California Air Resources Board

Appendix F

Technology Feasibility Assessment for the Proposed In-Use Locomotive Regulation

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I. Purpose of the Technology Feasibility Assessment

This technology feasibility assessment discusses various locomotive technologies that may be used to meet the requirements of the proposed In-Use Locomotive Regulation (Proposed Regulation). The Proposed Regulation does not prescribe any one technology and allows any technology to be used, provided it meets the requirements.

Some of the technologies described in this document are described in greater detail in the November 2016 Technology Assessment: Freight Locomotives and is incorporated here by reference.[1] Certain technologies are already available in 2022, and staff anticipates some technologies in development, as described in this appendix, will be available in time to comply with the Proposed Regulation. The technologies described in this appendix are not exhaustive and new ones are likely to emerge in the future.

II. Summary of Proposed Regulation

The Proposed Regulation has four main components. Each of the four components are described at a high level below. More details on the requirements in the Proposed Regulation may be found in Appendix A: Proposed Regulation Order.

A. Spending Account

For each locomotive operated in California, Locomotive Operators will deposit funds into a spending account annually. The amount deposited in the account is calculated by using the locomotive's annual usage in megawatt hours (MWh) or per gallon of fuel and the locomotive's emission factors. Emission factors reflect estimates of the health cost burden on Californians due to these locomotive emissions. Funds in the Spending Account may only be used for:

1. The purchase, lease, or rental of Tier 4 or cleaner locomotives, or for the remanufacture or repower to Tier 4 or cleaner locomotive until January 1, 2030.
2. The purchase, lease, or rental of zero emission (ZE) locomotives, ZE capable locomotive(s)[2], ZE rail equipment, or to repower to ZE locomotive(s) or ZE capable locomotive(s).
3. The purchase ZE infrastructure intended to support ZE locomotives, ZE capable locomotives or ZE rail equipment.
4. Pilot or demonstrate ZE locomotives or ZE rail equipment technologies.

[1] CARB, Technology Assessment: Freight Locomotives, November 2016. (weblink: https://ww2.arb.ca.gov/sites/default/files/classic//msprog/tech/techreport/final_rail_tech_assessment_11282016.pdf).
[2] The ZE capable Locomotive must only operate in a ZE capacity while operating in California.

1. Zero emission Credit

From the effective date of the Proposed Regulation through December 31, 2029, use of any ZE locomotive, ZE rail equipment[3] or wayside power (also known as "ground power" or "yard power"), in California will generate a credit that may be used toward future Spending Account deposit obligations. The credit amount is determined by how many MWhs each ZE locomotive or ZE rail equipment has operated and/or the MWhs of wayside power that has been used. Additionally, use of a ZE locomotive, ZE rail equipment, or wayside power in a disadvantaged community as defined by CalEnviroScreen[4] will accrue a double credit.

B. In-Use Operational Requirements (IUOR)

Starting January 1, 2030, only locomotives with original engine build dates less than 23 years may operate in California. Additionally, beginning January 1, 2030, all switch and passenger and industrial locomotives with an original engine build date of 2030 or newer will need to operate in a ZE configuration at all times while in California. Starting January 1, 2035, all line haul locomotives with an original engine build date of 2035 or newer will need to operate in a ZE configuration at all times while in California. As part of these requirements, in 2027 and 2032, staff will assess the progress made in ZE technologies for use with freight line haul, switch, industrial, and passenger locomotives, as well as the status of infrastructure improvements that may be needed to support ZE technologies.

C. Idling Requirement

The Proposed Regulation specifies that locomotives cannot idle in California for more than 30 minutes before the engine must be shut down. Certain exemptions permit idling in excess of 30 minutes consistent with those found in 40 CFR Part 1033.

D. Recordkeeping and Reporting

The Proposed Regulation requires each locomotive to annually report locomotive operations by California Air District.

III. Process for Developing the Technology Feasibility Assessment

For this technical feasibility assessment, staff conducted a literature search for each prospective technology and interviewed people with knowledge and expertise in advanced technologies including those from various institutions, such as national laboratories, university researchers, technology experts, original equipment manufacturers, dealers, ZE fuel suppliers, electric power companies, and engineering consultants.

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[3] Equipment capable of on-track operation that has a main function that is the same as a freight line haul, switch, industrial, or passenger locomotive.

