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Propulsion Systems for 21st Century Rail

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Abstract

This paper evaluates the practicality, costs and greenhouse gas-related benefits of different propulsion technologies and fuels for U.S. freight and passenger (i.e. intercity/commuter) rail. Two example routes, one existing (for passenger rail) and one devised (for freight), are used to construct the analysis and better understand the implications of fuel strategies in a “real world” context.

Although diesel-electric locomotives currently dominate freight and non-urban passenger rail, a number of other fuels could be considered in the near future. These include biodiesel and the new “renewable diesel” drop-in diesel replacement fuels. With the low prices of natural gas in recent years, it is another important fuel alternative. Though few longer-distance rail systems in the US run on electricity, this energy carrier is widely used in Europe. Finally, hydrogen and fuel cells are now being explored for non-urban rail systems and some rail yard applications. These options and the requisite locomotive technologies are all considered for our example routes.

Our two scenarios include a passenger rail analysis based on California’s Amtrak-Capitol Corridor line, and a freight analysis based on a generalized 2000-mile (3,218.7 km) corridor. These allow us to size and cost out the locomotive and refuelling infrastructure needed in each context. We find that costs and CO2 impacts of the technology/fuel options vary depending on these applications, particularly due to the much more energy- and fuel-intensive nature of freight rail; however all of the fuel options could, in principle, serve long-distance rail systems, though potentially involving some refuelling system compromises. For both submodes there are several alternatives to diesel that provide CO2e reductions and some that provide cost savings, but no options that are clear winners in both respects.

Keywords: passenger rail; freight rail; alternative fuels; intercity rail

1. Introduction

Transportation accounts for approximately 28% of all US energy consumption (ORNL, 2015) and about 20% of all global energy consumption (EIA, 2015). In terms of total transportation energy use, rail systems (excluding transit but including intercity and commuter passenger, along with freight rail), account for approximately 2% of the US transportation energy consumption total (ORNL, 2015), with over 90% of the US impact from freight rail (ORNL, 2015).

At the global level, rail is responsible for close to 4% of all transportation CO2 emissions (UIC, 2015), and the total CO2 emissions impact has increased by 50% since 1990 (UIC, 2015). (In many countries, the contribution from passenger rail is a significant part of this number.)

Looking specifically at the US, given the direct link between liquid fuels and GHG emissions, this suggests that rail, a sub-sector that is run largely on diesel fuel (ORNL, 2015), accounts for about ½ percent of all domestic GHG emissions.

While these shares for rail are relatively small, evidence points to rail as a growing subsector, both domestically as well as at the global level, and this means that these impacts will continue to increase, both absolutely as well as relatively, given the changes ongoing in the automotive sector. In addition, freight firms are highly cost-sensitive, and are always on the lookout for alternatives that might provide cost savings. 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/or environmental goals.

In general, the operation of rail systems is highly centralized, with a limited number of operators, and, as such, a shift within the sector, once underway, might demonstrate somewhat smoother coordination than a shift within the passenger automobile sector. Further, by establishing a technology/fuel shift in the rail sector, this may encourage the spread of such a transition to road vehicles, for example through the establishment of regional refuelling infrastructures.

This paper covers both U.S. passenger rail (i.e. local ‘commuter rail’ and regional ‘intercity rail’) and domestic freight rail, reviewing the potential for various low-carbon technology and fuel strategies (including LNG, biodiesel, electricity, and hydrogen). It compares both the energy/CO2 implications of different alternatives and the potential costs of developing these alternatives, with particular attention to developing the refuelling infrastructure associated with the example corridors. Thus while our results may be generally applicable to different situations in the U.S. and even internationally, differences in specific corridors will mean that absolute and relative costs will likely differ, due to differing fuel and material costs, and/or labor costs/practices.

The paper first gives some context to passenger and freight rail trends in the US, and then summarizes some of the key fuel technologies, providing insight into potential fuel choices in a generic manner and in the context of the example corridors we develop. Results are presented and discussed, with an emphasis on both cross-fuel comparison and variations between passenger and freight rail results.

2. Current Contextual Factors and Trends in Rail and Rail Propulsion

Diesel fuel and its associated locomotive technologies currently provide the power source for approximately 87% of U.S. domestic rail service (Vyas, 2013), while electricity and its associated infrastructure and locomotive technologies comprise the remaining 13% (Vyas, 2013).

By examining just the intercity/commuter passenger rail side, a more complex picture emerges. On the one hand, a mere 2-3% of track over which passenger rail operates in the United States is electrified (Amtrak, Unpublished data); however, due to the unusual density of passenger rail traffic in Amtrak’s ‘Northeast Corridor,’ operational energy is currently split about equally: about 48% of BTU are accounted for by diesel, 52% by electric (ORNL, 2015). Nonetheless, in 2012, commuter and intercity rail in the United States consumed close to 46 million gallons of diesel/year (based on petroleum barrels consumed (ORNL, 2015) and a US Energy Information Administration (EIA, 2014b) conversion rate of 12 gallons diesel fuel per barrel of crude oil (EIA, 2014b)). Even with the recently low retail costs of roughly $2/gallon (which coincided with crude oil prices that were well below $50/barrel (InvestmentMine, 2016)), that’s an expenditure of close to $100 million per year.

One of many U.S. passenger lines relying on diesel fuel, the Amtrak Capitol Corridor line between San Jose and Auburn, California, is the third busiest intercity (passenger) rail route in the country (CCJPA, 2015). In FY (fiscal year) 2015 this service had a record ridership of over 1.47 million (CCJPA, 2015). Believing that earlier ridership increases could double to over 3 million (AECOM, 2013), state planners have had ambitious goals to increase service levels—for example, by increasing top speed from 79 mph to 110 mph, adding track along the current right-of-way, and even adding new branch lines (AECOM, 2013).

Looking beyond California, Amtrak’s Northeast Corridor line posted its highest ridership ever in 2014 (Amtrak, 2014) (and it remained fairly steady into 2015 (Leeds, 2015)), the pause in growth perhaps due to the impact of low gas prices (Philly.com, 2016)), while commuter rail ridership nationwide increased by 2.9% in 2014 (APTA, 2014). (This somewhat mirrors an international trend, as, globally, passenger rail has more than doubled since the mid-1970’s) (UIC, 2015)**.**)

After a decades-long period in which, as one scholar notes, “preservation” rather than “modernization” prevailed in US policy towards passenger rail (Perl, 2016), recent years have seen rail agencies across the nation making key investments into their systems. For example, ongoing investment by both the Federal government and the state of Illinois to upgrade track between Chicago and St. Louis has begun to support frequent service at an increased speed (Dechert, 2014)---110 mph; up from 79 mph---(ProgressiveRailroading, 2013) and that state, along with Missouri, Michigan, and Washington, has recently been a part of a multi-state purchase of the new "Charger" locomotives (Cho, 2014).

Renewed interest in domestic passenger rail is likely a trend with several and complex explanations, but that is beyond the scope of this piece. This larger context, however, suggests that, looking ahead to the coming decades, ignoring fueling approaches within passenger rail would come at great risk, both cost-wise and in regard to the climate/environment.

Freight rail in the U.S. accounts for over 90% of the total energy consumed within the rail sector (not including city-oriented transit systems) (ORNL, 2015). While, as of 2007, there were more than 500 short line and regional freight firms (CambridgeSys, 2007), seven Class I firms account for about 69% of the freight route miles (AAR, Undated) over approximately 52,340 miles (84,233.1 km) of track (CambridgeSys, 2007)**.** While the average freight trip length is a bit less than 1,000 miles (Leonard et al., 2014) (1,609.3 km), actual lengths vary quite a bit, depending on the purpose of a given freight trip.

