Techno-Economic Analysis of Line Haul and Switcher Locomotive Propulsion by Diesel, Battery, and Hydrogen Fuel Cell Technologies

by

Benjamin D. Lerman
B.S., Mechanical Engineering
Northeastern University, 2019

Submitted to the MIT Sloan School of Management and
Department of Mechanical Engineering
in partial fulfillment of the requirements for the degrees of

Master of Business Administration

and

Master of Science in Mechanical Engineering

in conjunction with the Leaders for Global Operations program
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
May 2024

Author . . . .
MIT Sloan School of Management and
Department of Mechanical Engineering
May 16, 2022

Certified by. . . . .
Steven J. Spear, Thesis Supervisor
Senior Lecturer, System Dynamics

Certified by. . . . .
Wai Cheng, Thesis Supervisor
Professor of Mechanical Engineering; Director, Sloan Automotive Laboratory

Accepted by . . . .
Nicolas Hadjiconstantinou
Chair, Mechanical Engineering Committee on Graduate Students

Accepted by . . . .
Maura Herson
Assistant Dean, MBA Program, MIT Sloan School of Management

Techno-Economic Analysis of Line Haul and Switcher Locomotive Propulsion by Diesel, Battery, and Hydrogen Fuel Cell Technologies

by

Benjamin D. Lerman

Submitted to the MIT Sloan School of Management and
Department of Mechanical Engineering
on May 10, 2024, in partial fulfillment of the
requirements for the degrees of
Master of Business Administration
and
Master of Science in Mechanical Engineering

Abstract

This thesis examines the critical challenges of reducing greenhouse gas (GHG) emissions within the freight rail industry of the United States transportation sector. The transportation sector, being a significant contributor to the nation's GHG emissions, requires urgent attention to mitigate environmental and public health impacts. This thesis presents the emissions profile of the U.S. freight rail system and explores potential strategies for decarbonization. Previous research has established the freight rail system as a relatively more efficient mode of cargo transport in terms of emissions; however, to attain national goals set for GHG emissions, further reduction of its carbon footprint is required. Through a detailed analysis of the current propulsion technologies, ranging from conventional diesel-electric locomotives to emerging alternatives such as battery electric, hydrogen fuel cell, and electrified rail, the paper evaluates their potential to reduce emissions within the freight rail sector. The use of a Total Cost of Ownership (TCO) and Environmental Impact Analysis quantifies the financial and environmental implications of adopting these technologies. The findings reveal significant opportunities for reducing GHG emissions through the adoption of cleaner propulsion technologies. Challenges associated with their implementation include infrastructure requirements and technological readiness. A strategic roadmap for the decarbonization of freight rail is proposed, segmented into short-term (0-5 years), medium-term (5-15 years), and long-term (15+ years) objectives. Emphasis is placed on the importance of regulatory frameworks, technological advancements, and stakeholder collaboration in achieving a sustainable transition. The study aims to inform policymakers, industry stakeholders, and researchers about the pathways towards a sustainable and efficient freight rail system.

Thesis Supervisor: Steven J. Spear
Title: Senior Lecturer, System Dynamics

Thesis Supervisor: Wai Cheng
Title: Professor of Mechanical Engineering; Director, Sloan Automotive Laboratory

Acknowledgments

In the sweltering embrace of a Florida summer, where the sun reigns supreme and the humidity clings with unyielding persistence, I find solace in a silent hero: air conditioning. To this marvel of human ingenuity, I extend my heartfelt gratitude. You stand as a steadfast guardian against the relentless heat, a source of comfort when the outside world becomes a furnace unkind to the spirit of adventure.

Thank you to NextEra Energy and my colleagues.

Thank you to my peers in the LGO program. I have been constantly impressed by their perseverance, integrity, knowledge, and skill. You all have helped me to make the best of the opportunity I have been given as a student at MIT.

Thank you to my friends and colleagues at EPAM.

Most importantly, thank you to my partner, Joanna. You have always been incredibly supportive, but especially so over the last two years. Love you!

THIS PAGE INTENTIONALLY LEFT BLANK

Contents

THIS PAGE INTENTIONALLY LEFT BLANK

List of Figures

List of Tables

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 1

Introduction

1.1 Importance of Reducing Greenhouse Gas and other Emissions

This chapter will explore the significant role of the transportation sector in U.S. emissions, its impact on the environment and public health, and the challenges and benefits associated with reducing emissions in this sector. By doing so, I aim to highlight the urgency and necessity of addressing emissions in the transportation industry to meet international climate goals and ensure a sustainable future.

Human actions have led to the warming of the global surface temperature, a claim supported by scientific consensus. Through the emission of greenhouse gases (GHG), gases that absorb infrared light, the surface of Earth has reached 1.1 degrees Celsius above pre-industrial levels in 2011-2020. Global greenhouse gas emissions have continued to increase over 2010-2019 as a result of energy use, land use, patterns of consumption, and production. Global warming is creating changes to global climate and has led to widespread adverse impacts on human health, economies, and water and food security [1].

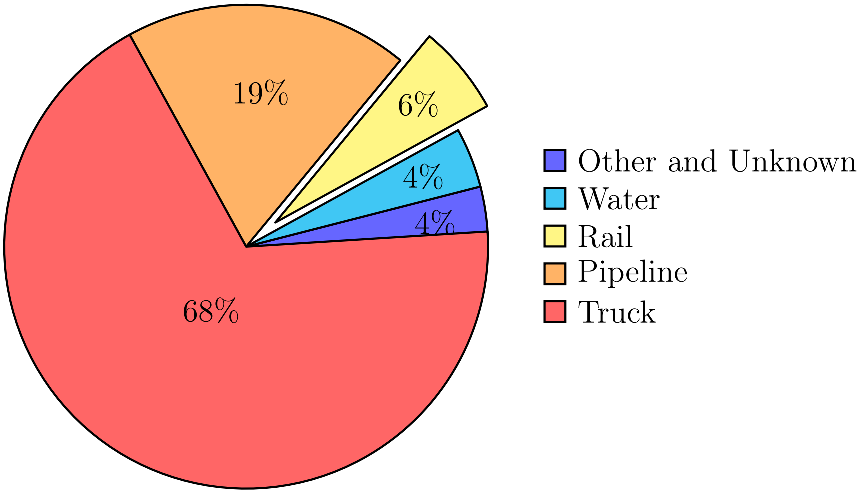
North America stands out for having the highest per capita anthropogenic greenhouse gas (GHG) emissions, revealing a stark asymmetry between the contributors and the impacted. Nations that contribute most to GHG emissions often experience fewer direct consequences compared to more vulnerable countries. Even though climate change is impacting human and natural systems across the globe, more vulnerable countries generally have lower emissions per capita [1]. This disproportionate production of GHG emissions has put a spotlight on the most emitting countries to reduce their emissions, which led to the creation of the Paris Agreement in 2015. This legally binding international treaty on climate change intends to limit global warming to well below 2 degrees Celsius below pre-industrial levels [2].

In response, the United States has created a long-term strategy to achieve net-zero GHG emissions by 2050. By decarbonizing electricity generation, electrifying end uses, switching to cleaner fuels, and reducing energy waste, it is expected that the United States can avoid $1-3 trillion in healthcare costs through 2050 [3].

1.2 United States Transportation Industry

The transportation sector in the United States provides vital services for people and goods to be transported locally and over long distances. Through the use of on-road vehicles, planes, trains, ships, public transportation, and a wide variety of other modes, the transportation sector enables people to carry out commerce, experience social interactions, and engage in productive pursuits. Thirty-eight percent of the U.S. gross economic output in 2020 depended on the Nation's Transportation and Logistics sector to move freight across the country. In 2020, the sector moved over 17 billion tons of domestic freight, equivalent to $14.5 trillion, through $7 trillion of assets including ports, highways, railroads, airports, and pipelines [4]. Shown in 1-1, in 2019 trucks were responsible for transporting 67 percent of total domestic freight by weight and rail transported roughly 7 percent of total domestic freight by weight. It is expected that total weight of domestic products transported will increase about 1.4 percent per year between 2022 and 2050 [5].

Figure 1-1: Weight of Shipments by Transportation Mode



1.2.1 Industry Emissions

The transportation sector is one of the largest contributors to US greenhouse gas emissions. Shown in Figure 1-2, in 2021, this sector accounted for the largest portion (29%) of all emissions in the US, greater than electric power generation, industry uses, commercial and residential uses, and agriculture. End-use sources of emissions include cars, trucks, aircraft, ships, and rail. Since 1990, U.S. gross GHG emissions have decreased by roughly 2%, however, transportation sector emissions have increased by 19%. This is due mostly to increased demand for travel, which is exhibited by an increase of the number of vehicle miles traveled by cars (45%). Emissions from the transportation sector include carbon dioxide (97.3%), methane (0.1%), nitrous oxide (0.7%), and hydrofluorocarbons (0.1%)[6].

Diesel engines are frequently employed to propel commercial freight transportation vehicles, including trucks and rail locomotives. Nonetheless, the emissions produced by diesel engines pose significant adverse effects on both the environment and public health. Diesel exhaust emissions contain notably elevated levels of particulate matter and its precursors, which have been linked to respiratory and cardiovascular issues, as well as premature mortality [7] [8] [9] [10].

It is simple to state that in order to meet international goals for reducing carbon emissions, the transportation industry must undergo change. Reducing emissions in transportation is more costly than other sectors, largely because of its reliance upon fossil fuels. A transition away from fossil fuels faces two barriers: incomplete international agreements and the high cost of clean technologies [11]. The benefits of reducing emissions include improvement of human health due to reduced exposure to diesel emissions and a reduction in the progression of climate change.

Figure 1-2: Share of US GHG Emissions by Sector, 2021

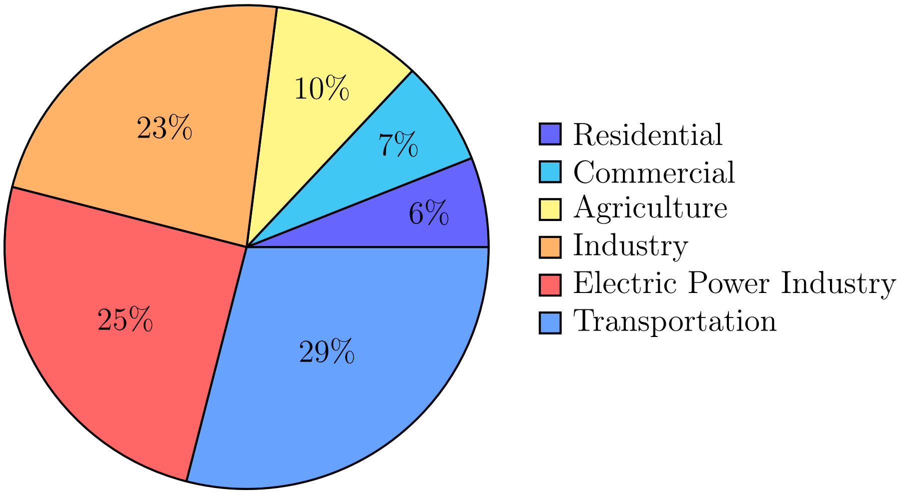
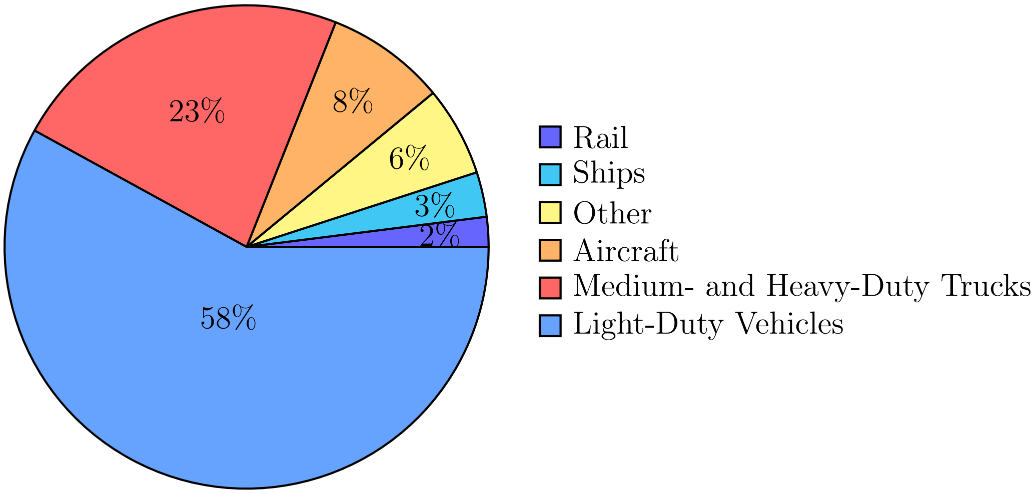


Figure 1-3: Transportation Sector GHG Emissions by Source, 2021



Chapter 2

U.S. Freight Rail Companies, Suppliers, and Regulators

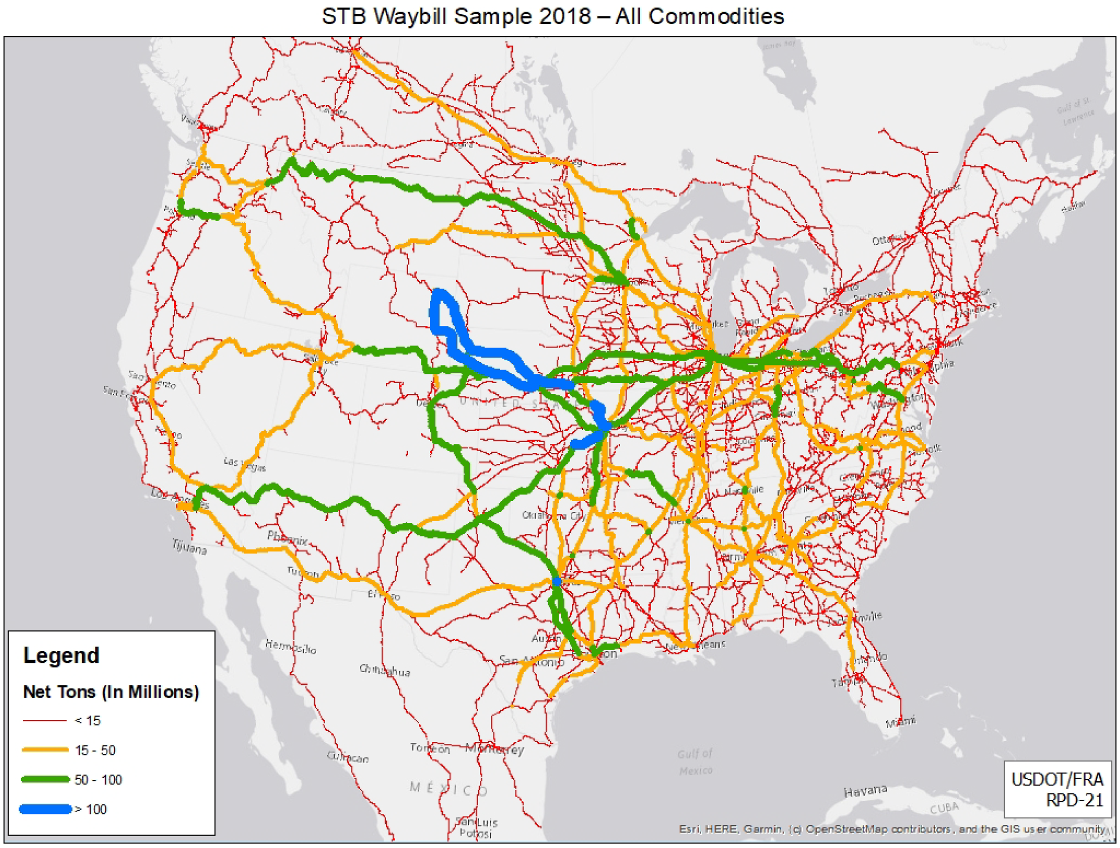
This chapter will provide important background information on U.S. Freight Rail Companies as well as an introduction to the industry's suppliers and regulators.

2.1 US Freight Rail

The U.S. freight rail system is considered to be the largest, safest, and most cost-efficient freight system in the world. In a typical year, the system carries 40% of all domestic freight (1.6 billion tons) across the US every year. In 2022, the average freight train carried 4,089 tons.

Goods are moved through different means depending on their value and distance travelled. A high percentage of freight value and weight is moved over short distances and is done primarily by truck. While trucks are responsible for moving the most amount of value, tons, and ton-miles for goods shipped up to 749 miles, rail leads in tonnage and ton-miles for goods shipped from 1,000 to 2,000 miles [4]. Freight rail is the primary method for moving heavy commodities like agricultural and food products, grain, chemicals, coal, construction products, pulp and paper, and crude oil. In addition, rail plays an important role in intermodal shipments which accounted for 27% of revenue, more than any other segment [12].

Figure 2-1: Map of freight travel by weight



America's freight railroads are almost entirely privately owned, unlike passenger railroads. The passage of the Staggers Rail Act in 1980 significantly reduced the cost of freight rail shipment, allowing the industry to invest additional funds into their railroads. Since the deregulation of rail in 1980, freight rail companies have invested $780 billion dollars into maintaining and upgrading their railroads [13], an average that is roughly six times more than the average US manufacturer spends on maintaining and upgrading their equipment [14].

