	Both prime movers, i.e. fuel cell stacks and diesel engine-generator technology, were assessed at half the cost of the full cost assessed for non-downsized configurations.	120 tanks required. (Tank cost same as in hydrogen fuel storage above)	LOW: $203 per kWh[158] HIGH: $481 per kWh[159]	Fuel Cost assumed same as corresponding, above; Prime Mover non-downsized same as corresponding, above
Caltrain	6,100,000		52 tanks required (Tank cost same as in hydrogen fuel storage above)		

[157] The downsized hydrogen hybrid vehicle required more energy than the non-downsized hybrids (as discussed in Chapter 5). As such, the higher hydrogen storage requirement of the downsized hybrid was assumed for all hydrogen hybrid locomotives.

[158] The cost methodology for batteries begins with an average 2017 cost of $1,130 per kWh for LTO battery packs (not counting any procurement and contracting costs) in 2017, according to (Aquino, Roling, Baker, & Rowland, 2017). The cost of lithium-ion batteries, generally speaking, then dropped by about 23.5% between 2017 and 2018 (Deloitte, 2018). This ratio was thus applied to the 2017 cost to get the 2018 cost. Then, from 2018 to 2030, a ratio of ~ 5/9 is found to reflect projected battery price drops, according to (Ambrose, 2019). Using this ratio, we come to ~$481 as the HIGH cost. (This cost could be seen as based on the status quo in battery cost trends, perhaps; however, a continued decline in battery costs seems fairly certain given the technology's indispensability in modern life; hence the author sees no reason to estimate costs higher than such a trend. Moreover, according to the California Air Resources Board, one battery manufacturer has stated, "Although there is insufficient data to develop a separate price trend for LTO batteries, Proterra confirms LTO battery prices are expected to continue to decline substantially." (California Air Resources Board, 2016) The low battery cost value assumes a rapid growth in production of LTO as a chemistry, specifically, whether for rail applications or perhaps both rail and other heavy duty applications. Based on the work of https://www.eprg.group.cam.ac.uk/wp-content/uploads/2014/01/eprg0703.pdf who found that, for PV technology, each doubling in production led to an approximately 35% reduction in cost, the LOW value was obtained by multiplying the HIGH cost value by 0.65, and then by 0.65 again (equivalent to one-time multiplication by 0.4225). In other words, this LOW value would materialize if production of LTO batteries quadrupled over the rate of production otherwise projected. We know from the broader lithium-ion battery market that rapid cost drops in short amounts of time have occurred (e.g. a drop of almost 80% between 2010 and 2017.) So a drop from ~$865 (estimated) in 2018 to ~$203 by 2030 does not seem out of the question.

[159] Ibid

Hydrogen storage cost estimates, in the case of passenger rail, were based on sizing the fuel system for the particular corridor in question, as it is suspected that different agencies may wish to have different amounts of hydrogen storage on a locomotive. (This flexibility has also been assumed since passenger locomotives are already designed with relatively specific requirements that can differ between agencies.) Beyond that, however, this has been done to get an idea of the kinds of differing space requirements for a hydrogen locomotive, depending on the actual needs of a given operation rather than solely based on the current size of a passenger locomotive fuel tank.)

While the hydrogen tanks are physically modeled (in terms of space assessment and weight, the latter described in more detail below) after a specific tank from a specific manufacturer(Hexagon Composites, 2017) [160], this has been done solely for the sake of modeling a sample system and assessing its physical feasibility. The author does not suggest that this size or even configuration of tank(s) is/are the right one(s).

Prior to performing the hydrogen simulations, the author conducted, with the help of industry partners with access to proprietary knowledge and data, research on interior space availability for a few different rail locomotives (in addition to research on the size of components that currently are required in a diesel-electric locomotive, which could be discarded if switching away from this form of propulsion). Once checked for general physical feasibility, based on this research, the number of tanks necessary (given the selected tank type) to hold the fuel were, not only incorporated into the simulations from a weight perspective, as described above (primarily for passenger rail), but also the necessary storage materials were incorporated

[160] Hexagon Composites' 'E' style Type IV (see glossary) cylinder has been assumed. This tank weighs 101 kg, and holds 7.5 kg of hydrogen. (Hexagon Composites, 2017)

into the cost assessment (based on available data on the general cost of hydrogen storage, by volume). Given that each hydrogen tank can hold a certain amount of hydrogen (7.5 kg, in this case), the number of tanks utilized was determined given the understanding that Capitol Corridor's locomotives will frequently refuel after two full round trips each (T. Andrews, personal communication, July, 2014). Thus, each passenger system has been modeled to carry enough fuel for two round-trips, along with the 20% fuel "buffer," as previously noted, beyond this amount.

In the case of the freight hydrogen simulations, it was determined, given the aforementioned research on available space (along with the fact that hydrogen tanks could be stored atop locomotive roofs) that additional vehicles to hold hydrogen would not always be required. That said, in the case of the two intermodal vehicles, it was determined that two 40-foot containers' worth of compressed hydrogen tanks would be necessary, barring a changing of typical refueling patterns for such vehicles[161] and, again, incorporating a buffer (of roughly 10 to 18%, though this could be larger depending on the exact tender size, tank size and number, and the resulting unused space within the tender car; see footnote 158, in Section 5.6). The cost analysis for the freight hydrogen scenarios assumes the cost of such additional infrastructure (see Table 20, in Chapter 5, for development of these costs).

Once assessed on a per-trip basis, the costs for the passenger and freight scenarios are expanded out towards the costs of a rail system over a much greater period of time. The period selected, in each case (excluding the switcher analysis), was 16 years. This number of years has

[161] Based on the route simulated, there is typically around 1,000 miles between refueling sessions for the intermodal trains. (Figure 20, in Section 4.6, indicates that the total route was approximately 1,800 miles in length. Refuelling was assumed to occur at Belen, New Mexico (personal communication, M. Cleveland, July 11, 2019), which is roughly the midway point.)

been selected as it is close to the median age of locomotives in the current domestic Class I freight fleet (AAR, 2019c) and it represents when a locomotive engine would typically require a second overhaul (which typically are required about every 8 years)[162][163].

In the case of the passenger scenarios, the rail systems are modeled as the author theorized that operations may look like during the given period. Capitol Corridor currently runs approximately 15 round trips daily (Capitol Corridor, 2019b), Using about 10 locomotives (D. Shepherd, personal communication, October 11, 2019). This system was assumed to have double this frequency of service, and equipment numbers, during this period, or 30 round trips per day with 20 locomotives. This assumption was made since the leadership of the CCJPA, which runs the Capitol Corridor service, has suggested that increased frequency of the service is very likely by that time (Rudick, 2019).

Caltrain service currently operates 29 locomotives on a route with approximately 46 round trips each day. For cost purposes, this service has been modeled to have 50 round trips per day, using 35 locomotives, i.e. with a service to equipment ratio that is similar to what is currently the case on that line, and very similar to the ratio assumed here for Capitol Corridor (roughly 3 round trips for every 2 locomotives).

For the freight analyses, 75 was selected as the number of new vehicles needing to be purchased (whether of the current diesel-electric locomotive or of an alternative locomotive type). Actual number of new locomotives purchased per year varies extensively. In the last ten

[162] While many locomotives may last significantly longer, perhaps even up to 32 years (with some lasting even longer than this), assessing comparative cost over a much longer period would entail more uncertainty in costs, which are likely to change over time, particularly for the less mature technologies. Moreover, costs over such a period are, in many cases, likely to be shared across more than one purchaser, as, e.g., when a locomotive or set of older locomotives is sold by one rail operating entity to another operating entity after many years of usage.
[163] As noted in Section 3.6, the figure of 8 years was estimated based on information provided by or, in some cases, confirmed by multiple people with the relevant knowledge and access to proprietary data.

years, for all of the Class I railroads, combined, it has averaged at, roughly, 608 per year, with a low of 236 and a high of 1073 (AAR, 2019c). However, 75 was chosen because it is a realistic number of locomotives given the service frequency (i.e. 10 trains per day) and route characteristics for the intermodal train that has been assessed in the cost analysis. This approach is valuable, in that it results in a realistic proportion of fuel costs to equipment costs. While actual locomotive purchases would typically be higher for a Class I railroad, during a 16-year period, this approach retains parity across fuel technology types. The equipment cost results provided can be scaled, as necessary, to a higher (or even lower) number.

In terms of service frequency, an assumption was made of ten trips per day for all freight trips (both intermodal and manifest.) As with new equipment, actual trips per day varies enormously by route; however, adjusting this value for a different number and obtaining the relevant results can be easily accomplished.

Lastly, for the switcher application, an assumption was made of 10 hours of operation each day, a number that could be realistic, but which could, again, also be easily adjusted, if necessary.

In previous research conducted by the author (IEA, 2019c; Isaac & Fulton, 2016), variations in locomotive maintenance costs has been found to be insignificant relative to system costs. (And overall maintenance costs, for freight rail, comprise a very small part of total equipment-related costs (IEA, 2019c; Isaac & Fulton, 2016).) Because of this, and because of the high uncertainty of maintenance costs for a locomotive that would run on hydrogen, via fuel cell (due to very limited information at this point in the technology's commercialization), this component of o&m costs was left out of this analysis.

On the other hand, lifetime of the prime mover and any batteries were taken into account, with overhaul/replacement costs calculated and included. As noted earlier, in the case of the diesel engine, an overhaul was estimated to be conducted about every 8 years , with 1/3 of the original engine cost assumed for this process. The timeline was assumed to be the same for natural gas engines, with 1/3 of the cost of that engine assumed for the cost of that procedure.

With fuel cell stacks, the question of when to replace the stacks (presumably at full cost) was deemed the key O&M issue. Freight locomotives have been assumed to run, on average, for approximately 16 hours per day for 350 days (with 15 days per year out of service, as per a suggestion from a Class I representative). This assumption was combined with an assumed fuel cell lifetime of 40,000 hours to come up with a lifetime for freight applications, which was just over 7 years (and rounded down to this value). The assumption for 40,000 hours was selected, as fuel cell lifetimes have been lengthening steadily over the last several years, with a current maximum of just above 31,000 hours (Leslie Eudy, 2019) (and several fuel cell bus stack lifetimes having now exceeded 25,000 (Ballard, 2018)[164] and even 30,000 (Ballard, 2019) hours), metrics that have met and, in some cases, surpassed goals that were set a little over a decade ago[165].

For the passenger systems, the formula used is slightly different, and has been based on the number of hours that the vehicle is in service along that specific route. Per trip time is taken from the passenger simulation results, with an additional hour of operation assumed for idling times

[164] An EU study, from 2018, also noted an expected lifetime of “well over 20,000 hours” (FCH-JU, 2018) .

[165] A 2005 report from the UK noted an expected fuel cell lifetime, at the time, of about 5,000 hours (for automotive fuel cell stacks), and suggested that a 30,000-40,000 hour lifetime would need to be achieved to reach competitiveness with the engines on diesel-fueled locomotives (RSSB, 2005). In a 2008 NREL report on fuel cell stacks in buses, a lifetime goal of 25,000 hours was noted in order to assure that stacks lasted as long as a typical bus lifetime, of 12 years (L. Eudy, Chandler, & Gikakis, 2008).

not incorporated into each trip simulation. Then the number of round trips per day per locomotive is calculated. This calculation is simply based on the number of system trips per day divided by the number of locomotives per passenger system (either 20 or 35, as noted above). That is,

$$\frac{\#\ Daily\ Round\ trips, system}{Number\ of\ locomotives} \tag{10}$$

As with the freight systems, 350 days of operation, per locomotive, are also assumed in the passenger operations.

Table 14, below, summarizes the lifetimes that resulted from the above described calculation approaches.

Table 14: Fuel Cell Lifetime by Service Type

Capitol Corridor	Caltrain	Freight
10 Years	22 Years (No need for replacement during 16-year period assessed)	7 Years

With batteries, lifetime is typically measured used cycle life, with cycles representing a full discharge and recharge. Since the hybrid passenger vehicles do not undergo a single clean full discharge and charge cycle along their roundtrip journeys, a rule-of-thumb approach was used to calculate battery cycles per round-trip. This rule involved the following formula:

$$\frac{A\ h\ discharged}{500 * (A\ h\ battery\ capacity)} \tag{11}$$

…where A h stands for Amp-hours. The A h discharged in the numerator refers to the total Amp-hours discharged during a single round-trip. Then, since 500 batteries were assumed, as noted earlier, the denominator compares this to the battery capacity of all 500 batteries, combined.

The resulting number of cycles per day per locomotive were then assessed for each route separately (as was done with the fuel cell stacks) given formula (11). Again, the number of locomotive days in operation per year were assumed as 350. The available information suggests that LTO batteries (which was described in some more detail in Section 3.7) have a roughly 20,000-cycle lifetime, currently (GWL Power, n.d.; M. Miller, personal communication, February 22, 2019; Padre Electronics Co., Limited, 2019). It was assumed that there might be a slight improvement in this statistic over the next few years, and so a 22,000-cycle life was the underlying assumption behind the battery life calculations.

In order to assess costs that are not necessarily incurred at the same time, the present value calculation was used to bring all costs to their value for the initial period. The PV calculation was used for both fuel costs and for capital equipment replacement or overhaul costs, while initial equipment acquisition was assumed to occur at the beginning of the purchase period and so needed no specific adjustment. The PV calculation can be demonstrated via the following formula, where i refers to the discount rate[166] and n refers to the year (from 1 to 16) when a given cost is incurred:

$$\mathrm{PV} = \sum_{n=1}^{16} C_n/(1+\mathrm{i})^n \qquad (12)$$

After the present value costs are combined with the initial equipment costs, a cost recovery factor, or ‘CRF,’ was then calculated, using the following formula:

$$i/[1-(1+i)^{-N}] \qquad (13)$$

[166] A discount rate (defined in the glossary) of 7% was assumed for passenger rail (based on (OMB, 1992), while 10% was assumed for the freight rail analysis.

Again, i refers to the discount rate and N refers to the number of years over which payments are to be made, 16 in this case. As shown in Formula 14, CRF is then multiplied by the total costs, in present value (shown as PV), to obtain the annual payment, also known as "total cost of ownership" (TCO), for a given system of locomotives and it associated fuel/propulsion technologies. This annual payment, or TCO, can be interpreted as an annual loan payment that serves to cover all costs that have been modeled over the 16-year period, including fuel costs, initial capital equipment costs, and capital replacement/overhaul costs, with the payments complete after 16 years.

$$Annual\ Payment = PV * CRF \tag{14}$$

4.11 Chapter Summary

This chapter provided significant background to the reader so that the analysis results, presented in Chapter 5, can be understood more clearly, and potentially even applied to a high-level decision-making process on fuel choice in rail. Additional notes and explanations will be provided in the next chapter for issues that may be specific to a particular set of results.

CHAPTER 5. RESULTS AND DISCUSSION

5.1 Overview

Previous chapters have laid the groundwork for the analyses covered by this study. In this chapter, all of the study results are presented, i.e. the key simulation results, as well as the emissions and cost results. Discussion of the results are interspersed throughout, with a summary of key takeaways following, which examine the overall messages that can be drawn from the findings, as well as some of the limitations involved. Chapter 6, the concluding chapter, will discuss the study's limitations in more detail.

Tables are presented in sections 5.3, 5.6, and 5.8. These include, respectively, the passenger simulation results for Capitol Corridor and Caltrain, the freight simulation results for the sub-routes that traverse the Kansas City to Los Angeles freight corridor, and the switcher energy analysis and consumption results. These results, in turn, form a foundation for the results presented in other sections.

5.2 Model Validation

In order to validate the simulation model (i.e. to verify the ability of it to simulate real-world conditions), the results of the Capitol Corridor (passenger service) benchmark simulation—i.e. a diesel-electric engine, with both mechanical and dynamic braking—were compared with actual data from a comparable locomotive with a comparable engine-generator configuration on this route. The result gave a value of approximately 1.886 gallons per train-mile, just under 6% off from the available observed data of 1.78 gallons per mile, which came from total fuel consumption observed in one of the actual Charger locomotives in use along this route (D. Shepherd, personal communication, August 2018). In other words, the simulation results required slightly more fuel energy per mile than has been observed along the corresponding route in operation. No adjustment was made for this variance, as the author deemed this error within an acceptable range, given that some variables were not able to be modeled exactly. For example, the gradient for the Capitol Corridor route was modeled fairly closely, but not precisely. Moreover, neither the traction motors nor the engine used for the simulations were specific to the particular vehicle whose data was used for validation. Lastly, assumptions made about total railcar (i.e. non-locomotive equipment) weights, while based on actual data for this vehicle, were based on some adjustments, due to the fact that actual vehicle trips along this line vary in the number and, even to some extent, type of cars that follow the locomotive (D.Shepherd, personal communication, September, 2018).

The validation noted above is presumed to hold for the freight analysis, especially as the author did not have access to the relevant data on the specific routes in order to validate. Of course, such data would have had to be adjusted since every freight trip carries a slightly different mix of items, both in type and quantity. All of this said, a ton-miles per gallon statistic was assessed for each of the simulated freight trips (see Table 15 or the corresponding figure, Figure 24, below)—based on the diesel/ICE results—and, in total, were found to average 456 ton-miles per gallon, which is within 5% of the value that the Association of American Railroads calculated for all domestic Class I Railroad (revenue) trips in 2017 (AAR, 2019c). (The intermodal trains displayed lower fuel efficiencies. This is likely due, in part, to their higher power to vehicle weight ratios, as discussed in section 4.6. Moreover, in the case of the 80-car train, which has the lowest fuel efficiency of all of the vehicles, the higher vehicle speeds play a significant role, also, while, in the case of the 120-car train, poorer aerodynamics due to double-stacking likely play a role. [Box 1, Section 4.2 reviewed the resistance forces encountered by a train.])

Table 15: Ton-miles per Gallon; Actual (i.e. Diesel/ICE) Compared to Association for American Railroads (AAR) Average

Ton-miles per gallon	Simulation Results - Average	AAR Average Value – 2017
Without intermodal vehicles	**517.4** ton-miles per gallon	**479** ton-miles per gallon
With intermodal vehicles	**-456.1** ton-miles per gallon	

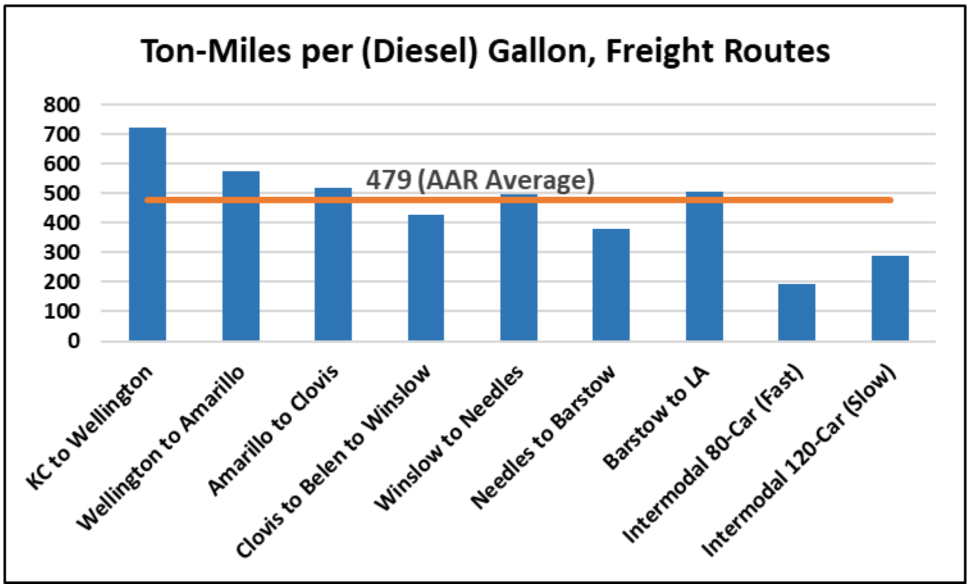


Figure 24: Ton-Miles per Diesel Gallon, Freight Routes

This chart demonstrates the ton-miles per gallon consumption rate demonstrated by each of the simulated freight vehicles. The horizontal orange line demonstrates the average value across all Class I trains in 2017, as recorded by (AAR, 2019c). (In the last 10 years of recorded data, this metric has varied between 457 and 484.) (AAR, 2019c)

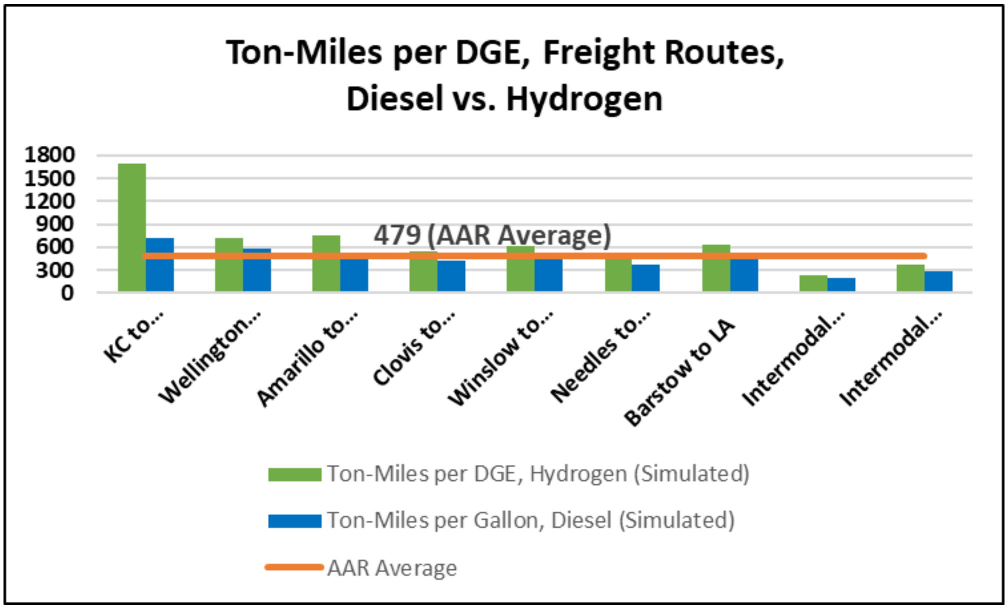


Figure 25: Ton-Miles per Diesel Gallon Equivalent, Freight Routes, Diesel vs. Hydrogen

Similar to Figure 24 above; however, this figure demonstrates the ton-miles per DGE (diesel gallon equivalent) fuel efficiency metric for both the trains running on diesel and those running on hydrogen (via fuel cell). The hydrogen results are based on the results for the near-current fuel cell system efficiency assumptions (see description of "Hydrogen 1" below)

5.3 Results – Passenger Simulations

Tables 16 and 17, below, show the simulation results for the passenger trains and routes modeled. The diesel-electric, hydrogen, and OLE results are shown first, followed by the results of the diesel-electric and hydrogen vehicles hybridized with batteries (and in which the power level of the original prime mover is unchanged), and, finally, the results of the hybridized vehicles in which the prime mover has also been reduced in size (or "downsized") in order to take advantage of additional room and lower cost of the prime mover.

For these passenger simulations, the diesel-electric powertrain was modeled both with the use of a) mechanical braking and dynamic braking, as well as under b) dynamic braking only conditions, i.e. with the mechanical braking use relegated to emergency usage only (i.e. assumed as 0 for these simulations). For all of the remaining simulations (including all freight simulations), however, and for the main portion of the remaining analyses, “dynamic braking only” served as the default, and, for the purpose of consistency across technologies, this mode, in the non-hybrid diesel scenario, served as the baseline for cross-technology comparison.

To give some background on this topic, trains have, broadly speaking, two braking systems. One relies on frictional forces (i.e. mechanical), activated and controlled by compressed air[167]. The other involves a form of dynamic braking called “rheostatic braking,” in which the traction motors are operated as generators, with the resulting electricity dissipated in resistors. In some cases, this electricity could be returned to wayside infrastructure or stored on-board of the vehicle, an approach referred to as regenerative braking.

(Simpson, 2018) suggests that the use of dynamic braking as “first order” for braking efforts under “non-emergency conditions” (Simpson, 2018) may be common practice (Simpson, 2018), and indicates that use of the dynamic braking system enables the vehicle operator to “avoid or substantially reduce the use of train air brakes for long periods of time (Simpson, 2018).” Given this context, because the author wished to optimize for energy consumption in the modelling, the “dynamic braking only” option was the primary focus of this work, as noted above.

For example, while not explicitly noted in tables 16 and 17, the diesel-electric (non-hybrid) scenario that relies only on dynamic braking demonstrates an energy reduction of approximately 7.8% (from the scenario in which both braking strategies are assumed) for the Capitol Corridor route while, for the Caltrain route, this reduction went up to 20.6%. On the

[167] This air/mechanical braking system is in fact made of two separate components, an automatic brake and an independent brake system (D. Cook, personal communication, December 9, 2019). The automatic one operates as a sort of default, with the latter system offering more flexible “fine tuning,” as needed (D. Cook, personal communication, December 9, 2019).

other hand, because the addition of mechanical braking adds to the total braking capacities of the train, the vehicle with both options at its disposal would, in the simulation, accelerate to higher speeds before slowing down. This resulted in reduced trip times in those scenarios vis-à-vis the dynamic braking only scenarios. For example, for the Capitol Corridor round-trip, the trip time was reduced by 24 minutes, i.e. by about 6%, while for Caltrain, the trip time was reduced by 33 minutes, or just over 15%.

Key values in Tables 16 and 17 include energy consumption, both in GJ[168] and in gallons/kg/kWh (depending on the propulsion involved), efficiency of the prime mover (i.e. the diesel engine-generator, or "genset" combination, or the fuel cell system), vehicle efficiency (including energy that goes towards auxiliary/hotel power), and the reduction in energy consumption vis-à-vis the diesel "benchmark" (which, again, refers to the diesel-electric powertrain that relies solely on dynamic braking in typical operations). Average and maximum power at the wheels are also shown, as the relationship between these numbers helps demonstrate the gap between typical power and maximum power, which offers one way to assess hybridization potential, discussed further below.

The number of tanks required for each hydrogen scenario is also noted (and the simulations, as noted earlier, took these values into account). This has mostly been done to give a sense of the varying amounts of space actually required by passenger trains that might operate on hydrogen. While locomotives are often customized a little, it is unlikely that locomotives would actually be constructed to always match exactly the number of tanks required per route; rather, one, two, or three set variations in tank number might comprise common templates.

[168] Lower heating values of 42.612 MJ per kg diesel and 120.21 MJ per kg of hydrogen were used. (US DOE, 2008)

Table 16: Simulation Outputs and Related Calculations for the Capitol Corridor Route (1 round-trip)

Capitol Corridor: Prime Mover/ Fuel	Maximum Power Capacity, Genset/ Fuel Cell (MW)	Braking Available	Primary Fuel (Diesel/H2/ Electricity[169]) Consumption 1 Round Trip (GJ)	Primary Fuel (Diesel/H2/ Electricity) Consumption 1 Round Trip *Switch2DGE?*	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency[170] Regen. Efficiency (Hybrids) (%)	Average Output Power[171], Genset/H2 Fuel Cell (kW)	Max. Output Power, Genset/H2 Fuel Cell (kW)	Average Power at Wheels (kW) (Maximum: 2389.1 kW)	Number of H2 Tanks	Energy Reduction from Diesel "Baseline" %
Diesel	3.3	Mech. & Regen.	78.846	5,932.2 gallons	35.8	32.5	1329.5	3114.2	1033.6	NA	NA
Diesel (Baseline)	3.3	Regen.	72.706	5470.2 gallons	35.7	33.7	1144.0	3114.4	1043.3	NA	NA
Hydrogen 1[172]	3.3	Regen.	52.020	432.7 kg	54.0	46.7	1142.7	3097.6	1022.2	138	28.5
Hydrogen 2	3.3	Regen.	47.225	392.9 kg	56.1	51.3	1058.3	3097.6	1020.6	124	35
Electricity (OLE)	3.3	Regen.	21.559	5,988.7 kWh	NA	87.7	NA	NA	997.6	NA	70.3
Diesel Hybrid	3.3	Regen.	58.788	4423.04 gallons	35.3	42.6 43.8	910.7	978.7	1073.7	NA	19.1
Hydrogen Hybrid 1	3.3	Regen.	36.685	305.2 kg	56.5	66.6 42.8	906.4	974.6	1035.1	98	49.5
Hydrogen Hybrid 2	3.3	Regen.	35.391	294.4 kg	58.6	69.1 42.7	906.4	974.6	1034.7	94	51.3
Diesel Hybrid	1.1	Regen.	64.143	4825.9 gallons	31.9	38.0 42.5	906.2	974.6	1031.8	NA	11.8
Hydrogen Hybrid 1	1.1	Regen.	45.492	378.4 kg	45.5	53.5 42.4	905.5	973.6	1027.5	120	37.4
Hydrogen Hybrid 2	1.1	Regen.	38.650	321.5 kg	53.5	62.9 42.4	904.4	972.6	1024.7	104	46.8

[169] OLE energy consumption is measured where the pantograph meets the catenary wire (see glossary), and also assumes regenerative braking energy is recycled through the OLE system. While this value is significantly lower than the values for the other powertrains, it does not take into account the total input power required to produce the electricity at the originating powerplant(s). Thus the efficiency values likely offer a superior method by which to compare this powertrain to the others.

[170] Vehicle efficiency values include the energy that goes towards the auxiliary/hotel power requirements.

[171] Included in these values (and in the max values to its right) is the energy required for auxiliary power (and attendant converter efficiency losses, e.g. see figure 27).

[172] "Hydrogen 1" uses an "average" fuel cell efficiency curve while "Hydrogen 2" uses a "best case" fuel cell efficiency curve (refer to Sections 5.3, 4.6 (Fig. 22) for more details).

Table 17: Simulation Outputs and Related Calculations for the Caltrain Route (1 round-trip)

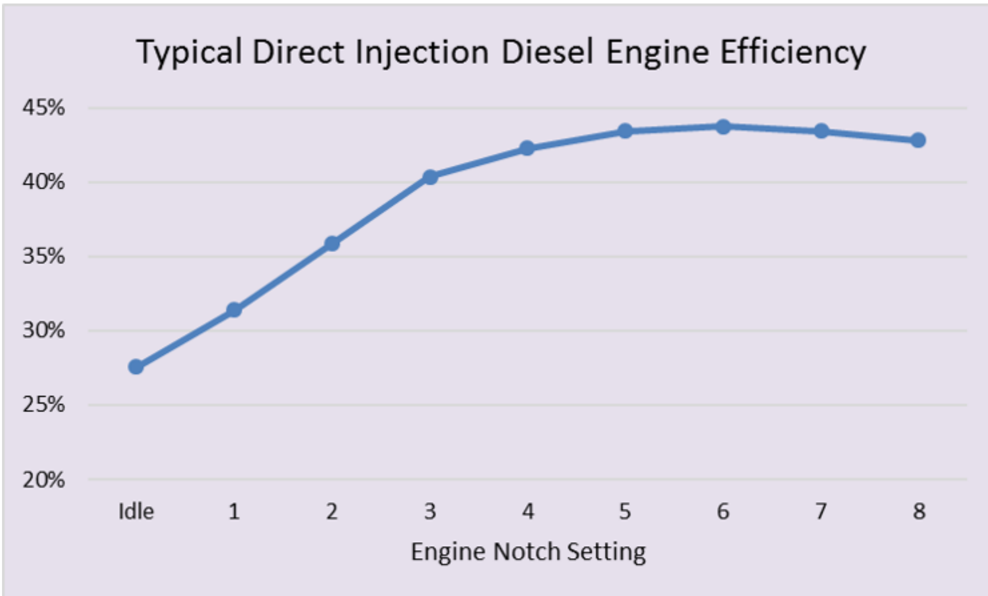
Caltrain: Prime Mover/ Fuel	Max. Power Capacity, Genset/ Fuel Cell (MW)	Braking Available	Primary Fuel Consumption (Diesel/H2/ Electricity) 1 Round Trip (GJ)	Primary Fuel (Diesel/H2/ Electricity) Consumption 1 Round Trip	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency Regen. Efficiency (Hybrids) (%)	Average Output Power, DE Genset/H2 Fuel Cell (kW)	Max. Output Power, Genset/H2 Fuel Cell (kW)	Average Power at Wheels (kW) (Maximum: 2389.1 kW)	Number of H2 Tanks	Energy Reduction from Diesel "Baseline" %
Diesel	3.3	Mechanical& Regen.	50.235	3779.6 gallons	36.1	32.2	1677.6	3109.2	1913.7	NA	NA
Diesel (Baseline)	3.3	Regen.	39.864	2999.3 gallons	35.4	34.2	1115.1	3107.3	1874.9	NA	NA
Hydrogen 1	3.3	Regen.	30.195	251.2 kg	52.3	44.4	1115.5	3090.7	1820.1	80	24.3
Hydrogen 2	3.3	Regen.	26.395	219.6 kg	54.9	50.8	1114.4	3088.7	1815.5	70	33.8
Electricity (OLE)	3.3	Regen.	9.473	2,631.4 kWh	NA	87.7	NA	NA	1818.8	NA	76.2
Diesel Hybrid	3.3	Regen.	25.292	1902.9 gallons	34.0	54.4 77.5	685.5	848.7	1884.2	NA	36.6
Hydrogen Hybrid 1	3.3	Regen.	15.408	128.2 kg	57.1	87.5 77.0	688.6	856.9	1860.1	42	61.3
Hydrogen Hybrid 2	3.3	Regen.	14.894	123.9 kg	59.1	90.4 77.2	688.5	856.9	1859.9	40	62.6
Diesel Hybrid	.95	Regen.	27.573	2074.5 gallons	30.6	48.9 77.1	688.5	856.9	1860.0	NA	30.8
Hydrogen Hybrid 1	.95	Regen.	19.449	161.8 kg	45.3	69.0 76.7	686.9	854.8	1829.157	52	51.2
Hydrogen Hybrid 2	.95	Regen.	16.427	136.7 kg	53.4	81.7 76.7	686.1	853.8	1824.1	44	58.8

Note: Please see the Capitol Corridor table (Table 16), above, for several relevant notes.

As Tables 16 and 17 show, the fuel cell system efficiencies are significantly higher than the diesel genset efficiencies, for both the Capitol Corridor and the Caltrain routes. One interesting feature is that, while the diesel genset efficiency drops between the non-hybrid and the non-downsized hybrid, and then between the non-downsized hybrid and the downsized hybrid, for the fuel cell system, the non-downsized hybrid demonstrates a higher efficiency than the non-hybrid, while the downsized version then loses much of this initial benefit. In both cases, these responses are directly related to the characteristics of the efficiency maps of the given prime movers. (Relevant fuel cell efficiency maps are shown in Figure 22, in Chapter 4, while two versions of notch-based diesel engine efficiency maps can be found in Figure 26. The diesel engine efficiency maps provided are based on notch-oriented data rather than the broader data set utilized in these simulations; nonetheless, the variations in efficiency that can be seen---with a peak somewhere in the higher mid-range of overall power capacity---demonstrate well the overall trend between diesel engine efficiency and the percent of maximum power utilized.*)* In the case of the diesel, the hybrids, whose engines operate at fixed points (see Table 18), are operating at points that are slightly less efficient than the combined average of the efficiencies at the different points utilized for the non-hybrid scenarios. In the case of the downsized diesel hybrids, the prime movers are, as designed, operating closer to their maximum power point. While this reduces the cost and would allow room for batteries and their associated equipment, this also ensures a lower operating efficiency. In the case of the hydrogen fuel cell vehicles, as Figure 22 (from Chapter 4) demonstrates, their prime movers are at their most efficient around 15-25% (for Hydrogen "1"[173]) and 20-30% (for Hydrogen "2"), with efficiencies dropping steadily the further one goes from these points. The non-downsized hybrid operating points are

[173] "Hydrogen 1" corresponds to the top chart in Figure 22, while "Hydrogen 2" corresponds to the bottom chart in Figure 22.

clearly just a bit closer to these ideal power levels than are the non-hybrids (averaging their power levels, and corresponding efficiencies, across the trip), while, in the case of the downsized fuel cell vehicles, there is a clear efficiency penalty to their operating at power points that are farther away from and, in fact, much higher than the ranges just noted. Hydrogen “1” has a much more steady efficiency drop-off on both sides of its peak operating range, and this explains the larger penalty that can be seen for operating this system close to its power maximum. (The anonymous data to which the author has, as noted earlier, access to suggests that more recent fuel cell efficiency maps would demonstrate a low-to-high efficiency gap that is somewhere between that of Hydrogen ”1” and Hydrogen “2”.)

a. 

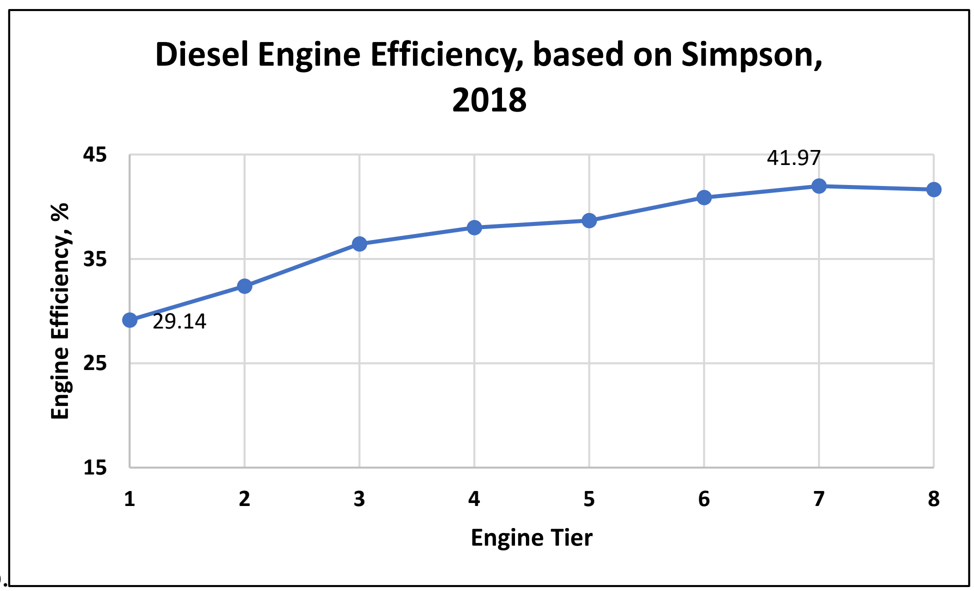
b. 

Figure 26 a-b. Diesel Engine Efficiency Maps, by Engine Notch

Figure 'a' comes from (Bloedt, 2019), 2018 and Fig 'b' was developed based on data for a GE Dash 9 locomotive, which was provided in (Simpson, 2018).

(Note: Efficiency for the idle notch was not provided in (Simpson, 2018). This likely reflects an assessment of tractive power efficiency, only.)

As for the overall most efficient vehicle powertrains, in the case of the Capitol Corridor route, the OLE is by far the most efficient. The hydrogen fuel cell powertrains have a distinct advantage in terms of vehicle efficiency and, in this case, even the downsized hybrids, while not as efficient as their non-downsized counterparts, maintain a significant advantage over their non-hybrid equivalent. The diesel-electric powertrain, on the other hand, clearly shows a benefit to hybridization, though this benefit is still somewhat reduced when the powertrain is downsized. Together, however, the results in tables 16 and 17 show just how key a role hybridization can play in reducing overall fuel usage.