Freight rail in the U.S. runs almost entirely on diesel operations, with the exceptions being very short isolated lines in Arizona (Railfan) and near the Colorado-Utah border (Railfan) (Clarke, 2013). While freight rail carloads decreased slightly in 2015, due to larger trends targeting a few specific commodity types (e.g. petroleum product shipments decreasing due to low oil prices and coal shipments continuing to decrease as the country and world move away from that energy source (AAR, 2016b)), transport, in ton-miles, has been on a fairly consistent trend upwards, and exceeded 1.8 trillion ton-miles in 2014 (AAR, 2016a) (2.9 trillion km).

3. Rail Propulsion System/ Fuel Alternatives to Diesel

Here we review a number of alternative (i.e. to diesel) fuel options for rail systems, including biodiesel, natural gas, hydrogen, and electricity via catenary. A brief review of the relevant technical literature (Hoffrichter, 2013) and related sources (GREET, 2015) makes it apparent that, from a purely thermodynamic efficiency perspective, only hydrogen and electricity provide significant efficiency benefits; however, the carbon intensity of each fuel is also an important consideration in any careful evaluation of all of the fuel options.

3.1. Biodiesel

Spurred on by federal standards and tax credits, domestic biodiesel production in the US, which is focused largely in the Midwestern part of the country (EIA, 2016), has increased steadily since 2005 (DOE, 2016). In fact, while worldwide biodiesel production also increased during this time period (REN21, 2015)---likely due to pro-biofuels policies in place throughout much of the globe (REN21, 2015), in 2014, the US led the world in biodiesel production (REN21, 2015).

Biodiesel is a renewable biofuel that is blendable with diesel fuel in a range of applications and specifications. The most widely available biodiesels today derive from vegetable oils such as soy or corn oil and waste oils and greases, such as from restaurants. These are typically used to produce fatty-acid methyl esters (FAME), which can be blended with conventional diesel fuel, in principle in any proportion. Recently a formulation known as "renewable diesel" has become available. Typically produced using hydro-treating to upgrade oils that may be produced from a wide range of feedstocks, the result is a true diesel-like specification, fully capable of 100% operation in any diesel engine (NREL, 2006). In the future, drop-in diesel fuels may also be made via gasification/hydrocarbon forming technologies, such as Fischer-Tropsch (F-T), and various biochemical pathways, allowing a much wider range of biomass to be converted to long-chain hydrocarbons. Currently, however, these processes remain expensive and are not yet commercial.

Biodiesel has demonstrated significantly lower pollutant emissions, including hydrocarbon, particulate matter, carbon monoxide, and sulfur (EPA, 2002); however, NOx levels for biodiesel do not demonstrate a drop as compared to conventional diesel for biodiesel, and may even be higher (EPA, 2002). Renewable diesel may, on the other hand, reduce NOx levels, though only by a little. (CalEPA, 2013) Moreover, while renewable diesel also leads to decreases in the pollutants noted above, it appears to do so by a smaller margin (CalEPA, 2013).

In part due to the range of possible feedstocks and pathways, biodiesel and renewable diesel fuels present a rather complex lifecycle CO_2 emissions picture. In principle, the CO2 emissions produced during combustion are offset by the CO2 absorbed from the atmosphere during the crop production phase; however, the CO_2 and other GHG emissions released during feedstock conversion and fuel production can be significant, as can other potential secondary effects (related, for example, to land use changes, soil carbon changes, co-product impacts, etc.). Many of these are not easily quantifiable, such as indirect land use change (e.g. [19]); however, efforts are being made to take these into account, such as the studies reviewed by Plevin et al [20], which suggest a significant range of possible effects.

As with life-cycle CO2 emissions, biodiesel fuel costs display a significant range. Feedstock cost alone can vary up to fourfold, depending on feedstock type and geographic source (Miranowski and Rosburg, 2012). In recent years, sugarcane and biomass have represented relatively low-cost sources and rapeseed oil the highest cost source (Miranowski and Rosburg, 2012).

3.2. Electricity via Catenary

While Europe, Japan, China, and India have all embraced electricity as a rail energy source (UIC, 2015), the same cannot be said of the U.S., which, as of the late 2000s, had less than 1% of its track electrified (Lewis and Verhelle, 2015). (The US has more track kilometers, perhaps as much as an order of magnitude higher (Lewis and Verhelle, 2015); however, even just from an absolute perspective, its less than 2,000 km (1,242.74 miles) of electrified track (Lewis and Verhelle, 2015) lags greatly behind many countries, eight of which each have greater than > 10,000 km of electric track**.** (Lewis and Verhelle, 2015)

Having developed quite a bit since the 1880s (Allen, 2003), electric catenary technology is moving towards an AC system based on 25kV. Now the Amtrak standard between New Haven and Boston (LTK, 2010), and similarly the likely choice for recent and planned domestic projects (Clarke, 2013)**,** 25 kV electrification currently operates throughout much of Europe (Luo, 2005) and Asia (Hitachi, 2013, Siemens, 2014)

Electricity is by far the most efficient of the rail "fuels" (Miller, 2012, (GREET, 2015)). CO_2 emissions can be significantly lower under electrified operations, but this depends on the fuel mix of electricity generation at the producing power plants, which varies, sometimes significantly, by region. For example, the GREET model, which is based on EIA Annual Energy Outlook data for 2013, suggests that the EIA's California electricity mix emits only 62% of the GHG emissions, per unit of electric power, as would result from relying on the agency's standard US mix (GREET, 2015).

The cost of converting a rail system to run on electricity can be very high. The initial buildout of catenary infrastructure can, based on recent U.S. projects, be estimated to cost between about $1 million per mile (Flynn, Kevin, Regional Transit District, personal conversation, July, 2014) (1.6 km) and $8 million per mile (Samtrans, 2014, ICF, 2014). While costs relative to the other technologies may be highest when the rail corridor lacks high levels of traffic (since larger numbers of locomotives reduce the cost of fixed catenary infrastructure per vehicle and mean an increased role for fuel costs), absolute costs are lower where train operations have not yet begun, as two of the more significant contributor to the high costs of catenary are right-of-way worker protection insurance (Verhelle, Bob, personal communication, June, 2015) and the need to work around existing, operating trains, which leads to low levels of productivity, especially during the daytime (Verrelle, Ray, personal communication, January, 2016 & Verhelle, Bob., personal communication, June, 2015).

While of a much smaller magnitude, costs to maintain electric locomotives can be significantly less than that of diesel locomotives (White, 2008, Broad, 2012, Hay, 1982), likely due to fewer moving parts. In addition, one rail expert noted, in a classic railroad engineering text, that, due to the higher availability of electric locomotives (due to the resulting decreased maintenance required), a rail system run on electric locomotives requires fewer total locomotives (Hay, 1982).

3.3. Natural Gas

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 (LNG) or compressed gaseous (CNG) state. Unlike CNG, LNG would requires large "cylindrical shaped pressure vessels with a surrounding vacuum space for thermal insulation" (Stewart et al., 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 a simpler system than LNG, CNG also provides considerably less energy per unit volume. This could result in limits on travel range, and, in fact, to date most CNG tests have involved rail-yard switcher locomotives. For example, Norfolk Southern, one class I railroad firm, has conducted extensive tests in this context (Rider, 2014, Rimer, 2014, Barbee, 2015). One Norfolk Southern engineering executive has suggested that eventually compressed natural gas (CNG) could be a viable fuel for some of the sub-1,000 mile (1,609.3 km) freight routes that it operates in the Eastern U.S. (Rider, 2014), though one engine designer believes it may be a while before a rail engine in class 1 line haul, where routes are typically long distance, runs entirely on natural gas [Jensen, Energy Conversions, Inc., personal conversation, July, 2015]).