Companies that operate railways in the US are classified into three groups. These classes are defined by the Surface Transportation board according to revenue metrics, with Class I being the highest earning, followed by Class II and III. The revenue thresholds are adjusted annually are currently [15]:

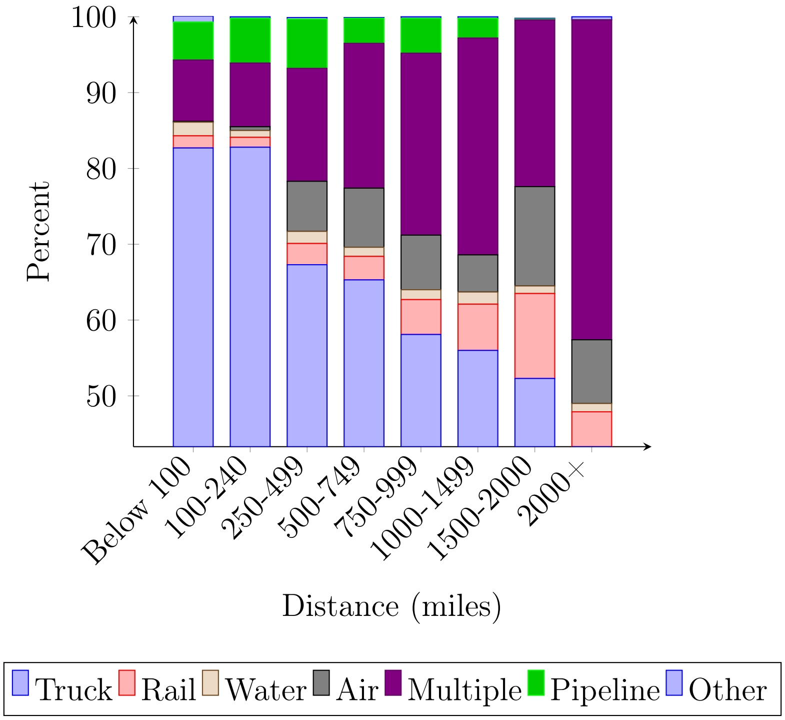
1. Class I: annual revenue greater than $900 million
2. Class II: annual revenue between $900 million and $40.4 million
3. Class III: annual revenue less than $40.4 million

2.1.1 Challenges of the US Freight Rail Industry

Infrastructure

Given that nearly all of the freight railroads in the US are privately owned, it is understood that they are maintained by freight rail companies. There is minimal government support in railroad maintenance, aside from a federal tax credit for class III rail companies that provides $0.50 for every $1.00 spent up to $3,500 per mile on track improvements. Since the tax credit began in 2005, $4 billion has been deployed, which is only 1% of the amount rail companies spent on maintenance. The need to expand, operate, and maintain the vast network of track requires heavy expenditure directly by rail companies.

Figure 2-2: Mode share of delivered goods by value



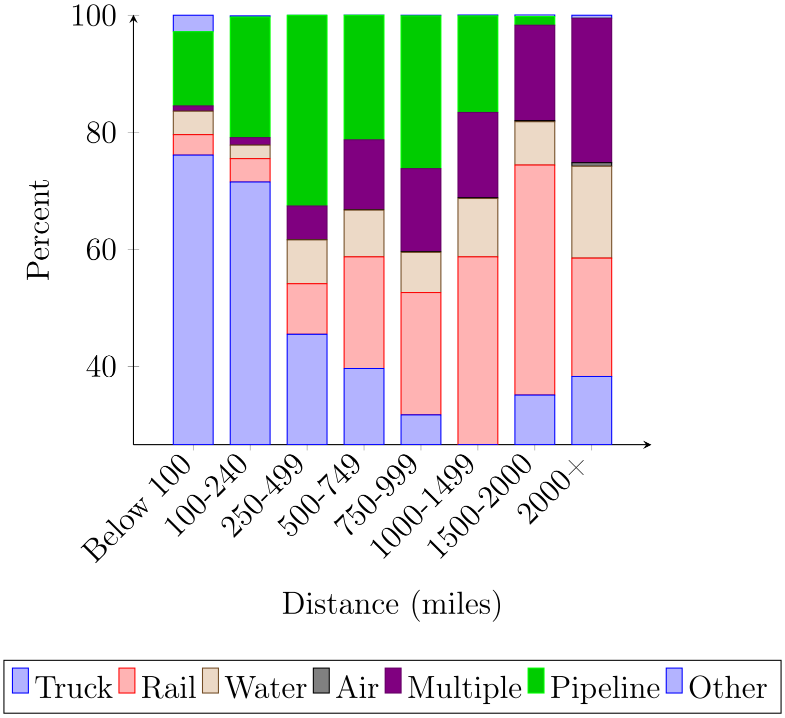
Competition from Freight Trucking

Railroads are regarded as the most efficient means to transport goods across the country, especially when travel distances are long. However, if looking at travel routes that are shorter, then other modes of transportation become favorable. Trucks are used to for the overwhelming majority of freight by weight over distances less than 500 miles because of their flexibility to operate on widespread road systems throughout the U.S. Further, trucking ships more valuable goods across all distances than rail. There have also been recent technological innovations for trucks to use cleaner fuels, lowering the emissions burden for that mode of transportation. For railroads to earn more revenue, they have to constantly compete with the trucking industry, especially in shorter distance deliveries [5].

Regulatory and Policy

The regulation of the U.S. freight rail industry involves several regulatory bodies at the federal and state levels. Federal agencies provide standards for emissions, economics

Figure 2-3: Mode share of delivered goods by weight



regulations, and safety requirements that directly impact the operations and viability of railroads. State agencies provide additional regulations around emissions and safety. Most recently, the state of California has created the most stringent locomotive emissions standards in the industry.

Labor Relations

Railroads employ a largely unionized workforce that operates locomotives, maintains tracks, and services equipment. Roughly 54% of the railroad workforce is unionized, a proportion higher than the trucking, airline, and all other industries combined [16]. Labor unions have power to negotiate staffing amounts, pay, and benefits, all which directly impact railroad operations.

Safety

Safety is a top priority for the industry that is integral to its operations. Railroad operators are constantly scrutinized for their safety records, especially given the 2023 train derailment in East Palestine, Ohio. Rail companies may struggle to introduce any new practices that may jeopardize their safety records.

Technological Advancements

The industry is constantly investigating new technologies that may be able to improve operations. New locomotive, control systems, sensors, and switches are tested by railroads across the U.S., but at a pace that is slower than other industries. Due to the high demand of the rail environment, streamlined operations, and high capital costs, rail companies are constrained by inertia and often takes years before a new technology can be proven to function for in-service use. Ultimately, this results in the industry's untimely adoption of promising technologies.

2.1.2 Class I Rail Companies

Class 1 rail companies are those that have operating revenues greater than $900 million annually. The current class I freight railroads are: BSNF, Union Pacific (UP), Canadian National (CN) Canadian Pacific Kansas City (CPKC), Norfolk Southern (NS), and CSX Transportation (CSX). All class I companies own and operate their own railroads, but also create special arrangements with each other to share track, locomotives, or rolling stock.

2.1.3 Class II and III Rail Companies

The Association of American Railroads, further classifies non-class I rail companies into three categories:

1. Regional: operate at least 350 miles or make at least $40 million in revenue annually.
2. Local: smaller than a regional railroad, but engage in line-haul service.
3. Switching and terminal: making up and breaking up trains, storing and classifying cars, serving industries within yard limits.

Table 2.1: Annual Energy Consumption and Emissions[14]

Metric	Year			
	2010	**2015**	**2020**	**2021**
Rail Diesel Fuel Consumed (millions gallons)	3,494	3,692	2,959	3,081
Energy Consumed (trillions of Btu)	480	507	407	423
Energy Intensity (Btu per ton-mile)	289	297	296	298
Emissions (millions of metric Ton CO2 equivalent)	38	39	31	32
Freight Rail Emissions (as a percentage of freight total)	8%	8%	6%	6%

2.1.4 Emissions Profile

In terms of greenhouse gas emissions, freight rail is generally considered to be more fuel-efficient and environmentally friendly compared to other modes of transportation, such as trucks and airplanes. This is because trains can move large amounts of freight over long distances with relatively lower fuel consumption per ton-mile. Although the transportation sector contributes to 29% of all GHG emissions in the United States, freight rail transportation stands out with only a 2% share within this sector, making it one of the smallest contributors compared to other emission sources. Nevertheless, a reduction of emissions is essential for a holistic approach to combat climate change and improve overall environmental sustainability in the transportation sector and beyond. Nearly all the emissions from freight rail are a result of the industry's dependence on diesel combustion locomotives to move goods across the country. In contrast to many European countries, the U.S. has no electrified fright rail. Diesel locomotives combust diesel fuel and release a significant amount of air pollutants, which has been shown to negatively affect human health [17]. Primary locomotive emissions include carbon dioxide (CO2), particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbons (HCs).

2.1.5 Association of American Railroads

The Association of American Railroads (AAR) is an advocacy group that plays a crucial role in representing the interests of the freight rail industry in the United States. As the leading trade association for Class I freight railroads, the AAR advocates for

Table 2.2: Scope 1 Emissions by Company[14]

Rail Company	**Scope 1 GHG Emissions, 2021 (mTons CO2e)**
Norfolk Southern	4,165,808
CSX	3,956,000
Union Pacific	9,236,750
BSNF	12,361,489
CPKC	2,629,020
Total	29,720,047

policies that support and advance the industry's growth and sustainability. Through its advocacy efforts, the AAR works to promote freight rail as an environmentally friendly and fuel-efficient mode of transportation. The association collaborates with policymakers, regulators, and stakeholders to ensure a favorable regulatory environment that encourages investment in rail infrastructure, safety initiatives, and technological advancements. The AAR has faced criticism for various aspects that may hinder positive progress in the freight rail industry. One concern is that the AAR, representing the interests of major Class I railroads, may prioritize profit-making objectives over broader societal interests. This focus on profitability can sometimes conflict with initiatives aimed at investing in sustainable technologies or reducing the environmental impact of freight rail operations.

2.2 Suppliers of US Freight Rail

This section delves into the crucial suppliers of freight rail companies, focusing on Energy Suppliers, Locomotive Suppliers, and Intermodal Yards and Equipment Suppliers. These suppliers have unique perspectives on the current and future states of the industry and ultimately serve rail companies and their interests.

2.2.1 Energy Suppliers

Energy providers for freight rail companies play a pivotal role in powering the locomotives and operations that keep goods moving efficiently across vast rail networks. These providers offer a diverse range of energy solutions, including diesel fuel, electricity, and, increasingly, environmentally friendly options like natural gas and sustainable electric sources. With the transportation industry's growing focus on sustainability and reducing carbon emissions, energy providers are working to offer cleaner and more efficient energy solutions to help freight rail companies meet their environmental goals. Reliability and cost-effectiveness are also critical factors for rail companies, as they depend on consistent, cost-efficient energy sources to ensure the smooth and timely movement of goods throughout the country.

2.2.2 Locomotive Suppliers

There are two main locomotive companies that supply the U.S. freight rail industry: Progress Rail and Wabtec, hold 35% and 65% of the market, respectively. These companies directly supply new locomotives, upgrade (repower) old locomotives, provide maintenance service, and test new locomotive technologies. Locomotive suppliers have mapped out their strategic interests in the short, medium, and long term, outlined here.

Progress Rail

Headquartered in Albertville, Alabama, Progress Rail, a subsidiary of Caterpillar Inc., is a globally recognized leader in the field of rail technology and services. The company is known for its solutions in locomotive and railcar manufacturing, as well as a wide array of services to support the rail industry. Progress Rail provides technology such as locomotive and track inspection systems, signaling and communication solutions, and maintenance services that enhance the safety, efficiency, and sustainability of rail operations. Their parent company's experience with marine motors gives Progress Rail a distinct advantage when building new engines that run on methanol.

Wabtec

Headquartered in Pittsburgh, PA, Wabtec, short for Westinghouse Air Brake Technologies Corporation, is a globally renowned leader in the rail and transportation industry. With a rich history dating back to the 19th century, Wabtec has evolved into a powerhouse in the design, production, and implementation of innovative solutions for the world's rail and transit systems. The company's offerings span a wide spectrum, including locomotives, freight and passenger transit systems, digital solutions, and safety equipment. in 2019, Wabtec announced the acquisition of General Electric Transportation, making Wabtec the biggest market share owner by far.

Strategic Perspective of Locomotive Suppliers

In the short term, the focus is on addressing the utilization of existing locomotives. Research is underway to demonstrate the viability of biodiesel as a practical alternative for railroads, with a particular emphasis on the companies UP and BNSF. This activity is driven by pricing considerations in California. Both B20 and R100 blends have received approval, and further research is ongoing to secure additional certifications.

In the medium term, locomotives to be produced within the next 3-5 years are of key interest. Customers are increasingly expressing interest in battery electric and hybrid locomotives as they strive to meet decarbonization objectives. Manufacturers have already released the first battery-electric locomotives and although some strides are being made in developing charging infrastructure for these locomotives, it is not the primary focus of the business. Hybrid locomotives, which use a combination of an internal combustion engine and battery bank, are easier to integrate into existing rail operations and represent a versatile platform that can be adapted for future power technologies. Hybrid locomotives, although frequently analyzed by suppliers, have yet to be widely produced.

Looking towards the long term, which extends well beyond the next 5 years, locomotive suppliers' exploration of hydrogen-based fuels, such as H2, methanol, ethanol, and ammonia, becomes a priority. Converting diesel engines to run on methanol or ethanol through spark ignition, while resulting in a reduction in power, shows promise, which could potentially be compensated for using battery technology. Currently, hydrogen (H2) fuel cells are leading the charge in long-term technological advancement, although a complete understanding of their potential is yet to be achieved, necessitating further research and development in this area.

2.2.3 Intermodal Yards and Equipment Suppliers

Intermodal rail yards have become increasingly significant in modern logistics due to their ability to reduce transportation costs, minimize congestion on highways, and lower the environmental impact of goods movement by promoting the use of trains. Intermodal rail yards facilitate the exchange of cargo containers between different modes of transportation, including ships, trucks, and trains. These yards are strategically located at key points in the transportation infrastructure, serving as crucial intermediaries for the efficient movement of goods. At intermodal rail yards, cargo containers are transferred between railcars, allowing the integration of rail transportation into the broader supply chain. This process, known as intermodal transportation, optimizes the movement of goods and is especially valuable for long-distance shipping. Intermodal yards are equipped with an array of specialized equipment, including container lifts and yard trucks, to move cargo within the yard. The yards also house extensive storage facilities, often with tracks and stack areas to accommodate the diverse array of cargo containers.

Container Lifts

Container lifts are specialized machines designed for the efficient loading and unloading of cargo containers onto and off of railcars. These heavy-duty devices are crucial for streamlining the intermodal transportation of goods, offering a swift and seamless transition between different modes of transport. Container lifts come in various configurations, including top-lift spreaders, side-lifters, and straddle carriers, each suited to handle different types and sizes of containers. Nearly all the container lifts are powered by diesel combustion engines, however an emergence of hybrid, battery-electric, and shore power versions of these machines are gaining popularity due to their promise of reduced emissions and operating costs.

Yard Trucks

Yard trucks, also known as terminal tractors or shunt trucks, are used to move trailers within the confined spaces of intermodal facilities. These specialized vehicles typically feature a diesel or, more recently, electric powertrain, with some models offering alternative fuel options like compressed natural gas (CNG) or hydrogen fuel cells. The fifth-wheel coupling, a critical component, allows yard trucks to rapidly engage and disengage trailers for efficient maneuvering and cargo handling.

2.3 Regulators of US Freight Rail

The history of freight rail regulation in the United States is marked by a series of significant developments and legislative acts that have shaped the industry. The earliest regulations date back to the late 19th century when railroads were expanding rapidly. The Interstate Commerce Act of 1887 established the Interstate Commerce Commission (ICC), one of the first federal regulatory agencies in the country. This act aimed to curb monopolistic practices, ensure fair rates, and prevent discrimination in rail transportation. However, the ICC struggled to have a substantial impact on regulating the industry effectively.

In 1920, the Transportation Act of 1920 expanded the regulatory powers of the ICC, enabling the setting of reasonable rates, classifications, and practices for railroads. It also created the Railway Labor Board, which played a role in labor disputes. In 1970, the Interstate Commerce Commission Termination Act (ICCTA) abolished the ICC and led to the creation of the Surface Transportation Board (STB) in 1995, which is the current regulatory authority responsible for overseeing freight rail in the US.

Environmental regulation in freight rail has become increasingly important. Federal agencies like the US Environmental Protection Agency (EPA) and the US Department of Transportation Federal Railroad Administration (FRA) have established emissions standards and safety regulations to mitigate the environmental impact of rail operations. Recently, state legislation of emissions has also been published, regulating operation of rail more tightly than national standards.

2.3.1 US Department of Transportation Federal Railroad Administration

The U.S. Department of Transportation Federal Railroad Administration (FRA) is a federal agency concerned with intermodal transportation. This agency creates regulations around railroad operations including safety, network development, and research and development. The FRA also provides grants and loans for new passenger and freight rail developments. The FRA collaborates with the Environmental Protection Agency (EPA) to establish and enforce emissions standards for the rail industry.