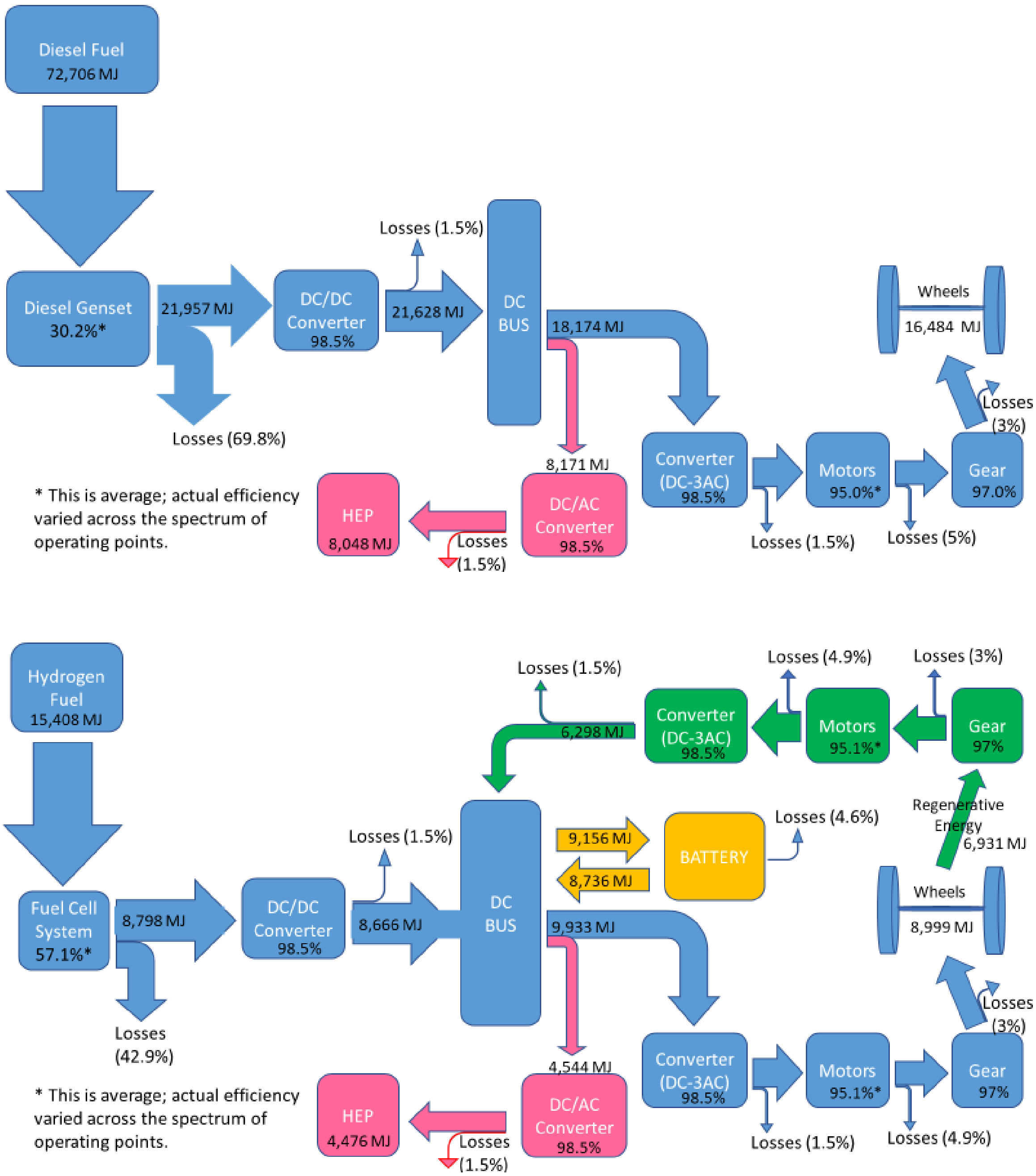


Figure 27: Diagrams of the Flow of Energy for Two of the Simulated Powertrains

The diagram on top represents the non-hybrid Capitol Corridor simulation, while the one on the bottom represents the (non-downsized) hybrid simulation of a vehicle along the Caltrain route. (with a fuel cell system efficiency typical of current equipment, also referred to as Hydrogen "1") As the hybrid diagram shows, regenerative energy is "recycled" back through the system (the same gears motors, and converters that convey energy from the DC BUS to the wheels), after which it will both recharge the battery and serve to boost the overall efficiency of the vehicle's operations to very high levels, levels that would never be seen in a non-hybrid vehicle. (Note: Due to rounding error, numbers may not add up exactly.)

In the case of Caltrain, while OLE has a very high efficiency here, too, Caltrain's duty cycle (which involves more frequent stops) means that the performance of the hybrid powertrains really shines. The increased vehicle efficiency of the diesel hybrid (non-downsized) is roughly double that of the Capitol Corridor case (again, with a slight penalty for the downsized version), and the Fuel Cell-powered hybrid vehicles also roughly double their efficiency increases, leading to efficiencies (for the non-downsized hybrids) approaching 90%, and rivaling that of the OLE vehicle.

$$\frac{100 * (Traction\ Energy\ at\ the\ Wheels + Aux.Power)}{Fuel\ Energy\ Consumed\ (Prime\ Mover)} \qquad (12)$$

Equation (12), above, demonstrates the formula that was used to calculate the "vehicle efficiency" (where "Aux. Power" refers to the vehicle's auxiliary/hotel power needs). Based on an approach derived from (Yamamoto, Hasegawa, Furuya, & Ogawa, 2010), this was determined a good way to represent the significant benefits of hybridization towards reducing the diesel or hydrogen fuel required to move the vehicle. Using this method presents regenerated energy as, in effect, "recycled" energy that recirculates through the system and can serve to boost the energy already provided by the prime mover. Figure 27, above, provides a visual representation of the processes involved. The "Regenerative Efficiency" (abbreviated "Regen." efficiency) metric provided in tables 16 and 17, alongside the vehicle efficiency value, is another way to represent the significance of this regenerative energy. The value is determined through the formula provided in Equation (13). (Traction Energy refers to the energy that moves the vehicle forward.)

$$\frac{100 * (Regenerative\ Energy\ at\ the\ Wheels)}{Traction\ Energy\ at\ the\ Wheels} \quad (13)$$

The hybrid vehicles were modeled such that the respective prime mover provided continuous energy at a power level very close to the trip's average power requirements. Table 18, below, shows the "fixed operating points" at which this power level was set, with data shown separately for each of the passenger routes.

Table 18: Fixed Operating Points Used for Simulations, Capitol Corridor and Caltrain

Prime Mover/Fuel	Fixed Operating Point (kW), Capitol Corridor	Fixed Operating Point (kW), Caltrain
Diesel Hybrid, 3.3 MW	964	836
Diesel Hybrid, 1.1 MW	965	848
Hydrogen "1" Hybrid, 3.3 MW	960	844
Hydrogen "2" Hybrid, 3.3 MW	960	844
Hydrogen "1" Hybrid, 1.1 MW	959	842
Hydrogen "2" Hybrid, 1.1 MW	958	841

5.4 Results – Emissions and Costs, Capitol Corridor

Most of the emissions outputs presented in this chapter are based on the GREET model's California grid assumptions. This was done based on the assumption that there will be continued movement away from fossil fuels and towards renewable fuels, nationwide, in the coming years. This topic is discussed in further detail, in Section 5.10. Nonetheless, figure 28, just below, gives an initial look at the backdrop of varying electric grids and how these can impact the kinds of emissions that will result, even from upstream processes of fuels that a casual observer might not normally associate with the electric grid.

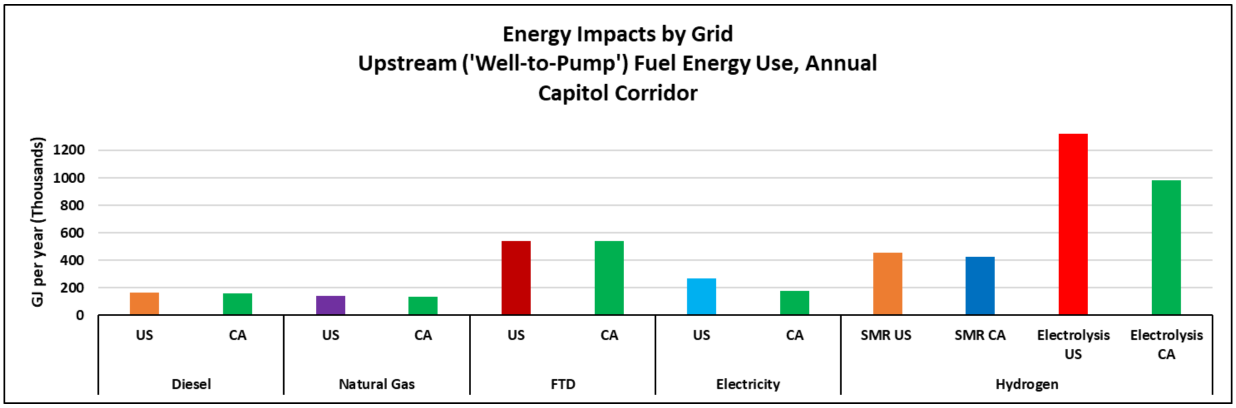


Figure 28: Impact of U.S. vs. CA grid on Upstream (i.e. 'Well-to-Pump') Energy Use

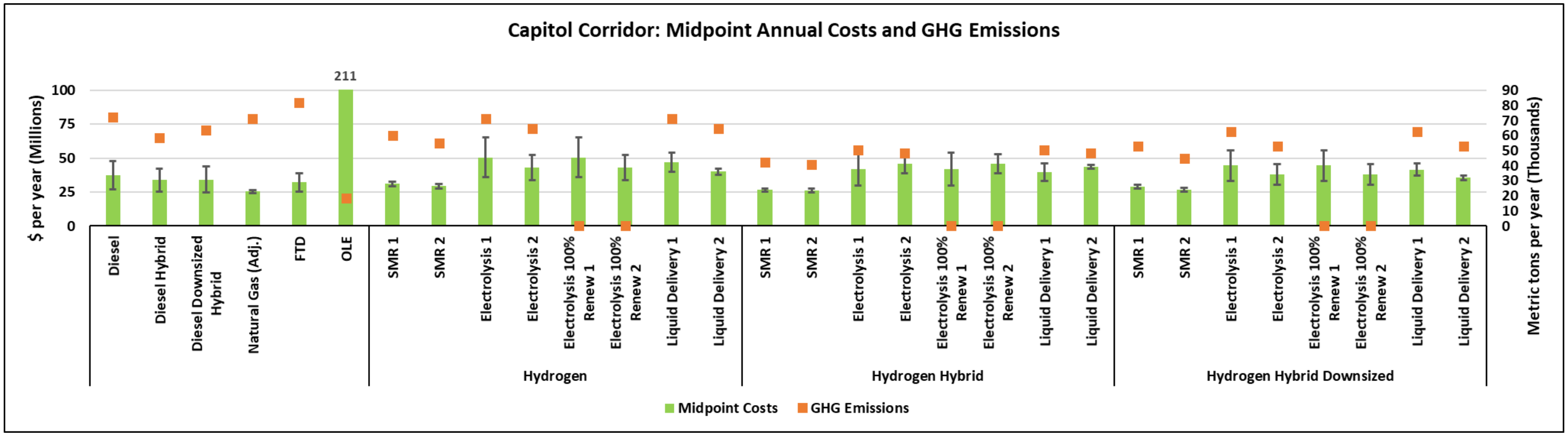


Figure 29: Capitol Corridor: Midpoint Annual Costs (Annual Payment) and GHG Emissions.

This chart provides a broad overview of the options explored and how they perform in the context of the Capitol Corridor passenger line. The green bars represent midpoint annual payment costs (see Formula (14), Section 4.10), i.e. averages of the lowest and highest annual payment costs that serve as range endpoints. The error bars show the potential cost range, based on the low and high endpoints estimated in this study. GHG Emissions are indicated by the orange squares also displayed on the chart.

Figure 29, above, shows the broad range of cost and GHG emissions results from the analysis of the Capitol Corridor line. This graph allows comparison of emissions reduction and cost for many alternative powertrains and fuels. The chart makes it clear that OLE represents one of the top choices---in fact the best choice, given the current make-up of the grid---from an emissions reduction perspective; however, one can immediately see the tremendous cost penalty that would be incurred given the relatively low levels of passenger traffic along this line, even during this 2022-2038 period (with greater service frequency than is currently the case) The diesel hybrid option, on the other hand, offers a compelling choice, with GHG reductions that would match hydrogen via SMR, especially at current fuel cell efficiency levels, and at a cost that is among the lowest of all of the options modeled. (The downsized diesel hybrid, as indicated above, is not as efficient as the non-downsized version, and so the GHG reductions are muted. It may offer cost savings over the non-downsized diesel hybrid; however, as Figure 31, below, hints at, this would depend on the cost of diesel fuel, the increased use of which will compensate for reduced prime mover costs [while battery cost profiles remain unchanged between the two diesel hybrid scenarios].)

Figure 29 also shows that natural gas offers the lowest cost of all of the options, but with a minimal GHG reduction (a decrease of about 1.7% from the diesel non-hybrid benchmark). Meanwhile, FTD has a higher emissions profile, mainly due to “well-to-pump” (WTP) impacts of what is, in this particular case, a natural gas-derived fuel (GREET’s default method for producing FTD).

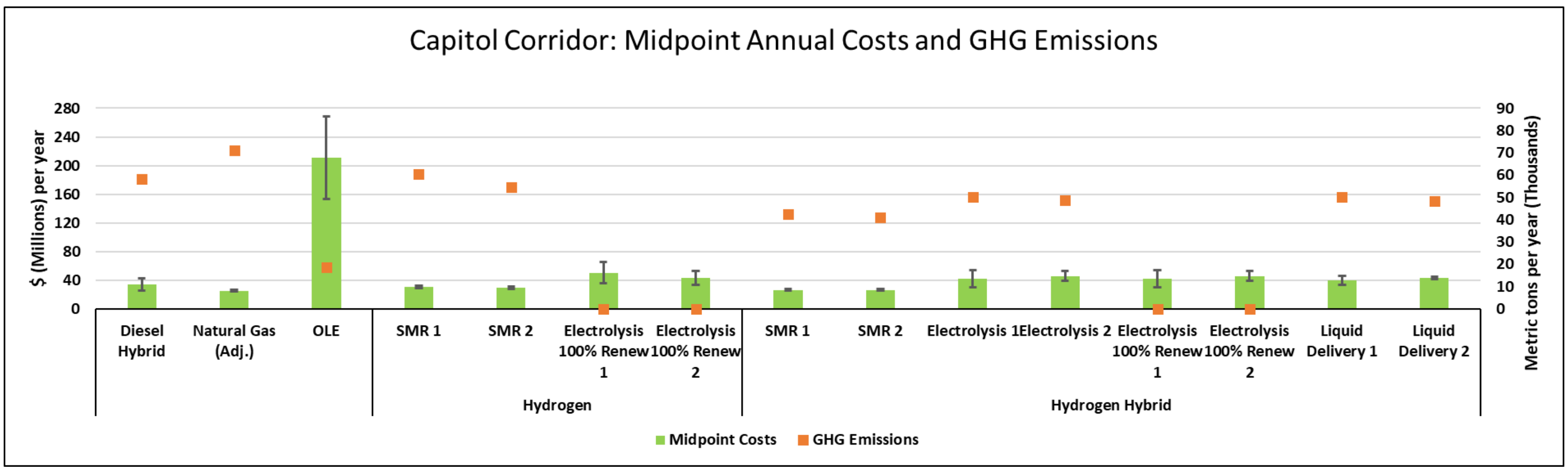


Figure 30: Capitol Corridor: Midpoint Annual Costs (Annual Payment) and Emissions, Selected Options

Figure 30, above, shows the full span of the potential costs for OLE alongside several of the other best candidate options, as indicated by Figure 29. (The downsized hydrogen hybrid options are not shown, as they don't offer the same GHG reductions as the non-downsized hybrid, and in only the high diesel cost, highly efficient fuel cell scenarios, do they appear to offer any cost savings vis-à-vis the diesel benchmark.) The downsized options do, however, remain important to consider should room within the locomotive become a crucial issue, perhaps even serve as a make-or-break factor in determining whether a technology shift would be feasible for a given rail system.

It can also be seen from both Figure 29 and Figure 30 that 100% renewable electrolysis would be ideal, from a GHG emissions perspective. (And even a significant further increase in renewables penetration into the electric grid could greatly reduce the GHG profile for electrolysis from where it stands now, a topic touched on more in Sections 5.9 and 5.10, below.) Generally speaking, moving to a hybridized hydrogen powertrain leads to among the best results, certainly in terms of GHG reductions for a given cost. Moreover, absolute fuel cell hydrogen hybrid costs appear to be competitive with the diesel hybrid, and could even be cheaper for this technology, though that will depend on cost trajectories, particularly the price of diesel fuel and, on the hydrogen end, just how far down fuel cell stack costs can come down. Figure 33 shows a breakdown of costs that make this apparent. (Note that battery cost profiles are the same across diesel and hydrogen and their respective hybrid versions).

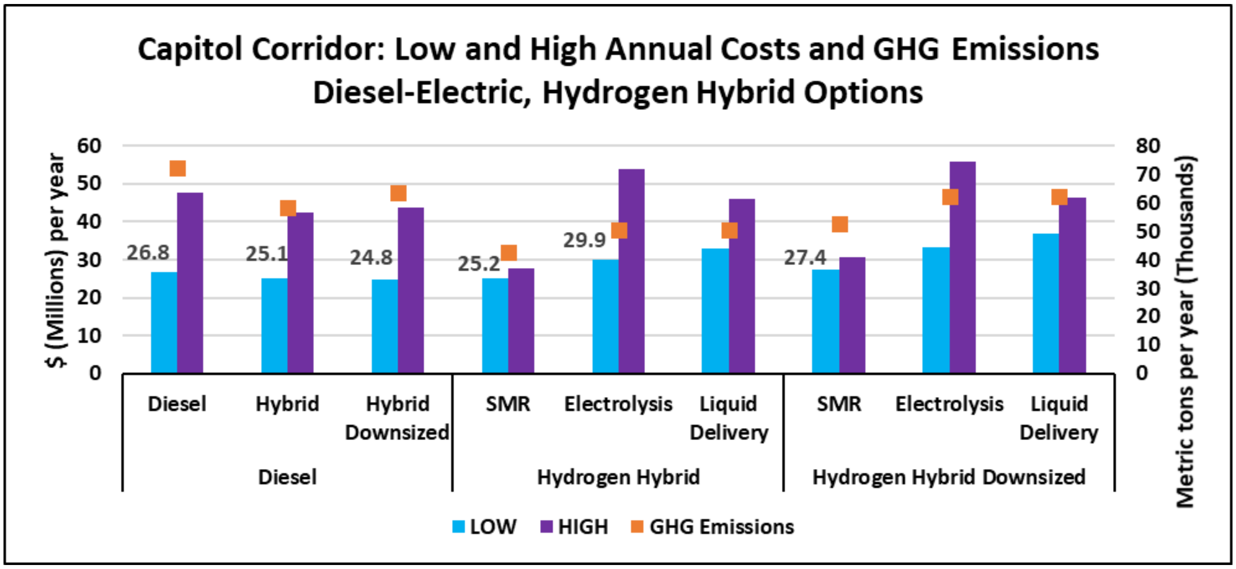


Figure 31: Low and High Costs (Annual Payment), and GHG Emissions, Highly Competitive Technologies

A look at low and high costs, as well as corresponding GHG emissions points for the most competitive technologies (from the standpoint of incumbent advantage, potential to reduce emissions vis-à-vis the incumbent technology, and cost competitiveness). Note that labels are utilized for several of the lower cost values, which are spaced quite closely together. (All of the hydrogen options correspond to the "Hydrogen 1" option.)

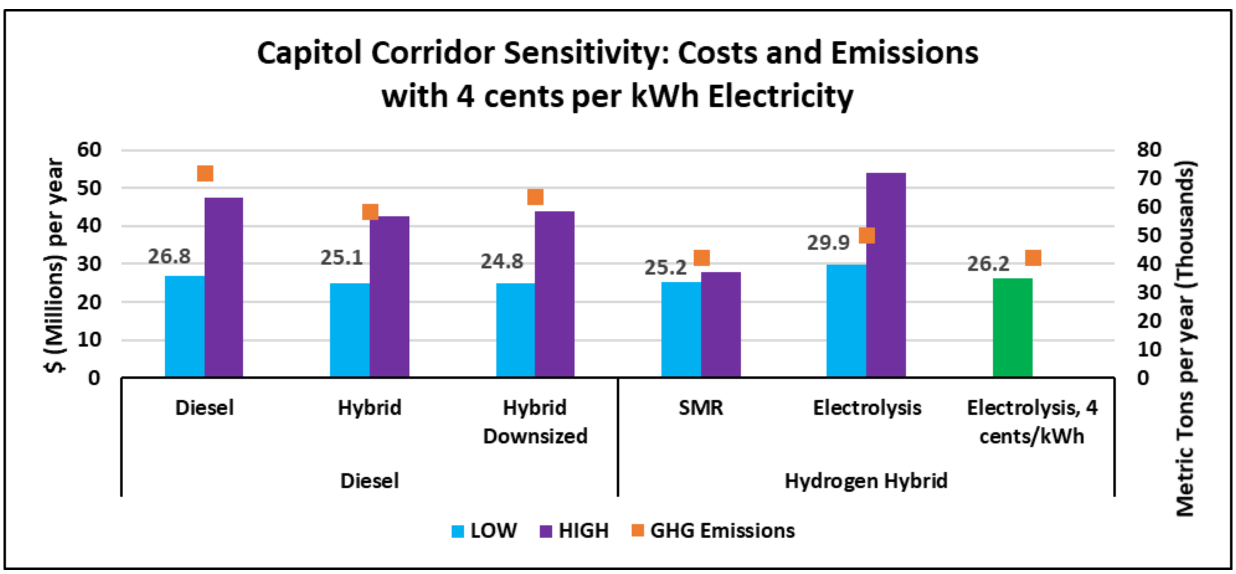


Figure 32: Electrolysis Sensitivity, Capitol Corridor. Low and High Costs (Annual Payment)

This chart aims to examine how cheap electrolysis could get with a very low, but feasible electricity cost of 4 cents per kWh. SMR still holds a slight advantage at this price. However, note that, while the emissions reduction from electrolysis is less than it is for SMR, as the grid becomes cleaner, this situation could change significantly. (This topic is covered further, in both Sections 5.9 and 5.10.) (Note: All of the hydrogen options correspond to "Hydrogen 1.")

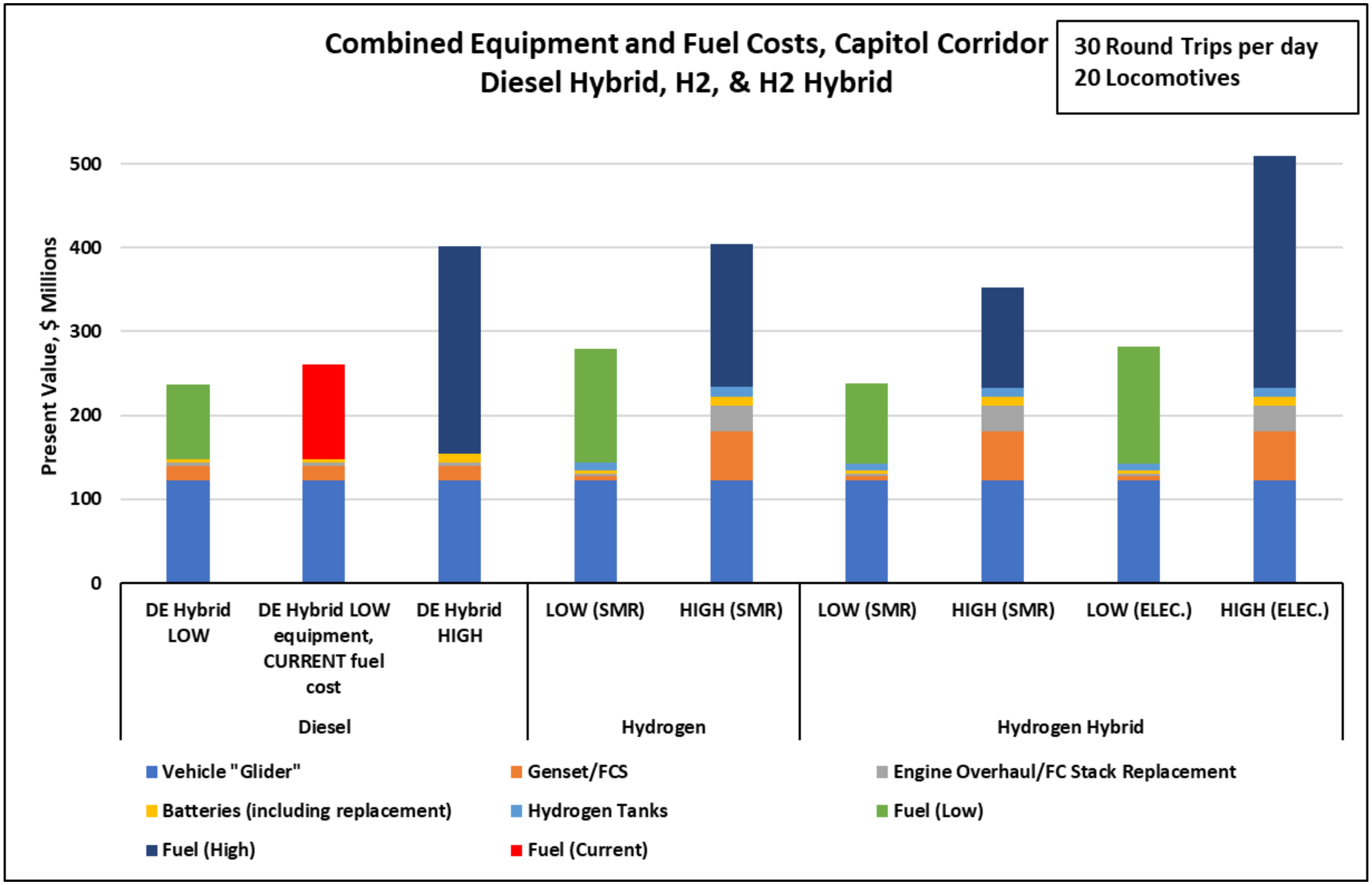


Figure 33: Combined Equipment and Fuel Costs (Present Value), over the 16-year Period: Capitol Corridor

This chart breaks down the components that make up the costs of the various fuel technology scenarios. Note that the red bar, in the second column, represents current diesel fuel costs. (Note: Elec. Stands for electrolysis.)

We saw, in Figures 30 and 31, above, that a hybridized powertrain using hydrogen via fuel cell may, according to this analysis, not only already be cost competitive with the incumbent diesel-electric technology, but in many cases it may be cheaper. Figure 33 emphasizes the message that hydrogen hybrid technology could also be cost competitive with a hybridized diesel-electric powertrain. Moreover, diesel fuel cost will make a big difference, as will, on the hydrogen end, the ability to reduce stack costs and related replacement costs (assumed as needing full replacement after ten years, as noted in Chapter 4).[174]

[174] Figure 34 offers another view of this. In the case of electrolysis, electricity cost is clearly the main driver of cost differences, but, even here, stack cost reductions will also be key to the viability of this method of hydrogen production for a rail application such as the Capitol Corridor line. (And, with the potential reduction in emissions that electrolysis brings the potential for, this method is likely to get increasing attention in the coming decade or two.)

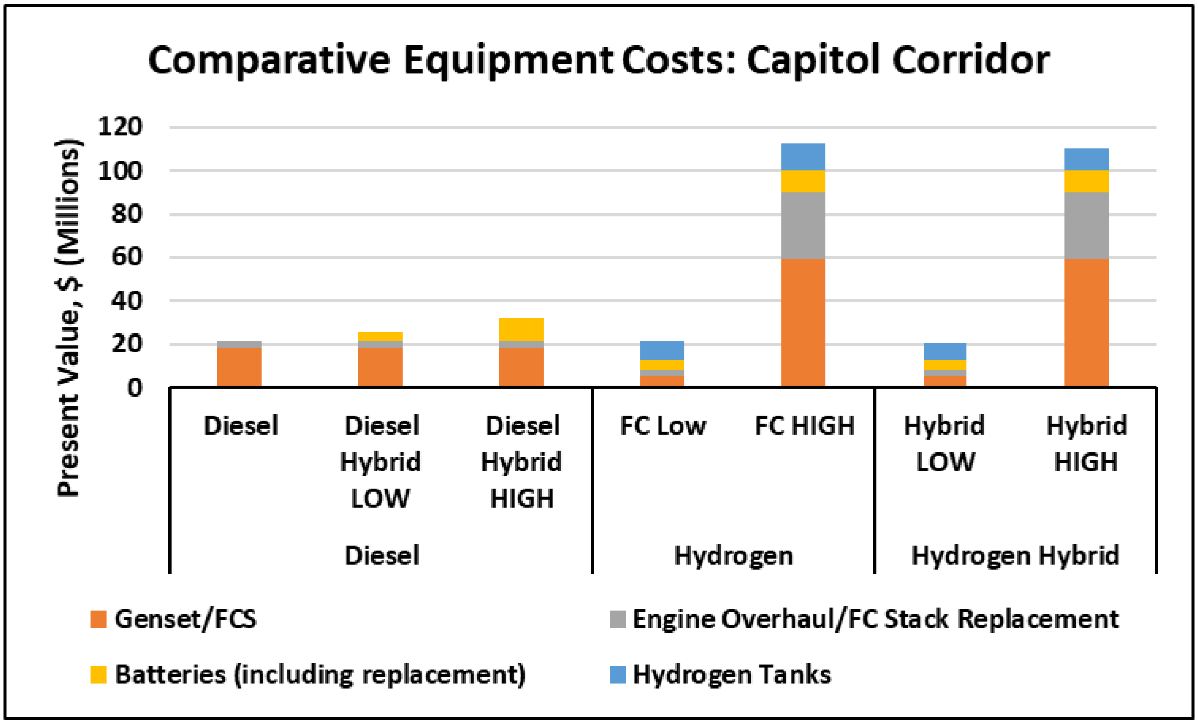


Figure 34: Comparative Equipment Costs (Present Value), Capitol Corridor.

This chart offers a closer look at where the distribution of cost differences lie between the different technologies, from an equipment standpoint. Locomotive "glider costs" were removed here, as that cost is the same for all technologies that were assessed.

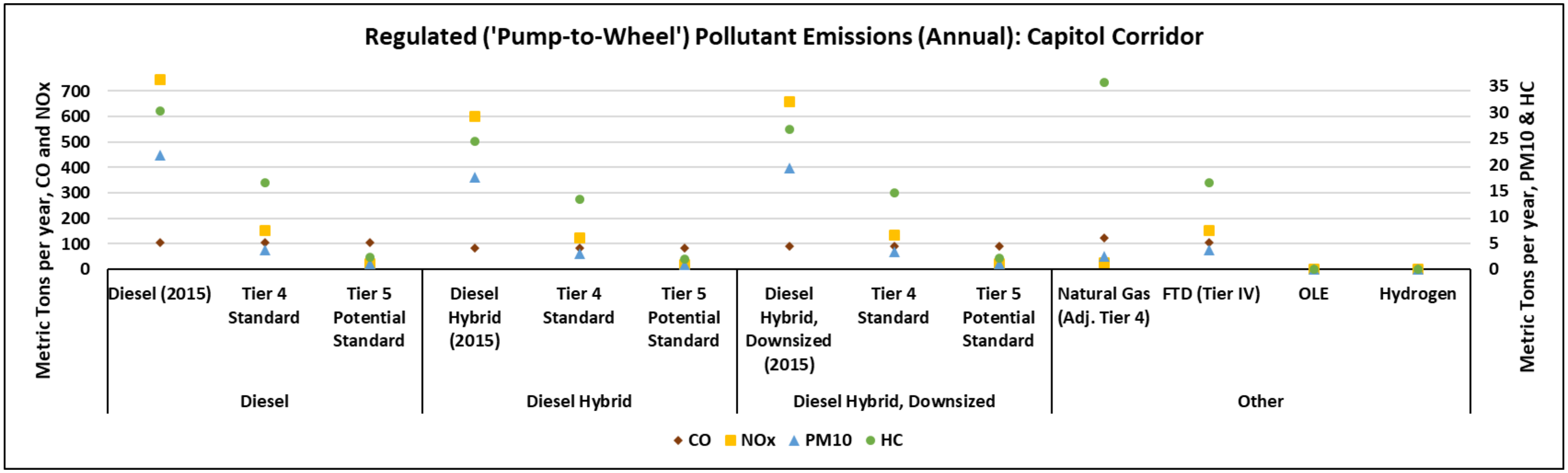


Figure 35: Regulated Pollutant Emissions, Capitol Corridor.

This chart shows the annual pollutant emissions that would result along the Capitol Corridor line, emphasizing the fossil fuel options, since OLE and hydrogen have no pollutant emissions during the operational (or "Pump-to-Wheel") phase.

Figure 35, above, shows that, while there are some pollutant emissions benefits to hybridization, if looking at diesel-electric only, it's really a higher standard that will lead to the greatest reductions in HC, NOx, and PM10. Natural gas, while assumed to benefit from a three-way catalytic converter, thus resulting in low CO and NOx, leads to increases in particulate matter (i.e. PM_{10}, here) and hydrocarbons (HC). Hydrogen and OLE operations have no emissions, of course.

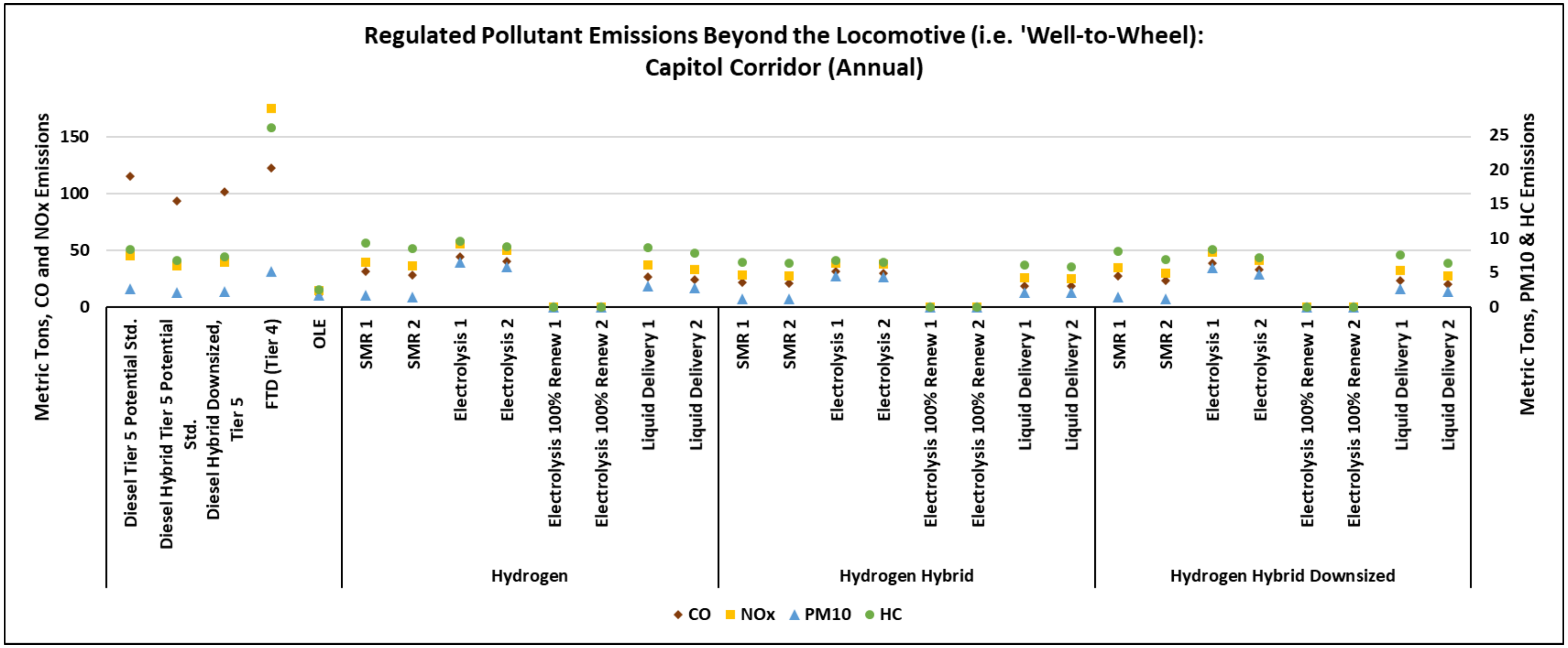


Figure 36: Regulated Pollutant Emissions Beyond the Locomotive, Capitol Corridor
(Note that the diesel options are all based on Tier 5.)

If one wanted to look beyond what is regulated, and also take into account that new regulations might wish to account for emissions produced at any onsite powerplants (or just be aware of the overall emissions impacts, including across fuel production facilities and when the fuel is in transit), Figures 35 and 36, above, demonstrate that a) with diesel, much of emissions come from operation, while, with hydrogen, a significant impact (and, in fact, the only impact) can come from upstream impacts (i.e. gas production). This topic is discussed more in Section, 5.8, which addresses the results of the switcher analysis. Figure 36 also elucidates the significant differences between the different hydrogen options. On the diesel end, the results remain similar to the results for the pump-to-wheel portion, again, due to the large role of operations. NOx levels don't look particularly high (but are very high for FTD), comparatively speaking; however, CO, again, remains much higher than with the non-diesel options. That said, resulting emissions from a Tier 5 standard (which has not yet been implemented, but only suggested) would be similar to what hydrogen can already bring (not counting hydrogen made from renewable resources, which has essentially zero fuel cycle emissions). Well-to-wheel PM_{10} emissions are lower under hydrogen via SMR (even lower than the diesel hybrid scenario), and this reduction is greater with a hydrogen hybrid. Overall, the downsized powertrains appear, from this analysis, to produce benefits partway between non-hybridized and hybridized powertrains, in the case of both diesel and hydrogen.

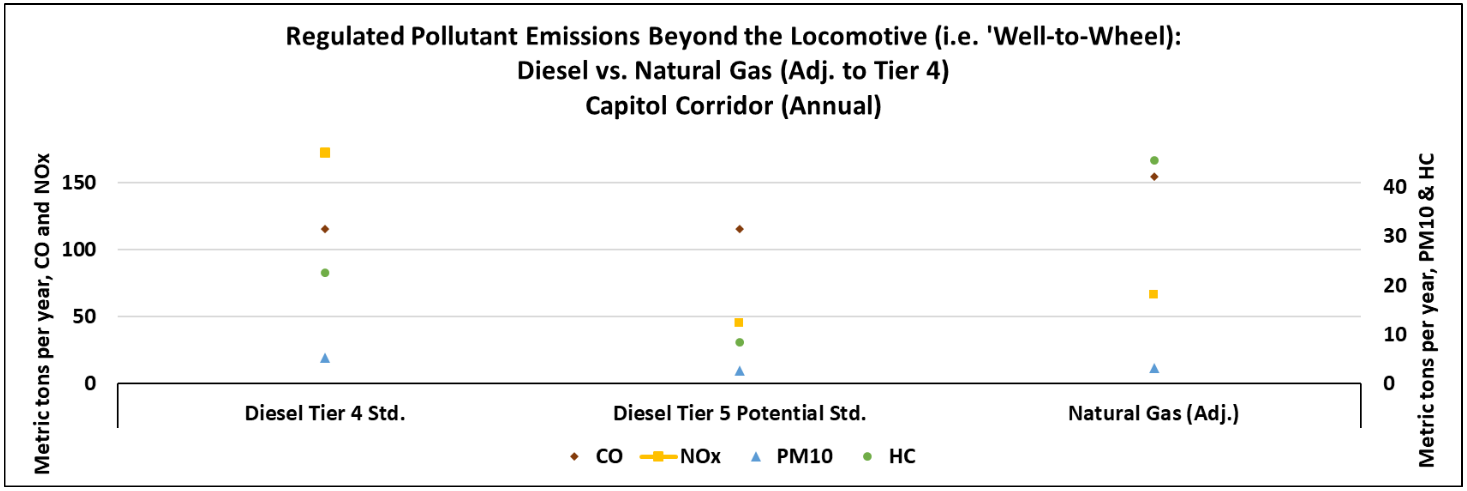


Figure 37: Well-to-Wheel Pollutant Emissions, Capitol Corridor, Diesel vs. Natural Gas

Natural Gas was not included in the above 'Beyond the Locomotive' figure (i.e. Figure 36) because of poor well-to-wheel performance, particularly with regard to hydrocarbons (HC) and with CO. Figure 37, which offers a bit of a close-up of this option relative to the diesel (non-hybrid) options, demonstrates that the NOx reductions are, on the other hand, almost comparable to going to a Tier 5 diesel standard, and the same with PM_{10} emissions.