With the low natural gas prices of the past few years, North American rail freight firms, for whom fuel purchases comprise a large proportion of operating expenses, have shown significant interest in this fuel and, in many cases, begun pilot studies. For example, one pilot is currently being undertaken by Canadian National Railways, a Canada-based firm, which has partnered with Electro-Motive Diesel (EMD) and Westport Innovations in a couple of different projects (Smith). Westport has developed an LNG tender (i.e. fuel supply car; necessary due to LNG's lower energy density, as compared with diesel) that could be used alongside a standard diesel-electric locomotive (Dracup, 2014, Vantuono, 2014) and is also in the process of developing a High Pressure Direct Injection (HPDI) engine technology that could be adapted to an EMD diesel-electric locomotive engine, and which would run on 95% LNG (Vantuono, 2014) . EMD, on its own, has also developed two other LNG engine technologies, one of which uses a diesel (compression ignition, or CI) engine with a mix of diesel fuel and LNG; the other a spark ignition (SI) engine running on 100% LNG (Vantuono, 2014).

In the passenger rail context, the North Carolina Department of Transportation, which is looking to expand its locomotive inventory by two units in the near future, is actively pursuing alternative fuel technology options that would enable natural gas propulsion or use of a blend of diesel and natural gas in one or more of its locomotives (L. Harris, McDowell Engineers & Associates, Consultant to NCDOT, personal communication, March, 2016). Outside of North America, India has just begun to use a part-LNG, part-diesel mix (TimesofIndia, 2015)

When natural gas prices are significantly lower than diesel, both CNG and LNG appear to be cost-effective fuels for rail systems, especially for passenger rail, the distances for which, in most cases, are unlikely to require addition of a tender car to hold the fuel. Despite the recent drop in petroleum fuel prices, the low price of natural gas has kept natural gas in a competitive range. The future picture is uncertain, as recent diesel prices have reminded us, but the EIA, in 2014, projected an annual growth rate, in price, between 2012 and 2040 of just above 1% for natural gas (EIA, 2014a). This may support a role for natural gas as a bridging fuel to very low GHG fuels over the long term, including renewable natural gas (from biomass) or possibly a conversion to hydrogen systems. The fact that CNG and LNG use is rising within the trucking sector is another plus for natural gas as a rail fuel. In fact, a sizeable number of micro-liquefaction plants and LNG refuelling stations (75 of the latter, according to DOE (AFDC, 2015)) already exist throughout the country (Lee, 2014).

Although LNG is denser 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 (if not more than one). For example, the low temperature at which it must be kept to remain a liquid (roughly - 260 F) is energy intensive and causes a loss in overall system efficiency compared to CNG. A related concern is the potential for boil-off of natural gas during refuelling and on-board storage.

Compression costs being typically lower than liquefaction costs, CNG costs less as a fuel; however, CNG also has a lower energy density per volume storage capacity, and thus would require more frequent refuelling. While a CNG tender could significantly increase storage capacity, it would also translate into increased cost. Refuelling time for CNG, based on recent experience, is likely to be somewhere around 45 minutes (Cook, Dave, Railway Propulsion Systems, personal communication, August, 2015), though, for a higher cost refuelling system, this time could be reduced (Cook, Dave, Railway Propulsion Systems, personal communication, March, 2016). Either way, CNG (without a fuel tender) may be at a disadvantage in a traffic-heavy commuter system where locomotive turnaround times may be tight.

Although natural gas contains about 25% less carbon per unit energy than diesel fuel, a range of factors result in a steep erosion of this advantage in practice. If the natural gas is used in a spark ignition engine, there will likely be a 10-20% reduction in efficiency compared to diesel. There are also efficiency losses from energy storage, particularly for LNG. Finally and, more generally, there is also a concern regarding methane leakage both on board and within the upstream transport of natural gas. The EPA's official estimate of methane leakage in the US natural gas system is about 1%, though one meta-analysis notes that it could in fact be as high as 2.6% (Brandt et al., 2014, BerkeleyEarth, Undated).

3.4. Hydrogen/Fuel Cell

Fuel cell powered automobiles have begun to enter the US auto market (Voelcker). More than anything else, the significant progress made in this arena reflects cost reductions; estimates are that automotive proton exchange membrane (PEM) fuel cells can now be produced in high volume for over 50% lower cost than was the case in 2006 (Ogden, 2014). In the global rail sector, Alstom has partnered with Hydrogenics, a Canadian PEM manufacturing firm, in order to fulfill "letter[s] of intent" that have been signed with several states in Germany noting the introduction of hydrogen-fueled trains to that country in the next few years (Bulletin, 2015).

Fuel cells offer two major advantages over internal-combustion engines (ICE): they produce zero pollutant or GHG emissions at the "tail pipe" (H_2O is the only emission), and they are more efficient than ICEs, up to two times as efficient depending on the details of a comparison. This reduces the fuel requirement and, potentially, the cost, though hydrogen, currently, is not an inexpensive fuel, where it is available at all.

Fuel cells are already being utilized in heavy-duty vehicle applications, notably in several bus systems throughout the country, AC Transit, in California's Bay Area, included. AC Transit's hydrogen is primarily delivered from an off-site location several hundred miles away approximately once a week (Byrne, D., personal conversation, July, 2014), a costly procedure. Local sourcing of natural gas and H2 production can of course save on trucking costs (and increase overall system efficiency); over the longer term, with a large enough distribution demand, H2 movement by dedicated pipeline may become optimal (Ogden, 2014). Such a pipeline could serve both rail facilities and other sources of demand, such as trucks or stationary fuel cell systems

Hydrogen has also now begun to emerge as an application for trams. In Qingdao, China, for example, a rolling stock firm named Sifang started operating, earlier this year, hydrogen-powered trams (Gazette, 2015) In these vehicles, which house a 150 kW fuel cell module manufactured by Ballard (Wong, Alfred, Ballard, personal conversation, August, 2015), a 3-minute fueling session enables the vehicle to travel for 100 km at speeds of up to 70 kilometers/hour (Gazette, 2015). A newer 200 kW Ballard module will soon replace the current module (McAree, 2015).

PEM fuel cell-battery hybrid locomotive designs have been experimented with in several countries over the last decade. In Japan, two early prototypes of fuel cell-battery hybrid locomotives were designed (Hoffrichter, 2013); however, issues of equipment size, cost, and fuel cell lifetimes prevented these projects from going commercial (Hoffrichter, 2013). Here in the U.S., a public-private consortium developed, in 2009, a prototype PEM-based fuel cell hybrid switcher locomotive with power of the on-vehicle fuel cell plant of 250 kW (Miller, 2011). In combination with an auxiliary traction battery, the locomotive had a maximum power of 1.5 MW, and thermodynamic efficiency was found to be 51% (Miller, 2011).

Finally, during the last year, French rolling stock manufacturer, Alstom, announced that it had selected Hydrogenics as a partner (Witty, 2015) in its commitment, made during 2014 (EVNews, 2014), to pilot and ultimately operate passenger trains propelled by hydrogen in the coming years. The route first being considered, from Bremerhaven to Buxtehude, is only 75 km long (just under 47 miles), and current top speeds do not exceed 80 km/hr (~ 50 mph) (Busche, Holger, personal conversation, March, 2016). The vehicles traditionally used on the line operate as multiple units (Busche, Holger, personal conversation, March, 2016). At the time of writing, H2 in its compressed form is the likely fuel specification for this application (Eggleton, Peter, personal conversation, July, 2015), also using a multiple unit design rather than a front-end locomotive (Eggleton, Peter, personal conversation, July, 2015). In effect, several smaller power plants distributed throughout the train would power it, rather than one large one.

While the majority of transportation fuel cell system designs are currently PEM-based, alternatives have been proposed. For example, one team of academic researchers has suggested that a solid oxide fuel cell (SOFC)-gas turbine (GT) hybrid system---in which a fuel is directly oxidized to form electricity---would have advantages over a PEM fuel cell (Martinez, 2011). For one, that research finds the potential to rely on more conventional fuels and existing infrastructure, at least in the near term of what might be a step-wise process (Martinez, 2011) of moving from diesel fuel eventually to pure hydrogen. Cost and longevity remain concerns with SOFC technology, however, and the ability of the materials to withstand the forces regularly placed upon them might also be problematic with an SOFC (Martinez, 2011).