2.3.2 US Surface Transportation Board

The primary regulator of freight rail is the Surface Transportation Board (STB), an independent federal agency which regulates the nation's surface transportation systems, including the economics of freight rail. The STB's primary role is to ensure a competitive, economically efficient, and reliable rail transportation system. It regulates various aspects of the industry, including mergers, rates, service quality, and environmental concerns. In addition to regulation, this agency tracks and publishes statistics on freight rail in the US. The STB has jurisdiction over rate setting, service issues, and restructuring transactions, thereby directly impacting the viability of privately-owned railroads. The STB collaborates with the EPA and FRA to ensure that rail transportation complies with federal emissions standards.

2.3.3 US Environmental Protection Agency

The United States Environmental Protection Agency plays a pivotal role in regulating locomotives to reduce their environmental impact and improve air quality. Through its authority under the Clean Air Act, in 1998 the EPA sets emission standards for locomotive engines to limit the release of harmful pollutants, such as oxides of nitrogen (NOx), hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM). The latest standard from the EPA was published in 2008 and established 4 locomotive tiers that regulate their emissions [**us_epa_final_2016**]. The EPA has recently proposed an additional publication in April 2023 that amend EPA's regulations relating to the Clean Air Act's prohibition against states applying emission standards to new locomotives or new engines used in locomotives. This regulation would allow states to independently set their own mandates for emissions.

2.3.4 State Regulator: California Air Resources Board

The California Air Resources Board (CARB) is one of six boards, departments, and offices serving under the California Environmental Protection Agency (CalEPA). It is tasked with addressing air quality and environmental concerns in California. Established in 1967, CARB plays a pivotal role in regulating emissions and combating air pollution across the state. As California is known for its unique air quality challenges, CARB has been at the forefront of pioneering stringent emissions standards and innovative regulations. The board is responsible for implementing programs and policies that promote cleaner vehicles, fuels, and transportation systems, with a focus on reducing greenhouse gas emissions and other pollutants.

In April 2023, CARB approved the In-Use Locomotive Regulation to reduce emissions from diesel-powered locomotives and prompt the adoption of zero-emission (ZE) technology. This regulation aligns with California's goals regarding public health, air quality, and climate by lowering levels of criteria pollutants, toxic air contaminants, and greenhouse gas emissions produced by locomotives in operation. The regulation includes several key elements for locomotive operators in California. First, they will be required to establish spending accounts based on the emissions produced by their locomotives. The dirtier the locomotive, the more funding is needed in these accounts. These funds will be utilized to purchase cleaner locomotives, zero-emission (ZE) locomotives and associated infrastructure, or to pilot ZE technologies.

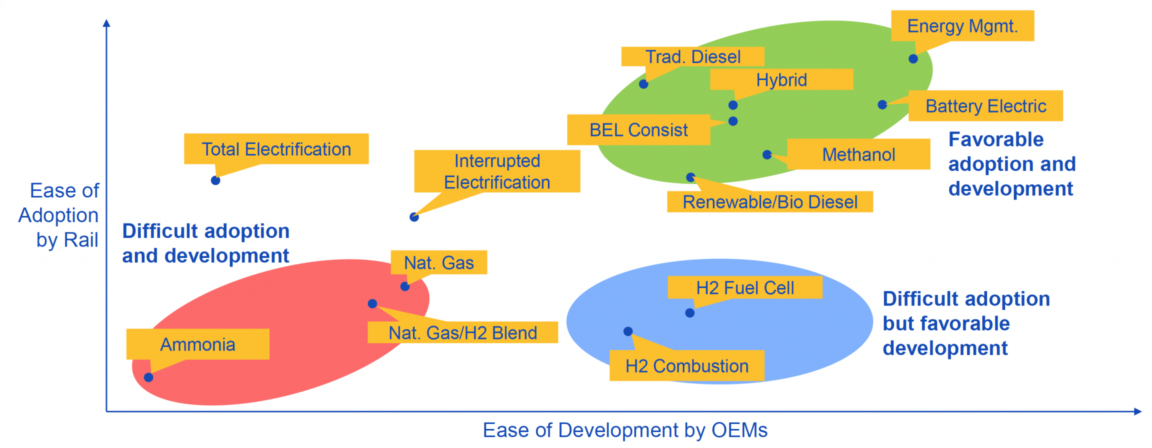
The In-Use Operational Requirements, set to begin in 2030, stipulate that only locomotives less than 23 years old can be used in California. Switchers, passenger locomotives, and Class I line haul locomotives with engine build dates from 2030 onwards must operate in ZE configurations in California. An idling limit of 30 minutes will be imposed for locomotives with automatic shutoff devices, with exemptions for specific reasons. Registration, reporting, and annual administrative payments will be mandatory, with required reporting of locomotive activity, emission levels, and idling data. Additionally, locomotive operators can choose alternative compliance plans, alternative fleet milestone options, or seek various compliance extensions, including temporary operating extensions, compliance extensions for equipment delays, small business hardship extensions, and historic railroad low-use exemptions.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 3

Railway Propulsion Technologies

Figure 3-1: Qualitative Railway Propulsion Solutions Map, showing an overview of technologies considered for widespread use in the industry. This figure weighs relative ease of adoption and development, highlighting which challenges these new technologies will face. This figure can serve as an overall guide for railway propulsion technologies. Figure adapted from conversations with industry experts.



This chapter discusses the intricacies of locomotives, beginning with an exploration of how energy is utilized within the locomotive, with attention to the power control system. A detailed comparison is drawn between Line Haul and Switcher locomotives, highlighting their duty cycles, uses, and energy requirements. Building on these fundamentals, the chapter then focuses on the diesel-electric locomotive, the most commonly used type in the U.S. today. Subsequently, the narrative expands to

Figure 3-2: Overview of Railway Propulsion Technologies

	Diesel-Electric	**Electrified Rail**	**Diesel Hybrid**	**Battery-Electric**	**Liquefied Natural Gas**	**Hydrogen Fuel Cell**
Description	Diesel fuel is burned to power an alternator that provides traction	Overhead electric lines provide direct power for traction	Diesel fuel is burned to provide traction and charge batteries. Regenerative braking available	Batteries are charged from the grid or via regenerative braking and provide traction	Burns either diesel or LNG/CNG to power an alternator that provides traction	Fuel cell provides electric power for batteries which provide traction
Year Deployed	1925	-	2010	2021	2020	2022
Rail Industry Readiness Level (RIRL)(1)	9	2	7	6	7	5
Fuel Source	Petroleum Diesel	Generated electricity	Diesel, generated electricity	Generated electricity	LNG, CNG, diesel (if spark ignited)	Hydrogen
Scope 1 Emissions	High	Zero	Med	Zero	Med	Zero

(1) https://www.railengineer.co.uk/rail-industry-readiness-levels-rirls-defined-and-explained/

RIRL 1: Conception
RIRL 2: Opportunity Development
RIRL 3: Proof of Concept
RIRL 4: Industry Specification
RIRL 5: Prototype
RIRL 6: Operational Transition
RIRL 7: Initial Deployment
RIRL 8: Roll Out
RIRL 9: Whole Life Management

encompass various locomotive power technologies, thoroughly examining the benefits and challenges of each, especially in terms of their potential for widespread adoption. Through this exploration, the chapter aims to provide a comprehensive and insightful look into the operational and technological aspects of locomotives, as well as outline technologies that have potential to be widely adopted for the movement of freight in the U.S.

After reading this chapter, you will have an understanding of the broad technological landscape as it currently stands and the unique requirements for each propulsion technology as it relates to the function of freight locomotives. You will recognize the prevalence and dependence on diesel fuel for locomotive power generation and compare this to a number of cleaner technologies that still face considerable technological and commercial challenges. You will also be able to deduce areas for immediate and long-term improvement, which will be summarized in Chapter 5.

Locomotive power technologies in the United States have evolved significantly over the years. Since the mid-1900s, diesel-electric locomotives have played a pivotal role in hauling freight. These locomotives are renowned for their power, and range. However, there is an increasing focus on sustainable and alternative power sources. Electrified rail systems, like those in the Northeast Corridor, reduce emissions and increase energy efficiency, while battery-electric locomotives provide a clean and flexible solution for shorter routes. Hybrid locomotives combine traditional and electric technologies, further enhancing fuel efficiency. Alternative fuels such as liquefied natural gas (LNG), hydrogen, and methanol are also being explored to reduce greenhouse gas emissions and promote a greener transportation system, but typically come with added complexity and disruption to an entrenched industry. Each technology has a relative ease with which it can be developed by locomotive original equipment suppliers (OEMs) and, just as importantly, adopted by rail companies, as depicted in 3-1.

3.1 Locomotive Power and Energy

Power Control

In a traditional diesel-electric locomotive, there are eight distinct power settings, referred to as "notches," available to the operator for controlling the power supplied to the traction motors. These notches, along with idle and dynamic brake settings, enable the locomotive operator to fine-tune the power output as needed. By adjusting the throttle lever in the locomotive, the operator selects a specific notch, which results in the locomotive's engine and generator/alternator adjusting their operating parameters to deliver the required power to the traction motor corresponding to the chosen notch. Although modern power electronics allow for more than eight notch settings, this standardized approach of eight notches is maintained to ensure compatibility between contemporary and legacy locomotives, facilitating ease of operation for locomotive operators. This is important context for understanding the methods of locomotive operation as they stand today.

Line Haul and Switcher Locomotives

Freight locomotives can be grouped into two main functions: line-haul and switching. Line-haul locomotives are used to transport trains of freight across long distances between yards and terminals, often across state lines. Switcher locomotives, also known as shunting locomotives, are used exclusively within yards and terminals to shunt freight and form a train that could then be moved by a line haul locomotive. These locomotives are often old line-haul locomotives that are fully depreciated and have been "downgraded" in service.

Table 3.1: Overview of Locomotive types and average specifications

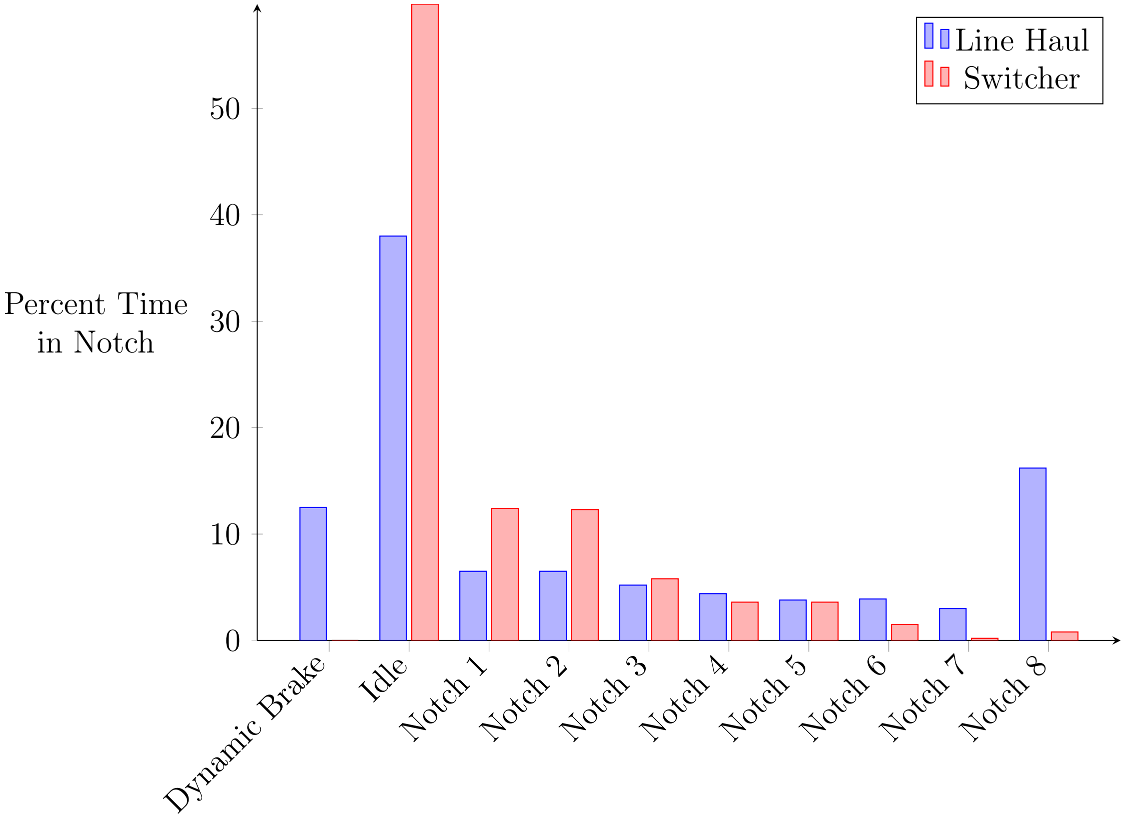
	Line Haul	**Switcher**
Function	Moves rolling stock over long distances outside of rail yards	Moves rolling stock over short distances, within rail yards
Power (H.P.)	4,400	3,600
Fuel Capacity (gal)	5,000	2,000
Price (USD)	3,000,000	1,350,000

Line haul locomotives exhibit distinctive operational duty cycles, where a significant portion of their time is spent operating at higher power settings (Notches 5-8) when traversing long distances on main rail lines. In contrast, switcher locomotives, which are active within rail yards, engaging in activities like rearranging railcars or undergoing fueling, servicing, or maintenance, typically operate at idle or lower power settings (Notches 1-3). 38 percent of the line haul operational time is occupied by idle periods. Conversely, switcher locomotives predominantly function at lower power settings (Idle-Notch 2), constituting around 84 percent of their operational time. These different duty cycles highlight two significant uses for locomotives that should be maintained when considering future changes.

Locomotive Energy Requirements

Locomotive energy requirements are important to understand as to establish a baseline for how much energy is required to move goods across the U.S. This will also serve as a foundation for estimating the effects of changing fuel types used to power locomotives. By examining annual railroad R-1 reports, which are required for all class I operators in the U.S., it is possible to ascertain the number of line haul and switcher locomotives owned by each operator. Additionally, it's possible to determine the amount of diesel fuel consumed daily by locomotives. One can then determine the average daily annual

Figure 3-3: Locomotive Duty Cycles [18]



energy consumption for each kind of locomotive using the following equation:

$$\begin{aligned}\text{Avg. Daily Energy Use (MWh/day)} = {} & \frac{\text{Diesel Consumed (gallons)}}{\text{Number of Locomotives}} \\ & \times \frac{0.041\ \text{MWh}}{\text{gallon}} \\ & \times \frac{1\ \text{year}}{365\ \text{days}}\end{aligned}$$

This amount of fuel consumed during a train's journey depends on many factors including weather, freight weight, route grade, route length, and number of stops. Therefore, the average can only be used as a general approximation for all train routes, not for any specific route. It is useful to also consider the maximum amount of energy available for traction use at the rails, which is calculated using the following equation:

$$\begin{aligned}\text{Max. Energy Capacity (MWh)} = {} & \frac{\text{Diesel Capacity (gal)}}{1} \\ & \times \frac{0.041\ \text{MWh}}{\text{gal}} \\ & \times \text{Engine Efficiency}\end{aligned}$$

Table 3.2: Diesel Energy Consumption per Locomotive for the Year 2022

	Line Haul	**Switcher**
Diesel Consumed (MMgal)	3,220	210
Number of Locomotives	23,398	2,809
Average Daily Diesel Energy per Locomotive (MWh)	5.67	3.08
Diesel Capacity (gal)	5000	2000
Diesel Engine Efficiency	37%	37%
Max. Power Capacity at Rail (MWh)	75.2	30.1

These calculations serve as a an important input into calculations done in Chapter 4, which serves to highlight the relative costs of certain types of locomotive power technologies.

3.2 Diesel Electric

Diesel-electric locomotives are by far the most common kind of locomotive in the U.S. These were the replacement to the steam-engine locomotive in the mid-1900s and have since had incremental upgrades to improve their efficiency and power output. They function on the principle of a diesel combustion engine that powers an electric generator, which powers the electric traction motors attached to the locomotive's wheels. These locomotives use either alternating current (AC) or direct current (DC) as power inputs to the motors. AC motors are controlled through frequency and voltage, while DC motors are controlled through current. Modern power electronics enabled AC motor control, which is now the industry standard. It is important to note that AC locomotives still have DC as a part of the power transfer process, which is a key enabler of other cleaner drivetrains that can be adopted to augment the standard diesel drivetrain, discussed later in this chapter.