[4] Office of Environmental Health Hazard Assessment (OEHHA) California Communities Environmental Health Screening Tool: CalEnviroScreen 4.0., accessed June 17, 2022. (weblink: https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-40).

A. Technology Feasibility Assessment Elements

For each technology, staff tried to include the following:

1. Technology Description – A description of the technology and how it works.
2. Emissions Benefits – A discussion of the overall emissions benefits that can be achieved from the technology.
3. Technology Readiness – A description of the stage of technology development (e.g., research and development, prototype/pilot demonstration, pre-commercial demonstration, or commercially available). Examples of completed, planned, or ongoing demonstration projects and the results. A discussion of the scope of commercial introduction (number in use), and how widely available it is.
4. Infrastructure Requirements – A description of the supporting infrastructure required.
5. Economics – A discussion of costs (e.g., capital, operational, maintenance, infrastructure), if known and a comparison to diesel costs.
6. Technology Outlook – A description of the advantages and challenges of the technology and any issues that may impact the technology's deployment or become a barrier to commercialization.

IV. Overview of Locomotives

Figure 1: Diesel Electric Locomotive

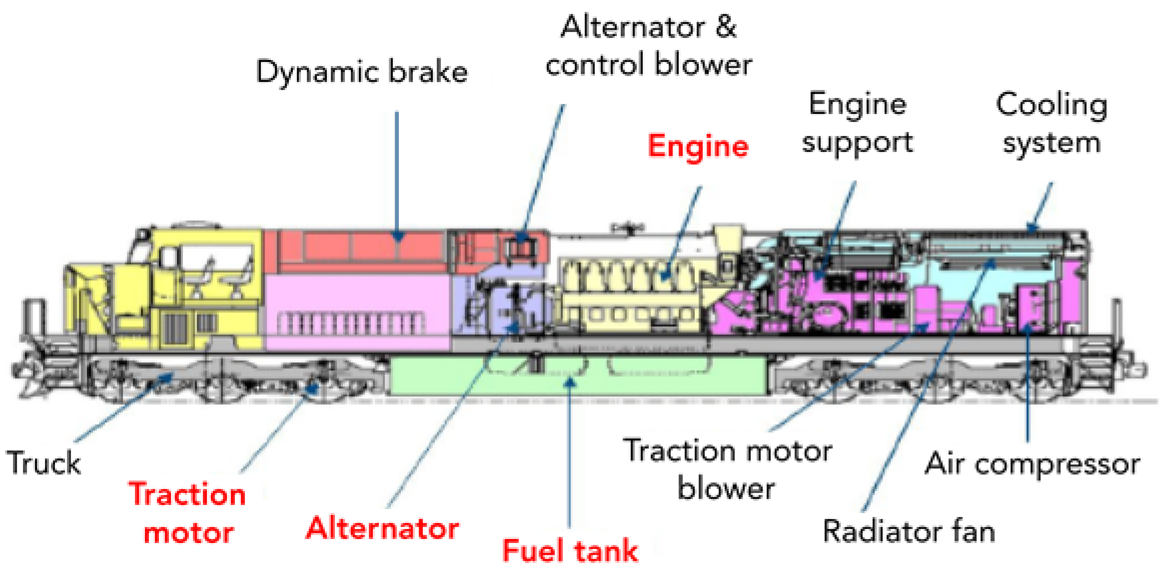


Figure 1 shows a conventional diesel-electric locomotive. A typical modern locomotive has a diesel engine that drives an alternator to generate electricity. The electricity generated powers traction motors located next to the wheels, which are used to propel the locomotive. Conventional locomotives are already electrified as they are propelled by electric motors. However, to achieve a ZE locomotive, the source of the electricity must be from a non-combustion engine.

Other parts of the locomotive seen in Figure 1 consist of a cab for the engineer and parts needed for braking, cooling, and supporting various functions. On the underside of the locomotive is a fuel tank capable of carrying approximately 5,000 gallons of diesel. The combination of a high horsepower diesel engine and a large fuel tank results in a high powered locomotive capable of traveling 1,000 miles or more between refueling.