SOFC and other non-PEM fuel cell options are still highly experimental technologies. Placing these aside for now, the expected cost of PEM fuel cells for trains is highly uncertain, and will depend on scale and volume of production, and the learning that comes from early industry experience. Thus, while a single fuel cell passenger locomotive might cost approximately $10 million in the early years of market expansion, as market development were to continue, it is possible that these costs would drop to closer to $7.5 million, about the current cost of diesel-electric passenger locomotives. Similarly, while near term hydrogen production would be fairly expensive, this cost is expected to drop over time as hydrogen systems expand around the country for various applications (Ogden, 2014). The resulting CO_2 emissions should also decline over time; initially, hydrogen would likely be derived mainly from natural gas due to the much lower costs of steam methane reforming compared to other methods. Eventually, however, producing hydrogen via electrolysis using a variety of photo-chemical or thermo-chemical methods, as well as from biomass sources, may become more viable, and each of these would result in lower carbon intensity hydrogen.

As with LNG, the colder, liquid form of hydrogen is advantageous from an energy density standpoint vis-à-vis its warmer, gaseous counterpart; however, it is also less efficient and more costly a process (Hoffrichter, 2013, Schwartz, 2011). Also, like LNG, the potential for within-tank boil-off remains a concern (Hoffrichter, 2013, Schwartz, 2011), though it can be minimized through proper insulation of the storage medium (Linde).

Energy density (volumetric basis), refueling, and lifetime pose challenges for hydrogen/fuel cells vis-à-vis 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. Exact refueling times are beyond the scope of this paper; however, previous research has noted that, no matter the storage medium, refueling time for hydrogen simply does not match up to the speed of conventional diesel refueling (Hoffrichter, 2013, Gambini et al.). Lifetime maxima are somewhere in the range of 15,000 (Hoffrichter, 2013) (Wancura, Herbert, Synergesis, personal conversation, May, 2015) to just over 20,000 hours (one of the stacks on an AC Transit bus has begun to approach 21,000 hours [Roland Fecteau, AC Transit, personal conversation, November, 2015], which, assuming 20 hours of operation per day (e.g. for a freight train), is equivalent to about 2-3 years. For comparison, the California Air Resources Board has noted that diesel-electric locomotives have lasted up to 30 years and even longer (Holmes et al., 2014); however, this very likely includes major refurbishments, including rebuilding of the engines. Additionally, engineers familiar with the rail industry suggest that increased complexity among recent tier engines is likely to reduce the lifetime of the diesel-electric locomotive engine (Wancura, Herbert, personal communication, July, 2015 & Cook, Dave, Rail Propulsion Systems, Inc., personal communication, July, 2015).

Due to the efficiency losses required to either compress or liquefy hydrogen (as occur also with natural gas), the ultimate potential of hydrogen may only be realized when solid state hydrogen technology can be further refined so as to offer benefits at typical storage temperatures. Solid state hydrogen refers to a variety of materials that can “reversibly and rapidly store hydrogen near ambient conditions at a density equal to or greater than liquid hydrogen,” (Murray et al., 2009). Candidate materials rely on the fact that hydrogen’s properties allow it to bind to surfaces through weak “dispersive” interactions, a processed called physisorption, or otherwise through stronger chemical “associations,” called chemisorption (Murray et al., 2009).

4. Case Studies/Methods

In this section, the above fuel technology options are considered in a specific passenger rail application and in a hypothetical freight (intermodal) scenario.

For the passenger case study, Amtrak’s “Capitol Corridor” passenger service was selected. Capitol Corridor operates several times a day between San Jose/Oakland and Sacramento, CA. Currently, 14 of the 15 daily round trips terminate, on the east end, in downtown Sacramento; however, Capitol Corridor Joint Powers Authority (CCJPA) is seeking to expand the service so that ten daily round trips would extend to Roseville (ICF, 2015), a suburb located one stop to the northeast of Sacramento, in an area that is expected to grow rapidly between 2010 and 2060 (ICF, 2015).

For this analysis it was assumed that all 15 of the round trips offered make the full trip between San Jose and Roseville, a one-way distance of roughly 150 miles (241.4 km). Energy, GHG, and cost characteristics of four alternative locomotive designs and associated fuels are compared to a base diesel-electric locomotive system in place today.

This modified Capitol Corridor system is used to scale this study’s passenger estimates and to include both system and train-level characteristics. Actual Capitol Corridor data thus provides a basis for how much fuel trains may use in a day and in a year (exact efficiency was adjusted slightly, as described in Table 1), and sets the default for the fuel supply system size and preferred refueling frequency. (Though, as described below, natural gas refueling would need to occur more often than is currently the operating practice.)

For both passenger and freight, fuel costs for diesel, biodiesel, and CNG fuel were gathered from the Alternative Fuels Data Center price reports (AFDC, 2016). Low and high retail prices from the last five years (i.e. starting from the January, 2016 report, and dating back to April, 2011) provide the basis for low and high costs for each fuel. For LNG, estimated compressions costs (Fulton and Miller, 2015) are removed from the CNG values and liquefaction costs (Fulton and Miller, 2015) substituted. For hydrogen, UC Davis and Department of Energy information (UCD/USDOE, 2014) were used to determine a low to high cost range.

The technology cost of building locomotives specifically for use with each fuel has then been estimated based on extensive research and consultation. (Both low and high prices for these technologies were analyzed.) Thus these values, combined with the fuel costs, allow for a comparison of life-cycle costs across the various options. These scenarios consider the types of technology costs that may be in play over the coming 5-10 years; however, they do assume fully built-out systems in a context where there are some economies of scale from similar projects in other spheres. Thus, e.g., in the case of passenger rail, the costs estimated here may not match what California would have to pay if the Capitol Corridor were among the first-of-a-kind of these various projects.

For the freight analysis, a hypothetical 2,000-mile (3,218.7 km) route was devised, with refueling occurring in intervals of 1,000 miles (1,609.3 km). (Refueling distance was set roughly by the physical limitations of operating a diesel train on three locomotives, and the validity of this value has been corroborated by other sources (O'Reilly, 2010).) This route length is fairly representative of a number of key cross-country intermodal routes e.g. Roseville, CA to Omaha, NE, Los Angeles to Kansas City, MO, etc. One Class I railroad firm provided general information regarding typical locomotive/train operations. Association of American Railroads (AAR) data for 2014 was utilized significantly, including for determining a default diesel fuel consumption rate.

AAR's 2014 consumption figure of 479 ton-miles/gallon was combined with data provided (confidentially) from a Class I railroad firm that allowed us to determine average weight for the intermodal trips on one of its well-traveled corridors. An adjustment of a 10% reduction in efficiency was then made, based on the likelihood that unit trains (i.e. trains that transport one commodity only, e.g. coal, oil, or often, though not always, some other natural resource), which are particularly efficient, somewhat skew what would otherwise be the average ton-mile/gallon value for freight trains upward. Intermodal trains, while overall highly efficient, are not as efficient as their unit counterparts (Tolliver et al., 2014) (Rowangould), perhaps due to higher speeds and the aerodynamic effects (Rowangould), but also perhaps due to other physical aspects of railway traction, including characteristic train length and car weight differences between these train types (Tolliver et al., 2014).

The freight case study, which considers an intermodal train, assumes 10 trains per day leaving one terminus and taking three days to reach the other end. (While on the smaller end of actual train frequencies, a figure of ten freight trains per day is indicative of a system size ripe for consideration for early adoption and experimentation.) Thus 60 trains, in total, operate on the route in the two directions at any time, each refueling at approximately every 1,000 miles (1,609.3 km), as noted earlier; thus three refueling stations serving ten trains per day, each, are needed.