Figure 3-4: Diesel Electric Locomotive Overview [19]

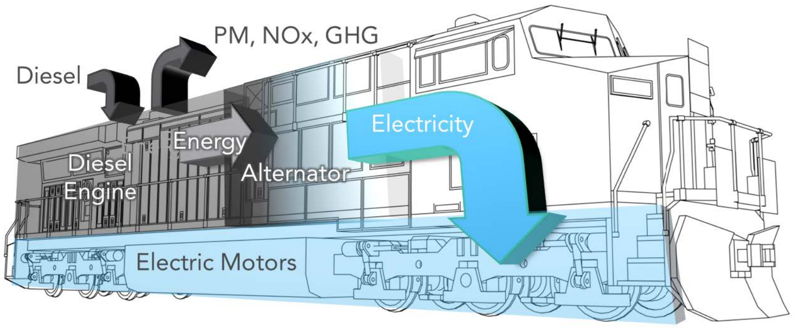
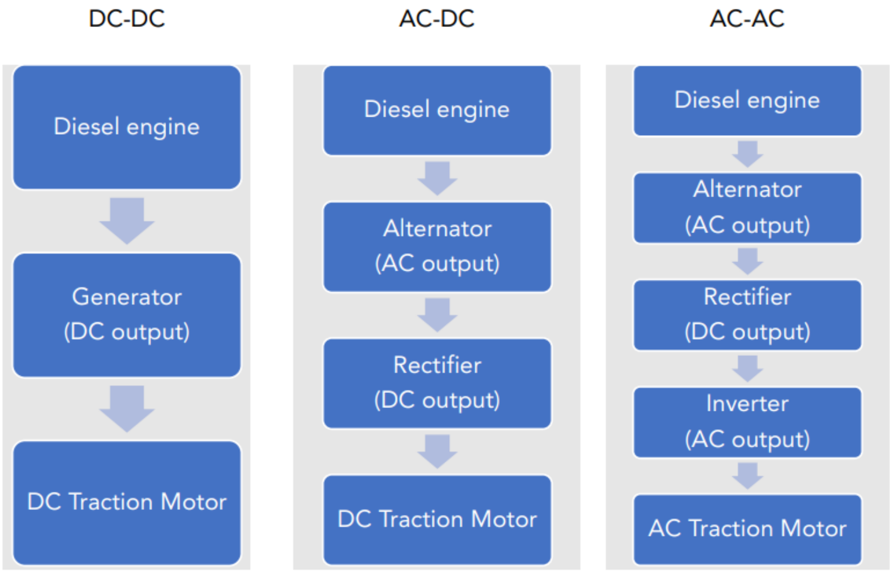


Figure 3-5: Types of Drivetrains Used in Diesel Electric Locomotives [19]



3.2.1 Fueling

Fueling practices of diesel-electric locomotives are important to note because they are the current industry standard. Any change to how locomotives are fueled will be compared directly to this existing method, and deviations will incur greater infrastructure costs. Diesel-electric locomotives are fueled with liquid diesel fuel by pump transfer from either a stationary tank or a mobile tanker truck at intermediary crew change locations. A train is typically stopped such that the head end, the location of the locomotives, is aligned with the fueling pad, a piece of fixed infrastructure that delivers fuel to a locomotive. However, in the event that a train includes a distributed power locomotive, one positioned somewhere along the trains' length that does not include the head end, then fuel must be delivered via tanker truck. Refueling a locomotive is typically done in less than 30 minutes. This operational method for refueling is done at hundreds of location across the U.S.

3.2.2 Diesel Emissions

The standard of Tiers was established by the U.S. EPA in the 1970s and is intended to control all emissions from the combustion of diesel in locomotives. These standards outline the permissible levels of emissions of nitrogen oxides (NOx), particulate matter (PM), hydrocarbons (HC), and carbon monoxide (CO), as shown in Table 3.3. Tier 0 through Tier 3 locomotives represent a significant phase in the evolution of emissions standards in the railroad industry. Tier 0, which emerged in the 1970s, marked the beginning of regulatory efforts aimed at controlling locomotive emissions, albeit with limited requirements for pollution reduction. Locomotives categorized under Tier 0 had minimal emission controls, but as the industry progressed, Tier 1, Tier 2, and Tier 3 standards were successively implemented. Tier 3, introduced in the early 2000s, represented a significant milestone by mandating substantial cuts in NOx and PM emissions compared to earlier tiers. In California, 95.2% of all locomotives are Tier 3 or older (Tiers 0, 1, or 2) [20]. The distribution of U.S. Line Haul Locomotives and Switcher Locomotives are shown in Figure 3-6, indicating that new cleaner locomotives are not being adopted quickly, especially for switcher duty cycles. This can be attributed to the high purchase price and long service life of locomotives, which also points to why there is a high proportion of rebuilt locomotives.

3.2.3 Biomass Based Diesel

Biomass based diesel fuels are more sustainable alternatives to conventional fossil based diesel. Two kinds of biomass based diesel fuels are biodiesel and renewable diesel.

Figure 3-6: 2020 Class I Locomotive Fleet Profile by Tier (Percentage)

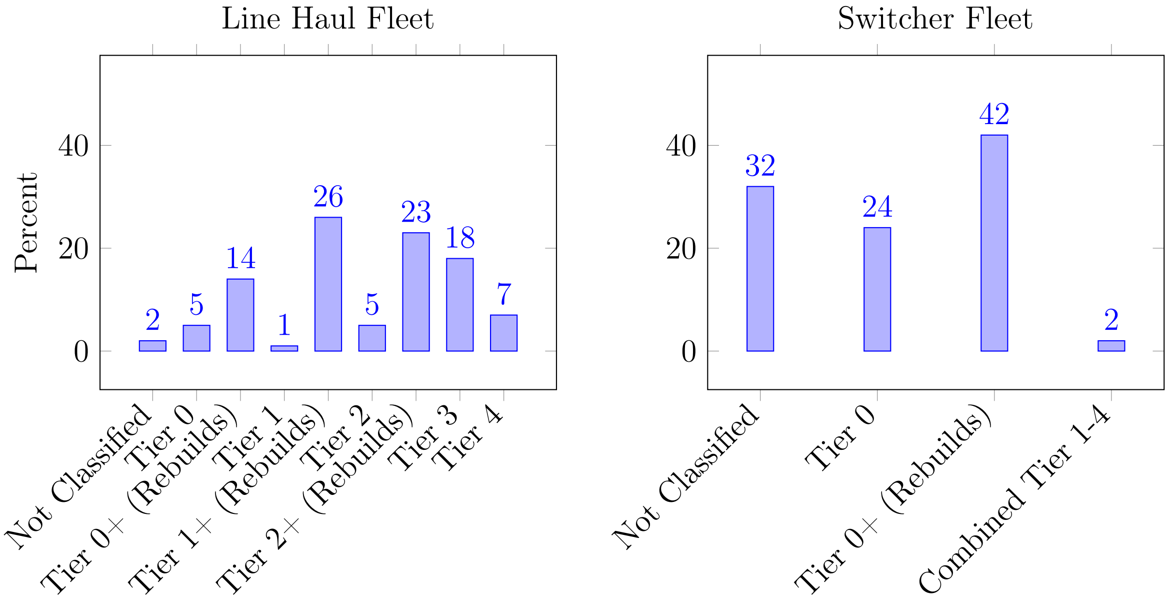


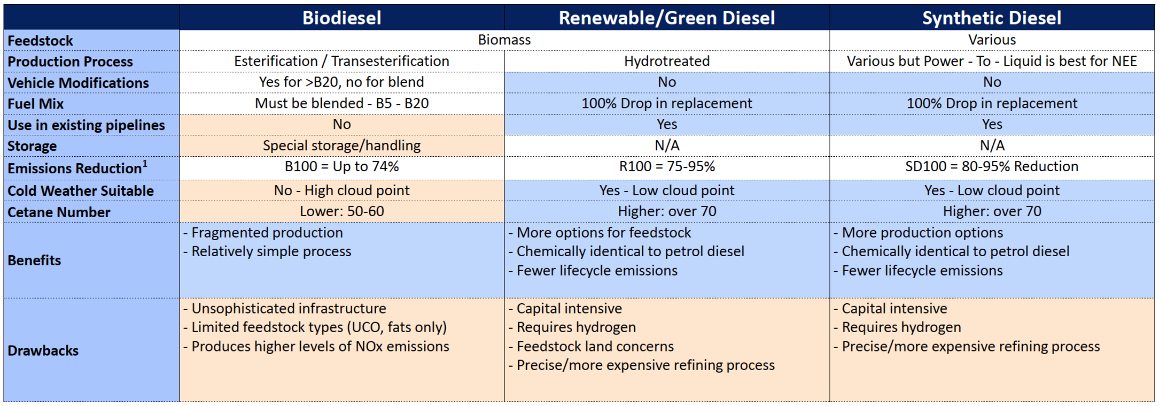
Table 3.3: Federal Exhaust Emissions Standards for Line Haul and Switcher Locomotives [21]

Line Haul								
	Tier 0 1973-1992	**Tier 0+**	**Tier 1 1993-2004**	**Tier 1+**	**Tier 2 2005-2011**	**Tier 2+**	**Tier 3 2012-2014**	**Tier 4 2015+**
HC	1.00	0.30	0.55	0.30	0.30	0.30	0.30	0.14
CO	5.00	1.50	2.20	1.50	1.50	1.50	1.50	1.50
NOx	9.50	5.50	7.40	5.50	5.50	5.50	5.50	1.30
PM	0.22	0.10	0.22	0.10	0.10	0.10	0.10	0.03

Switcher								
	Tier 0 1973-1992	**Tier 0+**	**Tier 1 1993-2004**	**Tier 1+**	**Tier 2 2005-2011**	**Tier 2+**	**Tier 3 2012-2014**	**Tier 4 2015+**
HC	2.10	0.60	1.20	0.60	0.60	0.60	0.60	0.14
CO	8.00	2.40	2.50	2.40	2.40	2.40	2.40	2.40
NOx	11.80	5.00	11.00	5.00	8.10	5.00	5.00	1.30
PM	0.26	0.10	0.26	0.10	0.13	0.10	0.10	0.03

Biodiesel is a type of fuel derived from biological sources such as vegetable oils, fats, and greases using esterification. Differentiated from fossil based fuel sources, biodiesel is a part of the carbon cycle, meaning that when it is burned, it can be reabsorbed

Figure 3-7: Comparison of three kinds of alternative diesel. This figure serves as a quick-reference guide for comparing various qualities of diesel fuel. It indicates that a combination of all three fuels will likely be necessary, as one does not satisfy all criteria for widespread adoption.



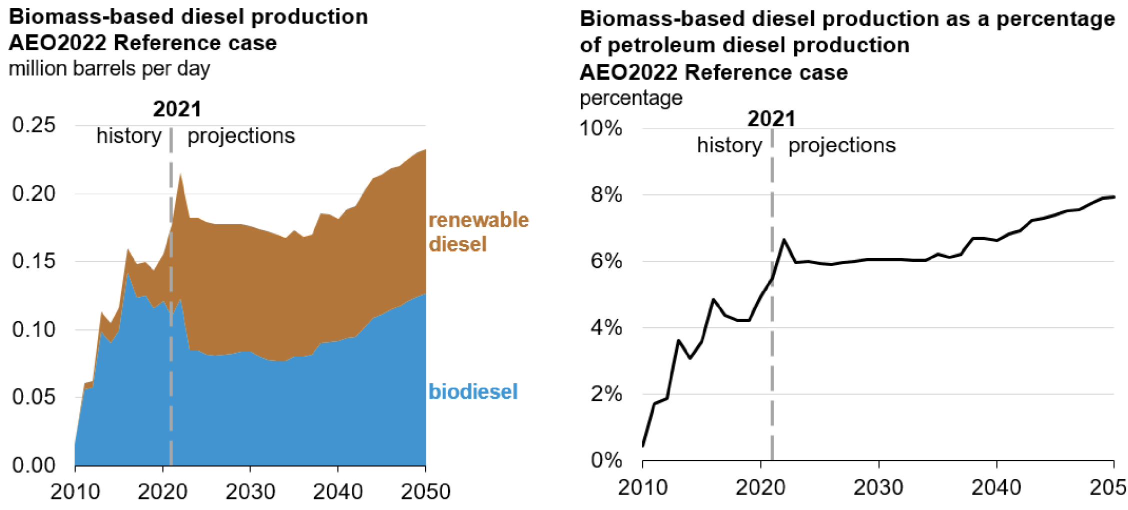
	Biodiesel	Renewable/Green Diesel	Synthetic Diesel
Feedstock	Biomass		Various
Production Process	Esterification / Transesterification	Hydrotreated	Various but Power - To - Liquid is best for NEE
Vehicle Modifications	Yes for >B20, no for blend	No	No
Fuel Mix	Must be blended - B5 - B20	100% Drop in replacement	100% Drop in replacement
Use in existing pipelines	No	Yes	Yes
Storage	Special storage/handling	N/A	N/A
Emissions Reduction[1]	B100 = Up to 74%	R100 = 75-95%	SD100 = 80-95% Reduction
Cold Weather Suitable	No - High cloud point	Yes - Low cloud point	Yes - Low cloud point
Cetane Number	Lower: 50-60	Higher: over 70	Higher: over 70
Benefits	- Fragmented production - Relatively simple process	- More options for feedstock - Chemically identical to petrol diesel - Fewer lifecycle emissions	- More production options - Chemically identical to petrol diesel - Fewer lifecycle emissions
Drawbacks	- Unsophisticated infrastructure - Limited feedstock types (UCO, fats only) - Produces higher levels of NOx emissions	- Capital intensive - Requires hydrogen - Feedstock land concerns - Precise/more expensive refining process	- Capital intensive - Requires hydrogen - Precise/more expensive refining process

by plants and then used to create more fuel. Biodiesel can be used in existing diesel engines with minimal modifications. It can be used in various proportions blended with conventional diesel fuel. B20, a blend of 20% biodiesel and 80% petroleum diesel, is a common formulation used in locomotives.

Renewable diesel is produced through the hydrotreating of triglycerides and fatty acids found in biomass. Renewable diesel is chemically identical to petroleum diesel, which means it can be used as a direct substitute for traditional diesel without engine modifications. R100, 100% renewable diesel, has already been approved for use in locomotive engines. This is a major advantage because no changes have to be made to existing locomotive operations to improve sustainability through the use of renewable diesel.

The market for biomass based diesel face issues from production capacity, availability of raw materials, and economic considerations. Given that both biodiesel and renewable diesel utilize the same limited feedstocks, expansion of one tends to hinder the other. Even though historically biodiesel production has outpaced renewable diesel production, it is expected that there will be shift towards renewable diesel production in the medium to long term, given incentives such as the Renewable Fuel Standard, the California Low-Carbon Fuel Standard, and the U.S. biomass-based diesel blender credit. Expected growth of fuel use is shown in 3-8, which indicates a significant increase in supply, but not nearly enough to match demand for diesel overall, indicating that this is not an ultimate solution.

Figure 3-8: Biomass Diesel Production Predictions through 2050 [22]



Given the growing availability and ease of use of biomass based diesel, it is expected that this will be a growing fuel choice for the freight rail industry to curb its emissions. However, it is important to note that biomass feedstock is limited and will not exceed 10% of the availability of conventional diesel by the year 2050 [22].

3.2.4 Synthetic Diesel

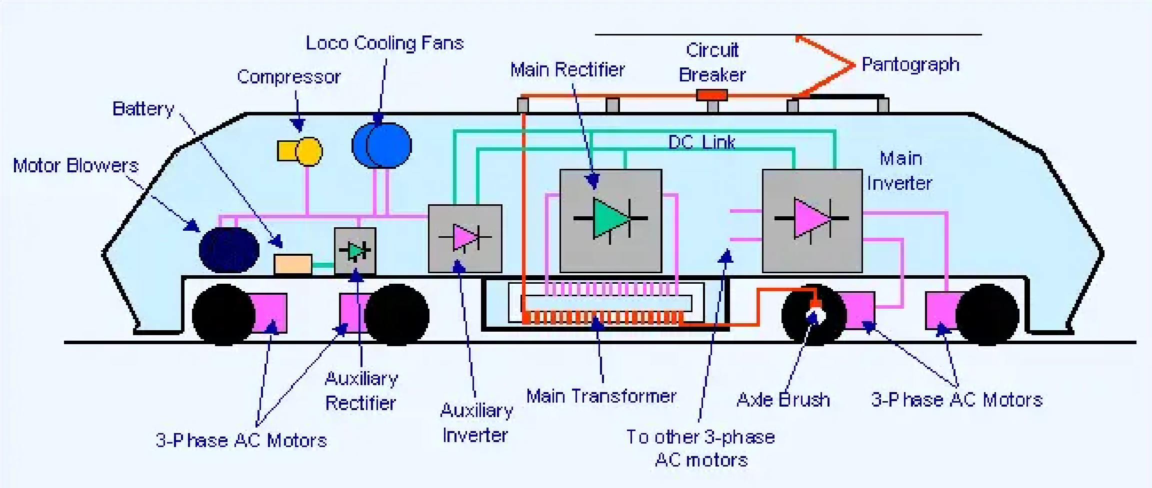
Synthetic diesel is a type of diesel that is manufactured through a chemical process, rather than refined from crude oil. There are several methods for the manufacture of this fuel that can utilize various feedstocks, but all rely on the Fischer-Tropsch (FT) Process. This chemical process converts a gaseous mixture of carbon monoxide and hydrogen, produced from coal, natural gas, or biomass, into liquid hydrocarbons. Refinement of the liquid then creates synthetic diesel. This can result in a high quality drop-in diesel fuel that does not need to be mixed with conventional diesel and has shown to reduce emissions when combusted in Class 8 trucks [23]. Current US capacity is limited to small-scale or experimental production. However, it has been shown that capturing carbon dioxide from industrial waste streams creates an opportunity to produce 58 billion gallons of FT fuels annually [24]. There is also a new company working to scale up synthetic diesel production using green hydrolysis as the basis for hydrogen production [25].