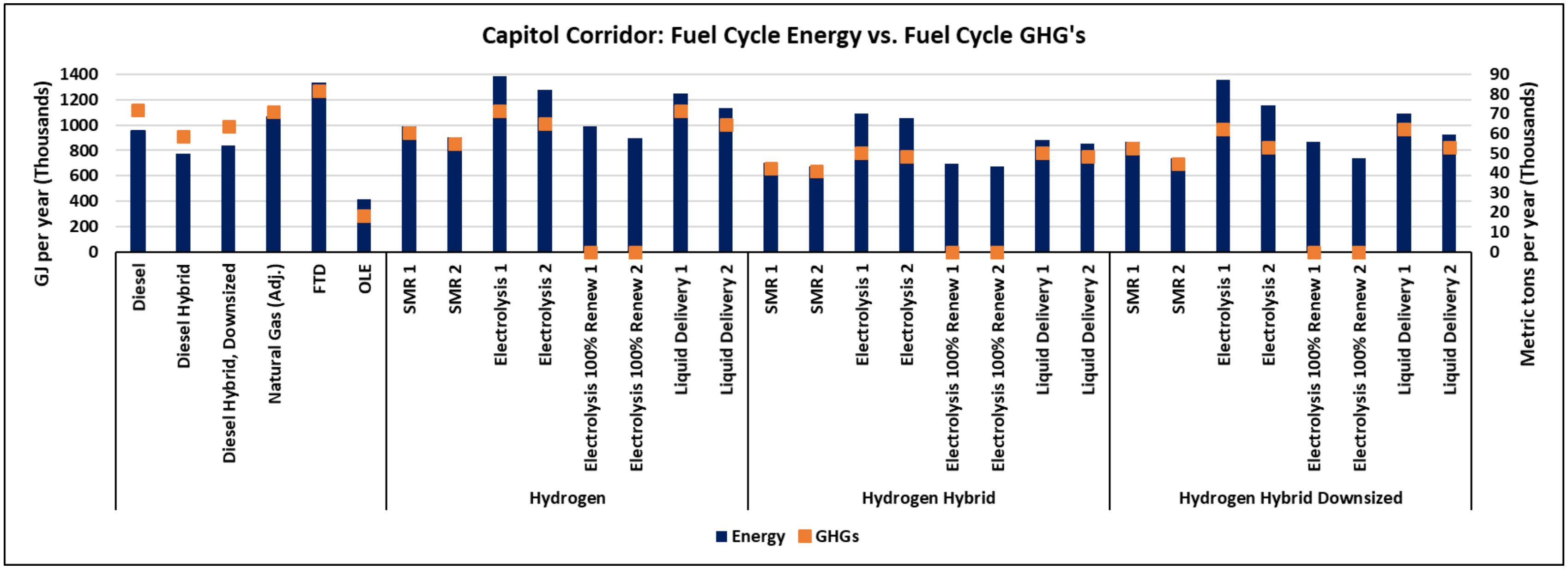


Figure 38: Fuel Cycle Energy vs. Fuel Cycle GHG's.
This chart reminds us that the link between energy and GHG emissions doesn't hold with fuels such as hydrogen. On the other hand, this chart does reiterate the relative unattractiveness of Fischer-Tropsch diesel, which, given the production assumptions used in this analysis, might even result in an increase in GHG emissions vis-à-vis the status quo of conventionally derived diesel fuel. (And it, too, displays a disproportionately high amount of energy consumed, mostly in the well-to-pump phase, given the resulting emissions.) Lastly, even energy reductions can occur with a fuel such as hydrogen. As the grid becomes cleaner, the underlying energy needed to produce the hydrogen will decrease. (Note: GHG's are represented by the orange squares.)

Lastly, from figure 38, above, it can clearly be seen how utilizing hydrogen as a fuel cell disrupts the strong link that exists when a fossil fuel is combusted between energy consumed and the resulting greenhouse gases. For example, the GREET data utilized for this analysis suggest that using hydrogen produced via electrolysis typically requires more energy, well-to-wheel, than does using diesel fuel. Yet in all of the scenarios displayed, the GHG well-to-wheel emissions are lower for electrolysis and, with the use of 100% renewables, they would all but disappear. (Many states are, in fact, decarbonizing their electric grids. As this proceeds, well-to-wheel emissions reductions will occur both for OLE trains as well as for trains running on hydrogen via electrolysis. This will be covered more throughout later sections of this chapter.)

5.5 Results - Emissions and Costs, Caltrain

The analysis of simulation results, in Section 5.3, indicated that a route such as the Caltrain route, with its more frequent stops, would be a good candidate for hybridization of a powertrain with batteries. The Caltrain route also has a high traffic flow, which suggests that OLE might be a lower cost option for the Caltrain route than it is for the Capitol Corridor; however, as shown in Figure 39, while the costs of OLE on the Caltrain route are closer in magnitude to the costs of the other fuel/powertrains, OLE remains uncompetitive with the other options.

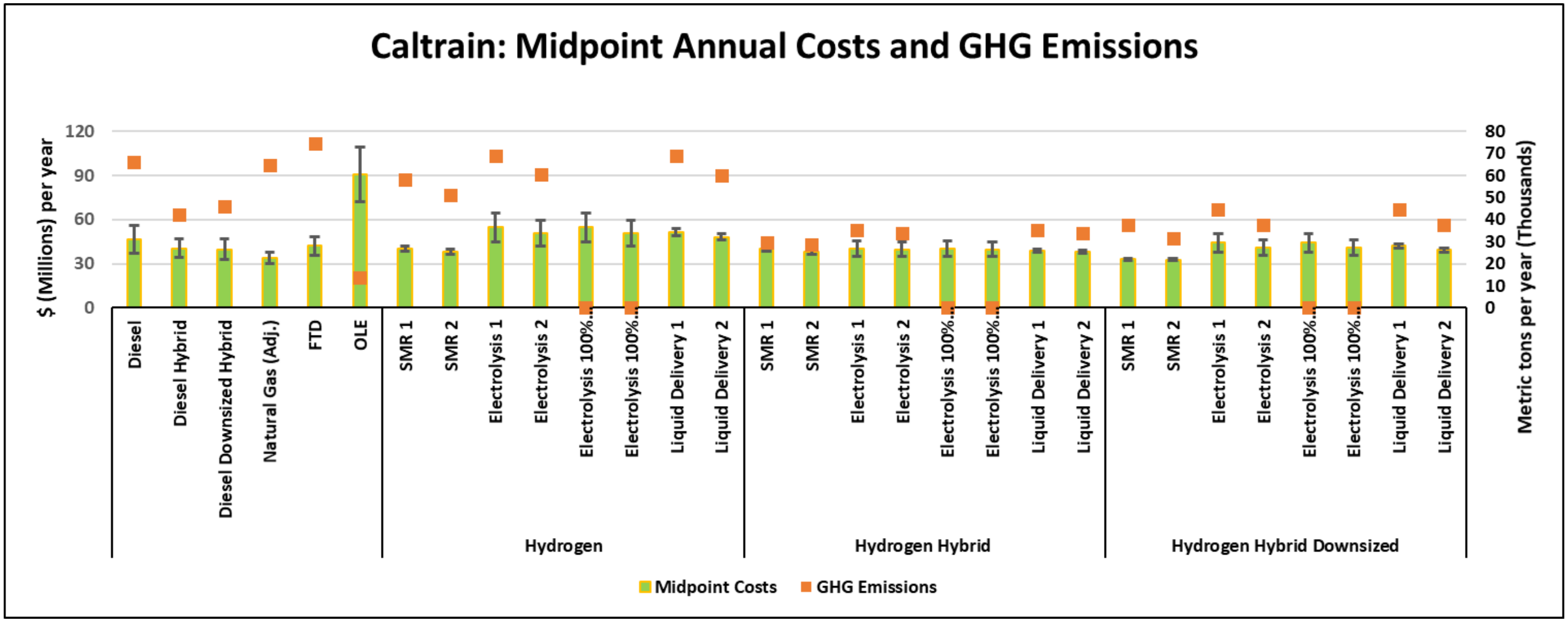


Figure 39: Caltrain: Midpoint Annual Costs (Annual Payment) and GHG Emissions

As with the table for Capitol Corridor, in the section above, the error bars represent the low and high cost range endpoints, while the orange squares represent GHG emissions.

In terms of the hybridization benefit, also from Figure 39, it can be seen that the drop in GHG emissions between the non-hybrid and the hybrid powertrains for the same fuel, is steeper than it was on the Capitol Corridor (Figure 29 shows equivalent emissions levels for Capitol Corridor). The drop is so substantial that the diesel hybrid option along this route leads to a GHG emissions level lower than any of the non-hybrid hydrogen options, except for electrolytic hydrogen produced via 100% renewable energy energy). However, all of the hydrogen hybrid options also lead to significant reductions in emissions vs. the equivalent non-hybrid hydrogen option. And, in fact, the hydrogen hybrid options reduce emissions even further than does the diesel hybrid options. The present analysis also estimates that costs for hydrogen hybrid systems may be, roughly, similarly competitive to the cost of the diesel hybrid system.

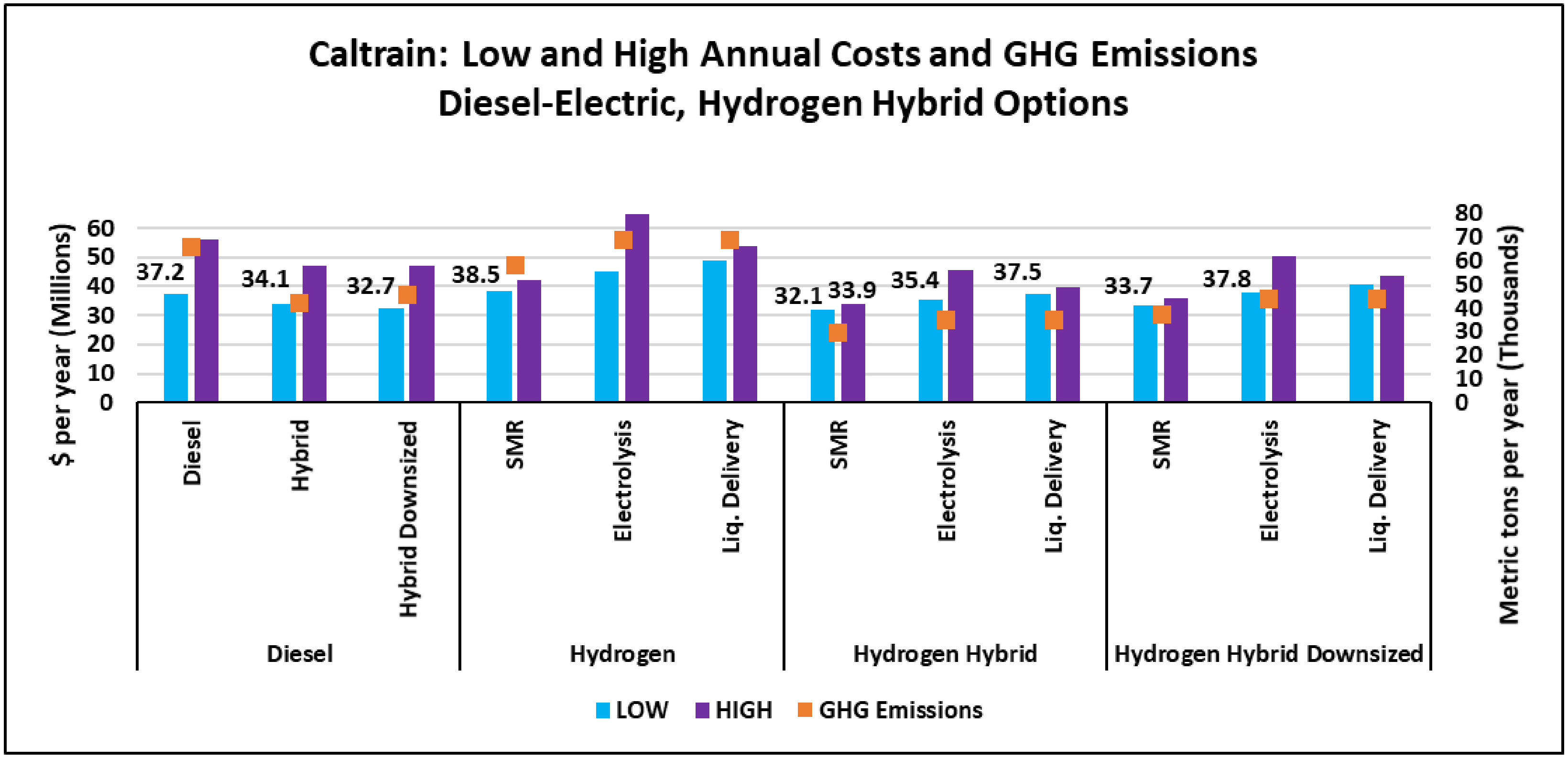


Figure 40: Caltrain: Low and High Annual Costs (Annual Payment) and GHG Emissions: Diesel-Electric and Hydrogen Hybrid Options

Figure 40, above, plots the low and high costs, and demonstrates, in a bit more precision, just how similar in cost the various hydrogen hybrid options are to the diesel hybrid option. In fact, for the SMR hybrid, not only is its low cost range the lowest range option of all of the diesel and hydrogen options, but even the high cost range for the SMR hybrid is, according to this study's findings, a lower cost option than the (non-downsized) diesel hybrid option under its low cost range.

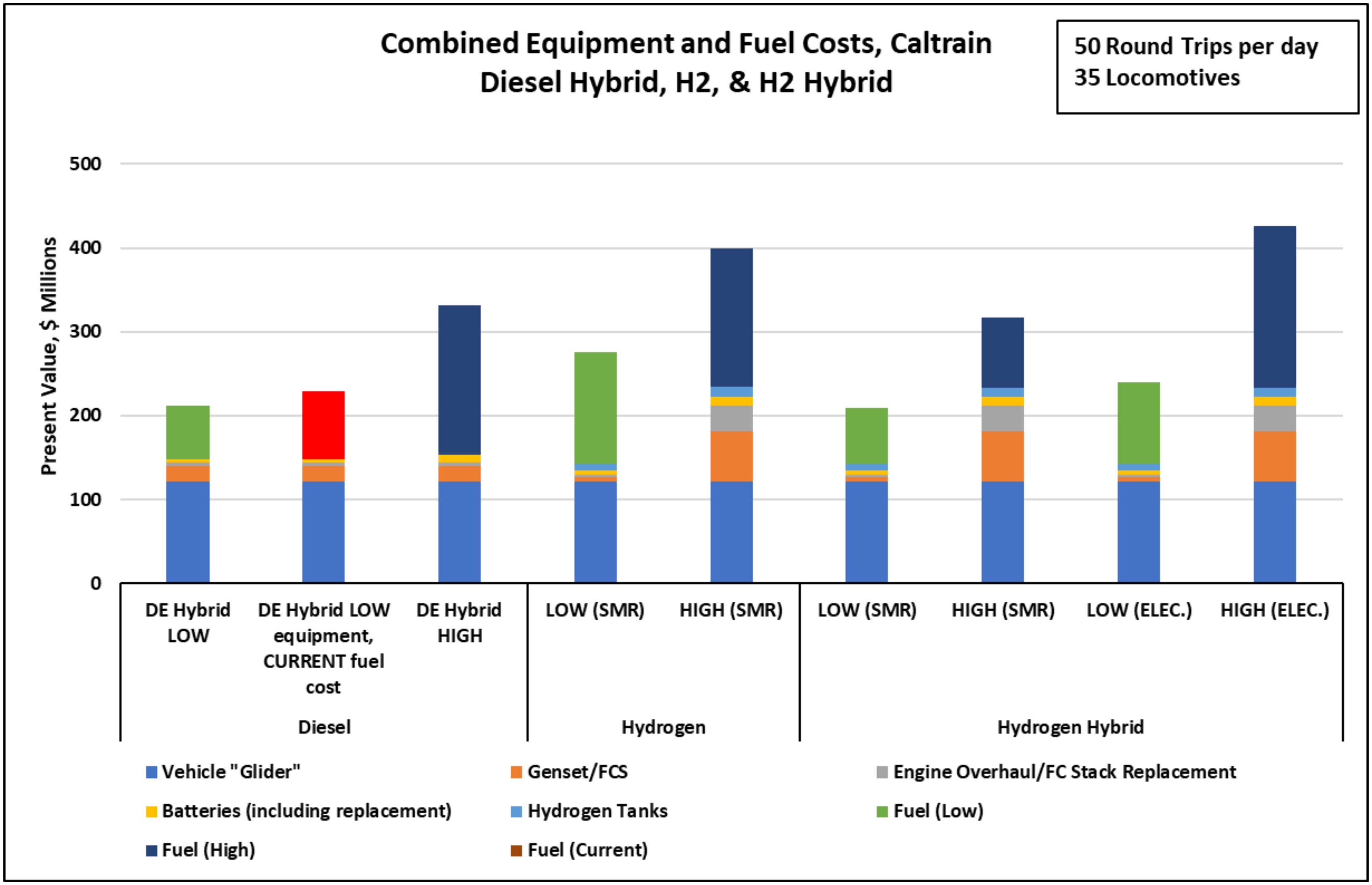


Figure 41: Combined Equipment and Fuel Costs (Present Value), over the 16-year Period: Caltrain.

Note that the red bar, in the second column, represents current diesel fuel costs. (Note: Elec. Stands for electrolysis.)

Similar to figure 33, above, figure 41 shows the component breakdown of the costs shown in the earlier cost charts. Since the Caltrain hybrid reduces the primary fuel energy by an even larger amount than is the case for the Capitol Corridor line, keeping fuel cell-related equipment and overhaul costs low are what will make the prime difference in the attractiveness of switching to a hydrogen fuel cell system (hybridized or not) for a rail system such as this. The low-high fuel cost disparity (for either diesel fuel or hydrogen) is less crucial than it is for the Capitol Corridor line (or a rail line like it).

As Figure 42, below, shows, the hybrid version of the diesel powertrain also reduces the regulated pollutant emissions more substantially for the Caltrain route than for the Capitol Corridor route (Figure 35). In fact, aside from hydrocarbons, a Tier 4-standard diesel hybrid powertrain shows reductions (in 'Pump-to-Wheel' emissions) nearly comparable to a non-hybrid locomotive that meets the Tier 5 potential standard that has been proposed. (The hydrocarbons in this Tier 4 diesel hybrid scenario would show a significant improvement over the non-hybrid Tier 4; however, the proposed Tier 5 would mean substantial additional reductions, potentially without hybridization [i.e. unless hybridization is in fact seen as the best way to meet this latest tier]).

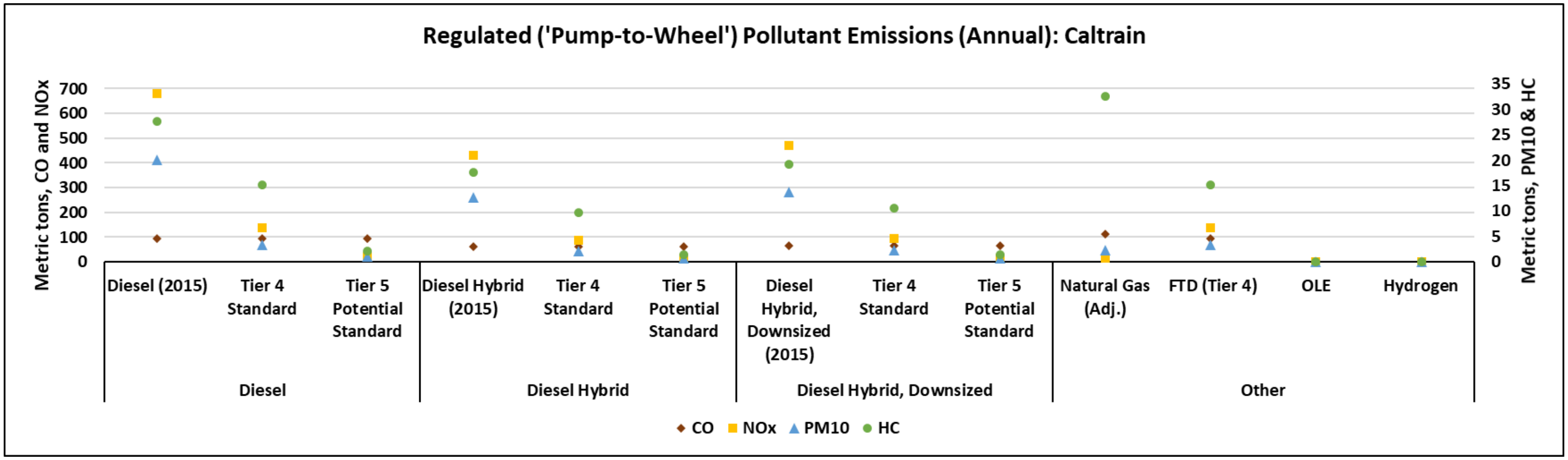


Figure 42: Regulated Pollutant Emissions, Caltrain

As can be seen here, a hybridized Tier 4 diesel-electric powertrain would achieve substantial pollutant emissions reductions over a non-hybridized Tier 4 powertrain; however, aside from with Carbon Monoxide (CO), it would not, in and of itself, achieve the full reductions that would be achieved via the Tier 5 standards that California has proposed to the EPA. And the OLE and hydrogen options remain the only solution for totally eliminating these pollutant emissions from an operational (vehicle) standpoint.

5.6 Results – Freight Simulations

Tables 19a-i show some of the key freight data outputs from the STS, including energy consumption and powertrain efficiency (with vehicle efficiency also calculated based on other outputs). The first seven tables represent the shorter, "manifest" train legs, while the last two represent the two intermodals, one with 120 cars, and another with 80, with the latter vehicle traveling at significantly higher speeds, as is common practice (see Section 4.4).

The simulator outputs demonstrate a very consistent profile, overall, across the different sub-routes, in terms of the potential energy reduction by switching from a diesel engine-generator setup to a hydrogen via fuel cell propulsion approach. "Hydrogen 1," which, again, lines up most closely with current fuel cell efficiency characteristics, shows an energy consumption reduction of around 20-22% from the diesel baseline. With advances in fuel cell efficiency, this reduction could increase to over 30% below the diesel baseline.

One caveat to note is that none of the displayed freight simulation results include the weight of any gaseous fuel tenders that might be necessary to carry the hydrogen fuel. While any specific freight vehicle fleet would require a thorough analysis as to how to design freight locomotives with fuel tanks, the author's initial research into this area suggests that fuel tenders would not be required for any of the shorter, manifest train-type journeys. In fact, the author estimates that there would be room for about 1600-1800 kg of hydrogen per locomotive (including the utilization of rooftop space), depending on design[175]. This means that each of the

[175] The designer would have to consider the exact amount of space taken up by the tank material, itself, as well as any empty space between the tanks, which would vary depending on the volume per tank and the shape of the tank. The 1600 kg value is based on the specific tank whose volume was modeled; however, this is not necessarily the ideal tank size.

shorter routes, including the Clovis to Winslow route, which goes over very hilly terrain and is longer than the other sub-routes, at roughly 825 km, could complete a run without carrying a tender (and with a 10-20% buffer between the amount needed and the amount carried on board; with this number varying depending on estimated space loss due to tank materials and tank shape characteristics)[176]. On many of these routes, the run could occur twice, or even three times, before the vehicle would need to refuel. (This is all based on the "Hydrogen 1" fuel consumption values. With an improvement in fuel cell system efficiency, the number of trips prior to re-fueling becomes necessary could increase further.)

The natural gas analysis was not specifically simulated; however, from the post-simulation analysis of the diesel values, it seems likely that the shorter leg trains running on natural gas would also not require a specific fuel tender car.

[176] Belen, located about halfway between Clovis and Winslow, is actually a common refueling point for freight locomotives along this line; however, for the purpose of analyzing the Clovis to Winslow sub-route (and others of approximately the same total length), this fact is ignored at this particular point in the discussion.

Table 19(a-i): Freight Simulation Results, Diesel-Electric and Hydrogen

19a.

KC to Wellington: Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Primary Fuel (Diesel/H2) Consumption 1-Way Trip	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Output Power per locomotive, Genset/H2 Fuel Cell (kW) (Maximum: 3249.7 kW)	Average Power at the DC BUS (kW), Train	Downsizing Factor	Energy Reduction from Diesel %
Diesel		292.429	2,140.5 Gallons	34.4	22.8				NA
Hydrogen 1	3	230.882	1,920.7 kg	48.0	41.1	1,897.2	7,475.2	.86	21
Hydrogen 2		199.535	1,659.9 kg	54.0	48.4				31.8

19b.

Wellington to Amarillo: Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Primary Fuel (Diesel/H2) Consumption 1-Way Trip	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Output Power per locomotive, Genset/H2 Fuel Cell (kW) (Maximum: 3245.7 kW)	Average Power at the DC BUS (kW), Train	Downsizing Factor	Energy Reduction from Diesel %
Diesel		642.635	4,704.0 gallons	34.9	32.6				NA
Hydrogen 1	4	509.445	4,238.0 kg	47.9	41.2	2,089.0	9,911.8	.75	20.7
Hydrogen 2		439.670	3,657.5 kg	54.0	47.7				31.6

Amarillo to Clovis: Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Primary Fuel (Diesel/H2) Consumption 1-Way Trip	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Output Power per locomotive, Genset/H2 Fuel Cell (kW) (Maximum: 3255.3 kW)	Average Power at the DC BUS (kW), Train	Downsizing Factor	Energy Reduction from Diesel %
Diesel		129.406	947.2 gallons	32.2	33.1				NA
Hydrogen 1	2	104.320	867.8 kg	47.1	41.1	2,015.9	5,617.4	.89	19.4
Hydrogen 2		88.833	739.0 kg	53.5	48.3				31.4

19c.

Clovis to Winslow (via Belen): Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Primary Fuel (Diesel/H2) Consumption 1-Way Trip	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Output Power per locomotive, Genset/H2 Fuel Cell (kW) (Maximum: 3255.7 kW)	Average Power at the DC BUS (kW), Train	Downsizing Factor	Energy Reduction from Diesel %
Diesel		643.866	4,713.0 gallons	34.0	31.8				NA
Hydrogen 1	3	507.040	4,218.0 kg	49.1	40.4	1,566.9	8,951.3	.46	21.2
Hydrogen 2		436.754	3,633.3 kg	54.3	46.9				32.2

19d.

Winslow to Needles: Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Primary Fuel (Diesel/H2) Consumption 1-Way Trip	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Output Power per locomotive, Genset/H2 Fuel Cell (kW) (Maximum: 3255.7 kW)	Average Power at the DC BUS (kW), Train	Downsizing Factor	Energy Reduction from Diesel %
Diesel		332.810	2,436.1 gallons	34.6	31.5				NA
Hydrogen 1	3	264.597	2,201.1 kg	47.4	39.6	1,497.0	7,801.6	.85	20.5
Hydrogen 2		226.271	1,882.3 kg	53.9	46.3				32.0

19e.

Needles to Barstow: Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Primary Fuel (Diesel/H2) Consumption 1-Way Trip	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Output Power per locomotive, Genset/H2 Fuel Cell (kW) (Maximum: 3255.7 kW)	Average Power at the DC BUS (kW), Train	Downsizing Factor	Energy Reduction from Diesel %
Diesel		240.460	1,760.1 gallons	34.7	32.3				NA
Hydrogen 1	2	194.753	1,620.1 kg	46.6	39.9	2,322.0	5,502.4	.95	19.0
Hydrogen 2		165.566	1,377.3 kg	53.6	46.9				31.2

19f.

Barstow to LA: Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Primary Fuel (Diesel/H2) Consumption 1-Way Trip	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Output Power per locomotive, Genset/H2 Fuel Cell (kW) (Maximum: 3255.7 kW)	Average Power at the DC BUS (kW), Train	Downsizing Factor	Energy Reduction from Diesel %
Diesel		145.817	1,067.4 gallons	33.6	32.7				NA
Hydrogen 1	2	116.025	965.2 kg	47.8	41.1	1,662.0	5,125.1	.81	20.4
Hydrogen 2		99.376	826.7 kg	53.8	48.0				31.9

19g.

Intermodal, 120 COFC: Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Primary Fuel (Diesel/H2) Consumption 1-Way Trip	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Output Power per locomotive, Genset/H2 Fuel Cell (kW) (Maximum: 3255.7 kW)	Average Power at the DC BUS (kW), Train	Downsizing Factor	Energy Reduction from Diesel %
Diesel	3	1,979.629	14490.7 gallons	34.8	32.9	1540.6	6566.8	0.69	NA
Hydrogen 1		1,529.318	12,722.1 kg	49.4	42.6				22.8
Hydrogen 2		1,336.058	11,114.4	54.6	48.8				32.5

19h.

Intermodal, 80 TOFC (Higher Speed): Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Primary Fuel (Diesel/H2) Consumption 1-Way Trip	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Output Power per locomotive, Genset/H2 Fuel Cell (kW) (Maximum: 3255.7 kW)	Average Power at the DC BUS (kW), Train	Downsizing Factor	Energy Reduction from Diesel %
Diesel	3	2,089.326	15,293.6 Gallons	35.1	33.2	1864.8	7,541.2	0.79	NA
Hydrogen 1		1,652.386	13,745.8 kg	47.8	42.0				20.9
Hydrogen 2		1,426.054	11,863.0 kg	54.0	48.7				31.8

19i.

Notes:

1) See the explanation below for the definition of downsizing factor.

2) As with the passenger simulations, “Hydrogen 1” uses an “average” fuel cell efficiency curve while “Hydrogen 2” uses a “best case” fuel cell efficiency curve (see text above, and Figure 22, for more information).

For the intermodal routes, which comprise the entire KC to LA span, stopping only at Belen, New Mexico, to refuel (as is typical procedure (personal communication, M. Cleveland, July 11, 2019)), it seems likely that at least some gaseous fuel tenders (storing compressed hydrogen at 350 bar) would be required for the trains running on hydrogen.

For natural gas, it seems that a tender could be avoided for the longer intermodal vehicles; however, this may only be accomplished with a 10% "buffer" storage beyond the required amount for the specific trips that were modeled. (The total amount stored aboard the locomotive is also well under the current amount of energy typically stored aboard a diesel locomotive; in energy terms, roughly 2/3 of the 5,000-diesel-gallon figure noted in table 5, in Section 4.6.) This assumes no diesel fuel tank aboard the locomotive; moreover, as might be inferred by the recently developed CNG tender currently undergoing testing by Norfolk Southern (W. C. Vantuono, 2019), going without a tender would mean a significant re-design to the locomotive interior (along with judicious use of rooftop space, as was also suggested for gaseous hydrogen storage), a step that freight railroads have not yet shown the willingness to take. For those companies willing to explore re-design of the locomotive (whether for hydrogen or natural gas), the specifics of fitting all of the required fuel for a given freight trip without a tender, particularly in the case of hydrogen, would also depend on the exact height flexibility atop the roof.

The requirement for (gaseous, but not liquid) fuel tenders in the hydrogen case, in particular, offers a potential obstacle; however, the obstacle does not really appear to be one of cost (see table 20), nor is it even much of an obstacle of reduced efficiency due to extra weight. In order to generally assess the latter proposition, in fact, the author re-ran the KC to Wellington simulation with the additional weight of (and additional drag resistance for) three gaseous fuel tenders (comprised of three 20-foot container cars on rail flatcars---see Figure 19 for an example of such “COFC”’s), which is roughly the amount of tender space that would be required. Table 20, below, includes information on the hydrogen tender composition and cost assumptions. For cost purposes, this was based on a 40-foot container car, due to the expectation that two of these should be adequate for the purposes of the intermodal vehicle routes as modeled here. However, the exact composition and approach would vary by route and perhaps even by railroad preference so, as with hydrogen fuel tanks, proposing an exact design methodology was not the intended goal, but rather it was to offer some guidance on how carrying the necessary fuel might be achieved. During the sample run on the KC to Wellington route, the fuel consumption increased by only about 1.5%, which means that the reduction noted in the relevant above table (which is 21%) would go down to just under 20%.

Broadly speaking, then, it appears that the impact of one or a few tenders on energy consumption is relatively minimal. The obstacle appears to be more one of logistics, as, with the need to use tenders only in certain areas and, even then, perhaps just for certain trains, ensuring their availability in these places at the right times (and, ideally, not purchasing many more tenders than would be required to cover these routes) would be crucial.

The specifics of tender design and layout within the vehicle would, again, require a more in-depth analysis tailored to a specific set of equipment; however, as alluded to above, the author believes that this equipment would not be particularly costly, with the tender structure made up largely of already existing rail and freight components, including flatcars and standard freight containers (outfitted with the same kind of hydrogen or natural gas tanks that would be used in and atop the locomotive). There is precedent to utilizing rail equipment/component types already in existence, flatcars included, to create a fuel tender. Natural gas is a key example (Ditmeyer, 2014), with a recently released CNG tender (see Figure 4, in section 3.5) that has an external structure that resembles, in part, a rail "boxcar" (W. C. Vantuono, 2019).

Table 20: Cost Components of the Gaseous (Hydrogen) Fuel Tenders

The tender design assumes a freight-style container car filled with hydrogen tanks, which could be transported on a flatcar (see figure 17 for photo of a flatcar)

Container Cost (Based on 40-ft container)	Flatcar cost	Connections between tender and locomotive, additional hydrogen sensors, etc.	Fuel Storage Costs	Notes
$5000	$50,000	$15,000	LOW: $13/kWh[177] HIGH: $18/kWh[178] Each tender has been modeled, for cost purposes, to contain 184 tanks[179].	Fuel storage cost per kWh same as for hydrogen scenarios, as described in the methodology section.

177 Both the low and high hydrogen storage cost values are derived from the work of Strategic Analysis, Inc. (James et al., 2016). These numbers also line up with industry-provided (anonymously) input.

178 Ibid.

179 The number of tanks estimated for the tender cost analysis assumes the same modeled hydrogen tank size as noted in Chapter 4. Then the total number of tanks selected here, 184, was based on the volumetric hydrogen contents (at 312 Liters, consisting of 7.5 kg of hydrogen, per tank (Hexagon Composites, 2017)) of the modeled tanks and the available volume within a 40-foot container (67.7 m^3 (DSV, 2019)), adjusted by a factor of .85 (i.e. divided by this value) to allow for the roughly estimated space that might actually be available for onboard storage (i.e. not counting the space between tanks, space taken up by tank material, etc.) for the modeled 40-foot container. That said, the actual height of the 40-foot container car, 2.39 meters (DSV, 2019), plus the actual height of a flatcar (estimated at .91 meters, or roughly 3 feet) adds up to 3.3 meters (10.83 feet). However, an exact replication of the current container car's dimensions would not be necessary nor should be assumed as a given for the broader analysis. Specifications for one boxcar model were located online, with the information from one of the Class I freight railroads (BNSF, n.d.). The data indicated that the internal height of the boxcar is approximately 3.96 meters (i.e. 13 feet), with a total height, when including the bogie (see glossary for definition) base, of 5.18 meters (17 feet) (BNSF, n.d.). This demonstrates that an actual hydrogen tender could in fact have a significantly larger volume than the container car model that was used to make a general cost estimate. (The container cost assumed, of $5,000, was somewhat conservative given the available data estimates obtained on actual 40-foot containers, from industry sources.) In fact, it is possible that more hydrogen could be stored in each tender than was assumed here (roughly 1,327 kg per tender car), depending on the exact size of the tender, as well as the tank number and tank size that might be selected for an actual fuel tender. (Note that the exact volume of the tanks modeled was not assumed for this tender analysis.) A lower

Another data metric that can be seen in Tables 19a-i is the downsizing factor. Derived by taking the ratio of the average power at the DC BUS to the maximum power at the DC BUS, this metric helps to determine whether downsizing the locomotive, or locomotives in the case of freight rail, and using batteries to cover the gap between these two points of operation, could significantly bring down cost. (Because of the nature of the formula, a lower ratio means a greater gap between the two points of operation, and thus the more viable downsizing may be.) This metric offers a good starting point for examining hybridization potential; however, it doesn't take in the full picture when assessing hybridization, which is further discussed just below.

For the most part, these values are quite high, with several over 85% and one even over 95%. However, the Clovis to Winslow route is a key exception, with a "downsizing factor" of just under 46%. (And, with the low value on this part of the route, this brings down the value for the full intermodal trips.) This is not surprising given the significant gradients, both upwards and downwards that comprise this route[180]. As a result of these steep gradients, significant power is required to achieving operating speeds in many places along the route, while in other places (i.e. when going downhill), significantly less power is required.

For comparison's sake, Capitol Corridor's downsizing factor (not shown in the tables) was calculated at a low 42.4% while Caltrain's is as high as 76.6%.

number of larger tanks carrying the equivalent amount of hydrogen (i.e. 1,327.50 kg, based on 7.5 kg hydrogen per tank) would be ideal, as it would mean less unutilized space between the tanks and should be technically feasible. Fewer, larger tanks might, if produced in volume, mean lower overall tank costs, too.

[180] Figure 20 (Chapter 4), the elevation map for the entire route, might help to elucidate what this portion of the route—right near the midpoint—looks like, elevation-wise.

However, there are many factors that go into the decision to hybridize and, in some cases, also downsize the prime mover in a rail vehicle (or set of vehicles).

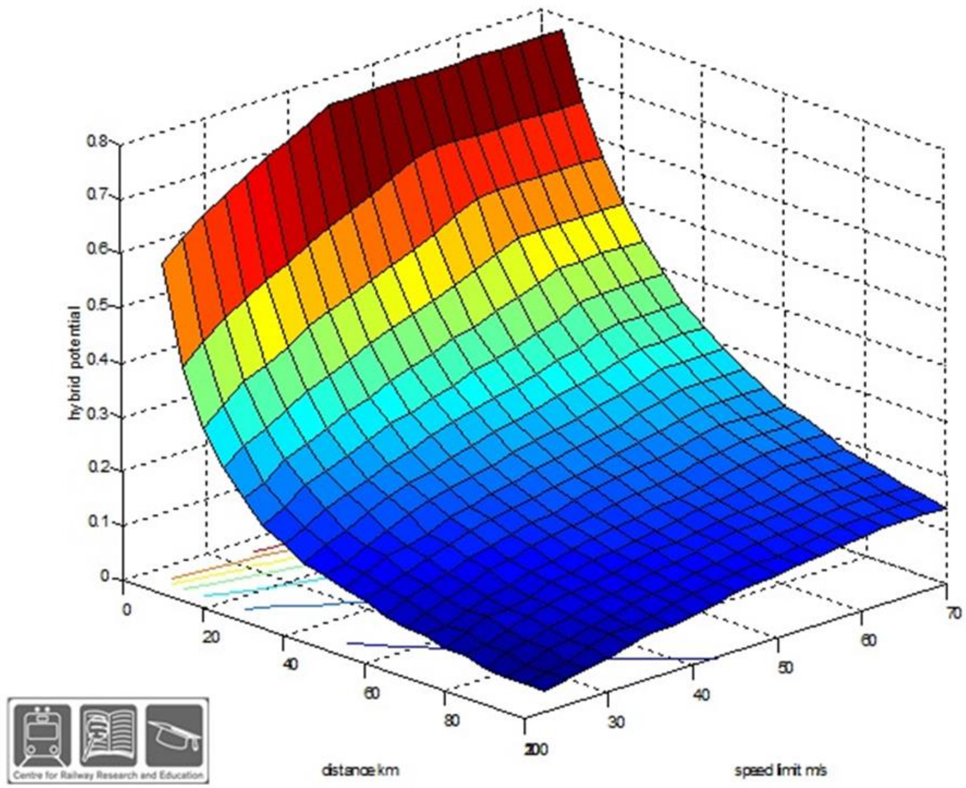


Figure 43: 3-D Hybridization Graphic

Source: (Shaofeng Lu et al., 2008)

This graphic (Shaofeng Lu et al., 2008) shows the factors that lead to high hybridization (i.e. with batteries) potential for a given railway line. The colors on the red end of the spectrum indicate characteristic values that are favorable for hybridization while those on the blue end indicate where hybridization is unlikely to be a good option

Figure 43, above, from (Shaofeng Lu et al., 2008), indicates the factors that are most conducive to hybridization (i.e. combining a prime mover with batteries) for a rail route. This 3-D illustration shows the two key components of a route that is likely to benefit from hybridization, with the z axis indicating how this translates into a metric known as hybridization potential. On the x axis, one of the characteristics that is really crucial is distance between station stops, with frequent station density greatly enhancing the favorability of hybridization. The y axis shows that speed limits (and, in essence, the typical corresponding speeds) also can play a role, with higher speeds increasing the potential due to the greater braking energy involved when the vehicle does stop (and perhaps due to more frequent partial decelerations, e.g. around curves). On the z axis, the higher the value the greater the potential for hybridization, and the color scale reinforces this message, with the red end of the spectrum indicating that hybridization should be quite valuable on a route with those characteristics, while the blue end of the spectrum indicates a combination of characteristics that indicate where hybridization is not likely to offer a valuable contribution given the money and complexity involved in implementing the necessary technology.

While Caltrain's downsizing potential is relatively high (i.e. above .75)—again, with high values not as promising—the Caltrain route, like many passenger routes, makes frequent stops. Mainline freight routes tend to make much fewer stops. For example, the Clovis to Winslow route was noted above to be over 800 km long. The only stop, which is roughly halfway between the two endpoints, is Belen. While braking, even without stopping, can also help to regenerate energy for uptake into batteries, as Figure 44, below, shows, much of the time the vehicle is struggling to even hit the allowable speed on the route. (In fact, the average speed of the vehicle---not including when it is stopped at the end points---along this trip is 64 km/h, whereas for the Kansas City to Wellington sub-route, the equivalent average speed is 72.3 km /hr.) Hence many of the decelerations in speed are not in fact a product of braking effort, but simply due to large upwards gradients. Towards the end of the route, where the prevailing gradient is downwards, the vehicle is finally able to hit the top speeds allowable. There is, in fact, according to the simulation output, a fair amount of braking utilized at this point. However, this is where practical concerns take over. Hybridizing a large system of locomotives when much of the time there is not much braking energy to be recaptured would likely not make sense from a cost value standpoint. Moreover, in the limited areas where there may be significant braking energy to re-capture, e.g. along significant downhill gradient, much of the energy cannot necessarily be recaptured due to the large amounts of space required for batteries. One approach that might be useful in such situations is the concept captured by the project mentioned in Section 3.7, the partnership between BNSF, General Electric, and the San Joaquin Valley Air Pollution Control District, to design and test an all-battery locomotive in Southern California (Railway Gazette, 2018c). With a total capacity of 2.4 MWh, that specialized equipment is being designed to work alongside conventional diesel-electric powertrains (Cleveland, 2019). Once utilized in areas where additional power is required (e.g. as is common over steep, ascending parts of a route, according to industry representatives with knowledge of freight rail operations), the battery locomotive could be removed, allowing the remaining, non-hybridized locomotives to serve as the primary equipment.