Our passenger and freight rail cost and CO2 analyses provide a rough comparison of fuels for each of the particular scenarios described above. The fuel production, distribution, and storage costs are based on sizing the fuel system for the particular corridors in question, and the on-board fuel storage, when involving more than just the locomotive fuel tanks, is likewise based on trains being able to complete journeys without excessive refuelling. Capitol Corridor locomotives often will refuel after two full round trips each (Andrews, Tommy, Amtrak, personal communication, July, 2014), so for our diesel and biodiesel passenger options, this remains the case. For hydrogen, we assumed a slightly larger tank than the current 1800 gallon (Andrews, Tommy, Amtrak, personal conversation, July, 2014) tank, which should fit in the locomotive due to removal of the large engine (Wancura, H., Personal Communication, September, 2015)**,** and which would also allow for two full round trips. For all of our natural gas options, refuelling would likely need to occur after each round trip. As noted above, this process could take about 45 minutes for CNG, so that may impact operations as they currently stand. With LNG, one expert notes that refuelling such a tank would likely occur in about 10-20 minutes (Jensen, Scott, personal communication, March, 2016), so any impact would likely be minimal.

In our scenarios, rolling stock capital costs have been amortized over a period of 20 years, with a 10% interest rate. Fixed electric infrastructure has been amortized over 30 years, also with a 10% interest rate.

Table 1 provides the remaining major assumptions around the costs of the different fuels, reflecting assumed efficiencies, fuel production costs, and feedstock costs. Relatively near-term technology costs at moderate (rather than very small) production volumes were assumed. CO2 emissions results have been compressed into general categories and a range of variants has been applied, resulting in ranges of possible CO2 reduction impacts from different fuels.

Table 1. Key Analysis Assumptions

	PASSENGER (INTER-CITY & COMMUTER) RAIL	**FREIGHT RAIL**

General system/scenario assumptions	15 round trips per day; 1 locomotive per train (with 5 cars), each round trip 300 miles[1] (482.8 km); **Locomotive Maintenance Costs: $1.20/mile** (Burns, David, Railroad Industrial Engineering Consultant, personal communication, November, 2014) for all technologies, except for electricity, for which 60% of this rate is assumed (Hay, 1982 , Albalate, 2012, White, 2008)[2]. Comparative thermodynamic efficiency adjustment/"energy consumption ratio" relative to diesel taken from GREET (GREET, 2015), unless otherwise stated.	10 trains leaving origin each day; 3 locomotives per train; each round trip--- 4,000 miles (6,437.4 km), takes 6 days (Average speed of intermodal train: approx. 30 mph (Pacific, 2015) (48.3 km/h)); Additional fuel equipment requirements determined as per demands of 1,000 mile (1,609.3 km) gap between refuelling. **Locomotive maintenance costs: $1/mile** (Burns, David), **except $0.60/mile for electricity (Hay, 1982 , Broad, 2012, White, 2008)**
Diesel, "Best New Model"	**Vehicle/Cost:** Assumed 3.5MW system, generally similar to EMD's newly released F125 or Siemens Charger [approx. 3.3 MW], soon to be delivered to several state rail agencies (Cho, 2014); Cap. Corridor operating FY 2013 fuel consumption data was adjusted based on 2014 Environmental Protection Agency (EPA) locomotive certification data on CO_2 emissions (Oeler, Larry, US EPA, Office of Transportation and Air Quality); Diesel-electric locomotive with lowest CO_2 emissions test rate (model year 2014) shows 3.9% reduction from modified F59PHI (Cap. Corridor locomotive equipment) emissions rate [(Tutein, 2011)][3]. **$7.5 Million per locomotive** (Hanrahan, Hubert, Personal Communication, April, 2014) **Fuel Cost: $2.23/gallon to $4.13/gallon** **Emissions:** Based on GREET (GREET, 2015), Default	**Vehicle/Cost:** Weight of intermodal train based on data provided by a Class I firm.; **$7.5 Million for 3 locomotives ($2.5 Million per locomotive)** (Tita and Hagerty, 2014)) **Emissions:** Based on GREET (GREET, 2015), Default Diesel

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[1] According to Capitol Corridor, the distance between San Jose and Auburn is 168 miles (270.4 km). Google maps shows road distance of 16.4 miles (26.4 km) between Auburn and Roseville (though the rail route appears a bit longer than this).

[2] Fuel cells have few moving parts and therefore the potential for low maintenance costs. On the other hand, their durability is an issue over the lifetime of a train. Given the uncertainty we have assumed similar maintenance costs to diesel.

[3] Admittedly, this adjustment is imperfect for both passenger rail, as the certification data is based on a line-haul duty cycle and the comparison is extended to a passenger locomotive; however, actual operating information on newest passenger locomotives undergoing manufacturing, while requested, was unable to be provided. Additionally, conversations with an engineer (Cook, Dave, personal communication, June, 2016) confirmed that such an improvement, while not guaranteed (due to efficiency losses among newer, cleaner engines), is within the realm of possibility over the coming few years.

Biodiesel (FAME and Renewable Diesel)	**Vehicle/Cost:** Assumed same equipment as best diesel (i.e. "Drop-in biofuel"); **$7.5 Million per locomotive** **Fuel Cost: $3.21/gallon to $4.44/gallon, FAME, with 1.1X price adjustment for Renewable Diesel** **Emissions:** Based on GREET (GREET, 2015)	**Vehicle/Cost:** Same as Freight Diesel 'Best New Model' **Fuel Cost:** Same as Passenger **Emissions:** Same as Passenger
LNG	**Vehicle Cost: $8.1 Million per locomotive** (and includes engine retrofit and specialized tank)[e] **Fuel Cost: $1.57/gallon to $1.94/gallon[4]** **Emissions:** Based on GREET; For 3X GREET Leakage Rate, loss factor adjusted. **Efficiency**: GREET (GREET, 2015) value, Spark Ignition (SI); Same as diesel, Compression Ignition (CI)	**Vehicle/Cost: $11.4 to 12.4 Million for 3 locomotives and 2 (3 for SI) 10,000 gallon tenders**[5] **Fuel Cost:** Same as Passenger **Emissions:** Same as Passenger
CNG	**Vehicle/Cost:** On-locomotive storage tank based on 600 Diesel Gallon Equivalent (or roughly 4200 gallons of CNG), which was estimated at $250,000. (S. Jensen, ECI, personal communication, August, 2015). **8.1 Million per locomotive (and includes engine retrofit and specialized CNG tanks)[6]** **Fuel Cost: $0.60/gallon to $0.66/gallon** **Emissions:** Based on GREET; Adapted Rail WTP Energy and Emissions to include CNG, based on NG or FG to Compressed Natural Gas' option **Efficiency:** 15% less efficient as diesel, Spark Ignition (Jaffe, 2015); Same as diesel, Compression Ignition	Not applicable.
Hydrogen	**Vehicle Cost: $8.05 to 9.95 Million per locomotive** (including fuel cell stacks and specialized H2 tank; cost of diesel engine and accessories subtracted)[7] **Fuel Cost: $5.16/gallon to $9.03/gallon (UCD/USDOE, 2014)**	**Cost: $14.47 to 19.43 Million for 3 locomotives and 2 25,000-gallon tenders**[8] **Fuel Cost:** Same as Passenger

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[4] Alternative Fuels Data Center AFDC 2016. Fuel Prices. Washington, DC: US Department of Energy. data adjusted with compression costs removed (based on AEO 2015 feedstock and CNG costs), and liquefaction costs (Fulton & Miller, 2015) added

[5] Calculations based on following (unpublished) sources: Trillanes, Graciela, GE Transportation; Dracup, Brian, Westport; Batley, Keith, NRE

[6] Calculations based on following (unpublished) sources: Trillanes, Graciela, GE Transportation; Cook, Dave, Rail Propulsion Systems.; Melissa McKinnon, Westport; Batley, Keith, NRE

[7] Calculations based on following (unpublished) sources: Wancura, Herbert, Synergesis; Eggleton, Peter, Telligence Group; Batley, Keith, NRE

[8] Calculations based on following (unpublished) sources: Wancura, Herbert, Synergesis; Eggleton, Peter, TELLIGENCE Group; Patel, Pinakin, FuelCell Energy