3.3 Electrified Rail

Figure 3-9: Catenary shape formed by power transmission equipment [26]

Electrified rail, also known as catenary rail (named for the shape of a hanging cable, shown in Figure 3-9), is a type of power system used to move locomotives. It substitutes the direct combustion of fuels with overhead power cables or an electrified track, to deliver power to electric systems onboard a locomotive, resulting in a traction force at the wheels. Locomotives powered by electric lines power AC traction motors by contact to a high voltage line using a pantograph, a specialized mechanical linkage. Electrified rail is distinct from other locomotive power systems in that it typically has fewer emissions and higher efficiency, but demands higher capital costs for infrastructure. This technology has seen widespread adoption in Europe. For instance, Switzerland serves as an example, with 99% of its rail system being electrified [27]. In contrast, electrified freight rail is virtually absent in the United States, where it constitutes 1% of the entire rail network [27]. This disparity highlights not only the potential environmental and efficiency gains offered by electrified rail, but also the challenges and investment hurdles that need to be overcome in the U.S.

Figure 3-10: Schematic of a Modern Catenary Locomotive [30]



3.3.1 Benefits of Adoption

Electrified Rail Emissions

Electrified rail locomotives have no direct emissions because they do not rely on combustion of fuel for traction power, making them well suited for the reduction of GHG emissions. It is important, however, to account for indirect emissions, or those created by the power generating plant that provides electric power to the locomotives through high-voltage lines. In the U.S., over 60% of electric energy is generated through the burning of coal or fossil fuels [28], however, renewable power generation is increasing steadily and the White House has recently outlined a plan to achieve carbon pollution-free electricity generation by the year 2030 [29].

Electrified Locomotive and Track Maintenance

Electric locomotives have fewer moving parts than combustion locomotives, and thereby also have less routine maintenance. This reduction in routine maintenance can provide some cost benefits over the lifetime of a locomotive. Additionally, these locomotives utilize regenerative braking, which further reduces wear of braking components.

Electrified Rail Energy Cost

The cost of energy for an electric locomotive is directly tied to the cost of delivered electricity in its operating region. These electricity prices vary depending on the geography in which the train is drawing power. Cost is also depended on the efficiency of the powertrain of the locomotive. The DC Bus-to-Tank efficiency, a characterization of the transmission of power from the catenary line to the DC distribution system, is 98% at full power, compared to that of a diesel locomotive which is 41% [31]. This efficiency contributes to reduced energy usage during operation of the locomotive.

3.3.2 Challenges of Adoption

Electrified Rail Infrastructure

The biggest challenges for adopting electrified rail in the U.S. is the need for substantial infrastructure investment. Given that all existing freight railways are not equipped for electrification, they would need to be reconstructed to accommodate electric locomotives. A 2012 analysis of freight rail electrification in Southern California concluded that construction of new electrified rail could cost $4.8 billion per mile [32]. The AAR has taken a strong stance on electrification of rail.

> "...catenary electrification of the freight rail network would be unworkable. Initiatives, such as catenary electrification, that are clearly not viable should be set aside to focus on and invest in policies and programs that will work to reduce GHG emissions and combat climate change, such as those noted above."[33].

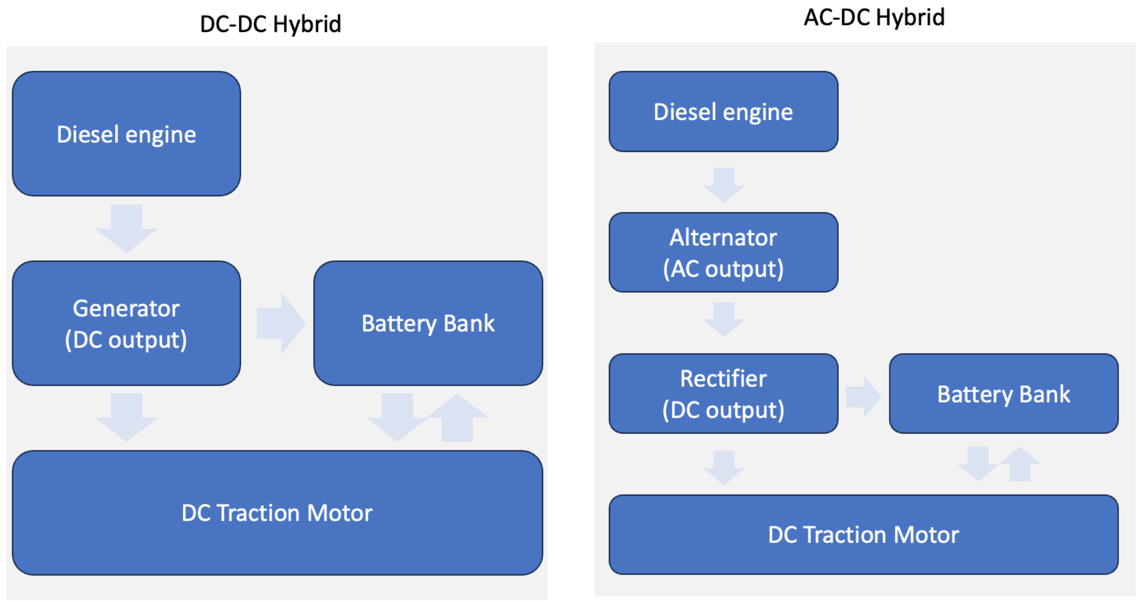
This stance clearly indicates it would take federal regulation to force a transition to electrified freight rail. Existing rail companies are not willing to pay the required upfront capitol for deployment, nor are they willing to accept the disruption it would have to their existing operations. Even when considering that electrification could be done for select segments of the rail network, The AAR has concluded that this, too, is challenging.

> "First, railroads would face major costs, delays, and inefficiencies associated with interchanging freight to and from diesel locomotives at the edges of electrified territory. Moreover, locomotives often travel on tracks owned by other railroads. Creating captive fleets of unique locomotives serving small geographic regions would work against this practice, harm the efficiency of railroad operations, and likely cause a shift of freight to trucks. Second, specific-area electrification would limit rail flexibility to respond to changing market conditions. Rail volumes in any given area often change substantially over time, meaning the economics associated with partial electrification would change drastically too. This would further increase costs and distort capital planning and investments, as additional areas might require electrification. Finally, specific-area electrification would lock in one technology when other more cost-effective alternatives could be developed."[34]

3.4 Diesel Hybrid

Diesel hybrid locomotives are an advancement in propulsion technology, combining traditional diesel-electric powerplants with battery-electric systems. This integration minimizes adaptations to the existing operational infrastructure, while adding the benefits of an electric system including regenerative braking, and emissions-free operation. A diesel hybrid locomotive consists of a diesel combustion engine that follows the same operating principle described in 3.2, however, energy is also transferred to an onboard battery bank. Considering that battery banks store DC energy, a DC-DC or AC-DC drivetrain configuration can be used as a hybrid locomotive, as depicted in Figure 3-11. Note that the DC Traction Motor also has the ability to transfer power back into the battery bank by the use of regenerative braking, converting kinetic energy of the motor into electric energy. This drivetrain requires the use of a sophisticated power management system that is constantly monitoring and directing energy to and from the battery bank.

Figure 3-11: Types of Drivetrains Used in Diesel Hybrid Locomotives. A key function of the battery bank is that it can capture energy while the locomotive is at idle or even using regenerative braking and then release that energy to help move the locomotive from a stop, the most energy intensive action.



Battery Tender Hybrid

One special configuration of a diesel hybrid locomotive is the battery tender hybrid. This is an innovative approach for increasing the battery capacity of a locomotive and can also function to retrofit existing diesel-electric locomotives with a battery bank. This type of hybrid consists of two separate pieces of rolling stock: i) a traditional electric-diesel locomotive and ii) a battery tender car, The battery tender is an additional car coupled to the locomotive that contains a large bank of rechargeable batteries that are charged and discharged by the diesel-electric locomotive. According to a paper presented at the 2014 ASME/IEEE Joint Rail Conference [35], a battery tender:

- lacks traction motors,
- should be coupled mechanically and electrically to a diesel-electric locomotive to serve a useful purpose,

- and it can store and provide energy for traction only when coupled to a diesel-electric locomotive.

3.4.1 Benefits of Adoption

Efficiency and Emissions

One key advantage of the hybrid technology is the efficiency gain and thereby reduction of emissions during operation. While a diesel-electric locomotive only transmits approximately 37% of the energy carried in its fuel tank to the rails, a hybrid locomotive would be able to capture energy through regenerative braking, store energy while the engine idles, and use battery power to move the train from a standstill. Any amount of reduction in the combustion of diesel would also result in a reduction of direct emissions. However, the hybrid locomotive would not be completely emissions-free, as it still relies mainly on combustion for power.

Operational Flexibility

The other big advantage to hybrid locomotives is that they are relatively easy to fit into existing railroad operations, when comparing to other power technologies. Given that they rely on a diesel-electric engine as the main power source, fueling operations would not have to be altered. Further, the drivetrain of the conventional diesel-electric locomotive is highly conducive for simple upgrades to become a hybrid locomotive. Most existing drivetrain components could remain in place, with upgrades only necessitating the addition of a battery bank and DC bus.

3.4.2 Challenges of Adoption

Weight and Space

The main challenge with the adoption of hybrid locomotives involves the need for additional volume to carry a battery bank. A battery bank is limited in volume to either the space available in a locomotive excluding the remainder of the drivetrain or the volume of a single rail car (in the case of the battery tender). It would be difficult for a battery bank included in the volume of a locomotive to hold a meaningful capacity for line haul use. Assuming a battery pack energy density of 0.36 kWh/L and a daily line haul locomotive energy requirement of 4.8 MWh, storing just 1% of a line haul locomotive's daily energy use would require a battery that is 13,000 liters in volume. This is battery would be roughly 10% of a locomotive's volume and weigh 30 metric tons. Expanding this the battery bank to occupy the size of one train car, as expected in the battery tender configuration, would reduce the amount of freight capacity of the train by one car, presenting a challenge to maximizing revenue per train.

3.5 Battery Electric

Battery electric locomotives hold promise to be a suitable replacement of diesel-electric for certain use cases. Modern battery electric locomotives (BEL) have recently been produced by both Wabtec and Progress Rail for the global market. A battery electric locomotive is the latest technological innovation to be released for widespread use. This locomotive lacks any form of combustion engine and fills the remaining space with a large battery bank, which provides power to the electric traction motors. The capacity of the battery bank directly determines the amount of time the locomotive can operate before having to be recharged by an external electrical power source. Regular charging can be expected, as current market offerings from Wabtec have battery capacities ranging from 1.5 to 8.5 MWh per locomotive.

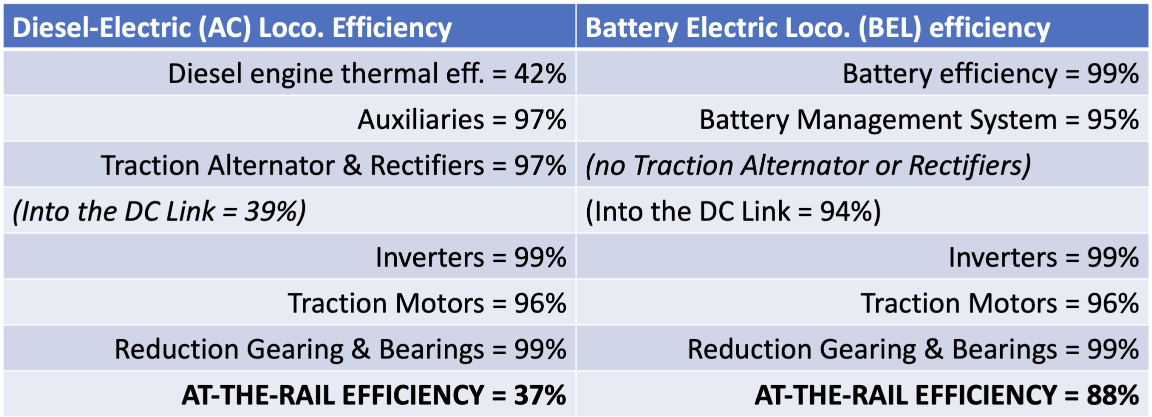
Charging of the batteries can be done in several ways. Regenerative braking provides power back to the batteries while the locomotive is in operation. This method is especially useful for rail routes that have frequent stops or long hills, as this energy is then converted into propulsion. Wabtec has unveiled a stationary pantograph charger for their BEL, which requires the construction of high voltage overhead lines at charging points. Although not a current offering, this pantograph could also be used while the BEL is in motion, much like an electric locomotive, to minimize operational disruption.

3.5.1 Benefits of Adoption

Efficiency and Emissions

Battery electric locomotives offer significant advantages in terms of efficiency and emissions compared to traditional diesel-electric locomotives. A battery electric locomotive can achieve a battery-to-wheels efficiency of 88%, over 2 times that of a diesel-electric locomotive's tank-to-wheels efficiency [36].

Figure 3-12: Efficiency Comparison of Diesel-Electric and Battery-Electric Locomotives. Adopted from [36]



Diesel-Electric (AC) Loco. Efficiency	**Battery Electric Loco. (BEL) efficiency**
Diesel engine thermal eff. = 42%	Battery efficiency = 99%
Auxiliaries = 97%	Battery Management System = 95%
Traction Alternator & Rectifiers = 97%	*(no Traction Alternator or Rectifiers)*
(Into the DC Link = 39%)	(Into the DC Link = 94%)
Inverters = 99%	Inverters = 99%
Traction Motors = 96%	Traction Motors = 96%
Reduction Gearing & Bearings = 99%	Reduction Gearing & Bearings = 99%
AT-THE-RAIL EFFICIENCY = 37%	**AT-THE-RAIL EFFICIENCY = 88%**

Additionally, BELs can be operated in consist with diesel-electric locomotives. In 2021 BNSF began operation of a consist comprising two Tier 4 Wabtec ET44C4 diesel locomotives and a single 2.4MWh BEL between the Barstow and Stockton stations in California. The battery was charged while stationary at a charging station and through the use of regenerative braking throughout the journey. The study measured the fuel consumption of a diesel-only consist and compared that to the BEL-diesel consist. The result of the study was that the inclusion of the BEL decreased total diesel consumption by an average of 12% [37].

The BEL, of course, does not directly combust any fuel for power generation and therefore has zero emissions during operation. Much like electric rail, indirect emissions are tied to how electricity is generated in the U.S.

Maintenance

The exact cost of maintenance of a BEL is considered to be less than that of a diesel-electric locomotive because it lacks an engine, engine support systems, and alternator. The California Air Resources Board has determined that annual maintenance cost of a BEL is 10% of diesel-electric annual maintenance [38].

3.5.2 Challenges of Adoption

Energy Capacity

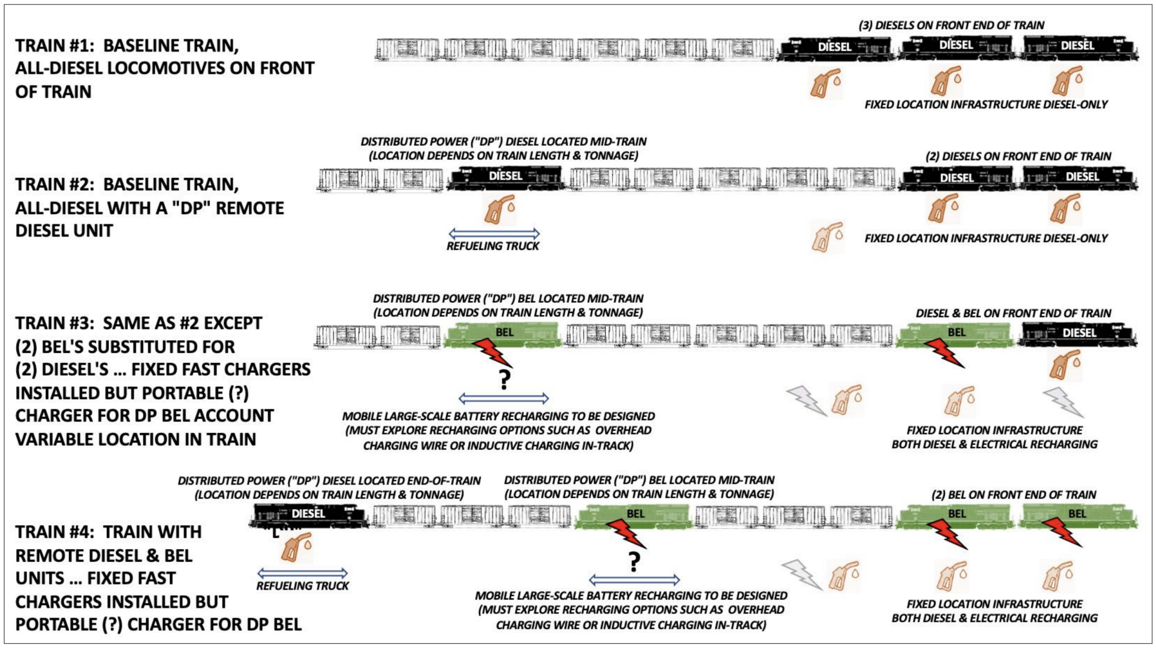
The biggest challenge to overcome is the energy capacity of a BEL, which is governed by the volume of the locomotive and the energy density of batteries. To match a diesel locomotive's maximum energy capacity, a BEL would have to store 85.5 MWh, assuming 88% battery-to-wheels efficiency. Modern BELs utilize lithium-ion batteries with a cell energy density of 0.47 kWh per liter and packing fraction of 0.77. This would mean that 236,000 liters of volume would be occupied by batteries, which exceeds the total volume of a 60-foot boxcar of 206,713 liters. This calculation does not account for additional volume needed for the operator's cabin, inverter, and cooling system.