That said, despite having recently improved significantly (Howell, 2017), lithium ion batteries have a low energy density, with LTO's particularly low. For example, at roughly 160-170 kWh per cubic meter (Cowie, 2015; Yole Developpement, 2017), LTO batteries take up about four times the amount of space as hydrogen fuel, for a given amount of energy[181]. While less of a concern for

[181] The exact figure depends on the (size and) number of hydrogen tanks. Perhaps, with the space between hydrogen tanks, the factor would be a bit under 4.

rail, batteries also bring with them significant weight. In fact, even with the weight of the tanks required to store hydrogen, the specific energy of hydrogen as a fuel is 25 to 50 times[182] that of an LTO battery[183] . So, depending on the characteristics of a given train and route, the advantage to carrying lots of batteries down steep inclines might be offset, at least in part, by the disadvantage of the increased power needed to carry the added weight of these batteries up these same inclines.

Also, this value does not take into account size of the fuel cell stack. Including this into the calculation (without accounting for cooling of the relevant sets of equipment) depends on factors that will vary depending on the amount of fuel carried and exact prime mover size; however, in the case of the Capitol Corridor non-hybrid locomotive modelled in this study, including these would reduce hydrogen's energy density advantage (vis-à-vis batteries) to somewhere around 2:1.

[182] This is based on tank E, from (Hexagon Composites, 2017), which is the same tank used in the cost portion of this study.

[183] Based on data from (Altairnano, 2011; Cowie, 2015; Yole Developpement, 2017)

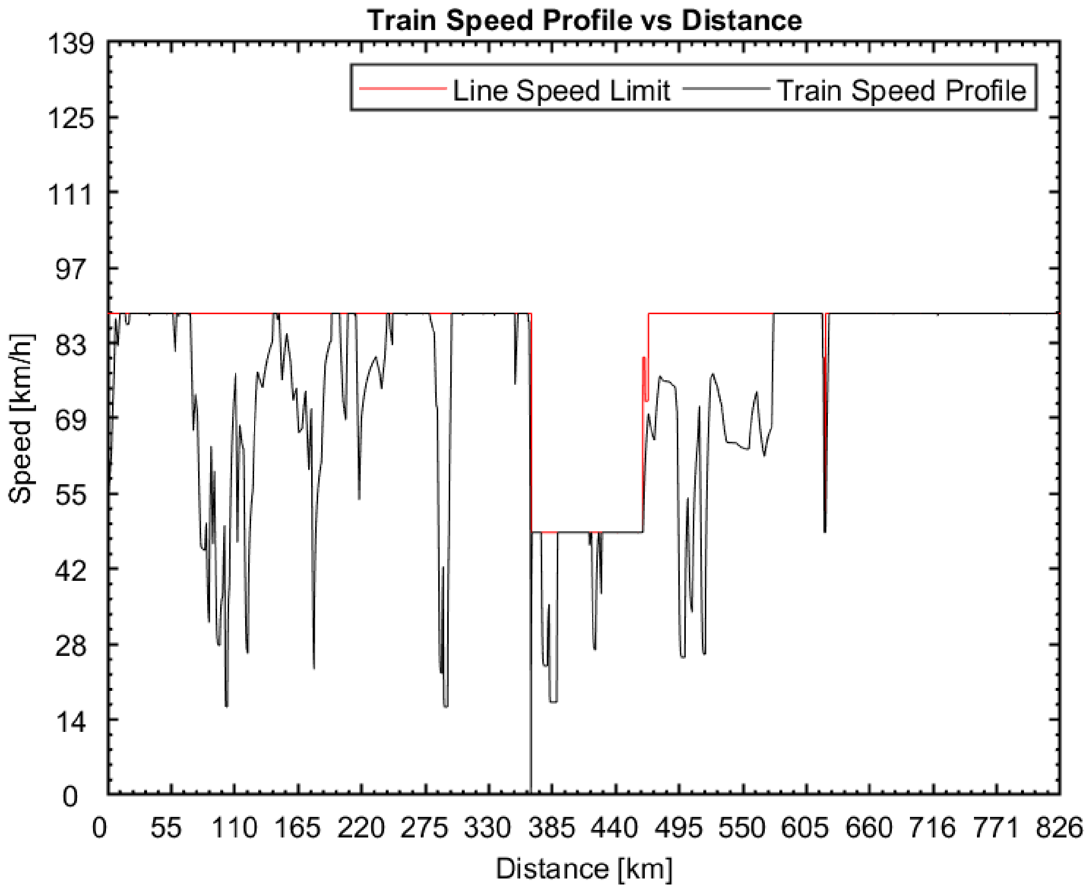


Figure 44: Train Speed Profile vs. Distance, Clovis to Winslow (via Belen).

This MATLAB chart demonstrates the simulated train speed of the freight vehicle along the route from Clovis to Winslow (stopping in Belen), juxtaposed (in red) against the set speed limits along the route. Note that the speed limits are rarely the main factor constraining speed along the line.

5.7 Results – Emissions and Costs, Freight

The simulation results for the freight routes, as summarized above, generally didn't vary much. Thus, the cost analysis for freight is based on one vehicle type, the higher speed intermodal vehicle (single-stacked, with 80 cars).

In the case of regulated pollutant emissions, the passenger results offer a good sense of the comparative differences that might be found in a freight context. Meanwhile, the switcher section that follows this one examines pollutant emissions impacts, particularly for diesel and hydrogen locomotives. Thus specific results for these are not displayed in this section, nor is an in-depth analysis of such emissions covered in this section. The charts presented in this section focus, instead, on cost and GHG emissions.

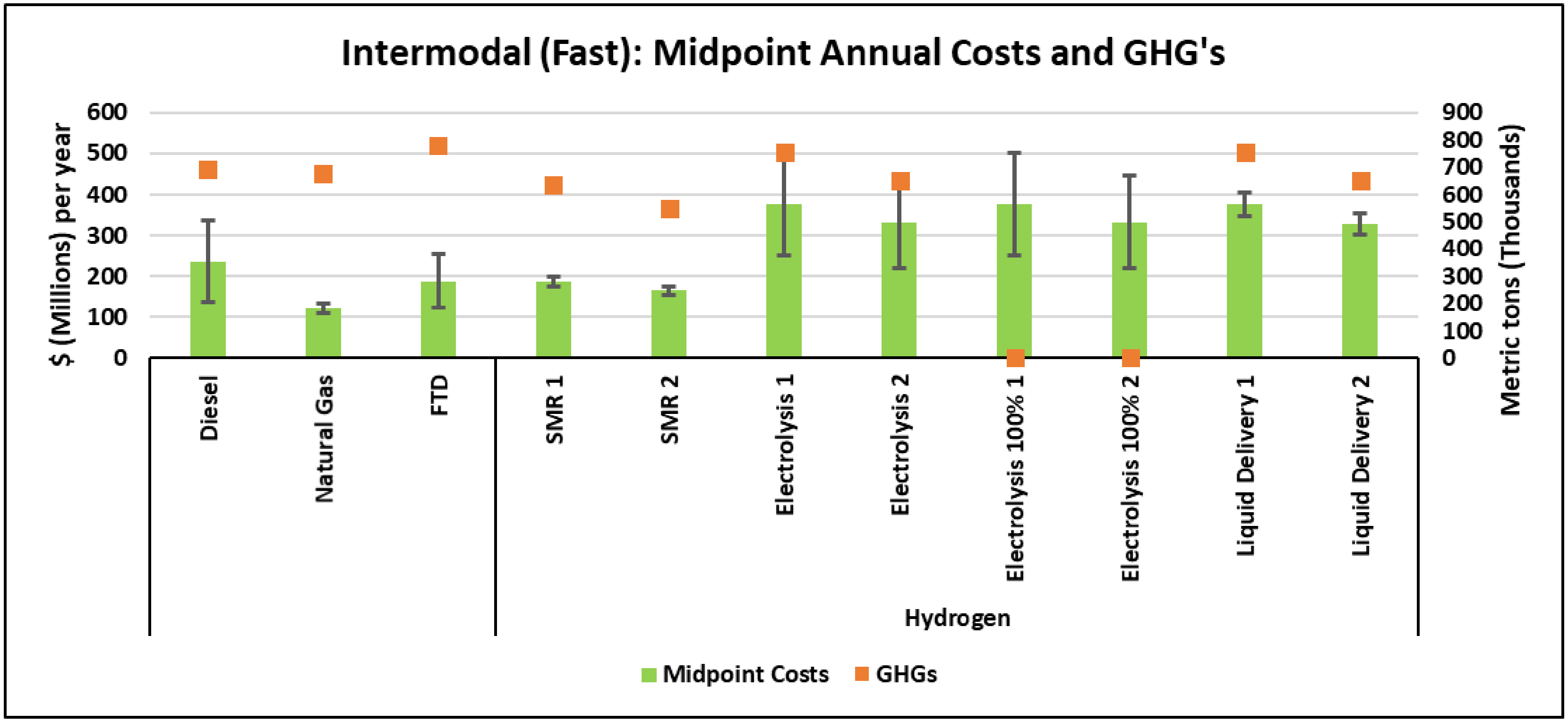


Figure 45: Intermodal (Fast): Midpoint Annual Costs (Annual Payment) and GHG's

As with the tables in the passenger sections, the error bars represent the low and high cost range endpoints, while the orange squares represent GHG emissions. (Note: As discussed in Section 5.6, fuel cost assumptions may need to be slightly adjusted, depending on the exact impact of gaseous fuel tenders on an intermodal route such as this one.) Hybrids were not presented here (nor in Section 5.6) because, as per the discussion in Section 5.6, they are unlikely to be cost-effective for freight routes, generally speaking.

As Figure 45 demonstrates, in the freight context, in which fuel costs are a very substantial portion of overall costs (as described in Chapter 1), natural gas is cheaper and cleaner than the benchmark diesel-electric. However, there would seem an unlikely motivation to switch given the minimal reduction in GHG emissions for the effort that would be required to transition over from the incumbent diesel-electric fuel and to a fuel that requires, at a minimum, high-pressure (gaseous) tank storage. (And such a transition would take time, time that would be lost should GHG emissions standards, at some point, be implemented in the rail sector.) Moreover, as Section 4.7 discussed, while natural gas's NOx emissions could be reduced, thanks to the catalytic converter, in the same way that diesel's could be (i.e. even to the Tier 5 standard), the latter, along with Carbon Monoxide (CO), might demonstrate a slight increase on a per-trip or per-period level, given the reduced efficiency of natural gas (SI). More importantly, there remains—as Figure 37 shows—a significant increase in Hydrocarbons (HC) when combusting natural gas rather than diesel fuel.

FTD shows that it could slightly reduce costs (though the cost figures for this technology are perhaps the most uncertain, given the lack of maturity of this technology), though at the cost of higher GHG emissions, at least given the GREET input assumption of deriving that fuel from natural gas. Thus it likely doesn't seem a promising solution for the railroads.

Figure 46, below, includes a closer look at the high and low costs within the diesel-electric scenario, the natural gas scenario, and some of the hydrogen fuel cell alternative scenarios while Figure 47, below that, breaks the (present value) costs down for the diesel and many of the hydrogen options into their constituent parts. (Note that, since the type of cost---i.e. present value vs. annual payment---varies between the two charts, rather than compare numbers across charts, the key messages are conveyed through the comparative height differences in the cost bars as well as the differences across columns within the same chart.)

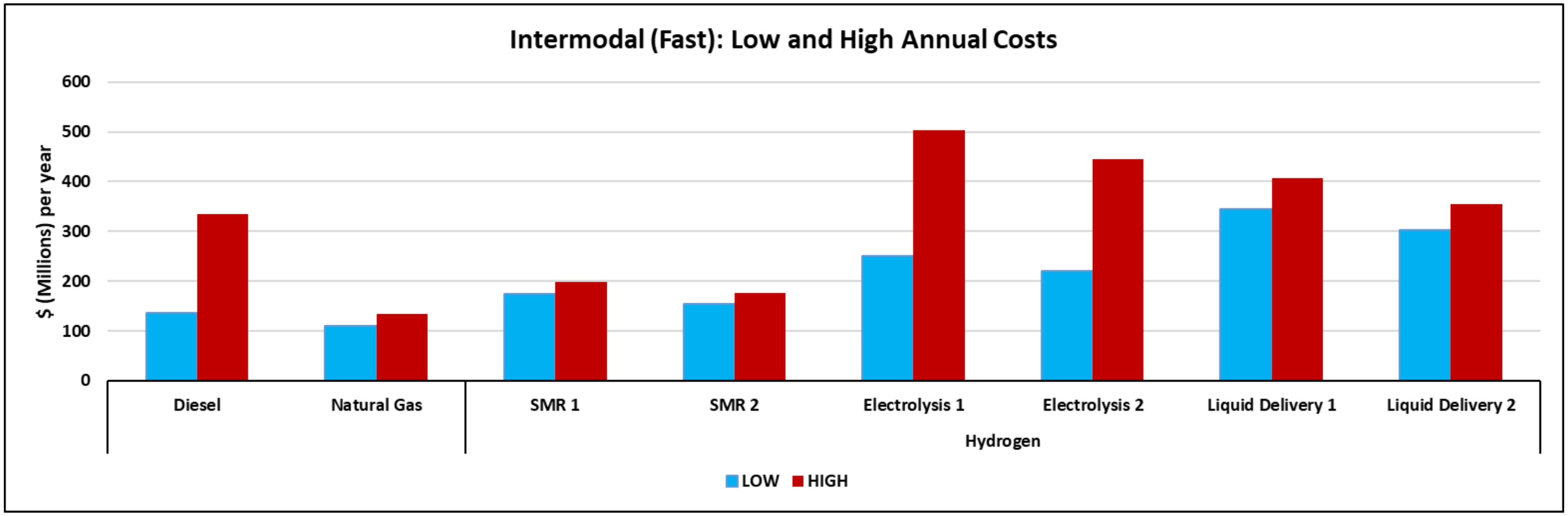


Figure 46: Low and High Annual Costs (Annual Payment)

(Note: As discussed in Section 5.6, fuel cost assumptions may need to be slightly adjusted, depending on the exact impact of gaseous fuel tenders on an intermodal route such as this one.)

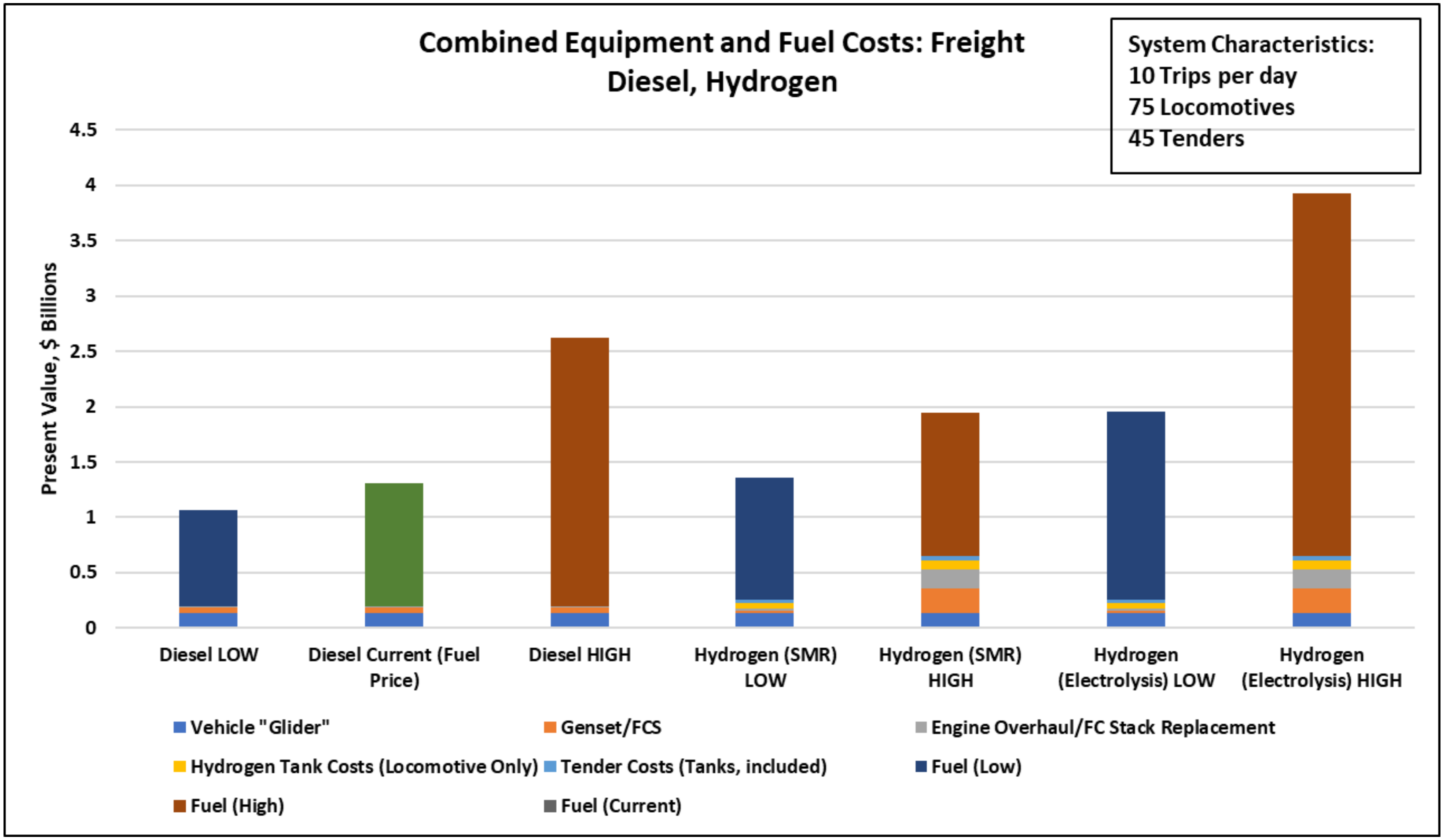


Figure 47: Combined Equipment and Fuel Costs (Present Value) over the 16-year period: Freight, Diesel and Hydrogen.

For some context to these numbers, the two largest Class 1 Freight Railroads, by operating revenue, in 2017, had annual operating expenses, that year, of roughly $13 Billion, each.(AAR, 2018b)

Note that the green bar in the second column represents current diesel fuel costs. Also, note that, as discussed in Section 5.6, fuel cost assumptions may need to be slightly adjusted, depending on the exact impact of gaseous fuel tenders on an intermodal route such as this one.

What is apparent from Figure 47 (if it wasn't already inferred from the difference between Figure 46 and the equivalent charts for the passenger systems) is that fuel costs dominate the differences between these scenarios. More specifically, examining the differences between fuels and fuel options, it is clear (or, in the case of natural gas, what might be inferred) that the cost in the scenarios for hydrogen via SMR, as with the natural gas scenario from which such hydrogen is derived, show the least low-to-high range, particularly with regard to the underlying fuel costs. (As the data provided in Chapter 4, on cost assumptions, in fact notes, the variation in low-to-high diesel cost varies by a factor of 250% while, for natural gas, the high unit cost selected---based on EIA projections---is a mere 30% above the low unit cost value.) And, most likely, SMR is the hydrogen option that, if any, might interest freight railroads the most, particularly in areas where electricity costs are higher. On the other hand, the costs of the electrolysis scenarios vary significantly, mostly due to the variable electricity prices that are likely to occur both over time and over geography.

The liquid delivery options don't vary much, mostly due to limited cost information (and presumably cost would be subject to competitive pressures from the various companies that wish to provide this service to the relevant customers.) The price for this latter production approach is also on the higher end (especially in terms of its low cost range), likely due to several additional costs. These would include the additional cost to transport the fuel (the exact distances over which the transport occurs can vary), along with the need for the outside party to make a profit on the fuel. On top of that, the cost to liquify is likely significant, and the underlying cost data used in this study demonstrate that the cost of at-station liquid storage is also very significant.

In Figure 47, unlike in the passenger cost charts, there is a new variable causing a cost gap between diesel and hydrogen. It is easier to see in Figure 48, which breaks down the equipment costs (not including the “glider” cost, which is constant across technology types). It is the relatively small cost of the fuel tenders---numbering 45 for the 75-locomotive system. (In reality, the same railroads that run the intermodal trains run shorter manifest trains, also; however, as noted in Section 5.6, above, the author has assessed that fuel tenders would not be required for these routes. Thus, relatively speaking, the little cost gap cause by the addition of fuel tenders would have an even smaller overall impact across a freight equipment system.)

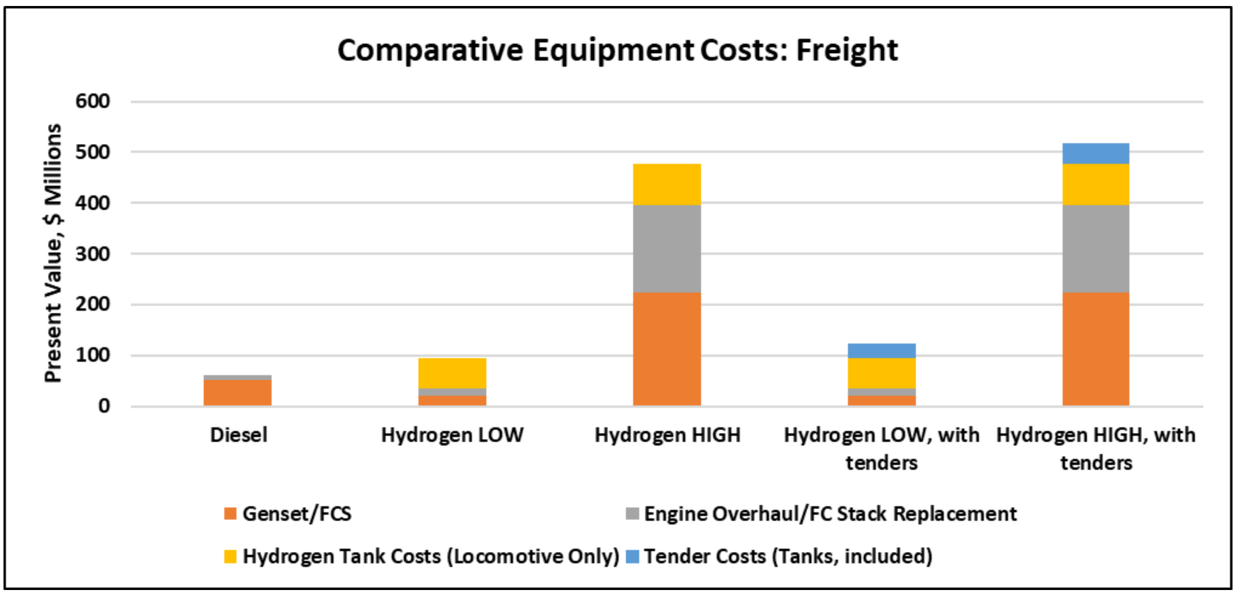


Figure 48: Comparative Equipment Costs (Present Value), Freight (Intermodal, 80 Cars)

As noted in section 5.6, the intermodal routes are likely to require fuel tenders (with costs shown in light blue here), barring any changes to refueling frequency. However, for shorter routes, tenders seem likely to not be necessary.

As was the case with the passenger equipment, Figure 48 demonstrates a potential for a continued significant gap in the costs of prime movers for diesel vs. hydrogen. It should be noted that diesel engine cost has been varied between passenger and freight (with the cost lower in the case of the latter, particularly due to higher purchase volumes and older equipment), whereas this was not done with the fuel cell stacks. During the period examined, fuel cell stacks for heavy duty are not likely to yet have much market differentiation between older and newer equipment, though market factors could certainly make the cost a bit lower in the case of freight purchasers. In addition to the key role for fuel costs to increase the uncertainty of hydrogen's competitiveness with diesel in a freight context, this role for the prime mover cost to either "make" or "break" hydrogen's viability is all the more apparent. As was alluded to in Chapter 3, it is possible that the use of certain materials, e.g. in the case of the bipolar plates, could mean an increased use of recycled stacks, and this would certainly bring down the replacement cost for the hydrogen scenarios.

While tank cost in these scenarios hardly varies, this component presents a clear financial penalty for fueling freight trains by hydrogen. As noted previously, this analysis assumes present approaches to (gaseous) storage; however, there is certainly a possibility that mobile hydrogen storage methods will advance (i.e. change to a very different method) during the next two decades, and that would have implications for this analysis. In any event, with system sizes that can be very large in the freight rail sector, the sheer number of locomotives makes all of the variables where hydrogen presents a penalty all the more relevant for targeted research that might bring down equipment costs.

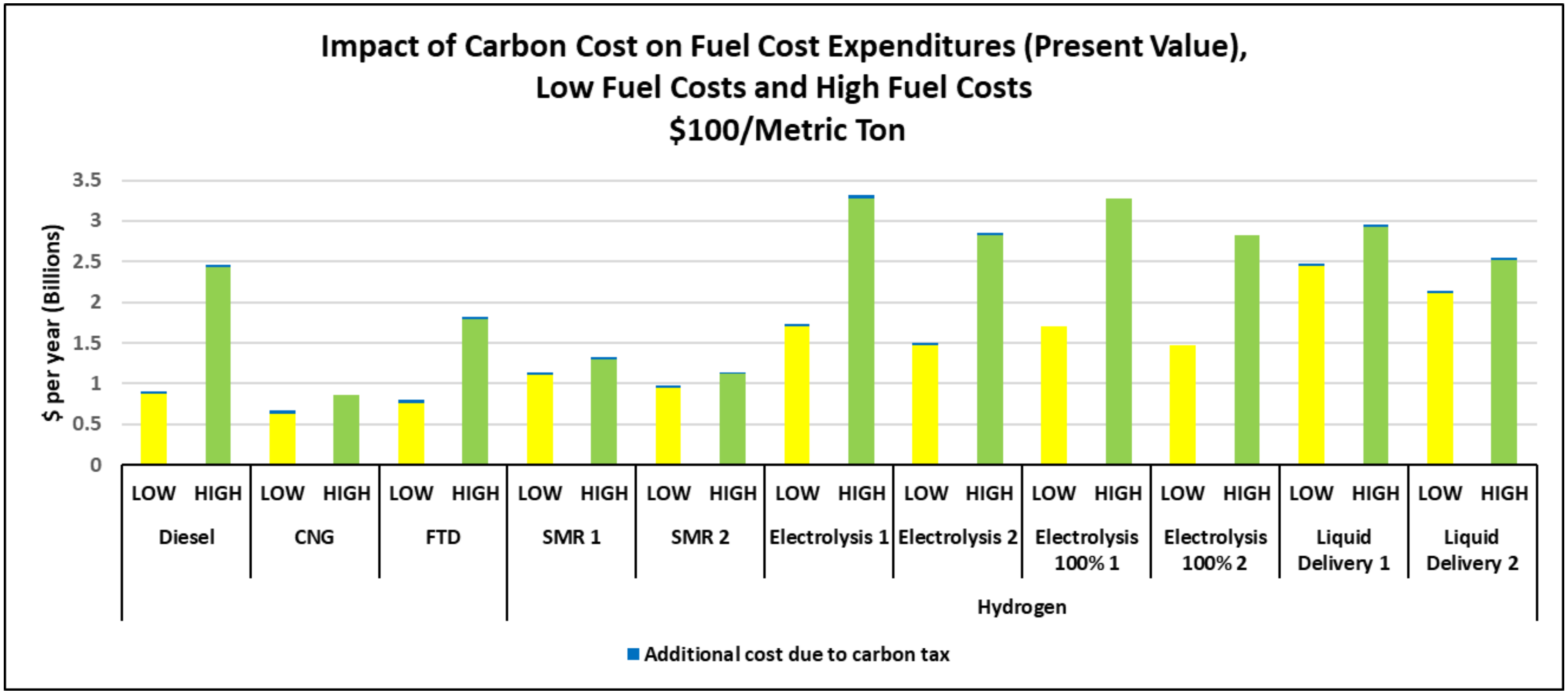


Figure 49: Carbon Cost Analysis

One sensitivity that was performed on the freight results relates to the potential for a cost of carbon, or "carbon price" to be implemented as part of Federal policy. While the exact design of such a tax can vary (C2ES, 2013), it was assumed for this analysis that this price would be charged on both the WTP and PTW portion of the GHG emissions and, inevitably, passed onto the consumer railroad. As Figure 49, above, demonstrates, however, even with a $100 per metric ton (roughly equivalent to 1.1 U.S. "short" tons) carbon price, any cost impact would be almost indistinguishable within each fuel scenario. Moreover, with hydrogen production's relatively high WTP emissions (unless operating on a 100% renewable grid), such a price wouldn't change the relative relationships between diesel and hydrogen in most of the scenarios. (And the impact vis-à-vis a 100% renewable electric grid would be, again, hardly noticeable.)

Figure 50: A Set of Petroleum Tanker Cars at the Emeryville, CA Station February, 2018.
(Photo from author's collection)
This configuration is one of the car-commodity combinations that was modeled.

5.8 Switcher Analysis: Overview and Energy Consumption Results

Switcher locomotives are locomotives which remain in railyards, where they are assigned the tasks of assembling and disassembling freight trains, generally a few cars a time. Because they remain within a limited area and haul only a few cars at a time, switcher engines exhibit a lower total power capacity, usually under about 2300 horsepower (~1.72 MW) (Norfolk Southern, 2014), with the maximum value varying widely between locomotives.

Figure 51: A Pair of Canadian Pacific Switcher Locomotives in a Yard near Vancouver, British Columbia.

Photo courtesy of Dr. Andreas Hoffrichter

Not serving defined routes, per se, switcher duty cycles and operational variables (e.g. any elevation changes) come in almost an infinite number of variations. As such, no specific switcher route was selected for simulation. Rather, information on fuel consumption relative to power output was obtained from data that was provided in a report on the retrofit (with a diesel particulate filter[184]) of a diesel "genset locomotive"[185] (Hedrick et al., 2012). This data was then

[184] A diesel particulate filter, or dpf, is a device that captures carbon resulting from incomplete combustion.
[185] The "genset locomotive" was initially developed by Union Pacific (Union Pacific, 2019) (and now operated by railroads across the industry) close to two decades ago. By Using a variable number of engines, depending on the power required, genset locomotives are able to minimize GHG and pollutant emissions. (Despite what seems like an ideal solution to reduce railyard emissions, however, some freight railroads have noted concerns with genset locomotive reliability and engine durability, a low weight that has caused difficulties when the track is wet, as well as a need to frequently rely on all engines. (Norfolk Southern, 2014))

combined, as noted earlier, with EPA data that serves to model the typical time spent in each notch for switcher locomotives(e-CFR, 2019) (see Table 21).

Table 21: Percentage of Time Spent by the Switcher in Each Notch. From (e-CFR, 2019)

Notch	Idle	1	2	3	4	5	6	7	8
% of time	.598	.124	.123	.058	.036	.036	.015	.002	.008

Table 23, below, shows the results of the switcher analysis that was performed as part of this study. (As noted in the methodology section, an assumption has been made of 10 hours of daily operation per switcher, and it is this period that the data is intended to represent.) Since, as described further in Section 5.8, railyard emissions concerns relate mostly to the emissions during operation (i.e. PTW emissions), this section doesn't explore natural gas and FTD impacts since, unlike hydrogen, the former two don't offer the potential for a 100% reduction in such emissions.

Diesel 1, in table 23, notes the results given the data that was taken directly from (Hedrick et al., 2012). However, in addition to the variation in maximum power, switchers can vary significantly in their efficiencies; as such, Diesel 2 data was developed by applying the efficiency values found by using EPA switcher guidelines (i.e. as used for testing such equipment) on time and percent of total power per notch (e-CFR, 2019) and applying these to publicly available fuel consumption per notch data for several switcher locomotives (GATX, n.d.-a, n.d.-b). The efficiency of Diesel 2 is, as apparent from table 23, a bit lower than the one obtained directly from the data presented by (Hedrick et al., 2012).

Table 22, below, shows the power by notch values for both Diesel 1 (as well as Hydrogen 1 and Hydrogen 2, which were also based on (Hedrick et al., 2012) and Diesel 2.

Table 22: Switcher Power by Notch

From (e-CFR, 2019)

*** Based on (Hedrick et al., 2012)**

 # Based on EPA (e-CFR, 2019), with adjustment (12 kW) for assumed auxiliary power

Notch		Idle	1	2	3	4	5	6	7	8
Power, in kW*	Diesel 1, Hydrogen 1, Hydrogen 2	12.0	150	258.3	462.7	627.3	768.7	1034.7	1248.3	1402.7
Power in kW#	Diesel 2 only	12.0	72.4	166.4	327.4	481.8	663.0	871.0	1152.9	1354.3

Hydrogen 1 and 2 represent, as in the previous parts of Chapter 5, two different sets of fuel cell system efficiency values (based on (Wipke et al., 2012)). Despite the data being several years old, Hydrogen '1''s data is quite similar to current heavy duty fuel cell efficiency values while the values for Hydrogen '2' are intended to represent future efficiency improvements which could occur during the intervening years. (Hydrogen consumption data has been derived from these curves, based on the percentage of total power being utilized at each notch.)

Hybrid scenarios are included in Table 23. These were devised for both the Diesel 1 and the two hydrogen datasets, based on an assumption that the hybrid will operate at a constant power setting, or operating point, which is set as the average of the power levels found during the non-hybrid duty cycle. Efficiency at these operating points, for the diesel-electric switcher, is based on an interpolation of the data provided by (Hedrick et al., 2012). Downsized hybrid scenarios are also included, and were formulated for the same three datasets, with an assumption that prime mover total power capacity is 25% greater than that of the fixed operating point. (Again, diesel-electric hybrid efficiencies were based on interpolated data.)

Lastly, the “ideal” hybrid is based on the original data, and represents a hybrid that would have its operating point set such that it maximizes efficiency of the engine. The value in the table, 37.12, represents the efficiency found at Notch 3 of the (Hedrick et al., 2012) data.

Table 23: Switcher Analysis (Non-Simulation) Results, Diesel-Electric (ICE) and Hydrogen Fuel Cell.

Results assume 10 hours of operation, and are intended to serve as an approximation of daily operations for a switcher locomotive

Switcher, 9 Notches: Fuel	Max. Power Output Genset/ Fuel Cell (kW)	Primary Fuel (Diesel/H2) Consumption 10 Hours of Operation (GJ)	Primary Fuel (Diesel/H2) Consumption 10 Hours of Operation	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)[186]	Average Genset/FC Output Power (kW)	Fuel Energy Reduction from Diesel "Baseline" %
Diesel 1	~1,400	18.093	132.44 gallons	32.6	27.7	163.9	NA
Diesel 2	~1,340	21.217	155. 30 gallons	27.3	23.2		-17.3
Hydrogen 1*	~1,400	11.024	91.7 kg	53.5	45.5		39.1
Hydrogen 2	~1,400	10.526	87.6 kg	56.1	47.6		41.8
Diesel 1 Hybrid	~1,400	18.832	137.85 gallons	31.3	26.6		-4.1
Hydrogen Hybrid 1	~1,400	10.134	84.3 kg	58.2	49.5		44.0
Hydrogen Hybrid 2	~1,400	10.553	87.8 kg	55.9	47.5		41.7
Diesel 1 Hybrid	~205	16.495	120.74 gallons	35.8	30.4		8.8
Diesel Hybrid, "Ideal"	~497	15.893	116.34 gallons	37.1	31.6		12.2
Hydrogen Hybrid 1	~205	12.420	103.3 kg	47.5	40.4		31.4
Hydrogen Hybrid 2	~205	10.967	91.2 kg	53.8	45.7		39.4

[186] Auxiliary power needs are included in these efficiency numbers. Vehicle efficiency figures have been calculated by Using a flat adjustment of .85 to estimate remaining drivetrain efficiencies (i.e. at 85%).

The results in Table 43 demonstrate the fact that a non-downsized diesel hybrid switcher may not necessarily lead to much improvement, if any. This is because, as was seen in Table 21, above, so much of the switcher's time is spent in engine idle mode (when the little energy that is being produced is used to meet auxiliary power needs), which generally (and, specifically, in this case) represents the notch with the lowest efficiency, along with significant amount of time in notches 1 and 2 (with notch 1 also displaying lower efficiency than many of the other notches).

Downsizing the engine before hybridizing leads to significant improvement, however, with close to about 9% reduction for the downsizing based on a 5:4 oversizing formula alluded to above, which minimizes the size of the diesel engine and generator. When the "ideal" hybrid is assessed, the energy consumption reduction increases to over 12% (though with less of a reduction in prime mover size).

One rail expert (D. Cook, personal communication, November 7, 2019) noted that, in fact, there is not much room in many switchers, and so that hybridizing a switcher would, in many cases, require downsizing. This topic is beyond the scope of this study, though certainly an area that requires further exploration. Moreover, whether the increased size of the "ideal" hybrid engine and generator would prove problematic due to its increased size vis-à-vis the 5:4 hybrid is also a question that should be addressed in any such future work.

One thing clear from the data, also, is that switching the prime mover over to hydrogen would greatly increase the energy savings, particularly due to the inefficiency of diesel at the lower notches of operation. (In the next section, the impact on GHG and regulated pollutants are discussed.) The reduction in fuel consumed is maximized with a non-downsized hybrid (and not a downsized hybrid, for the reasons noted in Section 5.3, on the passenger results). Again, the question of sizing switcher locomotives is beyond the scope of this study.

5.9 Switcher Pollutant Emissions Results

As has been alluded to several times previously, hydrogen production currently results in pollutant emissions; it is only during operations that hydrogen is zero emission, at the present. On the other hand, it is during operations that most of the pollutant emissions are produced for locomotives operating with a diesel-electric powertrain. Beyond the standards set by the EPA, it seems likely that the freight railroads would be particularly keen to reduce emissions in railyards from switcher locomotives since these locomotives are continuously operating over the same limited space (which leads to an accumulation of health-threatening pollutants that impact the health of both their own employees and of nearby residents). Figure 52, below, shows just how concentrated in the operational phase the pollutant emissions from the diesel-electric switcher locomotive powertrain are. On the left of the chart is the data representative of the 2015 fleet (as presented in the GREET Model). Tier 4, the current standard[187], is shown in the middle, along with its slight "PTW" reductions, particularly in Hydrocarbons (HC) and Particulate Matter (PM). Finally, the emissions that would result under California's proposed Tier 5 are shown on the right side. As can be seen, hydrocarbons (HC) from operations would be greatly reduced under this proposal. PM would see continued (though modest) reduction, while NOx would also see a modest reduction. (The recent fleets have already met the standards that have been set for Carbon Monoxide (CO), even for Tier 5.)

[187] As noted in Section 4.4, the CO standard for Tier 4 had already been met by the switcher fleet in 2015, according to data from (GREET, 2018); hence the Tier 4 level assumed in this section is lower than the actual Tier 4 standard for switcher locomotives (and lower, still, than the stricter Tier 4 standard set by line-haul locomotives (EPA, 2016b)). See the appendix for the actual values used in this study for the different emissions standards.