	Emissions: Based on GREET (GREET, 2015). SMR assumes NG default, Solar electrolysis assumes Solar Photovoltaics	**Emissions:** Same as Passenger
Electricity (via Catenary)	**Vehicle Cost: $8 million per locomotive.** Based on approximate cost of ACS-64 Amtrak locomotives (Sachse, 2011). **Fuel Cost: $0.105/kWh (low) to $0.18/kWh (high)** These values reflect approximate lower and upper bounds of 2014 cost estimates prepared by Amtrak's national office (Auve, Bill, Amtrak, personal communication, November, 2014) for this research paper. **Catenary Costs** **Construction: $1.25 Million/mile** (Regional Transit District, Unpublished data**) to $8.08 Million/mile** (calculation based on Caltrain electrification documents) (Board, 2014, Samtrans, 2014); applied to 300 track miles (150 miles, two tracks) **Maintenance:** Calculation based on Amtrak actual catenary maintenance data for FY 2013 (Amtrak, Unpublished data); Adjusted for differing track length and number, and rough estimation of train traffic ratios **Emissions:** Based on GREET (GREET, 2015), US Mix, CA Mix	**Vehicle Cost: $12 million for 3 locomotives** Based on significant 2012 study on regional goods movement in CA (CambridgeSys, 2012), which suggests $5 million for an electric locomotive and $3.5 million for a diesel-electric; Utilizing the price premium for electric over diesel-electric (while noting that study's focus on engines with higher power than most American freight locomotives, and its higher-cost diesel-electric estimate), leads to analysis assumption of $4 Million per locomotive **Emissions:** Same as Passenger **Fuel Cost:** Same as Passenger **Catenary Costs:** Same as Passenger (applied to 4,000 track miles)

5. Results and Discussion

Our passenger cost comparison (Figure 1) combines train capital and operating costs over a train life of 20 years but represented as average annual costs, in the application case study described above. The results demonstrate that, for passenger trains in the Capital Corridor or perhaps any corridor of similar length, fuel costs are generally about equal to or possibly greater than locomotive costs over a 20 year period (with electricity and CNG appearing as clear exceptions to this finding). It also shows that comparative differences in fuel costs are typically larger than are locomotive cost differences. For example, while the annual capital cost differences across technologies (not counting electric infrastructure) vary between about $8.8 million and $9.9 million and appear almost indistinguishable in the chart, a CNG train system shows annual fuel costs that range between $6 million and $8 million, while a train system operating on either biodiesel or renewable diesel might result in costs anywhere from nearly $10 to about $14 million. (Electric fuel costs are not even on the same scale as these others, though the fixed infrastructure required presents a very different overall picture.) With the relatively low cost of natural gas in the U.S. today, liquid natural gas might reduce cost if compression ignition were to be the primary technology; however, spark ignition technology, which imposes an efficiency penalty of about 20%, would add most likely add cost (depending, of course, on diesel prices). Electricity costs are very high due mainly to the high cost of the catenary electricity infrastructure, which would require very high volumes of trains to defray, much more than we assume in the default scenario. FAME biodiesel and especially Renewable Diesel from oil feedstocks are likely to add considerable fuel cost.

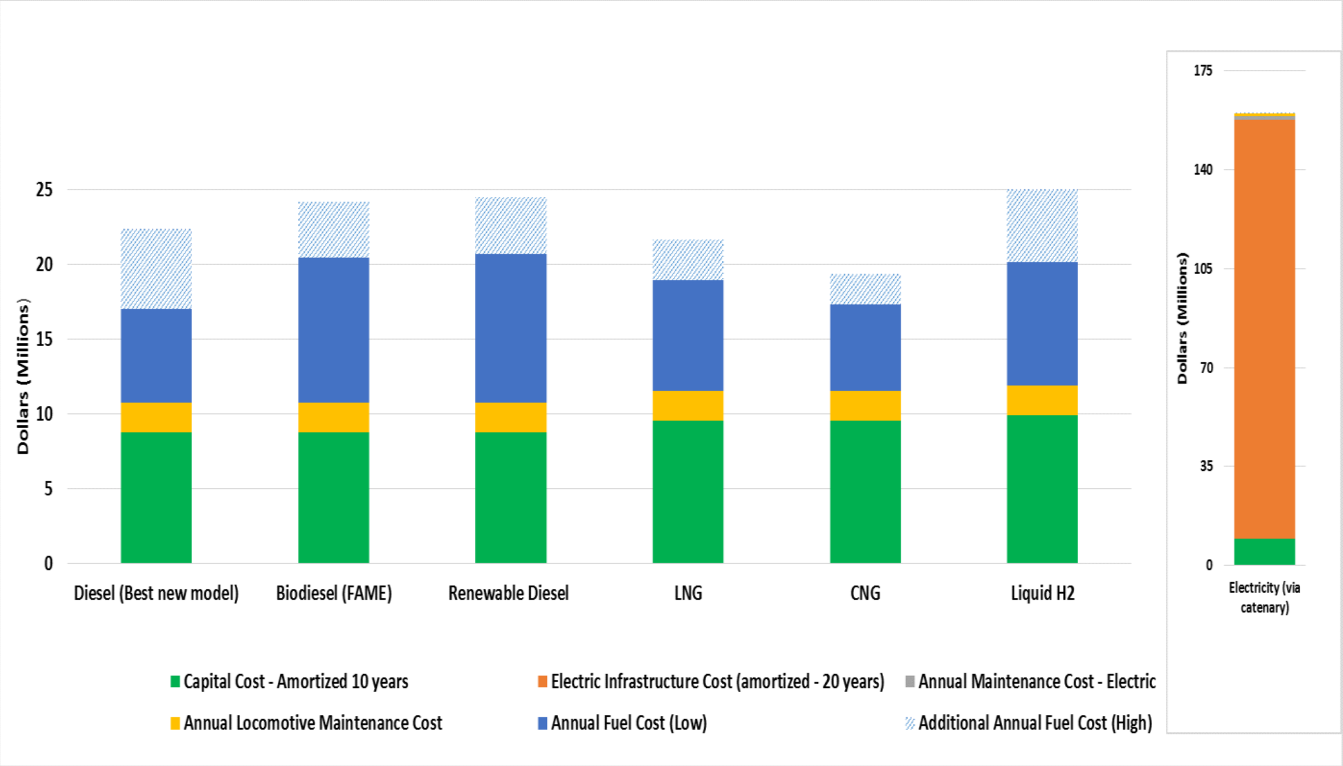

Figure 1. Passenger Annual Energy Technology Cost Comparison – Midpoint capital and maintenance costs, with fuel cost range, Millions of Dollars; LNG includes both SI and CI technologies; Annual fuel cost (low) represents minimum cost, based on low price (see Table I for additional detail). Additional fuel cost (high) represents remainder of the range, with the top of that bar reflecting maximum cost, based on high price.

From a cost-comparison standpoint, the freight costs, as depicted in Figure 2, provide a stark contrast to the passenger scenario in the sense that total costs are far higher, and fuel costs compose an even higher share of total costs due to the tremendous energy required to move freight around. (Hence the strong interest on the part of freight firms in cheaper fuel alternatives.) On the other hand, the freight annual cost scenario results compared across the different options don’t look exceptionally different from the passenger results. The freight hydrogen fuel cost variation largely reflects differences between the costs of relying on steam methane reformation (SMR) versus electrolysis, with hydrogen electrolysis demonstrating the higher fuel costs likely to be associated with this option in the near term. Also, because fuel usage is such a significant component of total costs, the electricity option, while still very high, is not as disproportionately high as in the passenger scenario. In this case of freight, with the large fuel requirements, the difference between compression ignition (CI) and spark ignition (SI) natural gas becomes more significant. An additional tender is required with the lower efficiency of a spark system; hence the two approaches are broken down into separate bars in the charts.