Charging

Charging a BEL is substantially different from refueling a diesel-electric locomotive, presenting another big challenge for their widespread use. To match the fueling speed of a diesel locomotive, a BEL would have to be fully charged in roughly 15 minutes. Current charging technology used by Wabtec is capable of charging a 2.4MWh BEL using a 480V connection in 8 hours.

There is also an operational problem in the case that a train consists of a remote power BEL. To solve this issue, railroads can construct long overhead power lines that span the length of a train, thereby creating an ability to deliver charging power anywhere in the train. This solution, however, does not match the infrastructure costs of a diesel tanker truck performing mobile fueling for a diesel-electric locomotive.

Figure 3-13: Refueling and recharging infrastructure for BEL and diesel trains [36]



Further, charging stations require additional infrastructure that includes high voltage power lines for energy delivery to the locomotive. This added infrastructure cost may increase substantially if new electrical grid interconnects are necessary. Costs associated with electric power are dependent on total consumption (number of MWhs) and demand (maximum MWh). If locomotives are to be charged simultaneously, this would create a significant spike in demand, which, if not controlled, can result in higher energy costs.

Currently, there is no suitable solution for fast battery swapping, but such a method could allow for reduced stationary times. It could also improve operations such that they more closely represent the way diesel locomotives must be fueled, by stopping in a designated station for less than one hour. Swappable batteries for locomotives are difficult to deploy because of the mass of the batteries, cooling requirements, and power routing needs.

Thermal Requirements

Lithium-ion batteries that are used in modern day BELs have strict environmental operating requirements. If operating temperatures are outside the nominal range, there can be significant decreases in power output of a battery bank. This can become problematic when locomotives are operating in tunnels, of which there are over 800 in the U.S. [39]. Especially in long train tunnels with high grades, BELs operating in consist with diesel-electric locomotives can see temperatures exceeding 100 degrees Celsius at their surface, as measured through an analysis of diesel intake temperatures at Donner Pass in California [40]. BELs use cooling systems to maintain nominal battery temperatures, which could be compromised in these scenarios.

3.6 Liquefied Natural Gas

Liquefied natural gas (LNG) locomotives operate in nearly the same way as diesel-electric locomotives, except that they use LNG in an internal combustion engine instead of diesel. As LNG can be a cleaner alternative to diesel, there would be some reduction in emissions, however, this would not be a stop-gap solution and requires a differentiated supply chain. LNG results when natural gas is cooled to very low temperatures, usually by cryogenic means (-162^{o}C/-260^{o}F). The liquification of natural gas provides significant benefits in terms of transportation and energy density. There are multiple designs of natural gas powered internal combustion engine (ICE). A spark-ignition (SI) LNG engine mixes air and fuel outside the combustion chamber that is then injected into the cylinder and ignited by a spark plug. Compression ignition (CI) engines, or dual-fuel engines, require some diesel to help with ignition and do not use a spark plug and are capable of running on diesel alone. When converting diesel (CI) engines to SI, there is typically a reduction in both power and thermal efficiency. This is because SI engines, despite natural gas's high octane level, need a lower compression ratio to prevent pre-ignition or knocking, unlike diesel engines that use compression ignition. Also, using a throttle for load control in SI engines leads to lower efficiency due to pumping losses [41].

The Florida East Coast Railway is the first and only rail company to adopt LNG fuel for their entire locomotive fleet. The railway uses dual-fuel tier 3 locomotives that run on both diesel fuel and LNG with up to 80% gas substitution or 100% diesel. [42]. These locomotives utilize a tender car, located adjacent to one or two locomotives, that stores LNG for combustion.

Figure 3-14: Florida East Coast Railway Locomotives and LNG Tender Car [43]

3.6.1 Benefits of Adoption

Emissions

Natural gas combustion has been shown to have significant reduction in NOx and GHG emissions compared to diesel combustion. Testing LNG locomotives confirmed the emission reduction of NOx by 70% and CO2 by 30% compared with the diesel-fueled locomotives [44], however additional sources of data are limited.

3.6.2 Challenges of Adoption

Fueling

New fueling infrastructure and methods with cryogenic capability would be necessary to provide reliable and timely fueling of LNG locomotives. Fueling times would not exceed 90 minutes, which is roughly three times as long as it takes to fuel a diesel locomotive [45].

Space Requirements

LNG has approximately 60 percent of the energy density of diesel fuel [46]. Therefore, a LNG locomotive would have to rely on a tender car to hold its fuel, which would sacrifice revenue capacity in the confines of a single train.

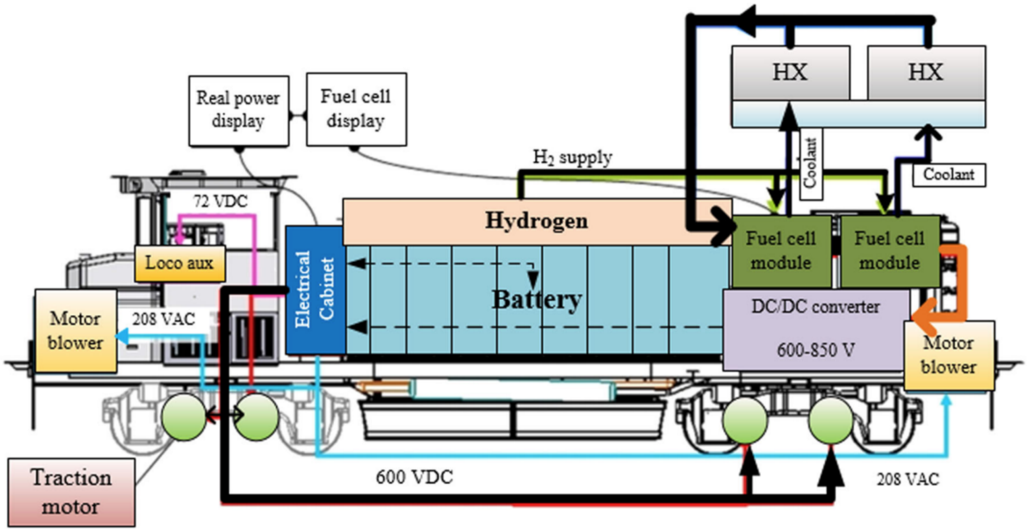
Maintenance

Maintenance of LNG locomotives is expected to be higher than that of diesel, mainly due to the additional cryogenics system that is required to provide constant cooling of the natural gas.

3.7 Hydrogen Fuel Cell

Hydrogen fuel cell locomotives are a promising technology that seeks to considerably reduce emissions while maintaining much of the operating environment of current freight rail. However, the technology has not yet been proven to be a suitable replacement for diesel, but manufacturers are placing big bets on this technology. A hydrogen fuel cell uses a chemical reaction to generate electric energy from hydrogen and oxygen gas. Inside the fuel cell, hydrogen gas is introduced to the anode, where it is split into protons and electrons by a catalyst. The electrons flow through an external circuit to the cathode, generating an electric current that drives the locomotive's electric motors. At the same time, oxygen and hydrogen combine to form water, the only product from the process, aside from unused hydrogen and oxygen. The electricity generated by the fuel cell is used to power the motors of the locomotive. Alternatively, the electricity could be stored in a battery, which would then be used to power the motors. A proposed layout can be found in Figure 3-15.j

Figure 3-15: Proposed Layout for a Hydrogen Fuel Cell Locomotive [47]



3.7.1 Benefits of Adoption

Emissions and Efficiency

Hydrogen fuel cells emit only water and unused fuel during operation, thereby generating no harmful emissions. This zero-emitting property is what makes this technology so desirable for the industry. A hydrogen fuel cell locomotive also exhibits a fuel-to-power efficiency of 80%, which is roughly double that of a diesel-electric locomotive [47].

3.7.2 Challenges of Adoption

Fueling Infrastructure

Since hydrogen is a gas with significantly different storage requirements than diesel, new fuel storage facilities would need to be constructed across a vast rail system. These facilities require specialized equipment to handle cryogenics of liquid hydrogen, which adds complexity and cost. Further, the equipment necessary for transfer and fueling in these two forms is technically advanced and involves substantial financial investment. Additionally, the option of onsite hydrogen generation introduces further complexity and expense. Some solutions have been proposed for vehicles, long-haul trucks and locomotives [48] [49] [50].

Cost of Hydrogen

Currently, the cost of hydrogen is high, at $9 per kilogram. This is mainly due to a low global supply, however, many hydrogen production plants are currently being constructed. The majority of hydrogen is produced as a product from natural gas, a process that emits harmful pollutants into the atmosphere. For hydrogen to be a feasible fuel with no emissions, cleaner methods of production must be adopted, like using electrolyzers powered by wind or solar energy. This method remains expensive because of the high energy requirements of electrolysis and the limited availability of emissions-free electricity generation. Relative to a $3 per gallon cost of diesel, the break-even price of hydrogen for a line haul and switcher locomotive is $3.30 and $5.60 per kilogram of hydrogen, respectively [51]. There is no clear indication that these prices can be achieved within the next 30 years.

Safety

Hydrogen inherently possesses undesirable chemical and physical properties that can make it unsafe. A gas, hydrogen, is highly flammable, and it can be ignited at relatively low concentrations and temperatures. Additionally, hydrogen is an especially small molecule, which enables it to leak through small openings and accumulate in enclosed spaces, potentially leading to explosive hazards if not properly managed. Further, public perception of hydrogen gas may pose a barrier to its adoption, as it is typically seen as a dangerous chemical.

Energy Density

Compared to diesel fuel, hydrogen has a higher energy density per unit mass (120MJ/kg), but a lower energy density per unit volume. Storing hydrogen gas for use in a locomotive requires that it either compressed at very high pressures (350 – 700 bar) or liquefied at very low temperatures. Assuming an 80% fuel-to-rails efficiency, the equivalent energy capacity of a 5000 gallon tank of diesel would be 2820 kilograms of hydrogen. At an immense pressure of 700 bar, this amount of hydrogen would occupy 71,212 liters (18812 gallons), which could fit into a single locomotive's volume. However, achieving 700 bar of pressure has not been proven to be feasible at this scale due to high energy requirements to compress hydrogen and safety concerns. Liquid hydrogen would occupy a much smaller volume: only 40,285 liters (10,642 gallons) for the same energy, but require additional cryogenics systems. An alternative design has been proposed that could accommodate enough fuel for an 8 to 10-hour duty cycle for a switcher locomotive [52].

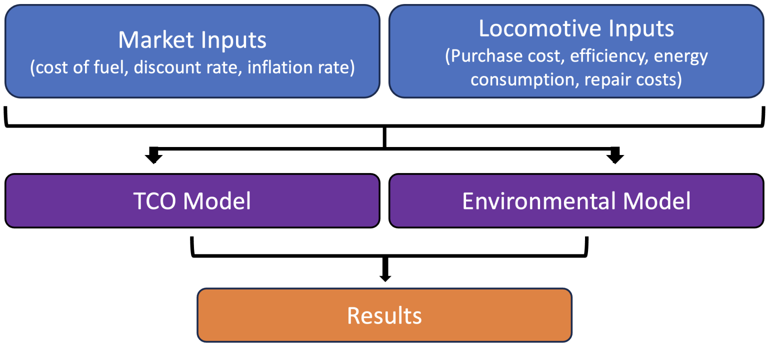
THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 4

Financial and Environmental Analysis

In this chapter, I describe the methods of a Total Cost of Ownership analysis (TCO) for line haul and switcher locomotives, specifically examining Diesel Electric, Battery Electric, and Hydrogen Fuel Cell powered locomotives. I define and employ specific methods to evaluate the total costs associated with acquiring, operating, maintaining, and eventually disposing of each type of locomotive over its lifecycle. Additionally, the chapter will assess the environmental impact of each locomotive type, considering factors such as emissions and energy consumption. Through both financial and environmental considerations, this chapter aims to provide a holistic view of the implications of selecting and utilizing different locomotive technologies for freight rail transportation. There may be considerable financial advantages for the adoption of battery electric or hydrogen fuel cell powered locomotives for both switcher and line haul use, however it requires accounting for external environmental impact of diesel locomotives. Even with potentially high costs of charging or fueling infrastructure, the annual cost associated with clean technologies is less than that of diesel, which is mainly attributed to lower maintenance costs and improved energy efficiency.

Figure 4-1: Analysis Models Overview



4.1 Methodology

Environmental Impact Analysis

To determine the environmental impact of each locomotive technology, it is necessary to quantify the pollution caused by the locomotives and estimate an externalized cost for each unit of pollution generated. Pollutants that were included in the analysis were carbon dioxide (CO2), Nitrogen Oxides (NOx), and Particulate Matter (PM), which contribute to significant negative environmental effects.

Term definitions

1. MWh: Megawatt-hours
2. kWh: Kilowatt-hours
3. MM: millions
4. mTon: metric ton
5. Btu: British Thermal Unit
6. g: gram

Model Inputs

1. CO2 Cost (\$/mTon CO2)

2. Diesel Consumption (Gallons/Year)
3. CO2 Emissions (mTon CO2/Year)
4. NOx Cost ($/mTon NOx)
5. NOx Emissions (mTon NOx/Year)
6. PM Cost ($/mTon PM)
7. NOx Emissions (mTon PM/Year)

For diesel locomotives, pollutant amounts were averaged across the proportion of locomotives at various emissions Tiers, as estimated in the state of California by CARB[53]. Tier emissions profiles are discussed in 3 and used to estimate the annual emissions for CO2, NOx, and PM for locomotives. It was assumed that the current Tier distribution is held constant through the year 2040. Diesel CO2 emissions were calculated using the following formulas.

$$\begin{aligned}\text{Annual Loco Energy (MWh)} &= \text{Avg Consumption per Loco (Gal)} \\ &\times \text{Drivetrain Efficiency} \\ &\times 0.041(\text{MWh/gal})\end{aligned}$$

$$\text{Diesel Consumption (gal)} = \text{Annual Loco Power (MWh)} * \frac{1}{0.041}(\text{MWh/gal})$$

For CO2:

$$\text{Emissions (mTon)} = \text{Diesel Consumption (gal)} \times \frac{10.19 \text{ (kg CO2 per gal)}}{1000(\text{kg per mTon})}$$

$$\text{Annual Damages (\$)} = \text{Cost (\$ per mTon emmitted)} \times \text{Emissions (mTon per year)}$$

For NOx and PM, constant rates of emissions were assumed between the year 2022 and 2040. Annual damages for the year 2022 were calculated using the following equations.

$$\text{Annual Damages (\$)} = \text{Cost (\$ per mTon emmitted)} \times \text{Emissions (mTon)}$$

For Line Haul duty cycle locomotives:

$$\text{Emissions per locomotive (mTon)} = \frac{\text{Weighted Emissions (mTon)}}{\text{(\# of Line Haul Locomotives)}}$$

$$\begin{aligned}\text{Weighted Emissions (mTon)} &= \text{Tier-Weighted Emissions Rates (g/MM Btu)} \\ &\times \text{Total Diesel Consumed (MM Btu)} \\ &\times \frac{\text{\# of Line Haul Locos}}{\text{Total \# of Locomotives}} \\ &\times \frac{1}{1000}\end{aligned}$$

For Switcher duty cycle locomotives, the same equations were used but considered the number of switcher locomotives, instead of line haul locomotives.

For locomotives powered by batteries, emissions costs and amounts were estimated from grid emissions estimated by the ReEDs model[54]. For hydrogen locomotives, it was assumed that hydrogen was generated using completely renewable energy and therefore had no direct emissions.

Costs for emissions of CO2 for the year 2022, 2030, 2040, and 2050 were acquired from the U.S. EPA [55]. The annual costs between these dates were calculated with a straight line slope. The cost for NOx emissions were assumed to be $200 per metric ton of NOx emitted between 2022 and 2040 [56]. The cost of PM emissions was assumed to be $1,170 per metric ton of PM emitted between 2022 and 2040 [56].

Total Cost of Ownership Analysis

A simple discounted cash flow was used to determine the total cost of ownership of a freight locomotive. With this model, stakeholders are able to gain an understanding of costs that drive the use of different locomotives as the adoption of greener technologies becomes more prevalent. It may indicate that some locomotives may be financially preferred to others, and that certain ownership costs can be targeted for improvement.

From conversations with industry stakeholders, a 23-year total life cycle was assumed before the locomotive could be sold at a depreciated price. Depreciation was assumed to be straight line over the 23 years to a resale value of 20% of the original sales price of the locomotive. Inputs into the model are split into market inputs and locomotive inputs. Environmental impact costs were also included in the analysis.

Market Inputs

1. Rail Diesel Price ($/Gallon)
2. Renewable Diesel Price ($/Gallon)
3. Rail Electricity Price ($/kWh)
4. Hydrogen Price ($/Kilogram)
5. Discount rate (%/Year)

Locomotive Inputs

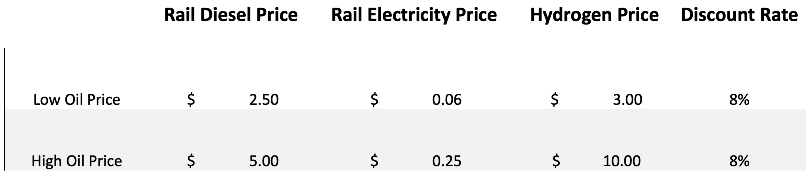
1. Drivetrain efficiency (%)
2. Maintenance and repair cost ($/Year)
3. Average energy usage per locomotive (MWh/Day)
4. Locomotive Cost ($)
5. Energy Source (diesel, hydrogen, or battery)

6. Duty Cycle (Line Haul or Switcher)

Market inputs that include the purchase price of energy were determined using two scenarios: Low Oil price and High Oil Price. These scenarios were calculated using data provided by the U.S. Energy Information Administration's (EIA) Long Term Energy Outlook. Energy costs were averaged over the time period between 2023 and 2046 and assumed to be constant. [22] A discount rate of 8% was assumed for each year.