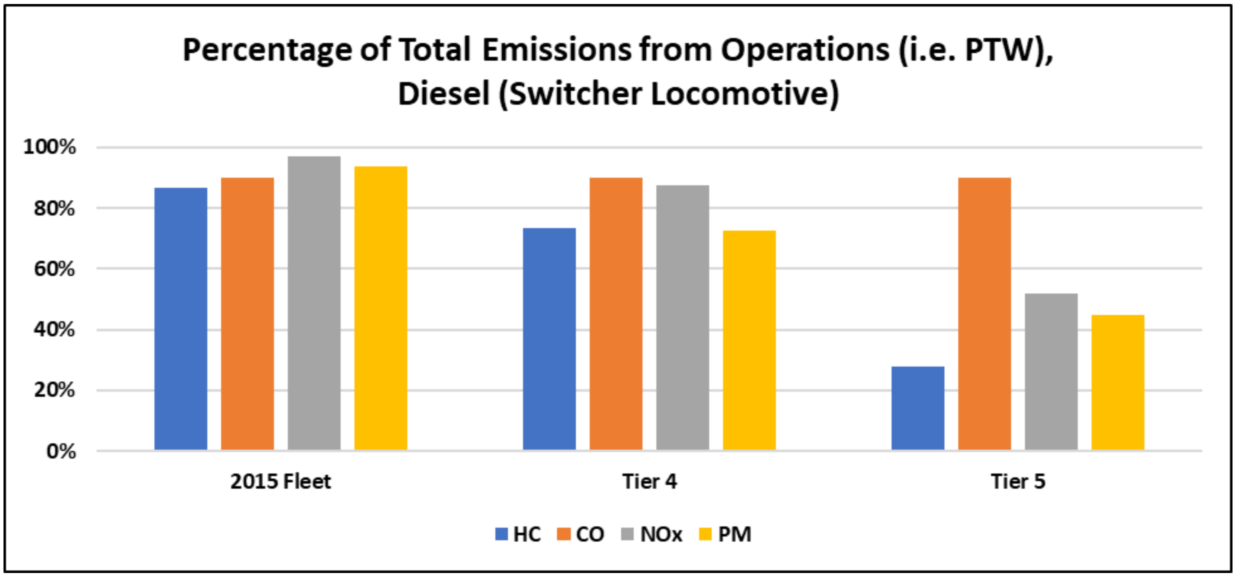


Figure 52: Percentage of Total Emissions from Operations (PTW), Diesel, Switcher Locomotive

Figure 53, below, shows the impacts of hybridizing the Tier 4 and Tier 5 fleets on regulated pollutant emissions, while also showing the impacts for the 2015 fleet. (As indicated in Section 5.11, a substantial amount of freight rail operations were, even in 2017, conducted with locomotive technology that is not reflective of Tier 4. This is very likely to be the case with switcher locomotives, in particular, whose fleet is typically even older in age than that of the mainline locomotive fleet, as can be inferred from (Humphrey, 2019).) As can be seen from Figure 53, the reductions achieved from hybridizing largely mirror the reductions in fuel consumption noted in Section 5.8. They are modest, at best. On the other hand, the EPA Tier 4 standards reduce many of the operational emissions, substantially, and Tier 5 would continue that trend. (The variations in this chart mirror, to some extent, the changes in Figure 52; only that Figure 52 presents the changes as a percentage of overall WTW emissions.)

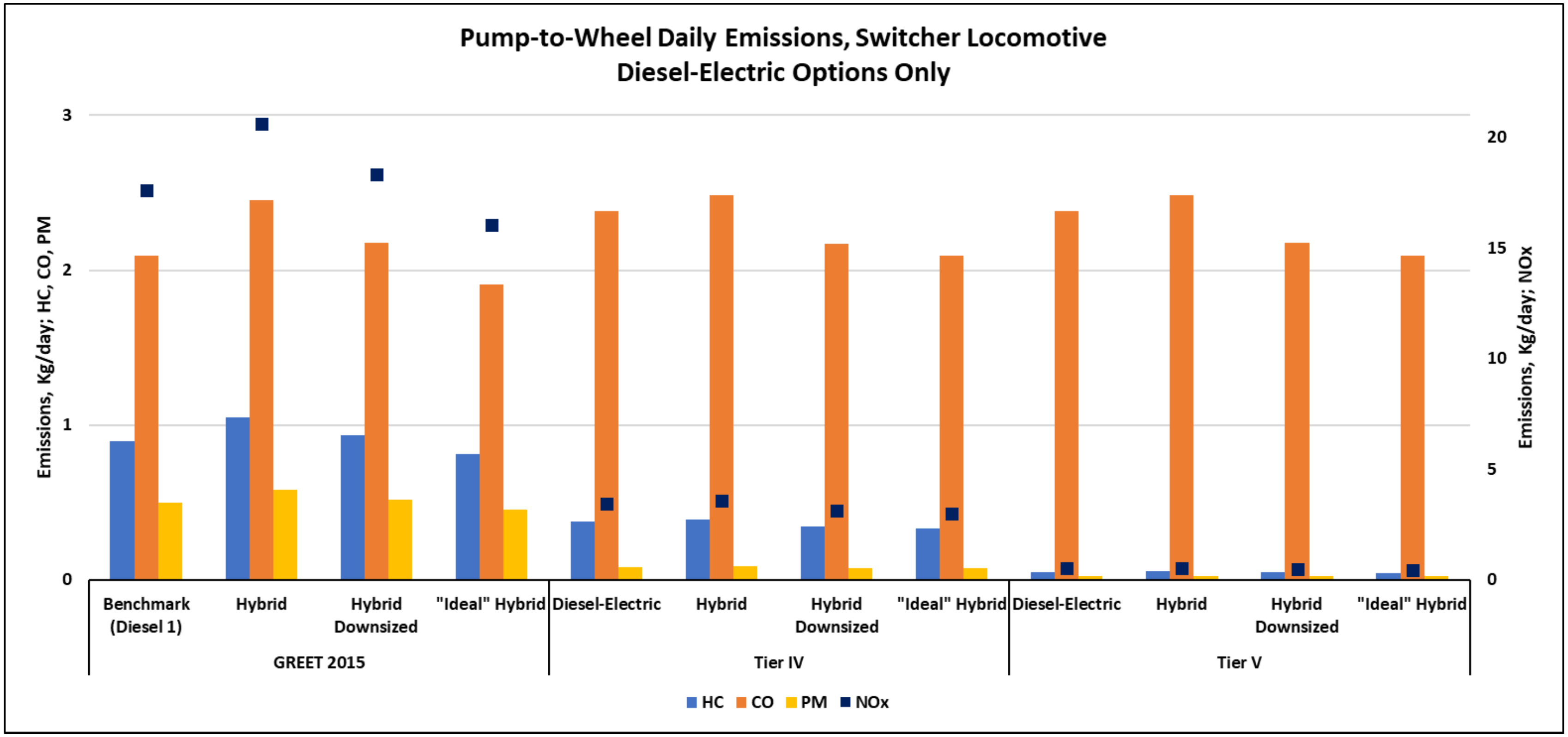


Figure 53: Pump-to-Wheel Daily Emissions, Switcher Locomotive, Diesel-Electric Options Only

HC, CO, and PM are indicated by columns, while NOx levels are indicated via a square notation.

(Note: 10 hours assumed for daily operation, as indicated in Section 5.8, above.)

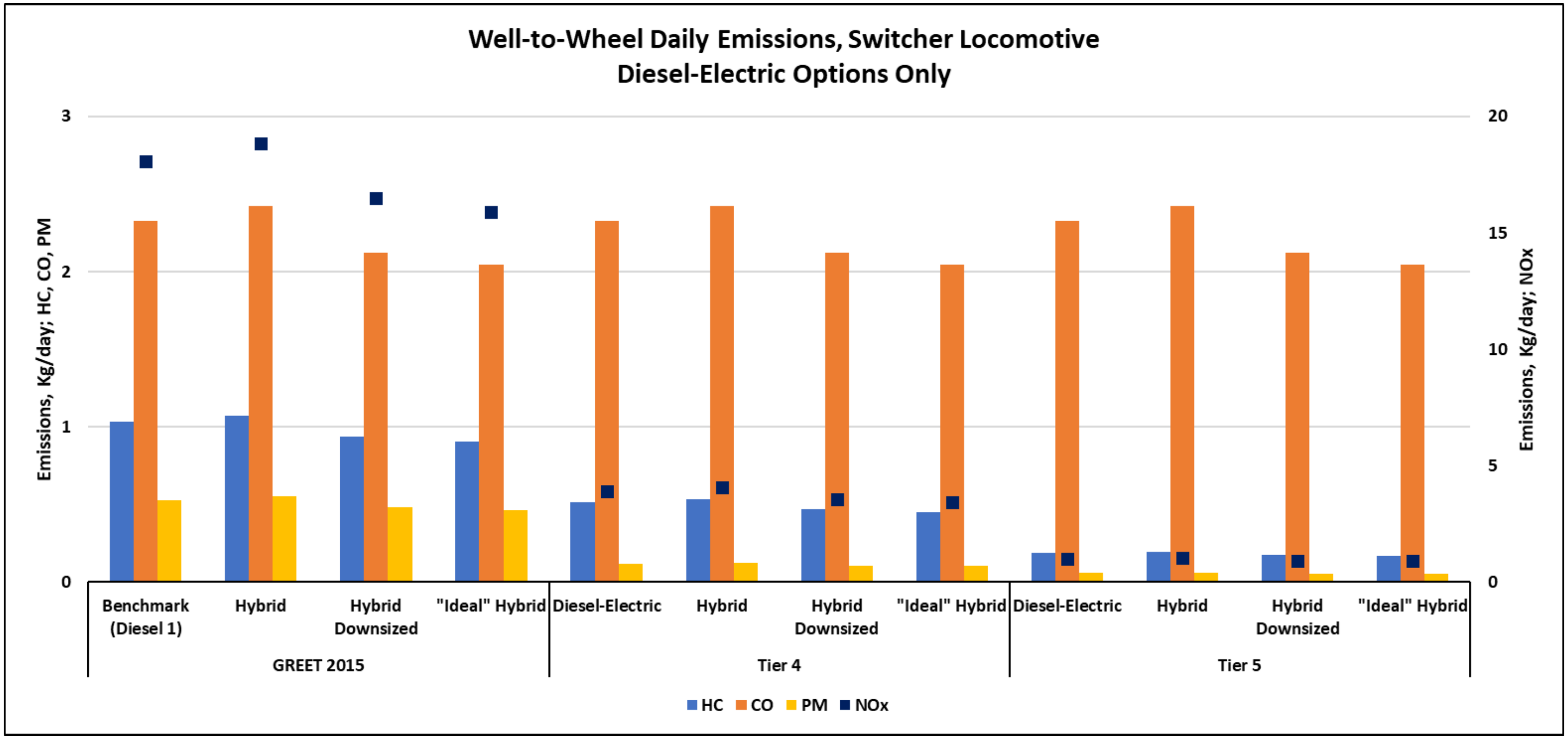


Figure 54: Well-to-Wheel Daily Emissions, Switcher Locomotive, Diesel-Electric Options Only

(Note: CO levels for the 2015 fleet already met the Tier 4 and Tier 5 standards, and so the latter values were adjusted to reflect this value remaining the same.)

Figure 54 shows overall, well-to-wheel impact on pollutant emissions. There are many similarities between the data in this figure and that of Figure 53, since operations account for the majority of diesel pollutant emissions at present (see Figure 52, above). However, Tier 5 is where many of the differences become more apparent. (CO is the one exception. As previously noted, CO levels for the 2015 fleet had already met the Tier 4 and 5 standards, and so the latter CO values are assumed as the same, lower level that has already been achieved.) This is because of the significant pump-to-wheel emissions reductions that would be required of such a tier. As a result of these reductions at the point of operation, the contrast between PM and, even more, HC for Tier 5 (in Figure 54) versus for the other emissions categories is not as great at a well-to-wheel level as it is for the pump-to-wheel level (Figure 53).

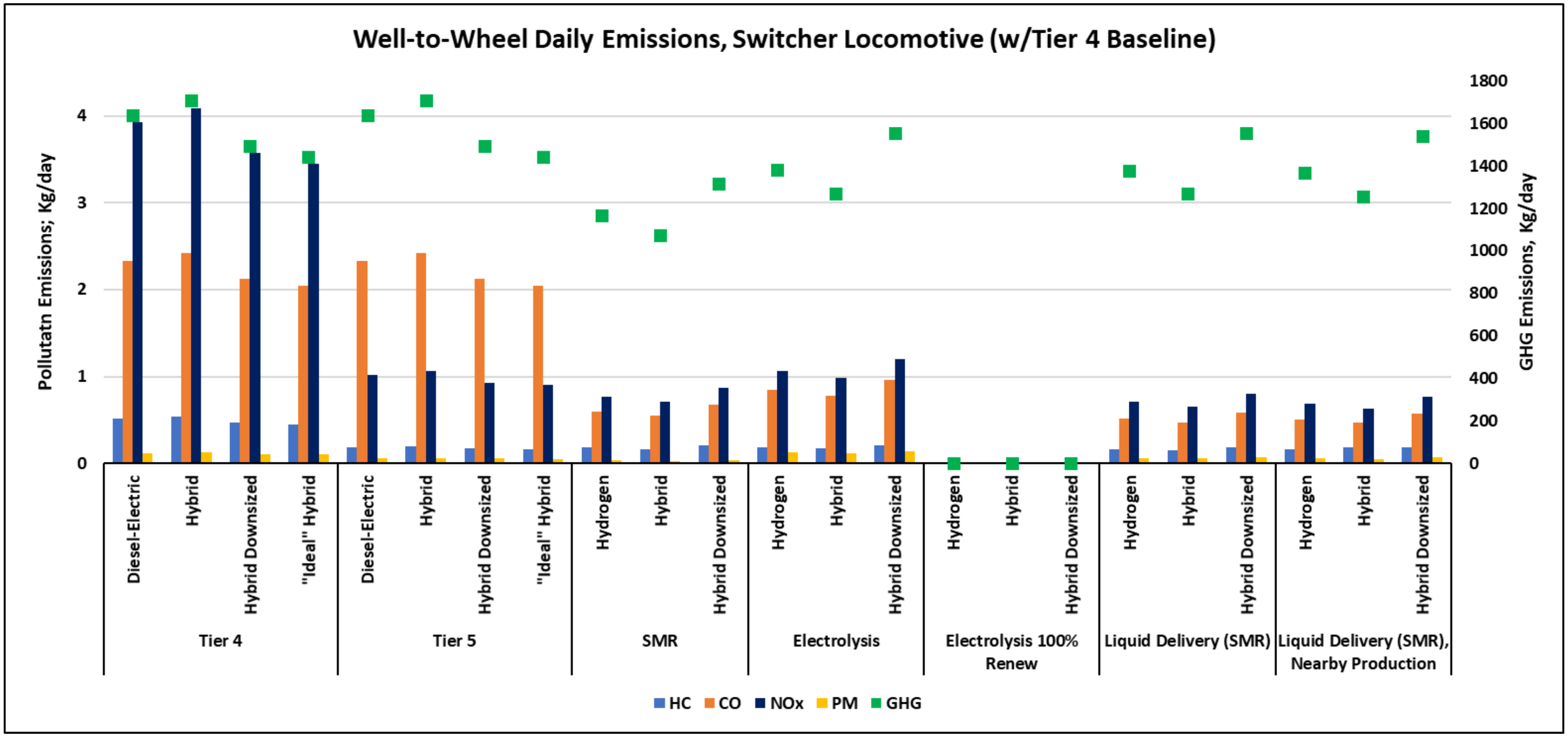


Figure 55: Well-to-Wheel Daily Emissions, Switcher Locomotive (with Tier 4 as a Baseline)

Figure 53 doesn't even show operational (i.e. Pump-to-Wheel) emissions for hydrogen since there are none. Figure 55, which examines well-to-wheel pollutant emissions across all of the assessed options demonstrates, also, that, even at this level, the diesel reductions, are all relatively modest as compared to the kinds of pollutant emissions reductions that would be seen under hydrogen powertrains. (It should be pointed out that, in the case of hydrogen produced via onsite SMR, the well-to-wheel picture becomes a bit more significant for the railyard as, in this case, at least some portion of the upstream, or "well-to-pump" emissions—particularly of CO and CO_2—would occur, also, at the yard.) Within the hydrogen production range, onsite SMR results in lower pollutant emissions than for conventional electrolysis (the latter with substantially higher PM emissions), which is not surprising given the amount of electric power required of electrolysis. (And, again, the lower WTW emissions of onsite SMR vis-à-vis electrolysis are all the more crucial given that, as noted above, some of the impacts of the WTP emissions may be felt directly at the yard.) Of course, the picture for electrolysis is highly dependent on the status of the electric grid. If based on a 100% renewable grid, it would not have any pollutant emissions at all, and that theme is explored a bit more below. While a bit difficult to see from the graphic, the pollutant emissions from liquid delivery—excluding PM emissions— are even lower than for SMR (liquid delivery assumes centralized SMR production, followed by liquefaction and transport). This likely reflects certain emissions reductions processes that go on at the plant level that can economically be achieved at scale, as the overall supply chain should result in higher emissions due to the transportation and, especially, the liquefaction components (see the discussion in Section 3.6, above). More key, in this situation, the WTP emissions would all occur away from the railyard, so the railyard emissions would truly be zero.

The last category in Figure 55 examines if nearby production would lead to a significant reduction in emissions. (The GREET default assumes over 800 miles of transport, whereas this sensitivity assumes 50 miles, only.) Likely because so much fuel is transported at once (some of this occurs by either rail or barge), the resulting difference is minimal. While NOx is reduced by 2.5%, the others pollutant emissions are reduced by roughly 1%. The GHG reduction is less than 1%.

Again, hydrogen's current advantage lies in the lack of operational emissions. At the WTW level, the GHG emissions result is not quite as impressive for hydrogen. Nonetheless, aside from the downsized hybrid options, which demonstrate the least efficiency of any of the hydrogen powertrains, all of the hydrogen options offer at least some GHG reduction. With SMR, non-hybrid and the non-downsized hybrid, this reduction would be more than 25%, whereas with electrolysis and liquid delivery the reduction would be much less. However, as with the pollutant emissions, electrolysis based on a 100% renewable grid would in fact produce no GHG's, a topic that, again, is discussed below, in some detail.

While a 100% renewable grid is not likely to be a reality in the short term, California is projected to continue to decarbonize its electric grid at a rapid rate (US EIA, 2019h). A sensitivity was performed to show what kind of emissions reductions might occur for electrolysis in regions such as California were that state (or other regions) to achieve the ambitious 2038 "base scenario" electric grid characteristics indicated by the U.S. EIA. The sensitivity also juxtaposes this sensitivity alongside a potential improvement in the efficiency of a typical electrolyzer, which could be a possibility during the time period, and so as to give a sense of where resources might best be focused.

As figure 56, below, shows, while a significant improvement in electrolyzer efficiency (from GREET's default of approximately 67% to 75%) would make a very modest reduction in both emissions and GHG's, electrolysis based on a future California grid (estimated as being comprised of, roughly, 84% renewables, with the remainder of production mostly natural gas (US EIA, 2019h)) would lead to a very substantial reduction in both GHG's and pollutant emissions.

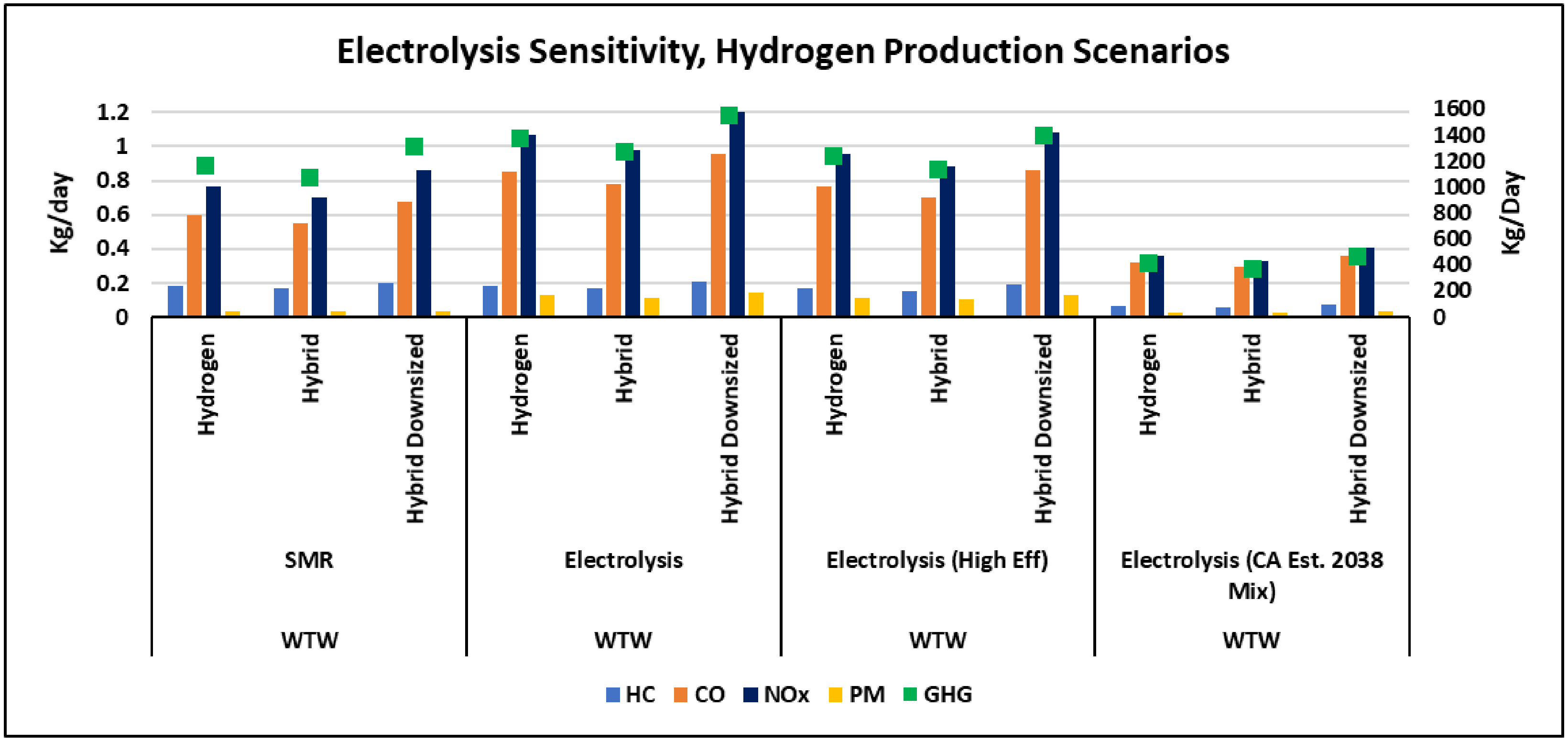


Figure 56: Electrolysis Sensitivity, Hydrogen Production Scenarios

(Note that the green squares indicate GHG emissions, while the columns represent the pollutant emissions.)

5.10 Hydrogen and the Electric Grid

Figure 28, introduced in the passenger section, and Figure 56, just above, can be tied together by a few overarching themes. The first is that the GHG and pollutant emissions for a hydrogen fuel cell rail powertrain come from the hydrogen production and delivery phases. The second is that, with much of the energy relevant to the production process coming from electricity, the electric grid mix used for electrolytic hydrogen production strongly influences the resulting well-to-wheel emissions levels. Finally, the make-up of the electric grid varies both over time and across geographic location.

Attempting to estimate resulting impacts over a broad period and in a broad region, as this analysis has attempted to do, requires making bold assumptions. The analyses performed here have assumed that the U.S. grid during the period from 2022-2038 will, roughly, resemble the California grid as it was in 2017 (as recorded by the authors of Argonne's GREET model). Table 24, below, summarizes this data.

Table 24: The Estimated Make-up of the 2017 California Grid, as recorded by the GREET Model

Source: (GREET, 2018)

GREET Assumptions (Primary Energy Source)	California (%)
Residual Oil	0.0
Natural Gas	41.3
Coal	6.3
Nuclear Power	9.7
Biomass	0.5
Others*	42.2

Note that the main components of the "Others" category include (noted here as a percentage of "Others") hydroelectric, at 42.4%, geothermal, at 11.8%, wind, at 16.7%, and solar PV, at 27.3%.

This table reflects the assumptions underlying the emissions analyses summarized above (except where noted otherwise).

Of course, the California grid is continually undergoing significant changes. The data in Table 25, below, from the California Energy Commission, show that natural gas's relative portion has already shrunk significantly from the estimated 2017 data. Similarly, coal's role has been reduced. (Interestingly, solar's relative size is little changed.)

Table 25 The Actual California Electric Grid, as of 2018

Source: (CEC, 2019)

Primary Energy Source	%
Coal	3.30
Large Hydro	10.68
Natural Gas	34.91
Nuclear	9.05
Oil	0.01
Other (Petroleum Coke/Waste Heat)	0.15
Renewables **(Solar & Wind, "S" and "W", Largest Components)**	31.36 S=11.40 W=11.46
Unspecified	10.54

For comparison's sake, Table 26, below, shows the U.S. grid in 2017, also as recorded in the GREET model, alongside the U.S. actual grid makeup, as assessed by the U.S. EIA. Here, too, there has been a (proportional) reduction in coal, though, unlike in California, it has occurred alongside an increase in natural gas.

Table 26: U.S. Electric Grid by Source, 2017, as Recorded in the "GREET" Model (on the left), U.S. Electric Grid, in 2018, Derived from U.S. EIA (on the right)

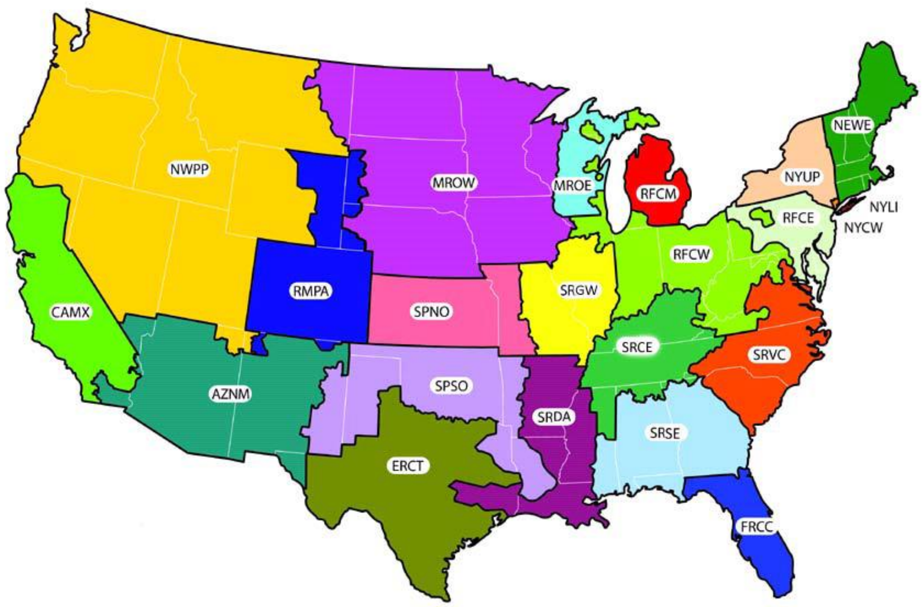
Sources:(GREET, 2018; US EIA, 2019e)

GREET Assumptions (Primary Energy)	U.S. (%), GREET		U.S. Actual (EIA), 2018 (Primary Energy)	U.S. (%), (EIA)
Residual Oil	0.5		**Coal**	28.3
Natural Gas	29.8		**Natural Gas**	34.0
Coal	32.7		**Nuclear**	20.1
Nuclear Power	20.6		**HydroPower**	7.2
Biomass	0.1		**Nonhydro Renewable**	9.7
Others**	16.3		**Other**	0.9

Note that the main components of the GREET model's "Others" category (noted here as a percentage of "Others") include hydroelectric, at 47.4%, wind, at 39.2%, and solar, at 7.5% *(GREET, 2018)*.

Alongside these changes that have already occurred, EIA indicated, early in the year, that it was expecting "non-hydroelectric renewable energy sources," including solar and wind, to be the "fastest growing source" (US EIA, 2019g) of electric generation, nationwide, through the end of 2020 (US EIA, 2019g), with an increase in the share of non-hydroelectric renewables across the grid increasing by 3% during this ensuing two year period (US EIA, 2019g). Moreover, EIA projected that utility-scale "solar generating units" would grow by 17% in 2020, alone (US EIA, 2019g).

Of course, fundamentally, electric grids will continue to vary significantly by market region (see figure 57 for a map of the many different electricity markets that cover the country), and this makes the story around hydrogen and its impacts on GHG's and pollutant emissions quite complex, which, in turn, makes the value analysis a bit less straightforward than has been presented here. (This would be particularly true if the hydrogen is in fact produced offsite, potentially in a different electric market region than where it is primarily consumed.)



.
Figure 57: Map of the U.S. Electric Grid
Source: (US EIA, 2019c)

Table 27, below, shows some of the projected changes in the relative roles of coal, natural gas, and renewables in a few different regions, according to the U.S. EIA. It is apparent from this data that regional differences are likely to persist for the next several decades.

Table 27(a-b): EIA "Reference Case" Projections: Coal, Natural gas, and Renewable Resources

This table provides EIA Reference Case" projections for proportions of coal, natural gas, and renewables resources that will serve the electric grid, for two areas in the Midwest and for New England, between 2018 and 2050 (US EIA, 2019h)

a.

	MRO East, % Coal	MRO West, % Coal	MRO East, % Natural Gas	MRO West, % Natural Gas	MRO East, % Renewables	MRO West, % Renewables
2018	68.5	45.5	22.4	9.1	8.2	33.4
2038	57.5	45.6	31.1	8.0	10.2	42.3
2050	59.8	41.4	28.1	7.7	10.9	46.8

b.

	NEPCC, New England % Coal	NEPCC, New England % Nat. Gas	NEPP, New England % Renewables
2018	1.6	48.9	17.3
2038	0	45.9	23.0
2050	0	48.3	22.7

Overall, however, the direction of change suggests that, despite regional differences, different places across the country are moving towards a higher consumption of renewables. In the context of this study, this is significant, as, if historical fuel transitions in rail can tell us one thing, it is that moving towards a new fuel system would be a very long-term decision. And if hydrogen were to be the direction that the rail industry takes, particularly if production via electrolysis becomes the prime production method, the industry could rest assured that the fuel's negative environmental impacts are almost certain to diminish over time, as the energy system decarbonizes.

5.11 Chapter Summary

This chapter summarized the many results that came directly from the simulation analyses, along with the cost and emissions results (and energy consumption results, in the case of switcher locomotives) that were produced as a result of additional analysis using a variety of government-developed models and high quality literature sources.

In many of the charts above, pollutant emissions levels have been shown for three different diesel cases---first for the diesel-electric fleet, as it was composed in, roughly, 2015 (according to the GREET model), second, what would result under 100% penetration of the newest standard, Tier 4, and third, what might be seen with a Tier 5 standard that has been proposed (again, assuming 100% penetration of this standard), but not implemented.

Differentiating such results is more than just an academic exercise. Freight rail locomotive fleets turn over gradually, so penetration of the Tier 4 standard is very low, at this point. Each year, the California Air Resources Board collects data from BNSF and UP, the previously noted two largest Class I railroads, and the two railroads that operate in the South Coast Air Basin. Measuring the freight activity in this region, as a function of total energy expended, CARB reported that, in 2018, Tier 4 activity represented only 3.8% of all UP activity and 4.3% of all BNSF activity in the basin. On the other hand, Tiers 1 and 2, combined, represented 53.2% of UP’s activity in the basin, while, for BNSF, Tiers 1 and 2 represented 71.5% of that railroad’s total activity in the basin!

Chapter 6 serves as a concluding chapter. It will review the need for a study such as the present one, review some of the methodological approaches utilized, present some of the key takeaways from the study results, and attempt to tie together the overall messages, while noting the relevance to rail systems across the country and globe.

CHAPTER 6. CONCLUSION/RECOMMENDATIONS FOR FURTHER STUDY

6.1 Study Review

This study began by introducing the need for further study of fuel/fuel technology alternatives to the diesel-electric powertrain (with diesel fuel as the primary fuel input) in rail. As was introduced in chapter 1, energy technologies are undergoing rapid change during the present era. At the same time, both the automotive and heavy-duty road sectors have taken advantage of such change and begun to transition to new fuel technologies and fuel sources that will improve human health and reduce negative impacts on the environment. The rail industry, it was noted, is a growing sector, both domestically and internationally; yet the domestic locomotive fleet is overwhelmingly composed of locomotives whose primary fuel input is diesel fuel. As such, the domestic rail system, a fairly centralized system with a limited number of equipment customers (as compared to, e.g., the light duty vehicle sector), stands to benefit from (and potentially contribute to) the same technological developments as the other transportation sectors.

Through single train simulation and detailed case studies of actual passenger and freight routes and applications, the author sought to determine whether a similar shift away from fossil fuels in the domestic rail sector could be a) helpful for human health and for the environment, b) feasible, from both a technical and operational perspective, and c) potentially cost-effective.

The present study sought to build on previous literature that has examined fuel alternatives in rail. While each of these studies contains aspects of the work conducted in this study, this work sought to be unique in its combined level of transparency of results and consideration of several viable fuel technology options across several different route types.

Following introduction of the study purpose, some of the growing body of research and, increasingly, pilot projects that have begun, in the area of fuel alternatives in rail over the last few decades, were presented and discussed. Some key fuel alternatives, selected based on either past interest and exploration by railroads or particular promise (as assessed by the author) were presented and reviewed, primarily in Chapter 3. Chapter 4 laid out the methodological approaches utilized for the present analysis, and Chapter 5 presented the key results that emerged from the analyses conducted. For both passenger and freight rail, the single train simulation tool, or STS, results were presented first, as the author considers these route-specific results as the primary unique methodological contribution of this paper. Emissions and cost results were then presented, developed based on the simulation results combined with relevant emissions and cost data that have been primarily compiled by other sources and well-established models. (Though, as previously noted, the author did explore and adapt the available models, in many cases, rather than take model outputs exactly as presented and displayed, upon a cursory look.)

The following are some key takeaways from the study results presented in Chapter 5:

Overall (i.e. rail sector-wide):

- Natural gas could bring down the combined locomotive equipment and fuel costs in both passenger and freight; however, it is very difficult to pinpoint by how much, as this will depend enormously on the trajectory of costs for each of these two commodities (diesel fuel, in particular). This study finds that the resulting costs range significantly. For passenger, the cost range is from -2% (an increase) to a high of 32%[188], as compared to the status quo diesel technology. For freight, the potential reduction from diesel ranges from 1% to 67%. Use of natural gas might also reduce the volatility that is associated with diesel fuel costs; however, the effect on (reducing) GHG emissions would be very slight[189]. Moreover, there also might be an overall increase in CO and Hydrocarbons (HC) when looked at from the perspective of the entire fuel cycle.

- FTD could reduce the combined equipment and fuel costs, but not by as much as natural gas. Moreover, at least for fuels derived from natural gas (the default assumption used in the GREET model), cost reductions for FTD would come at the expense of greater GHG emissions than the status quo diesel[190]. Cost estimates for FTD are also highly uncertain, a topic that will be explored further in Section 6.3, below.

- Adapting either a passenger or freight (or even switcher) locomotive for hydrogen will likely require significant locomotive redesign, but this should be feasible given the space available (including rooftop space) and an “outside-of-the-box” approach.

- Cost for hydrogen via electrolysis may be higher than the cost for hydrogen via SMR, but this would depend on electricity cost.

- With sharing of refueling stations between freight rail and passenger rail, passenger rail could benefit from the somewhat cheaper prices of hydrogen production via SMR. (In

---

[188] These are based on within-system-operator cost ranges rather than covering all passenger rail.

[189] Were renewable natural gas, or ‘RNG,’ able to expand to a scale beyond what appears to currently be the case (STEPS, UCD, 2017), overall emissions impacts could be reduced inasmuch as there is a transfer of emissions that would already be occurring in the atmosphere.

[190] While an FTD derived from a biomass would likely show some reduction in emissions(GREET, 2018), this would come with a cost trade-off (G. Liu et al., 2011) such that the system costs would end up right near the top of the FTD cost range observed in this study.

our analysis, Capitol Corridor trains are modeled as stopping regularly in Roseville, CA, which is also the location of a large freight yard.) Prices for electrolytic hydrogen are less sensitive to scale of the refueling station than is the case with SMR, but where this makes sense for freight (again, price would largely depend on electricity cost), again, there could be some benefit to resource sharing.

- Make-up of the electrical grid will be key to reducing Well-to-Pump (WTP) GHG and pollutant emissions from hydrogen via fuel cell (and thereby all such emissions, since operational emissions---H_2O aside---are non-existent with hydrogen via PEM fuel cell). This is particularly the case for hydrogen produced via electrolysis, but smaller impacts will also be evident for SMR production.

- There are many different technologies currently under exploration for hydrogen storage. Thus the hydrogen cost numbers (along with the logistics of refueling) discussed in this study are inherently highly uncertain, particularly towards the second half of the time period examined.

- Similarly, due to the key role that batteries play in daily life, battery technology development is subject to a lot of ongoing research and continues to develop rapidly. Battery technology developments that were unable to be foreseen in this study will impact the ultimate cost and feasibility of hybridization in rail.

For passenger systems:

- Hybridized hydrogen via fuel cell seems very viable as an alternative to the status quo diesel-electric powertrain. Even with medium distance stopping patterns it is advantageous, while with very frequent stopping patterns, it is particularly effective at reducing primary hydrogen consumption. In a “best case hydrogen” scenario (i.e. with low hydrogen and related equipment costs and high costs for diesel fuel), this study finds a reduction on the order of 43% to 47% (for SMR, in both cases) as a possibility. On the other hand, in a low diesel cost, high hydrogen (and electricity) and related equipment cost scenario, hydrogen via electrolysis could result in an 11% to 22% increase over diesel, for the costs studied. However, electrolysis costs could still be advantageous, particularly in the case of Caltrain or a system like it. A 5% reduction in costs for electrolysis is found possible even in a low hydrogen (and electricity) fuel and equipment[191], low diesel cost scenario. And a 37% reduction is found, in either system, in the case of a “best case hydrogen” scenario for the electrolysis option.

- For longer distance trains, such as those operated by Amtrak, that don’t stop at stations as frequently, perhaps minimally hybridized fuel cell locomotives would be adequate. However, if hybridized hydrogen locomotives become mainstream for passenger rail, using these would not pose a major problem for such routes. (Particularly if the present-day rail context, in which they may slow down or stop occasionally between stops to allow for freight trains to pass, holds into the future.)

- For public transit agencies, the additional cost of hydrogen via electrolysis may be worthwhile because of increasingly large reductions in GHG’s and pollutant emissions. (The emissions reductions would depend on both exact electricity mix as well as on the specific geography in question, due to locational differences in electric grids.)

[191] All numbers noted in this section are based on fuel cell system efficiencies close to where they are now. Any increase in fuel cell system efficiencies would reduce hydrogen scenario costs.

- Hydrogen costs using liquid delivery may be somewhat higher than for onsite SMR, particularly at the low cost range for both options. However, this may be an advantageous approach to take in the beginning for a rail system considering hydrogen, as it reduces the investment and risk initially required. Liquid delivery also incurs higher GHG emissions levels than SMR or electrolysis based on a renewables-heavy grid, if the original production method is SMR.

- Benefits to hydrogen would be directly experienced by the riders, and include quieter cars, high acceleration rates typical of electric drive, and the related potential for high vehicle frequencies. (The latter two benefits are offered also by OLE, but only at a very high cost that is cost-effective in very limited conditions. OLE also brings with it a dependence, for an entire rail system, on outside infrastructure that is susceptible to damage.)

- Were passenger rail systems (particularly those based on locomotives rather than multiple unit vehicles) to steadily move towards a norm of hydrogen via fuel cell, the question remains: How many hydrogen tanks would be carried per locomotive? Might there be two or three different "templates"?

For freight systems:

- Hydrogen could definitely work, but whether costs would be lower than for diesel is hard to predict from this study's findings. (And, in fact, costs could be significantly higher than for diesel.) This would depend, in part, on the selected hydrogen production methods and other variables, like the cost of electricity or natural gas, that are hard to predict. In a "best case scenario" in which diesel costs are high and hydrogen fuel and equipment costs are low, hydrogen via SMR could result in a 48% reduction in costs from the status quo. For electrolysis, the “best case” scenario would bring costs down a bit less, with a 25% reduction. Were diesel to remain at its lowest cost range (i.e. $2.00 per gallon) throughout the period, then the hydrogen scenarios always result in higher costs, beginning with a 27% increase. In fact, a “worst case scenario” for hydrogen would occur with $2.00 per gallon diesel prices and with the upper end of the projected range for hydrogen via electrolysis, which could lead to at least a tripling of costs over the diesel status quo, given this study’s assumptions. As the charts in Chapter 5 indicated, there are substantial cost differences between hydrogen via SMR and hydrogen via electrolysis, particularly if local electricity prices were to remain around 14 cents per kWh throughout the period. For example, if comparing the high cost scenarios for both diesel and hydrogen, hydrogen via electrolysis would incur a 50% increase in costs as compared to diesel, while with SMR, a 40% reduction versus diesel would nonetheless be seen.

- With fuel costs a major factor in the decision-making, hydrogen via SMR might be the primary hydrogen production method that the freight industry would consider. (This study finds that the combined cost of equipment and fuel, Using SMR, could range from a 45% increase vis-à-vis the equivalent diesel costs to a 48% decrease for the cost of hydrogen relative to diesel, given current fuel cell efficiencies. Future fuel cell efficiencies could bring the latter figure higher, while other methods of production would mean a much greater price increase than 45%. The additional cost of hydrogen via electrolysis will depend, ultimately, on the cost of electricity in a given region; so production method could vary by region, and based on any specific terms that a given producer is able to negotiate with their local electricity provider.