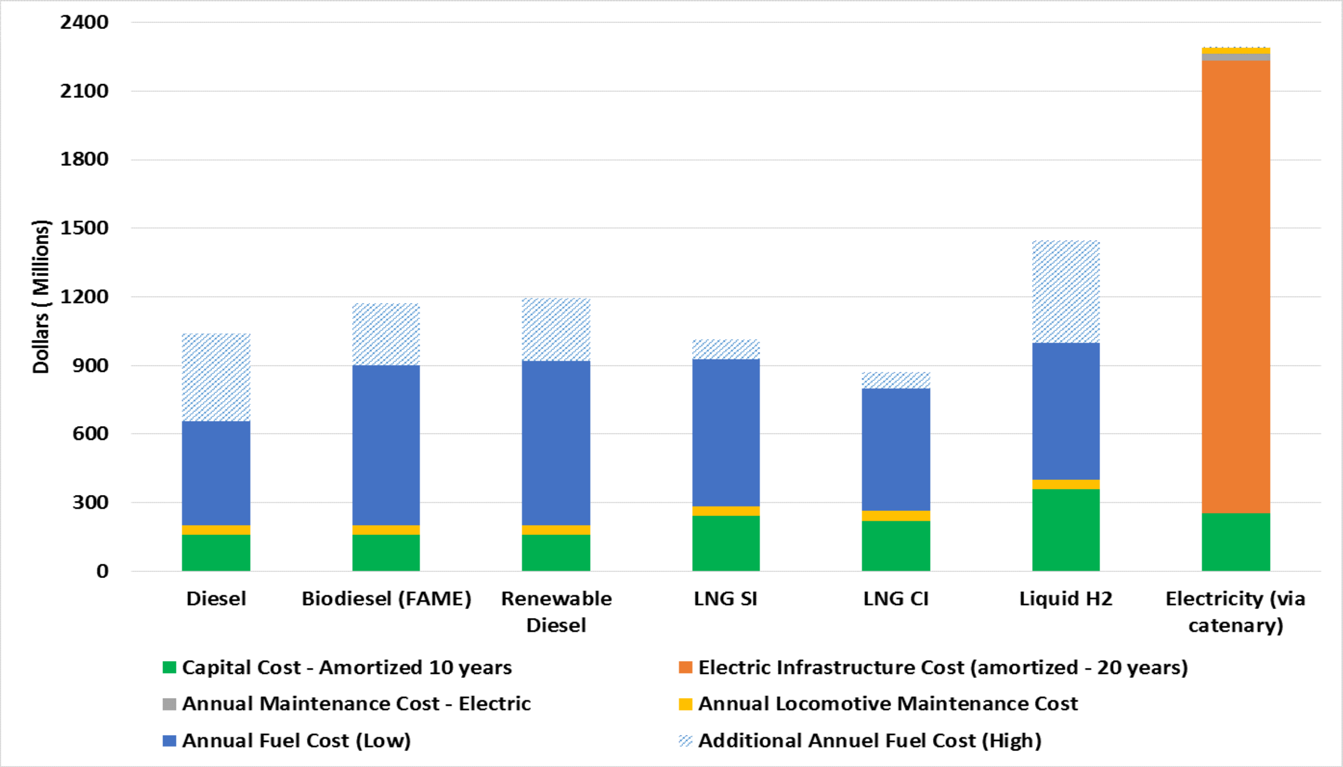

Figure 2. Freight Annual Energy Technology Cost Comparison – Midpoint capital and maintenance costs, with fuel cost range, Millions of Dollars (SI = Spark Ignition, CI = Compression Ignition); LNG SI and CI capital costs vary due to differing number of tenders required; See Figure 1 for fuel cost explanation

With increased train volume along the route, along with the increase in accompanying fuel required, the fixed catenary infrastructure costs begin to be outweighed by the additional locomotive capital costs and sheer amounts of fuel needed, given that electricity as a fuel (technically an “energy carrier”) is extremely cost-effective. Figure 3, below, shows that, for freight rail, electricity quickly becomes cheaper than liquid hydrogen via electrolysis (before traffic volume even doubles), and then becomes a better option, cost-wise, than all of the other fuels somewhere between about 2.5 times and 3.8 times the current (i.e. default) volume. Biodiesel and LNG SI are surpassed at the lower end, while diesel and LNG CI hold up as cost-effective the longest. (In the case of LNG, the lower efficiency of spark ignition also requires more supplemental infrastructure, in the former of fuel tenders, than does its CI counterpart. This partly explains the cost gap between the two.) For passenger rail or a combination of both passenger and freight, a similar trend would be seen, though the traffic volumes required for parity would be higher due to the lower number of locomotives per train and the lower overall fuel usage.

Moving beyond the cost part of the equation, figure 4 shows the CO2-equivalent greenhouse gas impacts of different technologies compared to a base diesel-electric locomotive over the years of operation (20 years for passenger trains, 30 years for freight), including the maximum percentage emissions reduction. As mentioned above, these are based primarily on the use of the GREET model (GREET, 2015)**,** with assumptions set appropriately for rail applications. While there is considerable variation for each fuel type, some appear to have greater potential than others. Electricity will likely cut GHGs by between approximately 44% (US Mix) and 65% (CA Mix) while for hydrogen a large range is evident; via SMR, hydrogen may only be marginally cleaner, if not higher emitting, than diesel whereas from electrolysis with CA electricity mix, it cuts CO2e considerably (perhaps by greater than 70%). LNG provides relatively small CO2e reductions at best, with the range dependent in part on assumptions around methane leakage, an uncertain element in the LNG fuel cycle. Biodiesel offers considerable reductions but with a wide range, depending on the specific feedstocks and fuel pathways assumed. This does not take into account the possibility of severe secondary effects, such as indirect land use changes spurring large GHG emission increases elsewhere in an agricultural system.

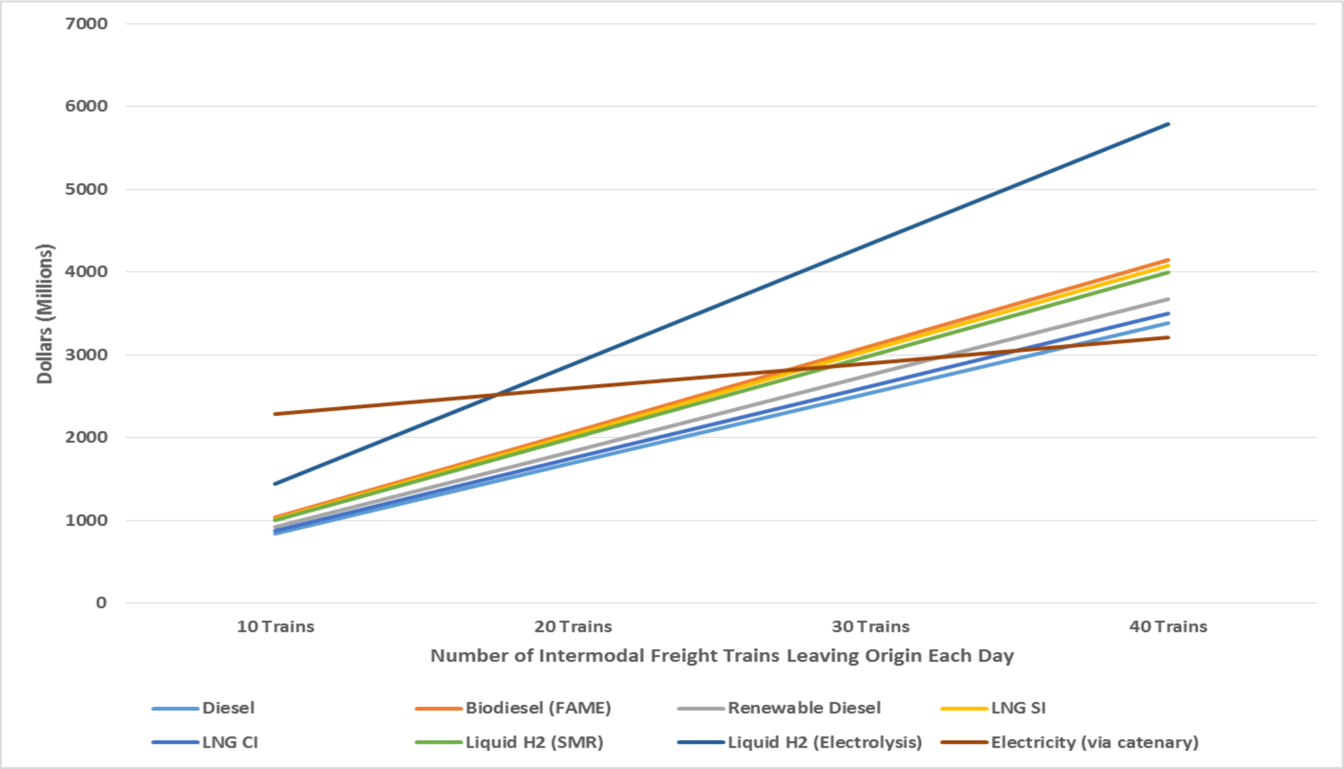

Figure 3. Freight Traffic Volume Cost Sensitivity – Midpoint costs, Millions of Dollars