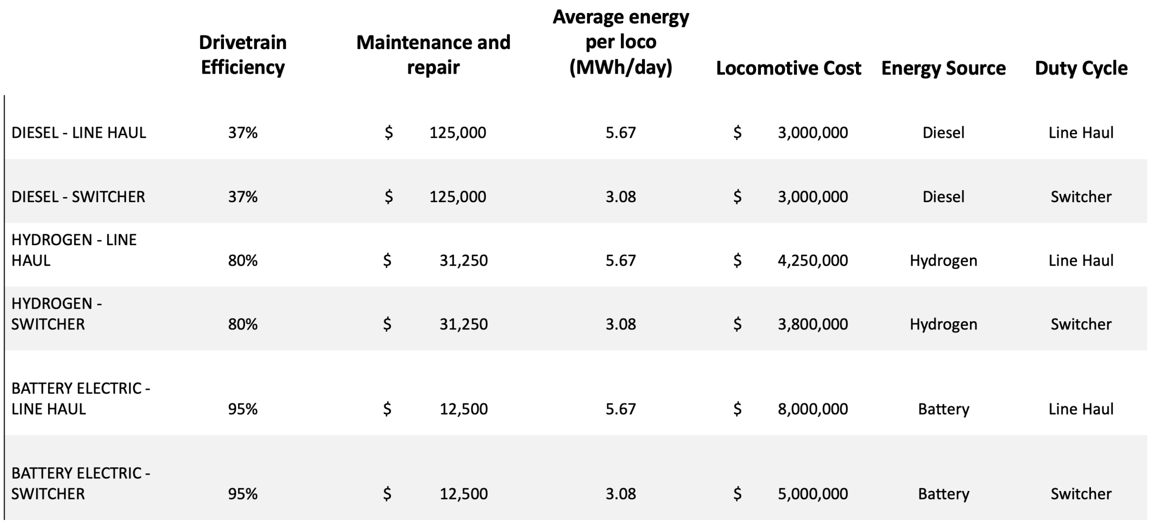
Locomotive inputs were determined through industry sources and municipal publications. Purchase, maintenance, and repair costs were approximated by the California Air Resources Board (CARB) [38][46]. The purchase cost of the battery electric locomotive includes the cost of the battery.

Figure 4-2: Model Market Inputs



	Rail Diesel Price	Rail Electricity Price	Hydrogen Price	Discount Rate
Low Oil Price	$ 2.50	$ 0.06	$ 3.00	8%
High Oil Price	$ 5.00	$ 0.25	$ 10.00	8%

Figure 4-3: Model Locomotive Inputs

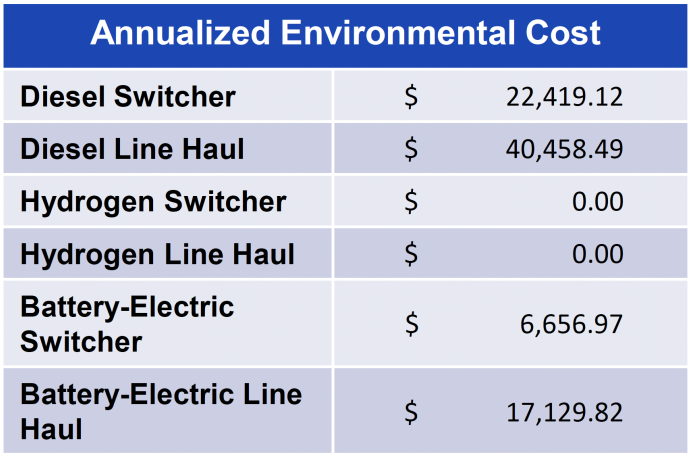


	Drivetrain Efficiency	Maintenance and repair	Average energy per loco (MWh/day)	Locomotive Cost	Energy Source	Duty Cycle
DIESEL - LINE HAUL	37%	$ 125,000	5.67	$ 3,000,000	Diesel	Line Haul
DIESEL - SWITCHER	37%	$ 125,000	3.08	$ 3,000,000	Diesel	Switcher
HYDROGEN - LINE HAUL	80%	$ 31,250	5.67	$ 4,250,000	Hydrogen	Line Haul
HYDROGEN - SWITCHER	80%	$ 31,250	3.08	$ 3,800,000	Hydrogen	Switcher
BATTERY ELECTRIC - LINE HAUL	95%	$ 12,500	5.67	$ 8,000,000	Battery	Line Haul
BATTERY ELECTRIC - SWITCHER	95%	$ 12,500	3.08	$ 5,000,000	Battery	Switcher

4.2 Environmental Impact Analysis Results

The annualized Environmental Impact Analysis is calculated and presented as the output of the model in 4-4.

Figure 4-4: Environmental Cost Output



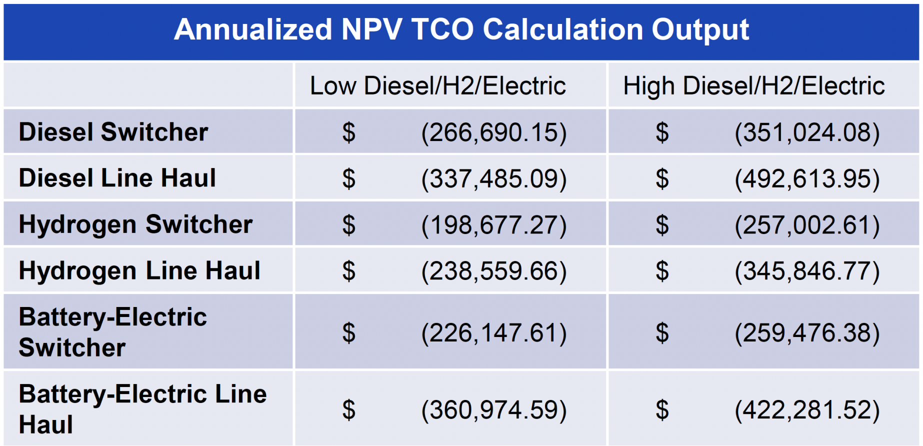
Annualized Environmental Cost		
Diesel Switcher	$	22,419.12
Diesel Line Haul	$	40,458.49
Hydrogen Switcher	$	0.00
Hydrogen Line Haul	$	0.00
Battery-Electric Switcher	$	6,656.97
Battery-Electric Line Haul	$	17,129.82

Overall, the analysis suggests a clear environmental advantage in operating hydrogen fuel cell and battery-electric locomotives over traditional diesel-powered models, especially for line haul use. While the model did not do this, assuming the energy used in battery-electric locomotives is created through non-emitting power generation, then the cost for these machines would be zero, along with hydrogen locomotives. This can be a reasonable assumption for future adoption as renewable energy becomes more prevalent. However, because battery-electric locomotives are already operating using the existing grid, the calculation was performed using current grid costs, as noted previously. Diesel-electric locomotives have high environmental impact costs due to the large amounts of pollutants produced when burning diesel fuel. The financial burden of these emissions may be taken into account when comparing different technologies, however, currently there is no financial penalty for using diesel-electric locomotives. This analysis suggests that creating one may provide for a better incentive to adopt non-emitting technologies like battery-electric and hydrogen fuel cell locomotives.

4.3 Total Cost of Ownership Analysis Results

The annualized TCO is calculated and presented as the output of the model in 4-5.

Figure 4-5: TCO Analysis Output, per locomotive



Annualized NPV TCO Calculation Output

	Low Diesel/H2/Electric	High Diesel/H2/Electric
Diesel Switcher	$ (266,690.15)	$ (351,024.08)
Diesel Line Haul	$ (337,485.09)	$ (492,613.95)
Hydrogen Switcher	$ (198,677.27)	$ (257,002.61)
Hydrogen Line Haul	$ (238,559.66)	$ (345,846.77)
Battery-Electric Switcher	$ (226,147.61)	$ (259,476.38)
Battery-Electric Line Haul	$ (360,974.59)	$ (422,281.52)

Diesel switchers and line haul locomotives show higher annualized NPV TCO, suggesting that traditional diesel-powered locomotives are more financially burdensome over time, especially if fuel prices rise. Hydrogen and battery-electric technologies show significantly lower annualized NPV TCOs compared to diesel. This financial advantage is due to lower fuel and maintenance costs. This adds a financial incentive on top of the already clear environmental benefit for the adoption of hydrogen and battery technologies. The increase in TCO from the low to high scenarios for all technologies indicates that fuel and energy prices are a critical factor in the overall cost analysis.

Chapter 5

Roadmap for Decarbonization

This chapter presents a high-level roadmap for the decarbonization of freight rail locomotives in the United States. Drawing from the insights of the preceding chapters, it is clear that this industry plays a significant role in the creation of GHG emissions, which are harmful to human and environmental health, and that the industry operates with many constraints that are significant barriers for the ultimate reduction of emissions.

Chapter 1 highlighted the critical role of the transportation sector in the U.S. economy while also juxtaposing this with the fact that it is the largest contributor to GHG emissions in the country, driving increased environmental and economic risk.

Chapter 2 outlined the critical role and landscape of U.S. freight rail companies, suppliers, and regulators, demonstrating the individual goals and attributes of each stakeholder. All share a common goal of moving goods throughout the country, but rail companies do not equally prioritize the reduction of emissions, which is opposite to the concerns of agencies like the U.S. EPA and the State of California, who seek to significantly and expediently reduce the amount of emissions from locomotives.

Chapter 3 provided a comprehensive overview of the current locomotive propulsion technology landscape, highlighting that emitting technologies are well established and utilized, while cleaner technologies face significant technical and commercialization challenges.

Chapter 4 provided a foundation from which to estimate relative costs for varying propulsion technologies, demonstrating that the adoption of cleaner technologies comes with high infrastructure and conversion costs, but can ultimately reduce expenses for rail companies once adopted.

The need to decarbonize the transportation sector as a whole, while also serving a growing amount of goods through reliable and safe transportation practices highlights the complexity of creating change in the industry. There are a considerable amount of constraints including reducing emissions, operating within regulations and policy, finite amounts of resources and immature power technologies. To operate within these constraints, a phased approach can be used to ensure practical adoption of new practices and overall reduction of emissions within the freight rail industry.

The roadmap for decarbonization of freight rail can be broken down into three phases:

1. Phase 1: Short Term (0-5 Years): a focus on incremental changes to existing diesel-burning power systems
2. Phase 2: Medium Term (5-15 Years): increased utilization of clean technologies
3. Phase 3: Long Term (15+ Years): Ultimate transition to non-emitting propulsion technologies

5.1 Phase 1: Short Term (0-5 Years)

In the short term, the focus is on incremental changes that can provide for a smoother transition away from diesel-burning power systems. Given the current state of freight rail and existing operational challenges, there is limited expectation that the short term will have significant changes to freight operations. However, incorporating changes can result in significant decreases in GHG emissions.

Enhancing the efficiency of existing diesel-electric locomotives does not require major operational changes, technological innovations, and can be done immediately. Given the high number of locomotives that are older than Tier 4 in operation today, it is easy to envision immediate retirement of some of these locomotives. Older locomotives can be readily retrofitted with cleaner exhaust systems. Further, the use of trip optimization calculators can further reduce needless fuel use, saving rail companies costs and reducing emissions. One difficulty will be the cost of converting and purchasing these locomotives, as their fuel efficiency gains are marginal, providing minimal financial benefit to rail companies.

Expansion of the use of alternative diesels can also immediately reduce direct and indirect emissions from freight locomotives. Biodiesel and synthetic diesel are drop-in fuels that can be readily fed into existing diesel-electric locomotives without modification. By incorporating these fuels, direct emissions from locomotives will decrease, however a larger impact will be the reduction in emissions created during the manufacture of these fuels. One challenge to this strategy is that the supply of alternative diesels is not yet high enough for immediate adoption across all locomotives, however, it is increasing annually. Currently, only the state of California has been able to maintain biodiesel prices to be comparable to those of conventional diesel, posing a financial challenge for the purchase of alternative diesels around the U.S.

The increased use of LNG and CNG locomotives would also have a direct reduction in GHG emissions across the U.S. While these locomotives are currently limited to regional railways, given that the technology has already been tested and proven, national railways should be less hesitant to adopt the technology in a larger capacity. While the introduction of a new fuel and locomotive type requires the creation of a new fuel supply chain with special transportation requirements, it is not infeasible for large rail companies to do so as they already handle CNG transportation for their customers.

Higher battery-electric locomotive prevalence would have a significant impact on total emissions, as each one would completely remove the need for a diesel locomotive. While battery-electric locomotives are still in development and being tested for freight service, the successful sale and use of these locomotives indicates that increased adoption is feasible. Manufacturers will ramp up production of these locomotives as freight rail companies find uses for them within rail yards and in consist with diesel locomotives on long distance routes. The purchase cost of these locomotives is still high, but investment into the battery platform now allows for easier upgrades in the future, setting up rail companies for a long-term transition.

Manufacturers of locomotives should continue investing capital into the research and development of cleaner locomotive technologies. Focusing on improving energy density, reducing costs, and ensuring safety are all paramount for the future adoption of clean locomotives. There is opportunity for increased collaboration with universities and technology companies for the creation of hydrogen fuel cell power systems, improved battery density, and optimized fuel usage. The development of hybrid locomotives is feasible in the near term as diesel and battery technologies are well understood. Manufacturers may face challenges as rail companies reduce the amount of locomotives purchased as they continue to recover from post-pandemic reduction in demand.

Adoption of the proposed solutions in Phase 1 is made difficult by the low margin operation of railroads. Historically, their use of capital for new technologies is limited due mainly to the need to upgrade and maintain the vast rail networks throughout the U.S. Additionally, rail companies operate like flowing rivers and any disruption to their process is like the creation of a dam. Without significant financial or operational advantages, rail companies will be reluctant to adopt changes. It is important that suppliers of locomotive solutions structure their products in a way that clearly demonstrates value for the end-user.

Alternatively, federal and state regulation can increase the uptake of greener solutions. While CARB has already demonstrated its ability to create legislation that necessitates a response from rail companies, it has yet to be seen whether this will result in decreased emissions within the state. Regulators will be tasked with the creation of new directives that result in favorable outcomes that progress the transition towards clean fuels.

5.2 Phase 2: Medium Term (5-15 Years)

In the medium term, there is a reliance on new technological innovations to be available for adoption and accompanying regulation that mandates it. The next 15 years will still heavily rely upon diesel-electric locomotives for freight transportation, but the use of cleaner technologies will be more prevalent.

The use of alternative diesels will continue to increase throughout the industry to match the increase in supply. Older locomotives will continue to be retired or upgraded to modern emissions technologies, further reducing GHG production across the country. The availability of modern low-emitting locomotives will be necessary for rail companies to make these purchases.

Technologies that are ready for deployment within Phase 1 will be tested and proven for several years after their release, indicating that they would be ready for widespread adoption within Phase 2. In this time frame, it is expected that battery-electric locomotives will be frequently running in consist and independently in rail yards and across state lines. Phase 2 will also see increased battery energy capacity, enabling these uses. Infrastructure for charging and servicing battery-electric locomotives will be widespread. Not only will locomotives be charged while stationary, but there should be some adoption of electrified rail segments for high energy-intensity portions of freight trips. Hybrid locomotives will also see use on the rails as freight rail companies will look towards fuel savings on a locomotive platform that is "future-proof" as hybrid locomotives could be readily upgraded.

LNG and CNG locomotives will likely continue to increase, but will reach stagnation within Phase 2 as they are not zero-emitting and will be phased out in Phase 3. Nonetheless, the use of CNG and LNG will continue to reduce the total emissions from the industry.

The cryogenic infrastructure developed for natural gas can also support the use of hydrogen within the industry. Hydrogen generation and transportation technologies will be readily available during Phase 2, which will be an instrumental time for their testing and initial adoption. Focusing on strategic adoption in certain areas, rail companies will work on advanced pilot projects to validate the use of hydrogen fuel cell technology.

The government will support these projects through grants and regulation. The adoption and scaling of some of these technologies will require significant capital investment, which rail companies will do alongside grant programs. Regulation will ensure that the adoption is done at a timely rate and that safety remains a top priority.

5.3 Phase 3: Long Term (15+ Years)

Long term decarbonization of freight rail involves the adoption of zero-emitting technologies, continuous improvement of performance, and evolving policy and regulations. The ultimate goal would be to completely eliminate direct and indirect emissions while still maintaining reliable and speedy transport of goods across the country. However, such a reality will not be achieved without the progressive overhaul of the freight rail locomotive fleet using new technologies to power locomotives.