- Due to high costs and the high fuel volumes required, liquid hydrogen delivery doesn't seem like a good choice in a freight context. In addition, it doesn't seem particularly practical, as, with the fuel capacities required of our freight system—68,000 kg per day—this would require 17 truck deliveries each day even if each truck were to carry 4,000 kg, each. (Moreover, as noted in Section 3.6, the freight system size that was assessed in this study is much smaller, in terms of fuel capacity required, than some of the larger freight refueling facilities.)

- Tenders (gaseous) are mostly required for the longer-distance intermodal freight trips, for hydrogen. These tenders should not present a significant cost issue; however, logistically, they could represent a bit of a barrier. (However, through flexibility in refueling patterns, freight systems might be able to avoid tenders altogether.) In the case of CNG, it seems possible that a tender could be avoided, even for the longer intermodal vehicles; however, this would only work should on-board storage amounts (in available energy terms) well under the current amount of energy typically able to be stored aboard a diesel locomotive be acceptable to the freight railroads. Moreover, avoiding the need for a CNG tender would mean a significant re-design to the locomotive interior (along with judicious use of rooftop space, as was also suggested for gaseous hydrogen storage). For those companies willing to explore re-design of the locomotive (whether for hydrogen or natural gas), the specifics of fitting all of the required fuel without a tender, particularly in the case of hydrogen, would also depend on the exact height flexibility atop the roof.

Switcher locomotives:

- Hybridization with batteries looks like a good fit. Energy reductions for a diesel hybrid powertrain max out at a modest ~12%, as a maximum (using diesel hybrid), to ~ 44% for a hybridized hybrid powertrain (though slightly less if not hybridized).
- The amount of hydrogen storage would be much less than with passenger or freight locomotives, plus, since the vehicle operates continuously in a railyard, refueling slightly more frequently than is currently the case should not pose a significant challenge.
- While no specific cost assessment was conducted for switcher locomotives, reduced fuel cell stack requirements (due to lower power values) and hydrogen tank requirements (due to lower overall energy requirements) should make any significant cost differences that might otherwise pose a concern in a high cost hydrogen scenario significantly less problematic.

Fuel safety was not part of the primary scope of this paper, and thus, for the alternatives considered, was only marginally addressed in this paper; that said, most, if not all, of the fuels and technologies covered have been used extensively enough that an understanding of safety approaches relevant to each are fairly well understood. It is the author's understanding that, assuming the latest safety protocols are implemented, safety does not pose a significant threat to the implementation of any of the fuel alternatives.

6.2 Limitations and Recommendations for Further Study

In the introductory chapter, the author introduced the reader to some of the key evaluative criteria that such technology evaluations might be based on, from the perspective of the key decision makers. This involved understanding different perspectives, such as that of the profit-driven, publicly listed company (e.g. in the case of freight rail) or the public agency usually tasked with operating commuter and regional rail (or, in the case of Amtrak, a bit of a hybrid, in terms of how a public agency sets its typical goals and a profit-oriented company and its pricing strategies). These criteria ranged: from cost, to safety, to environmental goals (or meeting regulatory requirements related to achieving such goals), to the disruption or new learning that comes with a new fuel technology, to the ease of use, once established. (See chapter 1 for the complete list.)

As for environmental goals and meeting regulatory requirements, the GHG and pollutant emissions portion of this analysis highly depended on assumptions made by ANL's "GREET" model. To the extent that the assumptions made in that model may not always hold, especially as we move further out in time, the analyses contained herein cannot answer some of these questions with high precision. For example, while the assumption of zero "pump-to-wheel" emissions under hydrogen operations seems certain, many of the assumptions vis-à-vis FTD and natural gas bring with them significant and even overwhelming uncertainty.

FTD, for example, can be produced from a variety of sources. The emissions impacts of each varies significantly (GREET, 2018). However, the sources that are likely to bring GHG emissions down the most (GREET, 2018)[192]—typically biomass-based, also known as BTL—tend to involve processes that are more costly (G. Liu, Larson, Williams, Kreutz, & Guo, 2011). Moreover, despite what one author considers "aggressive policy incentives" the transition to a low-cost, "mature" industry has not yet occurred in the case of these so-called "advanced biofuels" (Witcover, Julie and Williams, Rob, Manuscript in preparation, December 6, 2019,

[192] (GREET, 2018) suggests a reduction, for FTD produced via gasification of biomass, in WTP GHG emissions of 74% from petroleum-derived diesel, with a total WTW reduction of 15% (GREET, 2018).

“Advanced Biofuel Cost Estimates in the Literature: Review and Comparison”). The BTL industry has also be marred by some significant commercial failures (Wiryadinata, 2018) (Witcover, Julie and Williams, Rob, Manuscript in preparation, December 6, 2019, “Advanced Biofuel Cost Estimates in the Literature: Review and Comparison”), which, in the case of one European company, may have resulted in part due to the complexity of the processes involved (Wiryadinata, 2018). If this industry continues to flounder, then the viability of BTL as a systemic fuel alternative for rail may be in jeopardy (while this study showed that FTD derived from natural gas would only increase emissions). On the other hand, should a breakthrough occur, and scaling of the fuel to the kinds of amounts required by entire rail systems become a real possibility, and at the price levels projected in the literature, then the well-to-wheel emissions implications of BTL as an FTD should be explored in further detail (along with any relevant updates to the GREET model inputs, should process changes). Ideally, exploration of secondary effects related to biomass production should also be explored should high scales of production start to take root. Depending on the exact (biomass) feedstock used to achieve high production volumes, various unintended consequences may arise (e.g. related to land use changes, soil carbon changes, co-product impacts, etc.). Many of these impacts are not easily quantifiable, such as indirect land use change (Qin, Dunn, Kwon, Mueller, & Wander, 2014); however, efforts have been made to take these into account, such as the studies reviewed by (Plevin, Beckman, Golub, Witcover, & O’Hare, 2015), which suggest potentially significant effects.

Regarding natural gas, as alluded to in Chapter 2, there has been a long-standing debate regarding the extent of methane leakage that occurs, particularly during the early stages of natural gas production. The EPA’s most recent official estimate of this methane leakage is 1.4%

(Cornwall, 2018); however, one recent study found that the “published uncertainty ranges” of such emissions are “too narrow ” and “downwardly biased” (Brandt, Heath, & Cooley, 2016) while yet a newer (somewhat related) study estimated, as noted in Chapter 3, that the actual leakage rate may be closer to 2.3% (Alvarez et al., 2018). In getting to this figure, the study authors noted that other datasets that seek to measure such leakage, including that of the EPA, may be missing the impacts of “abnormal operating conditions” (Alvarez et al., 2018), which, the study authors note, tend to greatly increase the methane leakage rate (Alvarez et al., 2018). Moreover, one scientist has suggested that this estimate may still be low if one is seeking to look at the entire supply chain, implying that unmeasured leaks may also be occurring closer to where the fuel is actually consumed (Cornwall, 2018).

The 2018 GREET model default states that it is based on the EPA’s latest estimates, though because GREET uses a process-based approach, the actual leakage rate comes out closer to approximately 1% (based both on the author’s calculations and (A. Burnham, personal communication, December 5, 2019). GREET has actually addressed this issue in various pieces of documentation that have been released in recent years. In (Burnham, 2016), ANL had suggested that some of the higher leakage estimates were also attributing emissions from “oil and geologic seep sources” to natural gas, resulting in estimates as at least as high as, if not higher than, 3.6% (Burnham, 2016) More recently, (Burnham, 2018) notes that discrepancies that arise between the differing “top-down” and “bottom-up” analysis approaches can be difficult to reconcile (Burnham, 2018). Also noted is the fact that an option was added in the model to account for the (Alvarez et al., 2018) findings.

This study relied on the GREET default. If this is slightly underestimating the leakage rate, while the discrepancy is small, the natural gas GHG emissions reduction versus non-hybridized diesel result in this study was also small. It was 1.7%, a number that resulted, in part, due to the efficiency "hit" to SI natural gas energy consumption, as discussed in the methodology.

On the other later hand, it is possible that some newer after-treatment approach may be developed that would further reduce the Hydrocarbon (HC) and CO emissions that normally result from natural gas combustion, which were also cause for underperformance of the natural gas option as compared to the other fuel alternatives. Or perhaps even before that occurs, as briefly alluded to in Chapter 5, it is possible that the use of renewable natural gas, or "RNG" (which, as the term suggests, is natural gas developed from renewable resources, e.g. biomass) will become viable on a larger scale than is currently the case (STEPS, UCD, 2017).

Looking at emissions for the entire fuel cycle is a valuable approach, and superior to examining only operational emissions; however, the exploration of emissions beyond the fuel, itself, and of the prime mover and energy carriers and the production processes underlying these is an area ripe for research in the rail context.

(Evangelisti, Tagliaferri, Brett, & Lettieri, 2017) recently examined such questions in an automobile context. Exploring an ICE vehicle, a battery electric vehicle, and a fuel cell vehicle, they found that, over 150,000 km of operation, the latter two remained superior to the ICE vehicle, in terms of GHG emissions (Evangelisti et al., 2017). On the other hand, the contribution of the manufacturing stage to the battery electric vehicle's GHG emissions were greater than that of the ICE vehicle, while the fuel cell vehicle's manufacturing impacts were significantly greater, still, than that of the battery electric vehicle (Evangelisti, Tagliaferri, Brett, & Lettieri, 2017). (The overall GHG emissions impacts of the two non-ICE vehicles were almost identical.) The authors of the study broke down the contributions of the different components of each technology to that vehicle's overall manufacturing impact. Perhaps unsurprisingly, the physical components that (Evangelisti et al., 2017) found contribute the most to the increased GHG emissions of their "baseline" fuel cell vehicle's manufacturing phase—the fuel cell stacks and the hydrogen tanks (Evangelisti et al., 2017)—were found in the present study to be an area that, in the high cost scenarios, are responsible for much of the cost difference between diesel and hydrogen via fuel cell.

A study such as the one just mentioned is valuable not only for comparing across fueling technologies, but for assessing where improvements can be made within the production of a given technology. ((Evangelisti et al., 2017) perform some sensitivity analyses on different materials).

Rail locomotives and multiple unit vehicles are typically utilized to a great extent of their potential lifetime. So it seems likely that the dominance of the use phase that (Evangelisti et al., 2017) found in the light duty vehicle context would be only more evident in a rail context; however, actually carrying out such a study would be valuable, as heavy duty componentry (particularly in a rail context) is, of course, significantly larger that the equivalent light duty vehicle componentry.

One difficulty with carrying out such an all-encompassing "life cycle" analysis[193] may be the rapidity with which many of these technologies are evolving. As a result, when such data becomes available, it may already be from a technology that industry is moving away from relying on. However, the cost assessment conducted in this study is not, itself, immune to such contributors of uncertainty.

[193] The term, life cycle analysis, or LCA, typically refers to an established framework for assessing the environmental burdens from a product system. The methodology, as outlined by the International Organization for Standardization (ISO, 2006), is widely accepted.

Along those lines, Chapter 3 discussed the various hydrogen storage technologies that are currently under exploration, including LOHC, metal hydrides, and MOF's. Were one of those to move to a commercial phase, cost, manufacturing impact, and ease of use would all be subject to change, and in ways that are hard to predict without knowing which technology it is and which developments help enable it to leap, if you will, to a commercial stage.

Examining the hybridization of freight trains, in detail, was beyond the scope of this paper, as was examining the potential role for electrification via overhead wires (i.e. OLE) in freight. The author did suggest the challenges that hybridizing freight would encounter, at least given the current status of and likely near-term developments in battery technology; however, this is definitely an area that should be explored further, and that may need to be revisited a few years down the road, as battery technology continues to develop. In fact, should new battery technologies come with significant, further increases in energy density (as discussed in Section 3.7), hybridization may well become more viable for freight rail, while all-battery concepts may begin to become practical for some passenger rail applications. (This would particularly be the case in transit rail and other shorter distance rail applications, where frequent "plug-ins" might be possible.) Future research examining the break-even energy density point or specific energy at which hybridization of the prime mover would become viable in freight rail applications should also be explored.

As for OLE in a freight context, the obstacles that would be faced to transition the North American freight system over to electrification were touched on; in addition, it is a rather complex task to calculate the costs of electrifying such a large network over, presumably, quite a long period; however, in not including this option herein, the author does not mean to imply that a thorough analysis of the costs and other challenges of transitioning the entire freight system to OLE for U.S. freight rail is not worth exploration. If anything, this topic is multifaceted and complex enough that a full study could be devoted to it.

Since the present study's results suggest that, especially towards the end of the period examined (i.e. assuming the findings of the low-cost scenario), powering freight with hydrogen via fuel cells could begin to approach cost competitiveness with the status quo diesel-electric technology, an interesting side-by-side comparison of hydrogen vs. OLE during such a period would be an interesting study in and of itself, particularly if an increasing number of passenger lines were to become electrified (thus reducing the OLE cost to the freight railroads). Similarly, this would be an interesting study to conduct if focusing on those parts of the world where a significant portion of the rail lines are already electrified. Here in the U.S., also, perhaps some combination of hydrogen fuel cell freight trains along less traveled routes with OLE along the busier freight routes is an area that should be assessed for feasibility. (Though any developments on the storage front that would make freight tenders unnecessary for the longer-distance lines that typically run on the more highly trafficked lines would seem to erode one of OLE's likely few remaining advantages along such routes.) Also, one key challenge of such an approach, beyond the high up-front costs of the OLE infrastructure, would be relying on more than one technology for a freight system that, operationally speaking, is run in many ways at a national level (as discussed in chapter 2).

Regarding areas where OLE already exists, while not specifically assessed for the present study, further exploration of battery-OLE hybrids is warranted. Siemens' CityJe-Eco multiple-unit (EMU), noted in Chapter 3, is an example of such a vehicle. The role intended for this vehicle is most likely for branch lines that are not part of the larger OLE system that dominates Western Europe. For this purpose, such a hybrid version is both suitable and relatively simple to implement (i.e. there is no requirement for transitioning to an entirely new fuel supply system). While OLE is not so extensive in the United States, branch lines along parts of the Northeast Corridor, with its extensive OLE coverage, could be good candidates for such hybrid technology.

The hydrogen cost analysis performed here attempted to note the significant uncertainty in future hydrogen costs. One of the factors contributing to this uncertainty is production plant size, which plays a significant role in the cost of hydrogen, with larger plants leading to lower per kg production costs. The present study ran into some difficulty in modeling the specifics of a gaseous station due to both constraints with the model used (as it was intended for road vehicles) as well as the level of detail that would be required for an in-depth analysis. For example, the number of dispensers required for a rail refueling facility will be a key question; and this question, itself, will depend on if there are changes to the speed of the refueling process. Future work to develop a model that is able to account for a transportation refueling station of adequate size for the rail sector would be invaluable.

Moreover, while a liquid delivery option was among those options explored in the present study, some research has suggested, as was alluded to in Chapter 3, that pipeline delivery might be a good candidate option for many of the kinds of stations that are likely to serve as rail refueling facilities, i.e. particularly those stations that are in dense urban areas, and which are close to major hydrogen production facilities (Krishna Reddi et al., 2016; Yang & Ogden, 2007). Thus, if an individual rail agency or rail company seeks to assess the kinds of costs that they might encounter should they choose to switch to hydrogen as a rail fuel, a more in-depth analysis would need to be performed regarding both the ideal production approach (i.e.

centralized versus onsite) and, if onsite, the ideal production method (SMR or electrolysis), depending on the refueling station's expected daily fuel demand and other key characteristics.

A couple of related, key, limitations of this study relate to station size. There were only two station sizes examined in this study, one for passenger and one for freight. While the passenger station sizes were based on realistic demands of these two stations, each passenger rail system will have varying fuel demands. On the other hand, as noted in section 3.6, the freight system sized in this study was significantly smaller than would likely be the case with the refueling facility where intermodal trains such as these are likely to refuel. With freight, too, there is probably significant variation in station capacity requirements. A survey of the kinds of station sizes relevant to both passenger and freight rail would be interesting and might elucidate where the fuel costs in this study may have underestimated the potential cost reductions from large-scale hydrogen production such as could be found at many freight refueling stations.

Moving beyond just the rail system, key questions that remain with regard to station size and potential hydrogen capacities are what would be the likely hydrogen demands of the freight trucking industry and how feasible sharing of facilities between the freight trucking and the rail (either passenger or freight) sectors would be. One place to start might be a survey of all of the rail refueling facilities in the country, as well as a close examination of energy demands from trucking, by region, to see where the geographical alignments may potentially lie. Close to 40 billion gallons of diesel fuel were consumed by the freight trucking industry in 2016 (ATA, 2019), so, even if a small portion of that industry were to shift to hydrogen,[194] the potential for reduced hydrogen costs from increased station scale could be significant.

[194] Testing of hydrogen trucks has already begun in some places. The Port of Los Angeles and Long Beach is one such location (Bulktransporter, 2019; Carpenter, 2019).

In section 5.10, it was noted that locomotive maintenance costs were not assessed in this study due to their relatively minimal impact (Isaac & Fulton, 2016) and the limited data available on fuel cell maintenance costs. Should ongoing fuel cell stack maintenance costs prove to be significantly lower than that of the current diesel-electric technology, this could help ensure hydrogen's competitiveness in the passenger sector. Similarly, while modeled in HDRSAM, a close eye should be kept on station maintenance costs, as hydrogen dispensing in a transportation context expands. While relatively minimal, should such costs end up either higher or lower than expected, particularly at high volumes[195], that could work either for or against hydrogen's competitiveness.)

On the topic of fuel cell stacks, given the significant contribution of the fuel cell stack to high costs (and, as other researchers have noted, its contribution to manufacturing-stage emissions), fuel cell stack lifetime is a key variable that will impact the viability of hydrogen for rail systems, particularly for the freight sector, which tends to utilize individual locomotives for as long as the equipment will allow. Currently, much of the available data on heavy duty fuel cell stack performance (from a public transit bus context) over time comes from industry. There appears to be limited information available on voltage and current activity for such stacks. Assessing voltage degradation patterns, particularly over lifetime of the stack, as is done for light duty fuel cell stacks[196], would be helpful, particularly in terms of validating some of the industry-provided data on lifetime.

[195] Recent data from the light duty vehicle sector indicate maintenance costs in California have dropped steadily, as the total amount of hydrogen dispensed in the state has increased (Mike Peters, 2019). The dispenser is the component that, in terms of number of events and maintenance hours dedicated, has had the most significant impact.
[196] NREL has been conducting research into this area for a number of years. See, e.g. (Kurtz, Sprik, Saur, & Onorato, 2019).

Generally speaking, of course, continued positive developments on fuel cell lifetime and durability would bode particularly well for hydrogen-driven trains; however, a full-on breakthrough for just the stack technology may not be required. One group of researchers is currently exploring whether hybridizing and “downsizing” the fuel cell stack (which the present study simulated) may significantly extend the lifetime of the fuel cell stack, even while somewhat increasing the total fuel consumed (Houchins, James, & Huya Kouadio, 2019). (In the present study, no such lifetime adjustment was assumed.)

One last feature of the fuel cell equipment that could use further clarification is (gaseous) tank certification and related costs. Any such processes and related costs were beyond the scope of this study; however, from a logistical standpoint, this is a feature of a gaseous hydrogen refueling system that should be better understood, not only by researchers, but by any rail company or agency that chooses to use gaseous hydrogen as a fuel.

Figure 58: Refueling a Multiple Unit Vehicle with Hydrogen
Photo courtesy of Dr. Andreas Hoffrichter

In this photo, a hydrogen dispenser is connected to the onboard hydrogen fuel line of one of the multiple unit vehicles that comprise the Coradia iLint, the hydrogen rail vehicle operating in Lower Saxony, Germany. Analysis from NREL has found that, for light duty vehicle stations in California, the dispenser is the component that, in terms of both number of maintenance events and maintenance hours dedicated, has had the most significant impact.

Chapter 4 noted this study's evaluative period of 16 years. While this period, which, again, is close to the median age of locomotives in the current domestic Class I freight fleet (Association of American Railroads, 2019), was selected, in part, both to minimize the inherent uncertainty of examining technology systems and costs further out in time and because equipment may change after many years in service (and thus cost assessment becomes more complicated, involving multiple parties and transactions), this choice did introduce some potential distortion to the cost analysis. For example, OLE lifetime may be quite extensive. One study (NetworkRail, 2009) assumed a 60-year lifetime in a recent analysis. Of course, the danger of making an upfront investment that will take so long to pay off is that it can lead to a form of technology "lock-in," where the technology continues to be used even after superior alternatives may become available.

Finally, a lot of discussion in this section has focused on the role of markets. That said, government can and does play a role in advancing technologies and lowering cost, whether this comes through direct support of technology purchases (e.g. through incentives) or simply through the support of relevant research. Regarding the former approach, particularly if hydrogen becomes prevalent in the passenger rail space, it would be interesting, from a policy standpoint, to see what kinds of steps are viable for the Federal government to take to support that technology in the freight rail sector. In a related question, if a Tier 5 standard does get enacted at the Federal level, how might the cost of switching to hydrogen and fuel cell powertrains in the freight sector compare to other alternative technologies that would enable locomotives to achieve those standards? A policy step like this could significantly change the equation or at least, in the short-term, shift where the risk-reward threshold lies in terms of freight railroads being willing to pilot hydrogen fuel cell technology (which, itself, could set into motion market and learning effects that could reduce costs, particularly for rail applications).

6.3 Concluding Thoughts

It has often been noted that all models of the future are wrong. While this statement is a bit blunt and without nuance, the author encourages the reader to see the findings in this study as offering an opportunity to guide future research and encourage the consideration of ideas and concepts within the rail space perhaps not previously considered.

This study did make it clear that, for some of the alternative fuels and powertrains to become viable, vehicle re-design would be required. Moreover, the characteristics of individual components, e.g. tank design, particularly in the case of hydrogen, is an area that would require specific exploration in order to most efficiently use the available space, ensure the utmost safety, and maximize refueling efficacy. For some (but not all) freight applications, multiple gaseous fuel tenders would be required for trains relying on hydrogen via fuel cells. Or, alternatively, refueling practices might need to be adjusted a bit. It is these sorts of details that the author leaves to industry (and relevant research teams) to examine further.

Acronyms/Abbreviations

AAR	Association of American Railroads
AC	Alternating Current
ANL	Argonne National Laboratory
BTL	Biomass-to-Liquid (a form of FTD)
CARB	California Air Resources Board
CNG	Compressed Natural Gas
DC	Direct Current
DGE	Diesel Gallon Equivalent
DOE	United States Department of Energy
EIA	Energy Information Administration (of the DOE)
EPA	United States Environmental Protection Agency
FRA	Federal Railroad Administration (U.S. Department of Transportation)
FTD	Fischer-Tropsch Diesel
GJ	Gigajoule
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (Model) (from ANL)
HC	Hydrocarbons
H2A	Hydrogen Analysis, a hydrogen production model (from NREL)
HDRSAM	Heavy-Duty Vehicle Refueling Scenario Analysis Model (from ANL)
HSR	High Speed Rail
IEA	International Energy Agency
kN	KiloNewtons
kWh	Kilowatt hour
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LTO	Lithium Titanate-Oxide
MJ	Megajoule
MOF	Metal Organic Framework
NOx	Nitrogen oxides
OLE	Overhead Line Electrification
NREL	National Renewable Energy Laboratory
PM	Particulate Matter (Refers to PM_{10}, i.e. particles smaller than 10 microns)
PEM	Proton-Exchange Membrane/Polymer Electrolyte Membrane
PTW	Pump-to-Wheel
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SMR	Steam Methane Reformation
SOFC	Solid Oxide Fuel Cell
STS	Single Train Simulator
WTP	Well-to-Pump
WTW	Well-to-Wheel

Glossary

Auxiliary Power:

For the purposes of this study, auxiliary power has been used to refer to both what is sometime referred to as "hotel power," and what is more technically considered "auxiliary power." The former refers to lighting and heating/cooling needs aboard the train, while the latter includes such equipment as compressors and heat exchangers (e.g. radiators and other cooling equipment) that are required for proper management of the vehicle and its powertrain.

Balance of Plant (BoP):

Balance of Plant is a term used to describe the non-power-generating components of a prime mover; e.g., in the case of a fuel cell, this could include pumps, sensors, heat exchangers, compressors, etc.

Balance of Systems (BoS):

Additional to the fuel cell's balance of plant components, Balance of Systems here refers to some additional items that may be included alongside fuel cell stacks, particularly in a transportation application. These might include, but are not limited to "winter protection for start-up", power electronics, system control and energy management system, remote monitoring and datalogging, fire protection, and any other protective housing for the system. (Note: Information on many of these items came from an industry employee familiar with fuel cell equipment, and with access to proprietary information.)

Bar:

A measure of pressure of a gas, 1 bar is equivalent to ~14.5 PSI (pound-force per square inch) and to 100,000 Pascals (or 0.1 MPa [megapascal]). This value approximates the average atmospheric pressure at sea level.

Bogie:

A bogie (or "truck" in North American contexts) is a chassis that carries wheelsets for a railcar or locomotive. The exact number of bogies (and axles) varies by equipment, though a common structure is two, double-axled bogies per railcar or locomotive.

Bipolar plate:

A bipolar plate has many functions within a fuel cell. Its key roles include primary cooling, distributing hydrogen evenly across cell, and joining (and conducting electrical current between) the anode of one cell to the cathode of the next one (facilitated by its location between one fuel cell and its neighboring cell in a fuel cell stack).

Brake horsepower-hr (Bhp-hr):

Brake horsepower-hour is an energy value associated with combustion engine output that is typically used to measure emissions for a given energy output resulting from rail motive power vehicle operation. A related term is the corresponding energy input, referred to as "brake-specific fuel consumption."

Catenary:

Part of the Overhead Line Electrification equipment, the catenary is composed of several components, including messenger cables, droppers, contact wires, and others, all supported by masts that are distributed along the railway track. Together, these components ensure that the contact wire, which transmits electrical current from the electric grid to the vehicle (through the pantograph— *see definition below*), remains horizontal, and thus that continuous contact is made between the catenary and the vehicle.

Class I Railroads:

Of the 600 freight railroads that operate in the U.S. (AAR, 2018a), the seven "Class I" railroads are the largest. Each has a revenue of at least $450 million and has operations that cross multiple states. Together they comprise 69% of domestic freight rail mileage and 94% of total freight rail revenue (AAR, 2018a).

DC BUS:

The DC BUS consists of electrical conductors, such as cables and wires, that connect the various powertrain components.

Discount Rate:

Used in cost accounting, the discount rate is used to assess the present value of costs that will be incurred at a future time. Factors assumed when setting an annual discount rate typically include alternative uses for that money, uncertainty-related risks, changes in inflation over time, etc.

Dwell time:

This refers to the amount of time a public transit vehicle (typically a bus or train) stops at a station with its doors open, allowing additional passenger to board the vehicle (and existing passenger to exit).

Dynamic braking:

In dynamic braking, the traction motors act in reverse, as generators, Using the mechanical energy of the train's movement to power electricity. The resistance then created via the motor's magnetic field acts as a brake on the train's forward movement. In trains, the Use of dynamic braking is not new; however, trains have traditionally relied on a form of dynamic braking called "rheostatic braking," in which the energy returned from the wheels is dissipated, in resistors, rather than stored on-board of the vehicle or in wayside infrastructure.

Energy Density:

Energy capacity (e.g. of a fuel or fuel carrier, e.g. battery) for a given volume

Genset:

Not to be confused with a "genset locomotive," a genset is a portmanteau that refers to the prime mover of a diesel-electric locomotive, which includes a diesel engine whose resulting energy is used to drive a generator, producing electricity that is transferred to the wheels via traction motors.

Genset locomotive:

Separate from the term, "genset," used elsewhere in this piece as shorthand for an engine attached to a generator, a "genset locomotive" is a locomotive that contains several smaller engines and generators. The "genset locomotive" was initially developed by Union Pacific (Union Pacific, 2019) (and now operated by railroads across the industry) close to two decades ago. By using a variable number of engines, depending on the power required, genset locomotives are able to minimize GHG and pollutant emissions. (Despite what seems like an ideal solution to reduce railyard emissions, however, some freight railroads have noted concerns with genset locomotive reliability and engine durability, a low weight that has caused difficulties when the track is wet, as well as a need to frequently rely on all engines (Norfolk Southern, 2014)).

Glider:

In the context of this document, a glider refers to the parts of a locomotive that stand apart from the propulsion and propulsion-related accessory equipment.

Hotel Power:

See 'Auxiliary Power,' defined above

Intermodal:

Intermodal refers to typically long distance rail trips that are part of a larger chain of modes for the goods contained within the vehicle. These other modes include shipping and (typically shorter-distance) trucking. Often the goods will be transported in container cars that can easily be transferred between the modes (e.g. at coastal ports, in the case of shipping-to-rail). (Alternatively, trailers may be used, particularly for movements shared between rail and trucking.) A wide array of items may be carried on an intermodal train, including (but not limited to) electronics, automobiles, food products, and apparel.

Life Cycle Analysis:

A life cycle analysis, or LCA, typically refers to an established framework for assessing the environmental burdens from a product system. The methodology, as outlined by the International Organization for Standardization (ISO, 2006), is widely accepted.

Lithium Titanate Battery:

The Lithium-Titanate (LTO) battery is a lithium battery that uses lithium titanate as a cathode material. It is known for superior characteristics in terms of safety (Brady, 2017; Cowie, 2015), performance (including a large temperature range of operation (Brady, 2017)), speed of charging (Cowie, 2015), and lifetime (Brady, 2017; Cowie, 2015). It has also been used in several recent hybrid locomotive pilots.

Mainline:

Mainline freight rail refers to revenue-based service rather than movements undertaken during the switching of railcars and locomotives across trains.

Manifest train:

A manifest train is a freight train composed of various car types and cargoes, typically a blend of shipments for multiple customers. A freight train is often constructed this way so as to maximize frequency and business efficiency of movements.

Metal Hydride:

This refers to a metal-based compound that can take in and release hydrogen, as needed. It relies on strong chemical bonding of hydrogen to a solid, a process known as chemisorption (Murray et al., 2009).

Multiple Unit Vehicle:

A multiple unit vehicle, often referred to as a DMU (diesel), DEMU (diesel-electric), or EMU (electric), is an alternative to locomotive-hauled railcars. Frequently used for passenger services, each unit (which consists of either one or more railcars) contains its own propulsion system and space for passengers on the same vehicle(s), so a full train may be made up of any number of multiple units, depending on the needs of a specific route. Thanks to its high number of powered axles and a higher power to weight ratio than its locomotive equivalent, a multiple unit train can usually accelerate more quickly than a locomotive-powered train running on the same fuel.

Nonattainment area (NAA):

This refers to geographical regions that are considered not in "attainment" of national environmental standards, as set by the U.S. EPA. (See (EPA, 2019) for more information.)

Notch:

Most locomotives actually operate via power/throttle settings that are known as notches. Beyond the idle setting, there are typically an additional 8 notches (numbered 1 through 8). Each setting is associated with a specific maximum power level (for the prime mover), though the equipment's traction control system can slightly vary the final power output of the prime mover (Simpson, 2018).

Overhead Line Electrification:

Overhead Line Electrification (OLE) refers to a system of support structures, wires (i.e. electric catenary wires), and other equipment (e.g. pantograph, which lies atop the roof of an electric locomotive or coach) that collectively transmit electric power from the grid to a railway vehicle in order to provide propulsion power to the vehicle and to supply other power needs.

Pantograph:

An arm-like articulated feature that sits atop the roof of a locomotive (or multiple unit vehicle *see above for definition*). Carbon strips along the top of the pantograph make continuous contact with the contact wire of the catenary, thus transferring electrical current from the electric grid to the vehicle.

Prime mover:

As the name suggests, the prime mover is the primary technology that converts a fuel into motive power. Examples include an engine-generator or a fuel cell system.

Pump-to-wheel (PTW) emissions:

"PTW" energy/emissions include(s) the fuel consumed/emissions generated by a fuel while in a tank (in some cases, known as "boil-off" emissions, e.g. in the case of a fuel with a very low liquid condensing temperature) as well as the energy consumed/emissions generated as a result of the energy contained within the fuel in the tank(s) as it is processed through various energetic means by the prime mover and remainder of the powertrain, driving the vehicle (train, in this case) along the track and powering on-board equipment with various functions (including lighting, heating, etc.).

Regenerative braking:

Regenerative braking is a form of "dynamic braking" (see definition above), in which the electricity produced by the traction motors turned generators is either returned to wayside infrastructure (e.g. OLE) or, alternatively, to an on-board storage device

Selective Catalytic Reduction:

This refers to a technology that injects urea into a diesel engine's exhaust, which, through chemical reactions, lowers levels of NOx (nitrogen oxides). The technology has been applied to many of the Tier 4 passenger locomotives.

Specific Energy:

Energy capacity for a given mass

STS (Single Train Simulator):

A Single Train Simulator refers to a program that models the performance of a train over a given route. The methodology employed to determine impacts of vehicle and powertrain changes. However, it does not account for impacts from other trains on operations, as might occur in a railway network analysis.

Switcher Locomotive:

Switcher locomotives are locomotives which remain in railyards, where they are assigned the tasks of assembling and disassembling freight trains, generally a few cars a time. Because they remain within a limited area and haul only a few cars at a time, switcher engines exhibit a lower total power capacity, Usually under about 2300 horsepower (~1.72 MW) (Norfolk Southern, 2014).

Tier 4:

The EPA sets emissions standards for locomotive. Tier 4 represents the most recent set. Applying to all locomotives built in 2015 or later, it limited CO to 1.5 g/bhp-hr, HC to .14 g/bhp-hr g/bhp·hr, NOx to to 1.3 g/bhp-hr, and PM to 0.03 g/bhp-hr (EPA 2016), with the PM and NOx limits demonstrating the greatest reductions from tier III levels (which applied to production years 2012-2014).

Tractive effort:

Tractive effort, typically expressed in kilonewtons (kN) or pound-force (lbf), refers to the force at the wheel-rail interface used to overcome the resistance to motion, thereby leading to the (typically forward) movement of the vehicle along the track

Traction motor:

Traction motors are electrical machines that convert electricity into mechanical torque. They are typically attached to the axles and bogie of a rail vehicle, with the resulting torque converted to tractive effort (*see definition, above*) at the wheel-rail interface, which drives the train along the track. (A traction motor can be of either the AC or DC type.)

Type III/IV tank:

There are four different types of pressure vessels (numbered I through IV), with Type III and Type IV noted in the present study. Type III tanks have metal as their liner (often aluminum), with a surrounding composite carbon fiber wrap. Type IV is constructed with 100% composite material. The liner is typically a polymer combined with carbon fiber or a "hybrid carbon/glass fiber composite." (Legault, 2012) With less steel or aluminum contained within them (and none in Type IV), types III and IV are typically lighter than types I and II; however, they are also at least twice as costly (Legault, 2012).

Well-to-pump (WTP) energy/emissions:

WTP energy is consumed, and WTP emissions are generated, during the process of resource extraction, transportation of the resource to a processing facility/powerplant, fuel refinement/conversion/power generation, and delivery or transmission of the final fuel product to the point of Use or vehicle fuel tank(s). Emissions produced (or energy consumed) through vehicle operations are not included in WTP energy/emissions.

Well-to-Wheel energy/emissions:

WTW energy or emissions consists of the fuel consumed/emissions generated throughout the entire lifecycle of a fuel, covering production, transformation, distribution and, finally, use in the vehicle to power movement and other operations. This energy/these emissions are usually calculated as two components: well-to-pump (WTP) energy/emissions and pump-to-wheel (PTW) energy/emissions (*see definitions above)*.

Bibliography

A. Hoffrichter, S. Hillmansen, & C. Roberts. (2016). Conceptual propulsion system design for a hydrogen-powered regional train. *IET Electrical Systems in Transportation*, *6*(2), 56–66. https://doi.org/10.1049/iet-est.2014.0049

Aakko-Saksa, P. (2017, October). *Hydrogen Storage and Transport using Liquid Organic Hydrogen Carriers*. Presented at the MARANDA Seminar. Retrieved from https://www.vtt.fi/sites/maranda/Documents/Aakko-Saksa_public.pdf

AAR. (2017). *Railroad Ten-Year Trends: 2006-2015*. Washington, DC: Association of American Railroads.

AAR. (2018a). *Overview of America's Freight Railroads*. Retrieved from Association of American Railroads website: https://www.aar.org/wp-content/uploads/2018/05/AAR-Overview-Americas-Freight-Railroads.pdf

AAR. (2018b). *Preliminary Class I Railroad Statistics*. Washington, DC: Association of American Railroads.

AAR. (2019a). *Analysis of Class I Railroads: 2018*. Washington, DC: Association of American Railroads.

AAR. (2019b). *Freight Railroads Embrace Sustainability & Environmental Preservation*. Retrieved from Association of American Railroads website: https://www.aar.org/wp-content/uploads/2019/02/AAR-Sustainability-Fact-Sheet-2019.pdf

AAR. (2019c). *Railroad Facts: 2018*. Washington, DC: Association of American Railroads.

Aceves, S. M., Espinosa-Loza, F., Ledesma-Orozco, E., Ross, T. O., Weisberg, A. H., Brunner, T. C., & Kircher, O. (2010). High-density automotive hydrogen storage with cryogenic capable pressure vessels. *International Journal of Hydrogen Energy*, *35*(3), 1219–1226. https://doi.org/10.1016/j.ijhydene.2009.11.069

Ail, S. S., & Dasappa, S. (2016). Biomass to liquid transportation fuel via Fischer Tropsch synthesis – Technology review and current scenario. *Renewable and Sustainable Energy Reviews*, *58*, 267–286. https://doi.org/10.1016/j.rser.2015.12.143

Allen, J. (2017, January). *Redesigning Main Lines for Commuter Rail Electrification*. Presented at the Transportation Research Board Annual Meeting, Washington, DC.

Allen, J. G. (2019). Reasons for Commuter Rail Electrification: Early 20th Century and Since 2000. *Transportation Research Record: Journal of the Transportation Research Board*, *2673*.

Allen, J. G. & A. (2003). *Commuter Rail Re-electrification: Is it Still Justified?* Transportation Research Board.

Allen Rider. (2014, October). *Norfolk Southern's Natural Gas Locomotive Journey*. Presented at the HHP Summit 2014: Natural Gas for High Horsepower Applications.

Allis-Chalmers Fuel Cell Tractor. (2015, February 28). Retrieved November 29, 2019, from The Weekend Historian website: https://theweekendhistorian.com/2015/02/28/allis-chalmers-fuel-cell-tractor/

Alstom Communications. (2018). *Coradia iLint: Alstom's zero-emission train*. Retrieved from https://www.partners.alstom.com/Assets/View/92a183b6-b12a-4561-b356-76a587d0de4e

Altairnano. (2011). *24 V 60 AH Battery Module (NANO LITHIUM-TITANATE BATTERY MODULE): Information Sheet*. Altair Nanotechnologies.

Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., … Hamburg, S. P. (2018). Assessment of methane emissions from the U.S. oil and gas supply chain. *Science*, *361*(6398), 186. https://doi.org/10.1126/science.aar7204

Ambrose, H. (2019). *Environmental and economic costs, benefits and uncertainties of vehicle electrification: A life cycle approach* (Dissertation). University of California, Davis, Davis, CA.

Amtrak. (2016). *Amtrak Delivers Strong FY 2016 Financial Results*.

Amtrak. (2017). *Amtrak Sets Ridership, Revenue and Earnings Records*.

Amtrak. (2018). *Amtrak Sets Revenue and Earnings Records, Delivers Best Operating Performance in Company History*. Retrieved from https://media.amtrak.com/2018/11/amtrak-sets-revenue-and-earnings-records-delivers-best-operating-performance-in-company-history/

Amtrak. (2019). *Amtrak: FY 2018 Company Profile*. Retrieved from https://www.amtrak.com/content/dam/projects/dotcom/english/public/documents/corporate/nationalfactsheets/Amtrak-Corporate-Profile-FY2018-0919.pdf

Anderson, J. O., Thundiyil, J. G., & Stolbach, A. (2012). Clearing the air: A review of the effects of particulate matter air pollution on human health. *Journal of Medical Toxicology : Official Journal of the American College of Medical Toxicology*, *8*(2), 166–175. https://doi.org/10.1007/s13181-011-0203-1

Andersson, J., & Grönkvist, S. (2019). Large-scale storage of hydrogen. *International Journal of Hydrogen Energy*, *44*(23), 11901–11919. https://doi.org/10.1016/j.ijhydene.2019.03.063

ANL. (2017). HEAVY-DUTY REFUELING STATION ANALYSIS MODEL (HDRSAM). Retrieved December 4, 2019, from Argonne: Energy Systems website: https://hdsam.es.anl.gov/index.php?content=hdrsam

ANL. (2019). *BatPaC: Battery Manufacturing Cost Estimation (Version 3.1)*. Retrieved from https://www.anl.gov/tcp/batpac-battery-manufacturing-cost-estimation

Aquino, T., Roling, M., Baker, C., & Rowland, L. (2017). *Battery Energy Storage Technology Assessment Todd Aquino, PE Mathew Roling Chris Baker Lukas Rowland*. HDR/Platte River Power Authority.