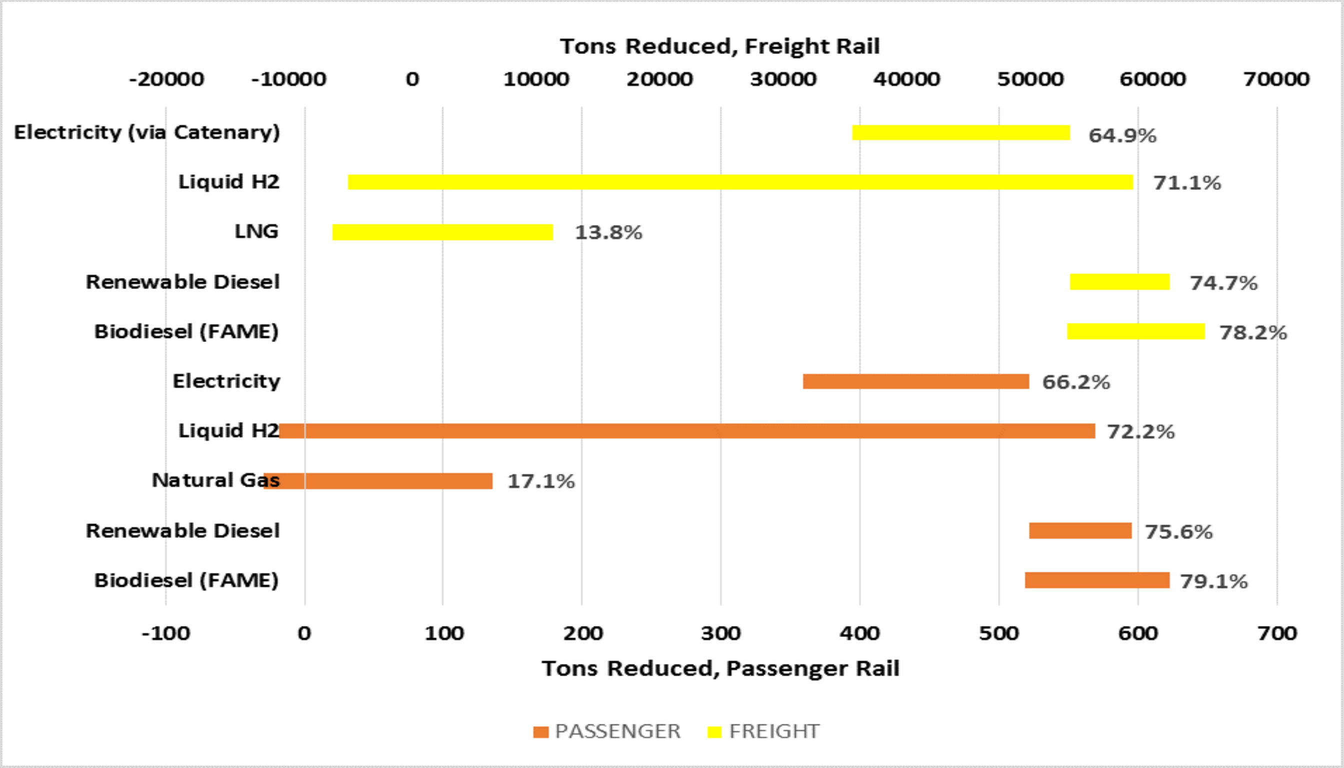

Figure 4. Lifetime reduction range, CO2-eq GHGs, compared to base diesel, Tons, Passenger and Freight Rail

Our GHG analysis includes only fuel cycle emissions (not rail infrastructure or train construction emissions) and, since the comparative proportions of emissions are the same whether passenger or freight, the relative position of different fuels for freight is nearly identical to passenger – the main difference is the much larger magnitude of GHGs reduced by all the different options (hence two separate horizontal axes), since so much more fuel is used in the freight example. This is a reasonable reflection of freight rail systems compared to passenger systems in general, given the more intensive use of freight locomotives and the much heavier loads they pull, resulting in far higher energy use and reflected in the much higher fuel costs.

The analysis does not consider the trend towards more CO2-intensive sources of conventional petroleum fuels (Martin, 2016); however, since the increased emissions come from changing petroleum sources and extraction techniques (Martin, 2016), given that the same petroleum would have been extracted for other purposes, it could be argued that such increased reductions may be academic from a pure rail fuel demand perspective.

6. Conclusions

All of the major propulsion and fuel technologies that are being considered to reduce greenhouse gas impacts of the on-road fleet could be applied to the rail sector as well. In many cases, however, due to the much higher power requirements involved as well as the quantities of fuel required to move a vehicle as large and heavy as a train, the transfer of these technologies requires various modifications, some of which could be rather significant (particular fuel supply and storage). Some technologies, such as fuel cells, have not been extensively tested, particularly in line-haul applications.

This paper offers an overview of the types and potential levels of cost along with fuel and CO_2 reduction benefits that might be expected by choosing among various alternatives in the relative near-term, in the context of real or hypothetical rail corridors in order to better estimate fuel requirements. The overall findings provide a rough idea of typical passenger and rail operations, though are not at the level of detail to compare these options in specific applications (e.g. taking into account changes in grade along a route, speed variations, or train volumes). In addition, all of the alternatives explored in the study are based on switches to single-fuel alternatives; however, in reality, variations of hybridized technologies may both prove helpful in cutting emissions and, moreover, help offset some of the challenges faced by some of the newer propulsion technologies. Such hybridized powertrains, in particular exploring a role for batteries and/or ultracapacitors to supplement the primary on-board power plant, warrant future research.

This study's estimates are based on reasonably large volume production of both rail and fuel components; initial demonstration projects may be much more expensive. One way that scale economies could be achieved, for example with LNG or hydrogen projects, is to use the same fuel infrastructure for rail as is used to provide fuel for road applications. Identifying ways to locate fuel production/storage equipment close to both rail and road refuelling locations is a promising area for future research.

The study findings suggest that there is significant uncertainty in both costs and emissions reductions by the alternatives examined as compared to the diesel default. From a cost standpoint, this is due to the uncertainty in the cost of diesel fuel, itself, combined with the uncertainty in the cost of the alternative fuel technologies, the processes for development of which are only beginning to be laid out, and the preferred feedstocks for which are, at the present time, not yet determined. From an emissions standpoint, as the processes involved become clearer, so will the resulting emissions reduction, as the varied energy conversion paths (including primary feedstocks) have widely varying emissions impacts.

Uncertainty aside, one challenge that is posed by the study findings is that, in the near-term, natural gas, the fuel most likely to keep costs relatively stable or even offer savings, may not offer a significant CO2 benefit. Beyond the near-term, future research and development are likely to bring some of the higher cost options into more reasonable cost territory; in the meantime, both public and private investment into this R&D, with more demonstrations and pilot projects, will be crucial.

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