To ensure the success and sustainability of this transition, it is important that rail propulsion technologies mature to a reliability and serviceability level equivalent to or above that of diesel-electric locomotives today. The adoption of new technologies must not only be non-emitting, but must also keep safety paramount. This creates a need for new innovations, especially given that battery-electric and hydrogen fuel cell locomotives, both of which have unique hazards, are likely to be commonly adopted. Further, it must be recognized that there is likely not a single power technology that will satisfy the diverse needs within freight rail, but rather that a combination of approaches will be necessary. This can mean electrifying portions of a line, using consists of hydrogen and battery-electric locomotives, while having older locomotives reserved as backups, all while maintaining interoperability across the country.

The adoption of new rail technologies brings with it complex needs for new infrastructure as fuels change and operations become more optimized. There will be an increased need for electrified rail lines and hydrogen generation and storage facilities. As more locomotives rely on the electrical grid for power, whether directly or by making fuels using electricity, there will need to be substantial increases in clean power generation capacity. Continuous improvement in the industry will allow for new innovations that decrease risk and barriers to adoption of new technologies. The rail industry will rely on new innovations in other industries such as construction, to reduce costs associated with rail projects, technology, to optimize route planning and power usage across locomotives, and power generation, to provide reliable and emissions-free power.

Finally, policy and regulation are the catalysts for propelling the industry into a greener future. As history has shown, freight rail operators are concerned with increased costs and operational complexities that come with the adoption of new zero-emitting technologies. As the need for freight rail to decarbonize grows, regulators must define a feasible plan for the industry to follow. Future policies and regulations are crucial for creating an environment that supports the long-term sustainability and competitiveness of the freight rail industry, while maintaining a low carbon footprint. This can be accomplished through consistent engagement with stakeholders, financial incentive programs, and sponsorship of research. By working in concert with rail companies, while also taking a strong stance towards decarbonization, regulators and policymakers will be the guide to this roadmap.

THIS PAGE INTENTIONALLY LEFT BLANK

Bibliography

[1] Katherine Calvin et al. *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* Edition: First. Intergovernmental Panel on Climate Change (IPCC), July 25, 2023. DOI: `10.59327/IPCC/AR6-9789291691647`. URL: `https://www.ipcc.ch/report/ar6/syr/` (visited on 08/11/2023).

[2] *The Paris Agreement | UNFCCC.* URL: `https://unfccc.int/process-and-meetings/the-paris-agreement` (visited on 08/11/2023).

[3] "The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050". In: *United States Department of State and the United States Executive Office of the President* (Nov. 2021).

[4] Patricia Hu et al. *Transportation Statistics Annual Report 2022.* Series: Transportation Statistics Annual Report (TSAR). Dec. 1, 2022. DOI: `10.21949/1528354`. URL: `https://rosap.ntl.bts.gov/view/dot/65841` (visited on 08/11/2023).

[5] *Moving Goods in the United States.* URL: `https://data.bts.gov/stories/s/Moving-Goods-in-the-United-States/bcyt-rqmu/` (visited on 08/11/2023).

[6] OAR US EPA. *Fast Facts on Transportation Greenhouse Gas Emissions.* Aug. 25, 2015. URL: `https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions` (visited on 10/10/2023).

[7] Michelle L. Bell et al. "Seasonal and Regional Short-term Effects of Fine Particles on Hospital Admissions in 202 US Counties, 1999–2005". In: *American Journal of Epidemiology* 168.11 (Dec. 1, 2008), pp. 1301–1310. ISSN: 0002-9262. DOI: `10.1093/aje/kwn252`. URL: `https://doi.org/10.1093/aje/kwn252` (visited on 10/30/2023).

[8] Johanna Lepeule et al. "Chronic Exposure to Fine Particles and Mortality: An Extended Follow-up of the Harvard Six Cities Study from 1974 to 2009". In: *Environmental Health Perspectives* 120.7 (July 2012). Publisher: Environmental Health Perspectives, pp. 965–970. DOI: `10.1289/ehp.1104660`. URL: `https://ehp.niehs.nih.gov/doi/10.1289/ehp.1104660` (visited on 10/30/2023).

[9] Daniel Krewski et al. "Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality". In: ().

[10] T. J. Woodruff, J. Grillo, and K. C. Schoendorf. “The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States.” In: *Environmental Health Perspectives* 105.6 (June 1997). Publisher: Environmental Health Perspectives, pp. 608–612. DOI: `10.1289/ehp.97105608`. URL: `https://ehp.niehs.nih.gov/doi/abs/10.1289/ehp.97105608` (visited on 10/30/2023).

[11] Georgina Santos. “Road transport and CO2 emissions: What are the challenges?” In: *Transport Policy* 59 (Oct. 1, 2017), pp. 71–74. ISSN: 0967-070X. DOI: `10.1016/j.tranpol.2017.06.007`. URL: `https://www.sciencedirect.com/science/article/pii/S0967070X17304262` (visited on 08/17/2023).

[12] *Freight Rail & The Staggers Act of 1980: The Turning Point for Railroads*. Association of American Railroads. URL: `https://www.aar.org/issue/staggers-act/` (visited on 09/11/2023).

[13] *Freight Rail & Investments: Privately Maintaining, Modernizing the Network*. Association of American Railroads. URL: `https://www.aar.org/issue/freight-rail-investments/` (visited on 09/11/2023).

[14] *Freight Transportation Energy Use & Environmental Impacts*. URL: `https://data.bts.gov/stories/s/Freight-Transportation-Energy-Use-Environmental-Im/f7sr-d4s8/` (visited on 10/23/2023).

[15] *Surface Transportation Board Adopts Final Rule Amending Thresholds for Classifying Rail Carriers*. Surface Transportation Board. URL: `https://www.stb.gov/news-communications/latest-news/pr-21-16/` (visited on 09/11/2023).

[16] *Union Membership and Coverage Database*. URL: `http://unionstats.com/` (visited on 09/13/2023).

[17] Andrew L. Goodkind et al. “Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions”. In: *Proceedings of the National Academy of Sciences* 116.18 (Apr. 30, 2019). Publisher: Proceedings of the National Academy of Sciences, pp. 8775–8780. DOI: `10.1073/pnas.1816102116`. URL: `https://www.pnas.org/doi/full/10.1073/pnas.1816102116` (visited on 10/10/2023).

[18] Robert G Ireson. “Development of Detailed Railyard Emissions to Capture”. In: ().

[19] State of California Air Resources Board. *CARB passes a new In-Use Locomotive Regulation estimated to yield over $32 billion in health benefits | California Air Resources Board*. URL: `https://ww2.arb.ca.gov/news/carb-passes-new-use-locomotive-regulation-estimated-yield-over-32-billion-health-benefits-0` (visited on 06/06/2023).

[20] State of California Air Resources Board. *CARB’s 2022 In-Use Locomotive Emission Inventory:Regulation Proposal and Scenarios*. Aug. 2022. URL: `https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/appg.pdf`.

[21] United States. Department of Transportation. Bureau of Transportation Statistics. “National Transportation Statistics (NTS)”. In: (2019). Publisher: Not Available. DOI: `10.21949/1503663`. URL: `https://tinyurl.com/rosapntlbtsNTS` (visited on 11/07/2023).

[22] U.S. Energy Information Administrator (EIA). *Annual Energy Outlook 2022*. 2022.

[23] Paul Norton et al. *Emissions from Trucks using Fischer-Tropsch Diesel Fuel*. SAE Technical Paper 982526. ISSN: 0148-7191, 2688-3627. Warrendale, PA: SAE International, Oct. 19, 1998. DOI: `10.4271/982526`. URL: `https://www.sae.org/publications/technical-papers/content/982526/` (visited on 01/16/2024).

[24] Guiyan Zang et al. “Synthetic Methanol/Fischer–Tropsch Fuel Production Capacity, Cost, and Carbon Intensity Utilizing CO2 from Industrial and Power Plants in the United States”. In: *Environmental Science & Technology* 55.11 (June 1, 2021). Publisher: American Chemical Society, pp. 7595–7604. ISSN: 0013-936X. DOI: `10.1021/acs.est.0c08674`. URL: `https://doi.org/10.1021/acs.est.0c08674` (visited on 01/16/2024).

[25] *Infinium Ultra-low Carbon eFuels*. Infinium. URL: `https://www.infiniumco.com` (visited on 01/16/2024).

[26] *How to Calculate Catenary*. Sciencing. URL: `https://sciencing.com/calculate-catenary-2651.html` (visited on 03/17/2024).

[27] Andreas Steimel. *Electric Traction - Motive Power and Energy Supply: Basics and Practical Experience*. Google-Books-ID: Hdvr82d23mkC. Oldenbourg Industrieverlag, 2008. 356 pp. ISBN: 978-3-8356-3132-8.

[28] *Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)*. URL: `https://www.eia.gov/tools/faqs/faq.php` (visited on 01/16/2024).

[29] The White House. *FACT SHEET: President Biden Signs Executive Order Catalyzing America’s Clean Energy Economy Through Federal Sustainability*. The White House. Dec. 8, 2021. URL: `https://www.whitehouse.gov/briefing-room/statements-releases/2021/12/08/fact-sheet-president-biden-signs-executive-order-catalyzing-americas-clean-energy-economy-through-federal-sustainability/` (visited on 01/16/2024).

[30] Mohamad Y. Mustafa et al. “Fuel cell technology application for Dubai rail systems”. In: *2018 Advances in Science and Engineering Technology International Conferences (ASET)*. 2018 Advances in Science and Engineering Technology International Conferences (ASET). Feb. 2018, pp. 1–7. DOI: `10.1109/ICASET.2018.8376798`. URL: `https://ieeexplore.ieee.org/document/8376798` (visited on 01/17/2024).

[31] Ahmed Aredah et al. "Comparative analysis of alternative powertrain technologies in freight trains: A numerical examination towards sustainable rail transport". In: *Applied Energy* 356 (Feb. 15, 2024), p. 122411. ISSN: 0306-2619. DOI: `10.1016/j.apenergy.2023.122411`. URL: `https://www.sciencedirect.com/science/article/pii/S0306261923017750` (visited on 01/17/2024).

[32] Cambridge Systematics, Inc. "Task 8: Analysis of Freight Rail Electrification in the SCAG Region". In: (Apr. 2012).

[33] Association of American Railroads. "Freight Railroads & Climate Change". In: (Mar. 2021).

[34] Association of American Railroads. *Oppose Rail Electrification & Support Sensible Climate Policy*. Jan. 2021. URL: `https://www.railwayage.com/wp-content/uploads/2021/02/AAR-Electrification-Fact-Sheet.pdf` (visited on 01/20/2024).

[35] Michael E. Iden. "Battery Storage of Propulsion-Energy for Locomotives". In: 2014 Joint Rail Conference. American Society of Mechanical Engineers Digital Collection, June 3, 2014. DOI: `10.1115/JRC2014-3805`. URL: `https://dx-doi-org.libproxy.mit.edu/10.1115/JRC2014-3805` (visited on 06/07/2023).

[36] Michael E. Iden. "Battery Electric Locomotives & Battery Tenders: Operational & Infrastructure Challenges to Widespread Adoption". In: 2021 Joint Rail Conference. American Society of Mechanical Engineers Digital Collection, June 8, 2021. DOI: `10.1115/JRC2021-58378`. URL: `https://dx.doi.org/10.1115/JRC2021-58378` (visited on 06/07/2023).

[37] Garrett Anderson. *BNSF ZERO-AND NEAR ZERO-EMISSION FREIGHT FACILITIES PROJECT (ZANZEFF) DATA ACQUISITION SUPPORT*. May 2021. URL: `https://ww2.arb.ca.gov/sites/default/files/2022-11/zanzeff-bnsf-belreport.pdf` (visited on 01/21/2024).

[38] California Air Resources Board. "Preliminary Cost Document for the In-Use Locomotive Regulation". In: ().

[39] U. S. Government Accountability Office. *Railroad Bridges and Tunnels: Federal Role in Providing Safety Oversight and Freight Infrastructure Investment Could Be Better Targeted | U.S. GAO*. URL: `https://www.gao.gov/products/gao-07-770` (visited on 01/21/2024).

[40] Joseph McDonald et al. "Locomotive Exhaust Temperatures During High Altitude Tunnel Operation in Donner Pass". In: ASME 2008 Internal Combustion Engine Division Spring Technical Conference. American Society of Mechanical Engineers Digital Collection, June 11, 2009, pp. 375–384. DOI: `10.1115/ICES2008-1625`. URL: `https://dx.doi.org/10.1115/ICES2008-1625` (visited on 01/21/2024).

[41] Fábio C. Barbosa. "LNG Use in Freight Rail Industry as an Economic and Environmental Driver: A Technical, Operational and Economic Assessment". In: 2017 Joint Rail Conference. American Society of Mechanical Engineers Digital Collection, July 19, 2017. DOI: `10.1115/JRC2017-2233`. URL: `https://dx.doi.org/10.1115/JRC2017-2233` (visited on 01/21/2024).

[42] William Vantuono. *Florida East Coast Railway converts locomotive fleet to LNG*. International Railway Journal. Nov. 13, 2017. URL: `https://www.railjournal.com/regions/north-america/florida-east-coast-railway-converts-locomotive-fleet-to-lng/` (visited on 01/21/2024).

[43] *Rail Insider-What's next in emerging technologies for short-line railroads? Quite a bit. Information For Rail Career Professionals From Progressive Railroading Magazine*. Progressive Railroading. URL: `https://www.progressiverailroading.com/short_lines_regionals/article/Whats-next-in-emerging-technologies-for-short-line-railroads-Quite-a-bit--49362` (visited on 01/21/2024).

[44] Viktorija Ditmonaite. "LNG in the rail freight industry : The case of the Nordland Line". Accepted: 2016-01-18T13:52:28Z. Master thesis. Høgskolen i Molde - Vitenskapelig høgskole i logistikk, 2015. URL: `https://himolde.brage.unit.no/himolde-xmlui/handle/11250/2374134` (visited on 01/21/2024).

[45] *FEC rolls out LNG*. Railway Age. Nov. 10, 2017. URL: `https://www.railwayage.com/mechanical/locomotives/fec-rolls-out-lng/` (visited on 01/21/2024).

[46] California Air Resources Board. "Technology Assessment: Freight Locomotives". In: (Nov. 2016).

[47] Osamah Siddiqui and Ibrahim Dincer. "A Review on Fuel Cell-Based Locomotive Powering Options for Sustainable Transportation". In: *Arabian Journal for Science and Engineering* 44.2 (Feb. 2019), pp. 677–693. ISSN: 2193-567X, 2191-4281. DOI: `10.1007/s13369-018-3607-2`. URL: `http://link.springer.com/10.1007/s13369-018-3607-2` (visited on 01/22/2024).

[48] Nawei Liu et al. "Evaluating national hydrogen refueling infrastructure requirement and economic competitiveness of fuel cell electric long-haul trucks". In: *Mitigation and Adaptation Strategies for Global Change* 25.3 (Mar. 1, 2020), pp. 477–493. ISSN: 1573-1596. DOI: `10.1007/s11027-019-09896-z`. URL: `https://doi.org/10.1007/s11027-019-09896-z` (visited on 01/22/2024).

[49] David L. Greene, Joan M. Ogden, and Zhenhong Lin. "Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles". In: *eTransportation* 6 (Nov. 1, 2020), p. 100086. ISSN: 2590-1168. DOI: `10.1016/j.etran.2020.100086`. URL: `https://www.sciencedirect.com/science/article/pii/S2590116820300436` (visited on 01/22/2024).

[50] Carlos Fúnez Guerra et al. "Sustainability of hydrogen refuelling stations for trains using electrolysers". In: *International Journal of Hydrogen Energy*. European Fuel Cell Conference & Exhibition 2019 46.26 (Apr. 14, 2021), pp. 13748–13759. ISSN: 0360-3199. DOI: `10.1016/j.ijhydene.2020.10.044`. URL: `https://www.sciencedirect.com/science/article/pii/S0360319920338106` (visited on 01/22/2024).

[51] Rajesh Ahluwalia et al. "Total Cost of Ownership for Line Haul, Yard Switchers, and Regional Passenger Locomotives: Preliminary Results". In: ().

[52] A. R. Miller et al. "System design of a large fuel cell hybrid locomotive". In: *Journal of Power Sources*. X Polish Conference on Systems with Fast Ionic Transport 173.2 (Nov. 15, 2007), pp. 935–942. ISSN: 0378-7753. DOI: `10.1016/j.jpowsour.2007.08.045`. URL: `https://www.sciencedirect.com/science/article/pii/S0378775307015856` (visited on 01/22/2024).

[53] State of California Air Resources Board. *Locomotive Fact Sheets | California Air Resources Board*. URL: `https://ww2.arb.ca.gov/our-work/programs/reducing-rail-emissions-california/locomotive-fact-sheets` (visited on 06/27/2023).

[54] Natalie D. Popovich et al. "Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric". In: *Nature Energy* 6.11 (Nov. 2021), pp. 1017–1025. ISSN: 2058-7546. DOI: `10.1038/s41560-021-00915-5`. URL: `https://www.nature.com/articles/s41560-021-00915-5` (visited on 06/07/2023).

[55] U.S. Environmental Protection Agency. "Supplementary Material for the Regulatory Impact Analysis for the Supplemental Proposed Rulemaking, "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review": EPA External Review Draft of Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances". In: ().

[56] *Weighing the Value of a Ton of Pollution*. Cato Institute. June 1, 2010. URL: `https://www.cato.org/regulation/summer-2010/weighing-value-ton-pollution` (visited on 02/18/2024).