Aratani, Lori. (2018, November). Amtrak passengers get stuck on stopped Boston-bound train for five hours. *Washington Post*. Retrieved from https://www.washingtonpost.com/nation/2018/11/26/amtrak-passengers-get-stuck-boston-bound-train-five-hours/?noredirect=on&utm_term=.5b67e78ad772

AREMA. (2014). *Manual for Railway Engineering*. Lanham, MD.

Arlington Transit. (2019). Riding ART. Retrieved December 11, 2019, from Arlington Transit website: https://www.arlingtontransit.com/riding-art/

ATA. (2019). *Fuel Consumption*. Retrieved from American Trucking Associations website: https://www.trucking.org/News_and_Information_Reports_Energy.aspx

Ballard. (2016). *Fuel Cell Power Module for Heavy Duty Motive Applications (FCveloCity-HD)*. Ballard Power Systems, Inc.

Ballard. (2017). *Fuel Cell Catalyst Materials: Non-Precious Metal Catalyst*. Retrieved from https://www.ballard.com/docs/default-source/web-pdf's/fuel-cell-catalyst-materials---final.pdf?sfvrsn=2&sfvrsn=2

Ballard. (2018). *Case Study: London Bus Fleet*. Vancouver, Canada: Ballard Power.

Ballard. (2019, May 13). *Ballard Announces Order From Wrightbus For 20 Fuel Cell Modules to Power London Buses*. Retrieved from https://www.ballard.com/about-ballard/newsroom/news-releases/2019/05/13/ballard-announces-order-from-wrightbus-for-20-fuel-cell-modules-to-power-london-buses

Barbee, G. (2015, June 22). *NS 999 Electric / Hybrid: Locomotive Research*. Presented at the Hydrail 2015. Retrieved from https://hydrail.appstate.edu/hydrail2015

Barkan, C. (2014). *Introduction to North American Rail Transportation*. Presented at the Railway Engineering Education Symposium 2014, Overland Park, KS. Retrieved from https://web.engr.uky.edu/~jrose/papers/REES%201-A(1)%20Intro%20to%20Railway%20Engineering%20-%202014.pdf

Barnes, D. L. (2005). *Fuel Cell Powered Front-End Loader Mining Vehicle: DOE Hydrogen Program, FY 2005 Progress Report*. Retrieved from https://www.hydrogen.energy.gov/pdfs/progress05/viii_a_6_barnes.pdf

Barrow, K. (2018a, August). CRRC hybrid locomotive heads for Germany. *International Railway Journal*. Retrieved from https://www.railjournal.com/locomotives/crrc-hybrid-locomotive-for-db-heads-for-germany/

Barrow, K. (2018b, August 7). Russian gas turbine locomotive hauls 9000-tonne train. *International Railway Journal*. Retrieved from https://www.railjournal.com/locomotives/russian-gas-turbine-locomotive-hauls-9000-tonne-train/

Barrow, K. (2018c, December 12). VIA Rail selects Siemens for flagship fleet renewal. *Railway Age*. Retrieved from https://www.railwayage.com/passenger/via-rail-selects-siemens-for-fleet-renewal/

BBC. (2018, November 1). *Electrification of Great Western Mainline to Swindon completed*. Retrieved from https://www.bbc.com/news/uk-england-wiltshire-46046984

Bellaby, M. (2017, May 4). What caused Hindenburg fire? Retired NASA expert digs in. *Florida Today*. Retrieved from https://www.floridatoday.com/story/news/2017/05/04/what-caused-hindenburg-fire-retired-nasa-expert-digs/101153648/

Bellis, M. (2019, July 3). *Hydrogen Fuel Cells Innovation for the 21st Century*. Retrieved from https://www.thoughtco.com/hydrogen-fuel-cells-1991799

Belmonte, F. (2017, October). *UIC Energy Efficiency Workshop*. Presented at the UIC Energy Efficiency Workshop, Rome, Italy.

Black, T., & Clough, R. (2014, October 4). How GE beat Caterpillar with new locomotives. *Fort Worth Star-Telegram*. Retrieved from https://www.star-telegram.com/news/business/article3876002.html

Bloedt, M. (2019, January). *Benefits of diesel/battery hybrid propulsion for passenger locomotives*. Presented at the Transportation Research Board, 2019, Washington, DC.

Blomgren, G. (2017). The Development and Future of Lithium Ion Batteries. *Journal of The Electrochemical Society*, *164*(1), A5019–A5025.

BNSF. (n.d.). *BNSF Railway: BOX CAR 60 FT. 286 GRL Model#BNSF 761000-761099*. Retrieved from https://www.bnsf.com/ship-with-bnsf/ways-of-shipping/equipment/pdf/60ft%20_BoxcarDiagram.pdf

Bocharnikov, Y. V. (2007). Optimal driving strategy for traction energy saving on DC suburban railways. *IET Electric Power Applications*, *1*(5), 675–682.

Bombardier. (2016, December 19). *Bombardier to Build 28 Additional SkyTrain Vehicles for TransLink in Vancouver*. Retrieved from https://www.bombardier.com/en/media/newsList/details.BT-20161219-Bombardier-to-Build-28-Additional-SkyTrain-Vehicules-for-TransLink-in-Vancouver.bombardiercom.html

Bombardier. (2019, January 2). *Bombardier to Supply 17 Additional Locomotives to New Jersey*. Retrieved from https://www.bombardier.com/en/media/newsList/details.bt_20180102_bombardier-to-supply-17-additional-locomotives-to-ne.bombardiercom.html

Bond Buyer. (2018, November 16). All Aboard Florida's Brightline trains to rebrand as Virgin. *The Bond Buyer*. Retrieved from https://www.bondbuyer.com/articles/all-aboard-floridas-brightline-trains-to-rebrand-as-virgin

Brady, M. (2017). *Assessment of Battery Technology for Rail Propulsion Application*. Washington, DC: FRA, US DOT.

Brandt, A. R., Heath, G. A., & Cooley, D. (2016). Methane Leaks from Natural Gas Systems Follow Extreme Distributions. *Environmental Science & Technology*, *50*(22), 12512–12520. https://doi.org/10.1021/acs.est.6b04303

Brecher, A., Sposato, J., & Kennedy, B. (2014). *Best Practices and Strategies for Improving Rail Energy Efficiency* (No. DOT/FRA/ORD-14/02). Retrieved from https://pdfs.semanticscholar.org/3f83/1d0829385a227262b0646e8d7326efca5c65.pdf?_ga=2.183331302.1524392627.1575236124-937976137.1573831734

Brian Ehrhart. (2019, March). *Impact of Hydrogen for Rail Applications*. Presented at the H2@Rail Workshop, Lansing, Michigan. Retrieved from https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-ehrhart.pdf

Briginshaw, D. (2016, August). All Aboard Florida: A New Approach for US Passenger Rail. *International Railway Journal*. Retrieved from https://www.railjournal.com/in_depth/all-aboard-florida-a-new-approach-for-us-passenger-rail

Brown, A., & Fulton, L. (2011). *Technology Roadmap: Biofuels for Transport*. Paris, France: International Energy Agency.

BTS. (2015). *Miles of Freight Railroad Operated by Class of Railroad*. Retrieved from Bureau of Transportation Statistics, US DOT website: https://www.bts.gov/print/node/205321

BTS. (2017). *DOT Releases 30-Year Freight Projections*. Retrieved from Bureau of Transportation Statistics, US DOT website: https://www.bts.gov/newsroom/dot-releases-30-year-freight-projections

Bulktransporter. (2019, May 23). Kenworth T680 with integrated Toyota hydrogen fuel cell technology shines at Port of Los Angeles. *BulkTransporter*. Retrieved from https://www.bulktransporter.com/trucks/kenworth-t680-integrated-toyota-hydrogen-fuel-cell-technology-shines-port-los-angeles

Burnham, A. (2016). *Updated Fugitive Greenhouse Gas Emissions for Natural Gas Pathways in the GREET 1_ 2016 Model*. Argonne, IL: Argonne National Laboratory, US DOE.

Burnham, A. (2018). *Updated Natural Gas Pathways in the GREET 1_ 2018 Model*. Argonne, IL: Argonne National Laboratory, US DOE.

Burnham, A. (2019, December 5). *Question about methane emissions from leakage*.

C2ES. (2013). *OPTIONS AND CONSIDERATIONS FOR A FEDERAL CARBON TAX*. Arlington, VA: Center for Climate and Energy Solutions.

CAFCP. (2018). Unsung Hydrogen Heroes—AC Transit. Retrieved December 11, 2019, from California Fuel Cell Partnership website: https://cafcp.org/blog/unsung-hydrogen-heroes-ac-transit

California Air Resources Board. (2016). *Advanced Clean Transit Battery Cost for Heavy-Duty Electric Vehicles (Discussion Draft) Revised August*.

Caltrain. (2014, January 13). The Dual Mode Locomotive, Elephant of the Rails. Retrieved November 29, 2019, from Caltrain HSR Compatibility Blog website: https://caltrain-hsr.blogspot.com/2014/01/the-dual-mode-locomotive-elephant-of.html

Caltrain. (2019). *PENINSULA CORRIDOR ELECTRIFICATION PROJECT (PCEP), JPB Board Meeting Q2, Quarterly Update #17 October 1 – December 31, 2018*. Retrieved from Samtrans website: http://www.caltrain.com/projectsplans/CaltrainModernization/CalMod_Document_Library.html

Caltrans. (2015). *Peninsula-Coast Subdivisions Schematic*. California Department of Transportation.

Cambridge Systematics. (2012). *Task 8.3: Analysis of Freight Rail Electrification in the SCAG Region* (No. 8114–008). Retrieved from Southern California Association of Governments website: http://www.freightworks.org/DocumentLibrary/CRGMSAIS%20-%20Analysis%20of%20Freight%20Rail%20Electrification%20in%20the%20SCAG%20Region.pdf

Capitol Corridor. (2019a). *Capitol Corridor: 25 Years of Connecting Northern California*. Retrieved from https://www.capitolcorridor.org/25_years/

Capitol Corridor. (2019b). *Capitol Corridor Schedules*. Retrieved from https://www.capitolcorridor.org/schedules/

Capitol Corridor Joint Powers Authority. (2019). *Performance Report: FY 2018*. Retrieved from https://capitolcorridor.org/about_ccjpa/2018_performance/

CARB. (2016). *TECHNOLOGY ASSESSMENT: FREIGHT LOCOMOTIVES*. Retrieved from https://ww3.arb.ca.gov/msprog/tech/techreport/final_rail_tech_assessment_11282016.pdf

Cardella, U., Decker, L., & Klein, H. (2017). Roadmap to economically viable hydrogen liquefaction. *Special Issue on The 21st World Hydrogen Energy Conference (WHEC 2016), 13-16 June 2016, Zaragoza, Spain*, *42*(19), 13329–13338. https://doi.org/10.1016/j.ijhydene.2017.01.068

Caron, D., & Beal, S. (2015, October). *Second Life for DC Locomotives*. Video format presented at the Locomotive Maintenance Officers Association, Minneapolis, MN. Retrieved from https://youtu.be/r30SsoEOeMU

Carpenter, S. (2019, March 18). Hydrogen Holds Long-Haul Trucking Promise But Faces Challenges. *Trucks.Com*. Retrieved from https://www.trucks.com/2019/03/18/hydrogen-long-haul-trucking-promise-challenges/

Carvalhaes, B. (2013). *Use of Natural Gas in Dash9 (3000KW) Locomotives Bernardo Carvalhaes*. Presented at the 10th International Heavy Haul Association Conference, 2013.

Casey, T. (2013, October 26). New Life For the “Green Weenie” Electric Locomotive. *CleanTechnica*. Retrieved from https://cleantechnica.com/2013/10/26/new-life-green-weenie-electric-locomotive/

Cavendish, R. (2001, December). Richard Trevithick’s First Steam Carriage. *History Today*, *51*(12). Retrieved from https://www.historytoday.com/archive/richard-trevithicks-first-steam-carriage

CCJPA. (2017, November 3). Make Way! New Charger Locomotives Coming Through. Retrieved August 30, 2019, from Capitol Corridor: Get on Board! website: https://www.capitolcorridor.org/blogs/get_on_board/make-way-chargers-coming/

CCJPA. (2019). *Schedules, Capitol Corridor*. Retrieved from https://www.capitolcorridor.org/schedules/

CDC. (n.d.). *Public Health Statement: Total Petroleum Hydrocarbons*. Retrieved from https://www.atsdr.cdc.gov/toxprofiles/tp123-c1.pdf

CEC. (2019). *Total System Electric Generation*. Retrieved from California Energy Commission website: https://ww2.energy.ca.gov/almanac/electricity_data/total_system_power.html

CH2M Hill Canada Limited (now Jacobs Engineering Group), Ernst & Young Orenda Corporate Finance Inc., & Canadian Nuclear Laboratories. (2018). *Regional Express Rail Program Hydrail Feasibility Study Report, Revision B* (No. CPG-PGM-RPT-245). Metrolinx.

Chandler, K., & Eudy, L. (2008). *SunLine Transit Agency Hydrogen-Powered Transit Buses: Third Evaluation Report—Appendices* (No. NREL/TP-560-43741-1). Golden, CO: National Renewable Energy Laboratory, US DOE.

Chandler, K., & Eudy, L. (2010). *National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2; Alameda-Contra Costa Transit District (AC Transit)* (No. NREL/TP-560-48106-1). Retrieved from http://www.actransit.org/wp-content/uploads/NREL_rept_JUN2010.pdf

ChinaDaily.com.cn. (2017, October 27). World's first hydrogen tram runs in China. *ChinaDaily.Com.Cn*. Retrieved from http://www.chinadaily.com.cn/china/2017-10/27/content_33769630.htm

Cho, E. (2014). Siemens Awarded $225 Million Contract for Multi-State Passenger Rail Locomotive Procurement. *BusinessWire*.

Clark, R. A. (1973, July). The Milwaukee Electrification: A Proud Era Passes. *The Milwaukee Road Magazine*.

Cleveland, M. (2019, March). *BNSF's Alternative Fuels*. Presented at the H2@Rail Workshop, USDOE & USDOT, East Lansing, Michigan.

CNG Motive. (2019). *CNGmotive Tender Solution*. Retrieved from https://cngmotive.com/

Colbow, K. (2018, March 29). What Are the Latest Developments in Fuel Cell Catalyst Technology? Retrieved December 2, 2019, from https://blog.ballard.com/latest-developments-in-fuel-cell-technology

Comati, B. (2018). *Amtrak Five Year Equipment Asset Line Plan: Base (FY 2019) + Five Year Strategic Plan (FY 2020–2024)*. Retrieved from Amtrak website: https://www.amtrak.com/content/dam/projects/dotcom/english/public/documents/corporate/businessplanning/Amtrak-Equipment-Asset-Line-Plan-FY20-24.pdf

Cook, D. (2019, December 9).

Cooper, D. (2018, May 25). The hydrogen train of the future is a lot like the train of today. *Engadget.Com*. Retrieved from https://www.engadget.com/2018/05/25/hydrogen-train-of-the-future/

Cornwall, W. (2018, June 21). Natural gas could warm the planet as much as coal in the short term. *Science*. Retrieved from https://www.sciencemag.org/news/2018/06/natural-gas-could-warm-planet-much-coal-short-term

Corporan, E., DeWitt, M. J., Belovich, V., Pawlik, R., Lynch, A. C., Gord, J. R., & Meyer, T. R. (2007). Emissions Characteristics of a Turbine Engine and Research Combustor Burning a Fischer−Tropsch Jet Fuel. *Energy & Fuels*, *21*(5), 2615–2626. https://doi.org/10.1021/ef070015j

Cousineau, R. (2006, February). Development of a Hybrid Switcher Locomotive: The Railpower Green Goat. *IEEE Instrumentation & Measurement Magazine*.

Cowie, I. (2015, January 21). All About Batteries, Part 12: Lithium Titanate (LTO). *EE Times*. Retrieved from https://www.eetimes.com/author.asp?section_id=36&doc_id=1325358#

Csele, M. (2019, October 20). The Newcomen Steam Engine. Retrieved from History website: http://www.technology.niagarac.on.ca/people/mcsele/interest/the-newcomen-steam-engine/

Cummins. (2018, September 19). *Cummins Unveils the Future of Diesel with Low NOx and Low CO2 Emissions Technology During IAA Commercial Vehicles Show*. Retrieved from https://www.cummins.com/news/releases/2018/09/19/cummins-unveils-future-diesel-low-nox-and-low-co2-emissions-technology

Curry, C. (2017). *Lithium-ion Battery Costs and Market*. Bloomberg New Energy Finance.

Cushman-Roisin, B., & Tanaka Cremonini, B. (2019). *Useful Numbers for Environmental Studies and Meaningful Comparisons*. Retrieved from http://www.dartmouth.edu/~cushman/books/Numbers.html

Das, M. (2018, October 12). Railways awaits regulatory nod for LNG trial run. *The Hindu Business Line*. Retrieved from https://www.thehindubusinessline.com/economy/logistics/railways-awaits-regulatory-nod-for-lng-trial-run/article25205304.ece

Davis, S., & Boundy, R. (2019). *Transportation Energy Data Book: Edition 37*. Retrieved from Oak Ridge National Laboratory, US DOE website: https://tedb.ornl.gov/data/

Davis, W. J., Jr. (1926). The Tractive Resistance of Electric Locomotives and Cars. *General Electric Review*, *29*(10), 685–707.

Deloitte. (2018). *Supercharged: Challenges and opportunities in global battery storage markets*. Retrieved from Deloitte Center for Energy Solutions website: https://www2.deloitte.com/content/dam/Deloitte/bg/Documents/energy-resources/gx-er-challenges-opportunities-global-battery-storage-markets.pdf

DieselShop. (2006). General Electric ES44AC. Retrieved December 4, 2019, from https://www.thedieselshop.us/Data%20ES44AC.HTML

Dincer, I., Hogerwaard, J., & Zamfirescu, C. (2015). *Clean Rail Transportation Options*. Springer.

Ditmeyer, S. (2014, October). *Natural Gas Locomotives*. Presented at the Railway Management Program, East Lansing, Michigan.

Douglas, H., Weston, P., Kirkwood, D., Hillmansen, S., & Roberts, C. (2016). Method for validating the train motion equations used for passenger rail vehicle simulation,. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *231*(4), 455–469.

DSIRE Insight. (2019). *Renewable & Clean Energy Standards*. Retrieved from NC Clean Energy Technology Center website: https://s3.amazonaws.com/ncsolarcen-prod/wp-content/uploads/2019/07/RPS-CES-June2019.pdf

DSV. (2019). Dry containers. Retrieved September 23, 2019, from DSV Global Transport and Logistics website: https://www.dsv.com/sea-freight/sea-container-description/dry-container

Duve, M. (2019, March). *Norfolk Southern – Locomotive Hydrogen Fuel Perspective*. Presented at the H2@Rail, East Lansing, Michigan. Retrieved from https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-duve.pdf

Duve, M. (2019, June 3). *Wondering if you have any updated information on the NS999*.

e-CFR. (2019). *Electronic Code of Federal Regulations (e-CFR): Duty Cycles and Calculations (1033.530)*. Retrieved from https://ecfr.io/Title-40/pt40.36.1033#se40.36.1033_1530

EERE. (n.d.). *Types of Fuel Cells*. Retrieved from https://www.energy.gov/eere/fuelcells/types-fuel-cells

EERE, US DOE. (2019). Natural Gas Fueling Station Locations. Retrieved December 2, 2019, from https://afdc.energy.gov/fuels/natural_gas_locations.html#/find/nearest?fuel=LNG&country=US

Ehrhart, B. (2019, December 12).

Electro-Motive Diesel. (2008, November). *The Merits of AC vs DC Locomotives*. Retrieved from https://www.slideshare.net/RailwaysandHarbours/merits-of-ac-vs-dc-locomotives-presentation

Elgowainy, A. (2018, July). *Hydrogen Refueling Analysis of Fuel Cell Heavy-Duty Vehicles Fleet Amgad Elgowainy, Krishna Reddi and Mohamed Aly*. Presented at the Argonne, IL. Argonne, IL.

Elgowainy, A., Han, J., Lee, U., Li, J., Dunn, J., & Wang, M. (2016, June). *Life-Cycle Analysis of Water Consumption for Hydrogen Production Amgad Elgowainy (PI), Jeongwoo Han (presenter), Uisung Lee, Jeff Li, Jennifer Dunn, and Michael Wang*. Presented at the 2016 DOE Hydrogen and Fuel Cells Program Annual Merit Review, Washington, DC. Retrieved from https://www.hydrogen.energy.gov/pdfs/review16/sa039_elgowainy_2016_o.pdf

Elgowainy, A., Vyas, A., Biruduganti, M., & Shurland, M. (2018). *Railroad Energy Intensity and Criteria Air Pollutant Emissions* (No. DOT/FRA/ORD-18/34). Argonne, IL: FRA, US DOT.

EPA. (2016a). *Effects of NO2*. Retrieved from https://www.epa.gov/no2-pollution/basic-information-about-no2#Effects

EPA. (2016b). *Locomotives: Exhaust Emissions Standards* (No. EPA-420-B-16-024). Retrieved from Office of Transportation and Air Quality, US Environmental Protection Authority website: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100OA09.pdf

EPA. (2019, October 31). Current Nonattainment Counties for All Criteria Pollutants. Retrieved December 2, 2019, from Nonattainment Areas for Criteria Pollutants (Green Book) website: https://www3.epa.gov/airquality/greenbook/ancl.html

Ernst, S. (2016, March 10). *What You Need to Know About Renewable Diesel*. Retrieved from https://www.government-fleet.com/156621/what-you-need-to-know-about-renewable-diesel

Eudy, L., Chandler, K., & Gikakis, C. (2008). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2008* (No. NREL/TP-560-44133). Retrieved from National Renewable Energy Laboratory, US DOE website: https://www.nrel.gov/docs/fy09osti/44133.pdf

Eudy, Leslie. (2019, May). *Technology Acceleration: Fuel Cell Bus Evaluations*. Presented at the Annual Merit Review and Peer Evaluation Meeting, 2019, US DOE Fuel Cells Hydrogen and Fuel Cells Program, Washington, DC. Retrieved from https://www.hydrogen.energy.gov/pdfs/review19/ta013_eudy_2019_o.pdf

Eudy, Leslie, & Post, M. (2018). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018* (No. NREL/TP-5400-72208). Retrieved from National Renewable Energy Laboratory, US DOE website: https://www.nrel.gov/docs/fy19osti/72208.pdf

Evangelisti, S., Tagliaferri, C., Brett, D. J. L., & Lettieri, P. (2017). Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. *Journal of Cleaner Production*, *142*, 4339–4355. https://doi.org/10.1016/j.jclepro.2016.11.159

FCH-JU. (2018). *Strategies for joint procurement of fuel cell buses: Final Report* (No. EG-01-18-508-EN-N). Retrieved from https://www.fch.europa.eu/sites/default/files/Strategies_%20for_joint_procurement_of_FCbuses_final_report.pdf

FEC. (2019). *Florida East Coast Railway: Network Map*. Retrieved from https://fecrwy.com/network-map/

Franco, A., & Casarosa, C. (2014). Thermodynamic and heat transfer analysis of LNG energy recovery for power production. *Journal of Physics: Conference Series*, *547*, 012012. https://doi.org/10.1088/1742-6596/547/1/012012

Frasinelli, M. (2011, May 11). NJ Transit unveils first dual-mode locomotive in North America. *Star-Ledger*. Retrieved from https://www.nj.com/news/2011/05/nj_transit_to_unveil_dual-mode.html

Frey, H. C., Graver, B. M., & Hu, J. (2016). *Locomotive Biofuel Study – Rail Yard and Over the Road Measurements Using Portable Emissions Measurement System* (No. DOT/FRA/ORD-16/04). Raleigh, NC: North Carolina State University & FRA, US DOT.

FTA. (2001). *Sunline Transit Agency Final Report* (No. CA-26-7022). Retrieved from https://www.energy.gov/sites/prod/files/2014/03/f10/sunline_final_report1.pdf

Fullerton, G., & Dick, C. T. (2015). *Operational Considerations of Transitioning to Emerging Ultra-Low Emission Locomotive Technologies for Heavy-Haul Freight Rail Applications*. Presented at the International Heavy Haul Association 2015 Conference.

Gambini, M., Manno, M., & Vellini, M. (2007, March). *Metal Hydride Storage Systems: State of the Art Analysis and Integration in FC-Based Energy Systems*. Presented at the HYPOTHESIS VII.

GATX. (n.d.-a). *Fuel Consumption*. Retrieved from http://www.gatx.com/wps/wcm/connect/d6109c4a-a86a-4d37-a0b4-a2d61a49f34f/Fuel_Consumption_Chart.pdf?MOD=AJPERES&CVID=kBD-GwT

GATX. (n.d.-b). *Locomotive Specifications*. Retrieved from http://www.gatx.com/wps/wcm/connect/e87c2cf7-52c1-4435-b21a-25654bca6e7e/Locomotive+Specifications.pdf?MOD=AJPERES&CVID=kBD-TGn

GE Transportation. (2016, August). *"A Continuing Legacy of Innovation": Full Locomotive Product Portfolio*. Retrieved from https://issuu.com/getransportation/docs/ge-locomotive-product-catalog-2016/8

Gieras, J., Piech, Z., & Bronislaw, T. (2017). *Linear Synchronous Motors: Transportation and Automation Systems, Second Edition*.

Goodman, E. (2019, July 23). Caltrain Ridership Numbers Drop. *Daily Post*. Retrieved from https://padailypost.com/2019/07/23/caltrain-annual-ridership-numbers-fall/

Gouvernement du Québec. (2019, November 27). *Quebec: Carbon monoxide poisoning*. Retrieved from https://www.quebec.ca/en/health/health-issues/a-z/carbon-monoxide-poisoning/

Grasman, S. (2013). *Hydrogen Energy and Vehicle Systems*. Boca Raton, FL: CRC Press.

GREET. (2018). *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET)* (Argonne National Laboratory (DOE), Ed.). Argonne National Lab.

Gruber, A. (2019, February 22).

GWL Power. (n.d.). *Lithium Titanate (LTO) Cells—Technical Advantages*. Retrieved from https://www.ev-power.eu/LTO-Tech/

Harris, L. (2019, January). *Plans for Hydrail Implementation on NCDOT's Piedmont Passenger Trains*. Presented at the 2019 TRB Annual Meeting, Washington, DC.

Hassanzadeh, H., & Mansouri, S. H. (2005). Efficiency of ideal fuel cell and Carnot cycle from a fundamental perspective. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *219*(4), 245–254. https://doi.org/10.1243/095765005X28571

Hay, W. W. (1982). *Railroad Engineering*. New York, NY: John Wiley & Sons.

Hedrick, J., Fritz, S., & Plunkett, K. (2012). Diesel Particulate Filter Retrofit of a 1500 kW Multi-Engine Genset Locomotive. *ICEF2012*, 577–582. https://doi.org/10.1115/ICEF2012-92130

Hess, K. S., Miller, A. R., Erickson, T. L., & Dippo, J. L. (2010, June). *Demonstration of a Hydrogen Fuel-Cell Locomotive Hess, Kris S Miller, Arnold R Erickson, Timothy L Dippo, James L.* Presented at the 2010 Rail Conference, Vancouver, CA.

Hexagon Composites. (2017, February). *Hydrogen Storage and Transportation Systems:Type 4 Hydrogen Cylinders*.

Hill, R. J. (1994). Electric Railway Traction, Part 1: Electric Traction and DC Traction Motor Drives. *Power Engineering Journal*, *8*(1).

Hillmansen, S., & Roberts, C. (2007). Energy storage devices in hybrid railway vehicles: A kinematic analysis. Https://doi.org/10.1243/09544097JRRT99. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *221*(1), 135–143.

Hillmansen, Stuart, Schmid, F., & Schmid, T. (2011, February). The rise of the permanent-magnet traction motor. *Railway Gazette International*, *167*(2).

History.com. (2009). This Day in History: December 24: Richard Trevithick introduces his "Puffing Devil." In *History.com*. Retrieved from https://www.history.com/this-day-in-history/richard-trevithick-introduces-his-puffing-devil

History.com. (2018, August 21). Oil Industry. Retrieved December 13, 2019, from https://www.history.com/topics/industrial-revolution/oil-industry

Hoffrichter, A. (2013). Feasibility of discontinuous electrification on the Great Western Main Line determined by train simulation. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *227*(3), 296–306.

Hoffrichter, Andreas. (2013). *Hydrogen as an Energy Carrier for Railway Traction*. University of Birmingham, Birmingham, UK.

Hoffrichter, Andreas. (2019, January). *Basics of Railway Vehicle Motion*. Presented at the Lansing, MI. Lansing, MI.

Hoffrichter, Andreas, Hillmansen, S., & Roberts, C. (2015). Conceptual propulsion system design for a hydrogen-powered regional train. *The Institution of Engineering and Technology Electric Systems in Transportation*, (ISSN 2042-9738), 1–11.

Holton, O. T., & Stevenson, J. W. (2013). The Role of Platinum in Proton Exchange Membrane Fuel Cells: Evaluation of platinum's unique properties for use in both the anode and cathode of a proton exchange membrane fuel cell. *Platinum Metals Review*, *57*(4), 259. https://doi.org/10.1595/147106713x671222

Houchins, C., James, B. D., & Huya Kouadio, J. (2019, November). *Hybridization Study*. Presented at the Fuel Cell Seminar, Long Beach, CA.

Howell, D. (2017). *Vehicle Technologies Office (VTO): Electrochemical Energy Storage R&D Overview*. Retrieved from https://www.energy.gov/sites/prod/files/2017/06/f34/es000_howell_2017_o.pdf

Humphrey, D. (2019, March). *North American Locomotive Review*. Presented at the Rail Equipment Finance Conference, La Quinta, California.

Huo, H., Wang, M., Bloyd, C., & Putsche, V. (2008). *Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels* (No. ANL/ESD/08-2). Oak Ridge, TN: Argonne National Laboratory, US DOe.

Hydrogenics. (2018). *HyPM-HD POWER MODULES for light and heavy duty mobility*. Retrieved from http://www.hydrogenics.com/wp-content/uploads/HyPM-HD-Brochure.pdf

HydrogenTools. (2019). *Flame Detection*. Retrieved from Pacific Northwest National Laboratory, US DOE website: Flame Detection

IEA. (2018). *Gas 2018: Analysis and Forecasts to 2023*. Paris, France: International Energy Agency, OECD.

IEA. (2019a). *Electric car deployment in selected countries, 2013-2018*. Retrieved from International Energy Agency, OECD website: https://www.iea.org/data-and-statistics/charts/electric-car-deployment-in-selected-countries-2013-2018

IEA. (2019b). *The Future of Hydrogen: Seizing Today's Opportunities*. Retrieved from International Energy Agency, OECD website: https://www.iea.org/hydrogen2019/

IEA. (2019c). *The Future of Rail*. Paris, France: International Energy Agency, OECD.

IEA & UIC. (2017). *Railway Handbook 2017: Energy Consumption and CO2 Emissions*. Paris, France.

IEEE. (2016, January 28). *Amtrak's Northend Electrification*. Retrieved from https://meetings.vtools.ieee.org/m/128310

Independent. (2013, January 22). *What exactly is Mercaptan?* Retrieved from https://www.independent.co.uk/news/uk/home-news/what-exactly-is-mercaptan-8462250.html

Isaac, R., & Fulton, L. (2016, July). *Propulsion Systems for 21st Century Rail*. Presented at the World Conference on Transport Research - WCTR 2016 Shanghai, Shanghai, China. Retrieved from https://pdfs.semanticscholar.org/52ba/7add103ba4564d379a04d4ca7837bdca7763.pdf?_ga=2.205414864.13045571.1575388391-937976137.1573831734

ISO. (2006). *Environmental Management—Life Cycle Assessment—Principles and Framework*. International Organization for Standardization.

James, B. (2018, July). *Fuel Cell Truck System Cost Analysis*. Presented at the Fuel Cell Truck Powertrain R&D Activities and Target Review Workshop: H2@ Scale End Use Applications.

James, B., Houchins, C., Huya-Kouadio, J., & DeSantis, D. (2016). *Final Report: Hydrogen Storage System Cost Analysis* (No. DE-EE0005253). Cassidy Houchins Jennie M. Huya-Kouadio Daniel A. DeSantis.

James, B., Huya-Kouadio, J., Bach, P., & Knights, S. (2019, November). *Making the Case for Graphite Bipolar Plates*. Presented at the 2019 Fuel Cell Seminar & Energy Exposition, Long Beach, CA.

Jensen, S. (2019, June 10). *RE: CNG refueling rates?*

Johnson Mathey Battery Systems. (2017). *Our Guide to Batteries: 3rd Edition*.

Kantola, K. (2008, September 4). *Allis-Chalmers Farm Tractor Was First Fuel Cell Vehicle*. Retrieved from https://www.hydrogencarsnow.com/index.php/fuel-cells/allis-chalmers-farm-tractor-was-first-fuel-cell-vehicle/

Kargul, J. J. (2012, October). *Efficient Use of Natural Gas Based Fuels in Heavy-Duty Engines*. Presented at the DEER Conference Fuels and High-Performance Lubricants. Retrieved from https://www.energy.gov/sites/prod/files/2014/03/f8/deer12_kargul.pdf

Keefe, R. (2018, January). *Rail Paradigm Shift*. Presented at the 2018 Annual Meeting of the Transportation Research Board, Washington, DC.

Keefe, R. (2019, January 4). *"re: One additional question*.

Kent, S. K., Gunawardana, D., Chicken, T., & Ellis, R. (2016). *Future Railway Powertrain Challenge Fuel Cell Electric Multiple Unit (FCEMU) Project*. Birmingham, England: University of Birmingham Hitachi Fuel Cell Systems.

Kidder, A. E. (1982). *Railroad Electrification Activity; A Summary Report: 1980-1981* (No. OTFR53-81-C–00226). Washington, DC: Federal Railroad Administration, US DOT.

Kingsford, P. (2019). James Watt: SCOTTISH INVENTOR. In *Encyclopedia Brittanica*. Retrieved from https://www.britannica.com/biography/James-Watt

Kirkpatrick, S., Wagner, C., & Northrup, C. (2019). *Crashworthiness and Puncture Protection Analyses of LNG Tenders: Final Report*. Retrieved from Association of American Railroads website: https://aar.com/standards/pdfs/LNG_report_cummulative_revised_07Mar2019.pdf

Kollatz Jr., H. (2004, May 4). Richmond's Moving First. *Richmondmag*. Retrieved from https://richmondmagazine.com/news/richmond-history/richmond-trolley-system/

Kolodziejczzyk, B., & Ong, W.-L. (2019). *Hydrogen power is safe and here to stay*. Retrieved from World Economic Forum website: https://www.weforum.org/agenda/2019/04/why-don-t-the-public-see-hydrogen-as-a-safe-energy-source/

Kongkanand, A., & Mathias, M. F. (2016). The Priority and Challenge of High-Power Performance of Low-Platinum Proton-Exchange Membrane Fuel Cells. *The Journal of Physical Chemistry Letters*, *7*(7), 1127–1137. https://doi.org/10.1021/acs.jpclett.6b00216

Kunze, K., & Kircher, O. (2012, September). *Cryo-Compressed Hydrogen Storage*. Presented at the Cryogenic Cluster Day, Oxford, England. Retrieved from https://stfc.ukri.org/stfc/cache/file/F45B669C-73BF-495B-B843DCDF50E8B5A5.pdf

Kurtz, J., Sprik, S., Saur, G., & Onorato, S. (2019). *Fuel Cell Electric Vehicle Durability and Fuel Cell Performance* (No. NREL/TP-5400-73011). Retrieved from National Renewable Energy Laboratory, US DOE website: https://www.nrel.gov/docs/fy19osti/73011.pdf

Kutrosky, D. (2019, January). *Sustainable Practcices at the Capitol Corridor: Strategies to Reduce Carbon-Based Fuel Emissions*. Presented at the 2013 TRB Annual Meeting, Washington, DC.

Kyodo News. (2018, September 27). *Toyota teams up with JR East to develop hydrogen-powered trains*. Retrieved from https://this.kiji.is/418056389112202337

Larsen, K. (2018, November 16). Virgin Group invests in Brightline, will rebrand as "Virgin Trains USA." *TheRealDeal*. Retrieved from https://therealdeal.com/miami/2018/11/16/virgin-group-invests-in-brightline-will-rebrand-as-virgin-trains-usa/

Legault, M. (2012, July 2). Pressure Vessel Tank Types. Retrieved December 10, 2019, from Composites World website: https://www.compositesworld.com/articles/pressure-vessel-tank-types

Lemelson. (2019). Rudolf Diesel. Retrieved November 29, 2019, from https://lemelson.mit.edu/resources/rudolf-diesel

Levin, J. (2019, May 2). *Refueling times*.

Liu, G., Larson, E. D., Williams, R. H., Kreutz, T. G., & Guo, X. (2011). Making Fischer−Tropsch Fuels and Electricity from Coal and Biomass: Performance and Cost Analysis. *Energy & Fuels*, *25*(1), 415–437. https://doi.org/10.1021/ef101184e

Liu, S., Jiang, J., Wang, Z., W., C., & Zhao, T. (2014). Research on Applicability of Lithium Titanate Battery for Low-Floor Vehicles. *Jia L., Liu Z., Qin Y., Zhao M., Diao L. (Eds) Proceedings of the 2013 International Conference on Electrical and Information Technologies for Rail Transportation (EITRT2013)*, *II*. Berlin: Springer.

LTK Engineering Services. (2012). *Caltrain/California HSR Blended Operations Analysis*. Retrieved from http://www.caltrain.com/Assets/Caltrain+Modernization+Program/Documents/Final-Caltrain-California+HSR+Blended+Operations+Analysis.pdf

Lu, S. (2013). Single-train trajectory optimization. *IEEE Transactions on Intelligent Transportation Systems*, *14*(2), 743–750.

Lu, Shaofeng, Meegahawatte, D. H., Guo, S., Hillmansen, S., Roberts, C., & Goodman, C. (2008). *Analysis of energy storage devices in hybrid railway vehicles* (Vol. 2008). https://doi.org/10.1049/ic:20080014

Lustig, D. (2010, May). AC vs. DC: What's the Difference? *Trains*, *70*(5), 18–19.

Lynn Harris. (2019, June 11). *RE: Update on natural gas locomotives in NC?*

Macrotrends.net. (2019). *Crude Oil Prices—70 Year Historical Chart*. Retrieved from https://www.macrotrends.net/1369/crude-oil-price-history-chart

Martin, J. (2016). *Fueling a Clean Transportation Future: Smart Fuel Choices for a Warming World*. Washington, DC.

Martinez, A. (2011). *Simulation of Dynamic Operation and Coke-Based Degradation for SOFC-GT-Powered Medium and Long Haul Locomotives DISSERTATION*. University of California, Irvine, Irvine, CA.

Mcilkenny, S. (2018, October). *Rail disruption: Delays on Edinburgh—Glasgow line due to overhead wires damage*. Retrieved from https://www.edinburghnews.scotsman.com/news/rail-disruption-delays-on-edinburgh-glasgow-line-due-to-overhead-wires-damage-1-4818392

Meegahawatte, D. (2010). Analysis of a fuel cell hybrid commuter railway vehicle. *Journal of Power Sources*, *195*(23), 7829–7837.

Melosi, M. (2010). *The Automobile and the Environment in American History*. Retrieved from http://www.autolife.umd.umich.edu/Environment/E_Overview/E_Overview3.htm

Mench, M. (2008). *Fuel Cell Engines*. Hoboken, New Jersey: John Wiley & Sons.

Mike Peters. (2019, November). *Technology Validation of Hydrogen Refueling Infrastructure*. Presented at the Fuel Cell Seminar, Long Beach, CA.

Miller, A.R., Hess, K. S., Barnes, D. L., & Erickson, T. L. (2007). System design of a large fuel cell hybrid locomotive A.R. Miller ∗, K.S. Hess, D.L. Barnes, T.L. Erickson. *Journal of Power Sources*, *173*, 935–942. https://doi.org/10.1016/j.jpowsour.2007.08.045

Miller, Arnold R. (2011). *Hydrogen Fuel-Cell Locomotive: Switching and Power-to-Grid Demonstrations*. Presented at the 9th World Congress on Railway Research.

Miller, Arnold R. (2018, January 17). *Vehicle Projects, Inc.* Retrieved from http://www.vehicleprojects.com/

Miller, M. (2019, February 22). *Re: LTO Cycle Life*.

Mitchell IV, A. D. (2019, March 26). Final effort to save Black Mesa & Lake Powell fails. *Trains*. Retrieved from http://trn.trains.com/news/news-wire/2019/03/26-final-effort-to-save-black-mesa--lake-powell-fails

Muraleedharakurup, G. (2011). *The Impact of Control Strategy of a Lightweight Plug-in Hybrid Electric Vehicle on CO 2 Emissions*.

Murray, L. J., Dinca, M., & Long, J. R. (2009). Hydrogen storage in metal-organic frameworks. *Chemical Society Reviews*, *38*(5), 1294–1314. https://doi.org/10.1039/B802256A

Nelson, D., & O’Neil, K. (2018). *The US Commuter Rail Renaissance: A 30 Year Progress Report*. Boston, MA.

Nelson Nygaard. (2014). *CAPITOL CORRIDOR 2014 Vision Plan Update Final Report*. Retrieved from https://www.capitolcorridor.org/downloads/CCJPAVisionPlanFinal.pdf

Nemet, G. (2012). Chapter 24: Solar Photovoltaics: Multiple Drivers of Technological Improvement. Historical Case Studies of Energy Technology Innovation. In *The Global Energy Assessment.* Cambridge, UK: Cambridge University Press.

NetworkRail. (2009). *Electrification*. London, England.

New Scientist. (2017, September 20). Beating the battery barrier. *New Scientist*. Retrieved from December 2, 2019

Nichols, M. D. (2017, April 13). *Proposal for Tier 5, to US EPA*. Retrieved from https://ww3.arb.ca.gov/railyard/docs/final_locomotive_petition_and_cover_letter_4_13_17.pdf

Niermann, M., Drünert, S., Kaltschmitt, M., & Bonhoff, K. (2019). Liquid organic hydrogen carriers (LOHCs) – techno-economic analysis of LOHCs in a defined process chain. *Energy & Environmental Science*, *12*(1), 290–307. https://doi.org/10.1039/C8EE02700E

Norfolk Southern. (2014, May). *Norfolk Southern Locomotive Fleet Overview*. Retrieved from https://www.epa.gov/sites/production/files/2014-08/documents/smith.pdf

NREL. (2018a). H2A: Hydrogen Analysis Production Case Studies. Retrieved December 4, 2019, from NREL: Hydrogen and Fuel Cells website: https://www.nrel.gov/hydrogen/h2a-production-case-studies.html

NREL. (2018b). H2A: Hydrogen Analysis Production Models. Retrieved December 4, 2019, from NREL: Hydrogen and Fuel Cells website: https://www.nrel.gov/hydrogen/h2a-production-models.html

NREL. (2019). *U.S. Solar Radiation Resource Maps: Atlas of the Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*. Retrieved from https://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/Table.html

Ogden, J., Jaffe, A. M., Scheitrum, D., McDonald, Z., & Miller, M. (2018). Natural gas as a bridge to hydrogen transportation fuel: Insights from the literature. *Energy Policy*, *115*, 317–329. https://doi.org/10.1016/j.enpol.2017.12.049

Ohlig, K., & Decker, L. (2015). *The latest developments and outlook for hydrogen liquefaction technology*. *1573*(1311).

OMB. (1992). *CIRCULAR A-94 GUIDELINES AND DISCOUNT RATES FOR BENEFIT-COST ANALYSIS OF FEDERAL PROGRAMS*. Office of Management and Budget (OMB).

Organization of Frontier Science and Innovation, Kanazawa University. (2014, May 9). Burning issue of hydrocarbons, impacts on human health. *ScienceDaily*. Retrieved from https://www.sciencedaily.com/releases/2014/05/140509131557.htm

ORNL, & USDOE. *Transportation Energy Data Book, 37th Edition*. , (2019).

OTAQ, EPA. (2019). *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions, 1990 –2017* (No. EPA-420-F-19-047). Retrieved from https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100WUHR.pdf

Otsuka, A. (2019, February 27).

Padre Electronics Co., Limited. (2019). *Products: Super Batteries*. Retrieved from https://www.pdbattery.com/20000-cycles-lto-battery.html

Palermo, E. (2014, March 19). Who Invented the Steam Engine? *Live Science*. Retrieved from https://www.livescience.com/44186-who-invented-the-steam-engine.html

Pasta, C. (2019, December 4).

PCJPB. (2014). *Peninsula Corridor Electrification: Frequently Asked Questions, Spring 2014*. Retrieved from http://www.caltrain.com/Assets/Caltrain+Modernization+Program/Documents/PCEP+FAQ.pdf

PCJPB. (2018, July). *2018 Annual Passenger Counts*. Presented at the Citizens Advisory Committee. Retrieved from http://www.caltrain.com/Assets/__Agendas+and+Minutes/JPB/CAC/Presentations/2018/7.18.18+JPB+CAC+2018+Annual+Passenger+Counts.pdf

Peters, D. (2019, August 4). *Quick question about ES44AC*.

Petitpas, G., & Moreno-Blanco, J. (2018). *1,000+ cycles of a 350 bar prototype cryo-compressed pressure vessel* (No. LLNL-TR-758596). Retrieved from https://www.osti.gov/servlets/purl/1476216

Pillot, C. (2017, October). *The Rechargeable Battery Market and Main Trends: 2016-2025*. Presented at the The International Energy and Power Supply Conference and Exhibition, Nice, France. Retrieved from http://www.avicenne.com/pdf/The%20Rechargeable%20Battery%20Market%20and%20Main%20Trends%202016-2025%20C.%20Pillot%20Presentation%20at%20BATTERIES%202017%20Nice%20France%20October%202017.pdf

Pillot, C. (2018, July). *Current Status and Future Trends of the Global Li-ion Battery Market*. Presented at the London, England. Retrieved from https://www.charles-hatchett.com/public/images/documents/2018/dr_christophe_pillot_current_status_and_future_trends_of_the_global_li-ion_battery_market.pdf

Plevin, R. J., Beckman, J., Golub, A. A., Witcover, J., & O'Hare, M. (2015). Carbon Accounting and Economic Model Uncertainty of Emissions from Biofuels-Induced Land Use Change. *Environmental Science & Technology*, *49*(5), 2656–2664. https://doi.org/10.1021/es505481d

Popov, Y. (2016, September 16). *Electrified segments of mainline railroads with passenger service in the United States and Canada (excluding urban transit)*. Retrieved from https://www.mrl.ucsb.edu/~yopopov/transit/electrification.html

Porterbrook. (2019, June 20). *Mainline Testing of UK's First Hydrogen Train Gets Green Light*. Retrieved from https://www.porterbrook.co.uk/news/mainline-testing-of-uks-first-hydrogen-train-gets-green-light

Poxon, J. (2010). *Determining a suitable all electric range for a light weight plug-in hybrid electric vehicle* (IEEE, Ed.).

Prabhukhot, P. R., Wagh, M. M., & Gangal, A. C. (2016). A Review on Solid State Hydrogen Storage Material. *Advances in Energy and Power, 4.2,* 11–22.

Propel Fuels. (2018). *Diesel HPR: Fuel Specification*. Retrieved from http://web-assets.propelfuels.com.s3.amazonaws.com/pfc15/DieselHPR_FuelSpecification_R95.pdf

Qin, Z., Dunn, J. B., Kwon, H., Mueller, S., & Wander, M. M. (2014). Soil carbon sequestration and land use change associated with biofuel production: Empirical evidence. *GCB Bioenergy*, n/a-n/a. https://doi.org/10.1111/gcbb.12237

Railway Gazette. (2018a, February 12). Hydrogen train to be tested in the UK by 2020. *Railway Gazette*. Retrieved from https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/hydrogen-train-to-be-tested-in-the-uk-by-2020.html

Railway Gazette. (2018b, September). Turkish Hybrid Shunter on Show. *Railway Gazette*. Retrieved from https://www.railwaygazette.com/news/single-view/view/turkish-hybrid-shunter-on-show.html

Railway Gazette. (2018c, October 19). *BNSF and GE to test battery freight loco*. Retrieved from https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/bnsf-and-ge-to-test-battery-freight-loco.html

Railway Technology. (2012, September 27). Canadian National Railway trials LNG-fueled locomotives in northern Alberta. *Railway Technology*. Retrieved from https://www.railway-technology.com/uncategorised/newscanadian-national-railway-trials-lng-fueled-locomotives-northern-alberta/

Railway Technology. (2018, November). Stadler delivers first bi-mode train to Greater Anglia in the UK. *Railway Technology*. Retrieved from https://www.railway-technology.com/news/stadler-delivers-first-bi-mode-train-greater-anglia-uk/

Railway Technology. (2019, November 15). Stadler to deliver hydrogen-powered train to SBCTA. *Railway Technology*. Retrieved from https://www.railway-technology.com/news/stadler-deliver-hydrogen-powered-train-sbcta/

Rajan, B. V. (2014). *Plug in hybrid electric vehicle energy management system for real world driving*. University of Warwick, Coventry, UK.

Reboul, C., Boissière, J., André, L., Meyer, G., Bideaux, P., Fouret, G., … Richard, S. (2017). Carbon monoxide pollution aggravates ischemic heart failure through oxidative stress pathway. *Scientific Reports*, *7*(1), 39715. https://doi.org/10.1038/srep39715

Reddi, K., Mintz, M., Elgowainy, A., & Sutherland, E. (2016). 13—Building a hydrogen infrastructure in the United States. In M. Ball, A. Basile, & T. N. Veziroğlu (Eds.), *Compendium of Hydrogen Energy* (pp. 293–319). https://doi.org/10.1016/B978-1-78242-364-5.00013-0

Reddi, Krishna, Elgowainy, A., Rustagi, N., & Gupta, E. (2017). Impact of hydrogen refueling configurations and market parameters on the refueling cost of hydrogen. *International Journal of Hydrogen Energy*, *42*(34), 21855–21865. https://doi.org/10.1016/j.ijhydene.2017.05.122

Reddi, Krishna, Mintz, M., Elgowainy, A., & Sutherland, E. (2016). Chapter 35: Challenges and Opportunities of Hydrogen Delivery via Pipeline, Tube-Trailer, LIQUID Tanker and Methanation-Natural Gas Grid. In *Hydrogen Science and Engineering: Materials, Processes, Systems and Technology*. Wiley-VCH Verlag GmbH & Co. KGaA.

Reidinger, Erwin. (2018, September). ÖBB and Siemens present battery-electric multiple unit. *International Railway Journal*. Retrieved from https://www.railjournal.com/rolling-stock/obb-and-siemens-present-battery-electric-multiple-unit/

Renewable Energy Group. (2018). *Reg Ultra Clean Diesel Fact Sheet*. Retrieved from https://www.regi.com/docs/default-source/products/reg-18043_ultra_clean_diesel_fact_sheet_updated_2.pdf?sfvrsn=bcba8d1a_0

Reuters. (2018, August 30). *Diesel guzzler Indian Railways turns to natural gas to cut cost*. Retrieved from https://in.reuters.com/article/india-railways/diesel-guzzler-indian-railways-turns-to-natural-gas-to-cut-cost-idINKCN1LF1PY

Rimer, J. (2014, October). *Natural Gas –An Alternative Fuel Source*. Presented at the HHP Summit 2014: Natural Gas for High Horsepower Applications.

Rochard, B. P., & Schmid, F. (2000). A review of methods to measure and calculate train resistances. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *214*(4), 185–199.

Rohée, J. (2018, September). World premiere: Alstom’s hydrogen trains enter passenger service in Lower Saxony. *Alstom.Com*. Retrieved from https://www.alstom.com/press-releases-news/2018/9/world-premiere-alstoms-hydrogen-trains-enter-passenger-service-lower

Rohée, J. (2019, January 7). Alstom and Eversholt Rail unveil a new hydrogen train design for the UK. *Alstom.Com*. Retrieved from https://www.alstom.com/press-releases-news/2019/1/alstom-and-eversholt-rail-unveil-new-hydrogen-train-design-uk

Roy, H. K. (2014). A generalized powertrain design optimization methodology to reduce fuel economy variability in hybrid electric vehicles. *IEEE Transactions on Vehicular Technology*, *63*(3), 1055–1070.

Roy, H. K. (2016). *Effect of powertrain design optimisation methodologies on battery system efficiency of a hybrid electric vehicle*.

RSSB. (2005). *Feasibility Study Into The Use Of Hydrogen Fuel: Final* (No. T531). London, England: Rail Safety and Standards Board (UK).

RSSB. (2007). *Engineering: Study on Further Electrification of Britain’s Railway Network, Final Report*. London, England: Rail Safety and Standards Board (UK).

Rudick, R. (2019, February). Amtrak to S.F. via a New Transbay Tube? Retrieved from Streetsblog SF website: https://sf.streetsblog.org/2019/02/06/amtrak-to-s-f-via-a-new-transbay-tube/

Ruf, Y., Zorn, T., Akcayoz de Neve, P., Andrae, P., Erofeeva, S., & Garrison, F. (2019). *STUDY ON THE USE OF FUEL CELLS & HYDROGEN IN THE RAILWAY ENVIRONMENT REPORT 2: Analysis of boundary conditions for potential hydrogen rail applications of selected case studies in Europe*. Shift2Rail, European Union.

Ruf, Y., Zorn, T., Akcayoz de Neve, P., Andrae, P., Erofeeva, S., Garrison, F., & Schwilling, A. (2019). *STUDY ON THE USE OF FUEL CELLS AND HYDROGEN IN THE RAILWAY ENVIRONMENT*. Retrieved from Shift2Rail, European Union website: https://shift2rail.org/wp-content/uploads/2019/05/Study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment_final.pdf

San Mateo County Transit District. (2018). *Caltrain 2018 Annual Passenger Count Key Findings*. Retrieved from http://www.caltrain.com/Assets/_Marketing/pdf/2018+Annual+Passenger+Counts.pdf

San Mateo County Transit District. (2019). *About Caltrain*. Retrieved from http://www.caltrain.com/about.html

Satyapal, S. (2019, April). *Hydrogen and Fuel Cell Program Overview*. Presented at the 2019 Annual Merit Review, US DOE Fuel Cell Technologies Office, Arlington, VA. Retrieved from https://www.hydrogen.energy.gov/pdfs/review19/plenary_overview_satyapal_2019.pdf

Schultz, J. (1992). Diesel/Liquid Natural Gas Locomotives: A Dual-Fuel Solution. *Diesel Era Magazine*, *3*(6), 14–17.

Schwartz, J. (2011). *Advanced Hydrogen Liquefaction Process: DOE Annual Merit Review Meeting*. Tonawanda, NY.

Sengodan, S., Lan, R., Humphreys, J., Du, D., Xu, W., Wang, H., & Tao, S. (2018). Advances in reforming and partial oxidation of hydrocarbons for hydrogen production and fuel cell applications. *Renewable and Sustainable Energy Reviews*, *82*, 761–780. https://doi.org/10.1016/j.rser.2017.09.071

Shea, J., & Broome, S. (2016). *Comments of GE Transportation on California Air Resources Board's Draft Technology Assessment for Freight Locomotives*. Retrieved from https://www.arb.ca.gov/lists/com-attach/71-techfuel-report-ws-BmFUN1EPVzRWZlVk.pdf

Sheffield, J. W., Martin, K. B., & Folkson, R. (2014). 5—Electricity and hydrogen as energy vectors for transportation vehicles. In R. Folkson (Ed.), *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance* (pp. 117–137). https://doi.org/10.1533/9780857097422.1.117

Shell. (2019). Military Jet Fuel. Retrieved December 2, 2019, from Aviation Fuel website: https://www.shell.com/business-customers/aviation/aviation-fuel/military-jet-fuel-grades.html

Shepherd, D. (2018, August).

Shepherd, D. (2019, January). *Re: Dimensions of Cap Corridor coaches?*

Shepherd, D. (2019, May 21). *Re: Status of renewable diesel testing?*

Shepherd, D. (2019, October 11). *Question about number of locomotives in the system*.

Shiraki, N., Satou, H., & Arai, S. (2010, June). *A Hybrid System for Diesel Railcar Series Ki-Ha E200*. 2853–2858. Sapporo, Japan.

Shurland, M., Smith, W., Fritz, S., & Frey, H. C. (2014). *Locomotive Biofuel Study: Preliminary Study on the Use and the Effects of Biodiesel in Locomotives* (No. DOT/FRA/ORD-14/12). Washington, DC: Federal Railroad Administration, US DOT.

Siemens. (2016). *Charger Diesel-Electric Locomotive*. Mobility Division, Siemens Industry, Inc.

Siemens. (2019). A detour to success: The world’s first electric streetcar. Retrieved November 27, 2019, from https://new.siemens.com/global/en/company/about/history/news/first-electric-streetcar.html

Siemens. (n.d.). *A detour to success: The world’s first electric streetcar*. Retrieved from https://new.siemens.com/global/en/company/about/history/news/first-electric-streetcar.html

Simmons, T., Betts, D., Roan, V., & Erickson, P. (2002). A Preliminary Assessment of the Possible Acceptance of Fuel Cell Bus Technology by Current Fleet Vehicle Operators. *International Truck & Bus Meeting & Exhibition*. https://doi.org/10.4271/2002-01-3057

Simpson, W. (2018). *Diesel-Electric Locomotives: How They Work, Use Energy, and Can Become More Efficient and Environmentally Sustainable*. Omaha, NE: Simmons-Boardman Books, Inc.

SINTEF. (2016). Alternative Railway Electrification in Norway.

Slovick, M. (2019, June 21). Imec Doubles the Energy Density of its Solid-State Batteries. *ElectronicDesign*. Retrieved from https://www.electronicdesign.com/markets/automotive/article/21808176/imec-doubles-the-energy-density-of-its-solidstate-batteries

Smil, V. (2017, January 23). *The Diesel Engine at 120*. Retrieved from https://spectrum.ieee.org/transportation/advanced-cars/the-diesel-engine-at-120

Smith, B. (2017, May 30).

Smith, K. (2013). LNG: Fuel of the Future? *International Railway Journal*. Retrieved from https://www.railjournal.com/in_depth/lng-fuel-of-the-future

Smith, K. (2018, January 15). Hydrogen: Fuel of the future? *International Railway Journal*. Retrieved from https://www.railjournal.com/in_depth/hydrogen-fuel-of-the-future

Smith, W., & Shurland, M. (2013). *Biodiesel Intercity Passenger Rail Revenue Service Test*. Washington, DC: Federal Railroad Administration, US DOT.

Southwest Railfan. (n.d.). Black Mesa & Lake Powell Rail Line.

Statista. (2019a, March 4). Silver—Statistics & Facts. Retrieved December 2, 2019, from Statista website: https://www.statista.com/topics/1335/silver/

Statista. (2019b, September 24). Major countries in global mine production of platinum from 2014 to 2018. Retrieved December 2, 2019, from Statista website: https://www.statista.com/statistics/273645/global-mine-production-of-platinum/

Steinbach, A. (2018, June). *Highly Active, Durable, and Ultra-low PGM NSTF Thin Film ORR Catalysts and Supports*. Presented at the U.S. DOE 2018 Annual Merit Review and Peer Evaluation Meeting Washington, DC, Washington, DC. Retrieved from https://www.hydrogen.energy.gov/pdfs/review18/fc143_steinbach_2018_o.pdf

STEPS, UCD. (2017). *Policy Brief – Renewable Natural Gas Provides Viable Commercial Pathway for Sustainable Freight*. Retrieved from UC Davis Institute of Transportation Studies website: https://steps.ucdavis.edu/wp-content/uploads/2017/10/RNG-policy-brief-FINAL-WITH-ABSTRACT-Sep2017.pdf

Stewart, I., Olson, L., & Cook, D. (2015, March). *Development of a Crashworthy High Capacity Under Frame CNG Storage Solution for Locomotives*. Presented at the ASME Joint Rail Conference.

Sussex Steam Co. (2011). *Richard Trevithick's Puffing Devil*. Retrieved from http://www.sussexsteam.co.uk/PuffingDevil.html

Tang, H., Chen, W., Wang, J., Dugger, T., Cruz, L., & Kisailus, D. (2018). Tang, H. Chen, W. Wang, J. Dugger, T. Cruz, L. Kisailus, D. Electrocatalytic N-Doped Graphitic Nanofiber—Metal/Metal Oxide Nanoparticle

Composites. *Small (Weinheim an Der Bergstrasse, Germany)*, *14*(11), e1703459. https://doi.org/10.1002/smll.201703459

Taube, K., Lutz, M., Bürger, I., & Jepsen, J. (2019, June). *Low Pressure, High Capacity Hydrogen Storage in a Combined Metal Hydride-Heat Storage System*. Presented at the International Hydrail Conference, 2019, Hamburg, Germany. Retrieved from https://hydrail.appstate.edu/sites/hydrail.appstate.edu/files/14_Hydrail-2019_HZG_Adiabatic-Tank_Presentation_short_v1.pdf

Telci, Y. (2018, November 7). *LinkedIn message*.

Thiruvengadam, A., Pradhan, S., Thiruvengadam, P., Besch, M., Carder, D., & Delgado, O. (2014). *Heavy-Duty Vehicle Diesel Engine Efficiency Evaluation and Energy Audit: Final Report*. Retrieved from West Virginia University website: https://theicct.org/sites/default/files/publications/HDV_engine-efficiency-eval_WVU-rpt_oct2014.pdf

Tita, B., & Hagerty, J. (2014). Caterpillar Falls Behind GE in Locomotives Race. *Wall Street Journal*.

Tock, L., Gassner, M., & Maréchal, F. (2010). Thermochemical production of liquid fuels from biomass: Thermo-economic modeling, process design and process integration analysis. *Current and Potential Capabilities of Wood Production Systems in the Southeastern U.S.*, *34*(12), 1838–1854. https://doi.org/10.1016/j.biombioe.2010.07.018

Total. (2019). BIOTFUEL: DEVELOPING SECOND-GENERATION BIOFUELS [Total]. Retrieved December 8, 2019, from https://www.total.com/en/energy-expertise/projects/bioenergies/biotfuel-converting-plant-wastes-into-fuel

Townsend, C. L., & Maynard, R. L. (2002). Effects on health of prolonged exposure to low concentrations of carbon monoxide. *Occupational and Environmental Medicine*, *59*(10), 708. https://doi.org/10.1136/oem.59.10.708

TranSysResearchLtd, UIUC-RailTEC, CPCS Transcom, & Lawson Economics Research Inc. (2015). *Comparison of Passenger Rail Energy Consumption with Competing Modes* (No. 3). Washington, DC: Federal Railroad Administration.

Trillanes, G. (2019, December 2). *Question about tank size used in the CNG tender*.

Trippe, F., Fröhling, M., Schultmann, F., Stahl, R., Henrich, E., & Dalai, A. (2013). Comprehensive techno-economic assessment of dimethyl ether (DME) synthesis and Fischer–Tropsch synthesis as alternative process steps within biomass-to-liquid production. *Fuel Processing Technology*, *106*, 577–586. https://doi.org/10.1016/j.fuproc.2012.09.029

Turner, J. (2018, December). Brightline back on track for Orlando rail extension – for now. *Miami Herald*. Retrieved from https://www.miamiherald.com/news/business/article223634510.html

UIC. (2018). *High Speed Rail: Fast Track to Sustainable Mobility*. Retrieved from https://uic.org/IMG/pdf/uic_high_speed_2018_ph08_web.pdf

UIUC-RailTEC. (2016). *Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System in California: Operational and Economic Considerations: Final Report*. Urbana, IL.

UN. (2018, May 16). *68% of the world population projected to live in urban areas by 2050, says UN*. Retrieved from https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

Union Pacific. (2019). *Environmental Management: Technology*. Retrieved from https://www.up.com/aboutup/environment/technology/index.htm.

University of Calgary. (2015, November 13). *Volatile organic compound*. Retrieved from https://energyeducation.ca/encyclopedia/Volatile_organic_compound

University of Strathclyde. (2009). *Hydrogen Use for Transportation*. Retrieved from http://www.esru.strath.ac.uk/EandE/Web_sites/08-09/Hydrogen_Buffering/Website%20Hydrogen%20Fuel%20Cell%20Transport.html

US Department of Transportation. (2017). *National Transit Database*. Retrieved from https://www.transit.dot.gov/ntd

US DOE. (2008). *Hydrogen Analysis Resource Center: Lower and Higher Heating Values of Hydrogen and Fuels* [Spreadsheet]. Washington, DC.

US DOE. (2017, May). *Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan*. Retrieved from https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

US DOE. (2018). *Clean Cities: Alternative Fuel Price Report*. Retrieved from https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_july_2018.pdf

US DOE. (2019). Hydrogen Storage—Basics. Retrieved November 28, 2019, from https://www.energy.gov/eere/fuelcells/hydrogen-storage-basics-0

US DRIVE. (2017). *Hydrogen Delivery Technical Team Roadmap July 2017*. Retrieved from https://www.energy.gov/eere/vehicles/downloads/us-drive-hydrogen-delivery-technical-team-roadmap

US EIA. (2012, January 31). Global natural gas production doubled between 1980 and 2010. Retrieved November 29, 2019, from Today in Energy website: https://www.eia.gov/todayinenergy/detail.php?id=4790

US EIA. (2019a). *Assumptions to the Annual Energy Outlook 2019: Natural Gas Market Module*. Retrieved from https://www.eia.gov/outlooks/aeo/assumptions/pdf/natgas.pdf

US EIA. (2019b). *Electric Power Monthly, with Data for July, 2019*. Washington, DC: US EIA.

US EIA. (2019c). Electricity Market Module Regions. Retrieved December 3, 2019, from https://www.eia.gov/outlooks/aeo/pdf/nerc_map.pdf

US EIA. (2019d). *Gasoline explained: Factors affecting gasoline prices*. Retrieved from US EIA website: https://www.eia.gov/energyexplained/gasoline/factors-affecting-gasoline-prices.php

US EIA. (2019e). *SHORT-TERM ENERGY OUTLOOK*. Retrieved from US EIA website: https://www.eia.gov/outlooks/steo/report/electricity.php

US EIA. (2019f, January 9). How much electricity is lost in electricity transmission and distribution in the United States? Retrieved December 8, 2019, from Frequently Asked Questions website: https://www.eia.gov/tools/faqs/faq.php?id=105&t=3

US EIA. (2019g, January 18). Today in Energy: EIA forecasts renewables will be fastest growing source of electricity generation. Retrieved November 14, 2019, from Today in Energy website: https://www.eia.gov/todayinenergy/detail.php?id=38053

US EIA. (2019h, January 24). *Annual Energy Outlook, 2019*. Retrieved from https://www.eia.gov/outlooks/aeo/

US EPA. (2017, February). *Understanding Global Warming Potentials*. Retrieved from https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

US EPA. (2018, March). *Criteria Air Pollutants*. Retrieved from https://www.epa.gov/criteria-air-pollutants

US EPA. (2019). *EPA Green Book Data Download Data Dictionary*. Retrieved from US EPA website: https://www3.epa.gov/airquality/greenbook/downld/greenbook_exportdoc.pdf

US EPA, Office of Transportation and Air Quality. *Locomotives: Exhaust Emission Standards*. , (2016).

US Federal Railroad Administration. (2017). *FRA Crossing and Inventory Reports*. Retrieved from Office of Safety Analysis, Federal Railroad Administration, US DOT website: https://safetydata.fra.dot.gov/OfficeofSafety/PublicSite/Crossing/Crossing.aspx

Vantuono, W. (2018, March 21). Turning on the gas: Florida East Coast Railway embraces LNG locomotives. *International Railway Journal*. Retrieved from https://www.railjournal.com/in_depth/turning-on-the-gas-florida-east-coast-embraces-lng/

Vantuono, W. C. (2013, November 8). A closer look at LNG. *Railway Age*. Retrieved from https://www.railwayage.com/freight/class-i/a-closer-look-at-lng/

Vantuono, W. C. (2019, September 19). CNGMotive Moves to the Next Level. *Railway Age*. Retrieved from https://www.railwayage.com/news/cngmotive-moves-to-the-next-level/

Varney, J. (2019, November). *Alstom iLint*. Presented at the Fuell Cell Seminar, 2019, Long Beach, CA.

Vassallo, J. M., & Fagan, M. (2007). Nature or Nurture: Why do Railroads Carry Greater Freight Share in the United States than in Europe? *Transportation*, *34*, 177–193.

Viswanathan, B., & Scibioh, M. (2007). *Fuel Cells: Principles and Applications*. Hyderabad, India: Universities Press.

Weiss, W., Hayes, I., & Shaw, P. (1983). *Comparative Catenary Costs—European and U.S. Mainline Railroad Electrification* (pp. 44–48). Washington, DC: TRB.

White, R. (2019). *Capitol Corridor To Expand Train Service To And From Roseville*. Retrieved from http://www.capradio.org/articles/2019/01/22/capitol-corridor-to-expand-train-service-to-and-from-roseville/

Wilhelmsen, Ø., Berstad, D., Aasen, A., Nekså, P., & Skaugen, G. (2018). Reducing the exergy destruction in the cryogenic heat exchangers of hydrogen liquefaction processes. *International Journal of Hydrogen Energy*, *43*(10), 5033–5047. https://doi.org/10.1016/j.ijhydene.2018.01.094

William C. Vantuono. (2014). Locomotives: Is LNG the next generation? *Railway Age*, (September 2014).

Wilson, J. (2017). *TRAINS: Guide to North American Diesel Locomotives*. Kalmbach Books.

Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., & Saur, G. (2012). *All Composite Data Products: National FCEV Learning Demonstration With Updates Through January 18, 2012 Keith Wipke, Sam Sprik, Jennifer Kurtz, Todd Ramsden, Chris Ainscough, and Genevieve Saur* (No. NREL/TP-5600-54021).

Retrieved from National Renewable Energy Laboratory, US DOE website: https://www.nrel.gov/docs/fy12osti/54021.pdf

Wiryadinata, S. (2018). *Heat and Mass Transfer Enhancement of the Packed Bed Fischer-Tropsch Reactor: Investigation into the Effects of Passive Flow Disturbance and Reactor Aspect Ratio* (Dissertation). University of California, Davis, Davis, CA.

Withuhn, W. L. (1999). Risk and the Real Cost of Electrification. *Railroad History*, (181, Autumn, 1999). Retrieved from https://www.jstor.org/stable/43524019

Wolchover, N. (2012, March 2). Why It Took So Long to Invent the Wheel. *Live Science*. Retrieved from https://www.livescience.com/18808-invention-wheel.html

World Bank. (2019). *Population Density (people per square km of land area)*. Retrieved from https://data.worldbank.org/indicator/EN.POP.DNST

Worldatlas.com. (2019). *Most Densely Populated U.S. States*. Retrieved from https://www.worldatlas.com/articles/most-densely-populated-u-s-states.html

Yamamoto, T., Hasegawa, H., Furuya, T., & Ogawa, K. (2010). Energy Efficiency Evaluation of Fuel Cells and Batteries Hybrid Railway Test Vehicles. *Quarterly Report of RTRI*, *51*(3), 115–121. https://doi.org/10.2219/rtriqr.51.115

Yang, C., & Ogden, J. (2007). Determining the lowest-cost hydrogen delivery mode. *International Journal of Hydrogen Energy*, *32*(2), 268–286. https://doi.org/10.1016/j.ijhydene.2006.05.009

Yeh, S., Ghandi, A., Scanlon, B. R., Brandt, A. R., Cai, H., Wang, M. Q., … Reedy, R. C. (2017). Energy Intensity and Greenhouse Gas Emissions from Oil Production in the Eagle Ford Shale. *Energy & Fuels*, *31*(2), 1440–1449. https://doi.org/10.1021/acs.energyfuels.6b02916

Yole Developpement. (2017). *Status of the Rechargeable Li-Ion Battery Industry*. Retrieved from https://www.slideshare.net/Yole_Developpement/status-of-the-rechargeable-liion-battery-industry-2017-report-by-yole-developpement

Zenith, F., Isaac, R., Hoffrichter, A., Thomassen, M. S., & Møller-Holst, S. (2019). Techno-economic analysis of freight railway electrification by overhead line, hydrogen and batteries: Case studies in Norway and USA. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*. https://doi.org/10.1177/0954409719867495

Zenith, F., Moller-Holst, S., & Thomassen, M. (2016, July 4). *Hydrogen and Batteries for Propulsion of Freight Trains in Norway*. Presented at the Hydrail 2016. Retrieved from https://www.fch.europa.eu/sites/default/files/default_images/10.%20SINTEF_Norway%20case%20%28ID%202902217%29.pdf

Appendix

Table A1: Davis Equation"/Equation of Resistance Variables by Passenger Train Trip

Capitol Corridor Scenario	**Davis Equation Factors A unit: kN B unit: kN/(meter/sec) C unit: kN/(meter/sec^2)**	**Caltrain Scenario**	**Davis Equation Factors A unit: kN B unit: kN/(meter/sec) C unit: kN/(meter/sec^2)**
Diesel 3.3 MW Mech + Regen	A: 5.35763 B: 0.06872 C: 0.01429	Diesel 3.3 MW Mech + Regen	A: 5.35763 B: 0.06872 C: 0.01429
Diesel 3.3 Regen Only	A: 5.35763 B: 0.06872 C: 0.01429	Diesel 3.3 Regen Only	A: 5.35763 B: 0.06872 C: 0.01429
Hydrogen 3.3 MW, #1	A: 5.15113 B: 0.06459 C: 0.01505	Hydrogen 3.3 MW, #1	A: 5.10808 B: 0.06373 C: 0.01505
Hydrogen 3.3 MW, #2	A: 5.14076 B: 0.06438 C: 0.01505	Hydrogen 3.3 MW, #2	A: 5.10065 B: 0.06358 C: 0.01505
Electricity (OLE)	A: 5.10876 B: 0.06374 C: 0.01429	Electricity (OLE)	A: 5.10876 B: 0.06374 C: 0.01429
Diesel Hybrid 3.3 MW	A: 5.45839 B: 0.07074 C: 0.01505	Diesel Hybrid 3.3 MW	A: 5.45839 B: 0.07074 C: 0.01505
Hydrogen Hybrid 3.3 MW #1	A: 5.22221 B: 0.06601 C: 0.01505	Hydrogen Hybrid 3.3 MW #1	A: 5.18061 B: 0.065181 C: 0.01505
Hydrogen Hybrid 3.3 MW #2	A: 5.21924 B: 0.06595 C: 0.01505	Hydrogen Hybrid 3.3 MW #2	A: 5.17912 B: 0.065152 C: 0.01505
Diesel Hybrid 1.1 MW	A: 5.19635 B: 0.0655 C: 0.01505	Diesel Hybrid .95 MW	A: 5.17897 B: 0.06515 C: 0.01505
Hydrogen Hybrid 1.1 MW #1	A: 5.17545 B: 0.06508 C: 0.01505	Hydrogen Hybrid .95 MW #1	A: 5.1206 B: 0.06398 C: 0.01505
Hydrogen Hybrid 1.1 MW #2	A: 5.16356 B: 0.06484 C: 0.01505	Hydrogen Hybrid .95 MW #2	A: 5.11465 B: 0.06386 C: 0.01505

Table A2: Freight train Vehicle Weight, by Route/Sub-Route

Route/Sub-route	**Train Weight (including Locomotives), Metric Tons**
KC to Wellington	9676.04
Wellington to Amarillo	10894.38
Amarillo to Clovis	7398.3
Clovis to Winslow (via Belen)	6759.62
Winslow to Needles	6765.11
Needles to Barstow	5971.55
Barstow to Los Angeles	6571.5
Intermodal, 80-car (Fast)	5320.22
Intermodal, 120-car (Slow)	5387.75

Table A3: EPA Tier Levels, 1973 - Present

Year of original manufacture	Tier	Standards (g/bhp-hr)			
		NOX	**PM**	**HC**	**CO**
1973-1992a	0	9.5	0.22	1	5
1993a-2004	1	7.4	0.22	0.55	2.2
2005-2011	2	5.5	0.10	0.3	1.5
2012-2014	3	5.5	0.1	0.3	1.5
2015 or later	4	1.3	0.03	0.14	1.5

Source: (EPA, 2016b)

Table A4: Emissions Values Used, By Tier, Diesel

Line-Haul	**Grams/Million BTU**			
	HC#	**CO$^{\alpha}$**	**NOx**	**PM**
Based on GREET, 2015 Fleet*	40.175	139	986	29
Tier 4 Standards	22	139	200	5
Tier 5 Standards	3.084	139	30.84	1.542

Switcher	**Grams/Million BTU**			
	HC	**CO**	**NOx**	**PM**
Based on GREET, 2015 Switcher Fleet	52.175	122	1026	29

Conversion factor used for conversion to Tier 4 and Tier 5 standards: 154.2 (Methodology, based on line-haul locomotives, derived from (Elgowainy, Vyas, Biruduganti, & Shurland, 2018)

* These values come directly from (GREET, 2018); however, values are adjusted slightly from the default (as obtained from the Rail_PTW tab) to reflect the value for line-haul locomotives, only. (The switcher values, in the lower table, are adjusted to reflect the data for switcher locomotive, only.)

VOC (Volatile Organic Compounds) is used here interchangeably with HC.

α The Tier 4 standard for CO had already been met by 2015 (according to data from (GREET, 2018); hence the CO emissions level achieved by the 2015 fleet was assumed as the Tier 4 standard. (And Tier 5, as recently proposed (Nichols, 2017), does not suggest a further reduction in CO emissions.)

Note: Tier 4 and 5 Standards for the switcher fleet assumed the same values as for the line-haul fleet, except for CO, which was assumed at a lower level, to account for its already having met and even exceeded the required CO reductions (based on 2015 fleet average data (GREET, 2018)). (In fact, despite having higher allowable CO emissions under its modified Tier 4 standard than is the case with the line-haul standard, the switcher locomotive fleet, in 2015, had achieved lower CO levels than had the line-haul fleet during that year (based on data from (GREET, 2018)).

Table A5: Well-to-Pump Energy for Selected Fuels[197]

Fuel	Mix	BTU per Million BTU
Hydrogen	**SMR U.S.**	**793,641**
	SMR CA	**742,516**
	Electrolysis 100% Renewables/Other	***Defined below***
	Electrolysis U.S. Mix	**2,314,409**
	Electrolysis CA Mix	**1,721,732**
CNG	**U.S.**	**152,305**
	CA	**143,536**
OLE	**U.S.**	**1,129,002**
	CA	**738,885**
	Estimated losses due to transmission and distribution losses (between the powerplants and the OLE)	0.95
	Input values (below) obtained directly from GREET	
	U.S.	1,072,552
	CA	701,941

Note: For Electrolysis 100% Renewables/Other, operational usage was divided by .576, with operational usage then subtracted from the resulting value. 0.576, or 57.6% was derived based on the below input values:

95.0	Based on (US EIA, 2019f)
66.8	GREET electrolysis efficiency assumption
90.7	GREET compressor efficiency

[197] This table displays well-to-pump energy values that were obtained based on data from (GREET, 2018), but for methods that are not specifically included in the model's rail assumptions. (Or, in the case of OLE, where additional adjustments were made.) The 'Results' and 'Hydrogen' tabs of the model were a source of much of this information.

Table A6: Well-to-Pump Emissions for Selected Fuels[198]

Grams per Million BTU			
Fuel/Fuel Mix	**Natural Gas, CA**	**Hydrogen SMR, CA**	**Hydrogen Electrolysis, CA**
GHGs	16218.21	111684.89	132200.71
HC	10.97	17.21	17.77
CO	35.2	57.42	81.38
NOx	43.82	73.4	102.26
PM	0.63	3.07	11.95

[198] This table displays well-to-pump emisssions values that were obtained based on data from (GREET, 2018), but for methods that are not specifically included in the model's rail assumptions. The 'Results' tab of the model was the source of this information. (Numbers have been rounded.)

Box A1. Summary Table, Recommendations

Recommendations for Further Study
General
- Assess well-to-wheel impacts of the technologies explored (e.g. including component manufacturing impacts)
- How does the cost of switching to hydrogen via fuel cell powertrain in the freight sector compare, in cost, to other alternative technologies that would enable locomotives to achieve Tier 5?
Natural Gas
- Assess emissions results with higher, potentially more accurate, methane leakage rates
FTD
- Secondary emissions impacts of biofuels (with mass scaling)
OLE
- Assess, quantitatively, the costs of converting the U.S. freight system to OLE, and explore, in some detail, the associated challenges
Hybridization
- Re-visit hybridization costs as battery costs and characteristics develop over time
Assess viability of battery-OLE hybrids
Hydrogen
- Validation of current fuel cell lifetimes and accompanying voltage degradation
- Assess costs and logistics of delivering hydrogen to rail refueling sites via pipeline
- Survey actual rail refueling site sizes (i.e. diesel fuel volumes) across the rail industry to better understand potential hydrogen fuel demands
- Assess hydrogen demand in the trucking industry, and the potential for coordinating between the two sectors
- Assess costs and implications of tank certification processes
Other
- Explore the feasibility and implications of combining OLE (e.g. along high traffic lines) and hydrogen (via fuel cell) propulsion for freight rail