ZE locomotives may share some common components and features with diesel-electric locomotives, such as the structure underneath a locomotive to which axles and wheels are attached (truck), traction motor, traction motor blower, and air compressor. Other locomotive systems may require replacement or modifications depending on the ZE technology used. For both battery-electric and fuel cell locomotives, the engine, alternator, fuel tank, and engine support systems will be replaced with batteries or fuel cells, and control systems. As a safety precaution, fuel cell locomotives may require a different fuel tank configuration or liquid hydrogen storage location than what is seen on diesel locomotives. Additionally, battery-electric technologies and fuel cell technologies may require a separate battery or hydrogen tender due to larger volume needs.

It may be possible for diesel locomotives to be converted into ZE locomotives. Depending on size and configuration, portions of the diesel locomotive may be replaced for fuel cells or batteries. Reusing an existing locomotive for a new ZE locomotive may reduce total capital costs of replacing the locomotive.

A. Locomotive Types

1. Line Haul Locomotives

Line haul locomotives are primarily used for long-distance freight transport. By federal definition, line haul locomotives are powered by an engine with a maximum rated power (or a combination of engines having a total rated power) greater than 2,300 hp.[3] Line haul Locomotives carry freight throughout the North American rail system, often between states (interstate) for example a commonly used route being Chicago to Los Angeles. Line haul locomotives are generally operated by Class I locomotive operators.

2. Switch Locomotives

Industry refers to locomotives that are typically used within the state (intrastate) for short-distance and for work at railyards (in-yard) as “switch” locomotives. Switch locomotives or “switchers” are often older locomotives because they are used in lower power settings than line haul locomotives, and they remain close to a base, which satisfies a need for more frequent maintenance if needed. Generally, road Switcher Locomotives are operated by Class I, II and III Railroads for both in-yard work and short distance hauls. Although they can be used by any operators, yard Switch locomotives are primarily operated by Industrial Operators within a localized area, moving locomotives or railcars throughout a railyard or industrial facility.

3. Passenger Locomotives

Passenger locomotives are highly specialized and designed to pull Passenger cars. They may travel over long (cross-country) or short (intrastate or local commuter) distances. One major difference between Passenger locomotives and Freight locomotives is that Passenger locomotives generally have a main propulsion engine and onboard hotel power, sometimes referred to as head-end power. The head-end power can be powered by the primary engine or by a separate diesel generator that provides electricity via cable for the lights, air conditioning, and other material comforts to connected Passenger railcars.

Figure 2: Metrolink Tier 4 Passenger Locomotive[5] and Caltrans Tier 4 Passenger Locomotive operated by LOSSAN Pacific Surfliner Corridor[6]

B. California Railroads and Locomotive Operators

For regulatory purposes, the federal Surface Transportation Board (STB) categorizes railroads by Class. Class I (major), Class II (regional), and Class III (shortline) freight railroads designation is based on annual operating revenue.[7] Class I railroads use large fleets of line haul locomotives to move freight throughout the country. Class II railroads move freight over smaller regions, such as between two or three states. Class III railroads operate very small fleets, sometimes one or two locomotives, to move freight over local routes, such as from an industrial area to a local railyard. Industrial and Passenger locomotive operators do not fall into any of the STB categories. Industrial operators use locomotives to move their products within and around their facilities such as grain mills and cement plants. Passenger locomotive operators such as Amtrak and Metrolink service passenger routes. In 2021, California had:

- 2 Class I line haul locomotive operators (Union Pacific Railroad (UP) and BNSF Railway (BNSF)
    - 8,250 line haul locomotives on average

[5] Image of Tier 4 Locomotive, Courtesy of Metrolink, 2021.
[6] Image of Tier 4 Locomotive, Courtesy of LOSSAN Rail Corridor Agency, 2021.
[7] Surface Transportation Board, Economic Data, 2022, accessed March 22, 2022. (weblink: https://www.stb.gov/reports-data/economic-data/).

    - 298 switchers on average
- 1 Class II railroad
    - Unknown
- 25 Class III locomotive operators
    - 6 switchers on average
- 42 Industrial operators
    - 1.5 switchers on average
- 6 Passenger railroads
    - 21 passenger locomotives on average

C. Existing Locomotive Emission Requirements

Under the Clean Air Act, the United States Environmental Protection Agency (U.S. EPA) has authority to establish emissions standards for new locomotives. The first set of locomotive emission regulations was approved in 1998, and specified control levels for pollutants in engine Tiers 0, 1, and 2. In 2008, U.S. EPA approved the second set of locomotive emission regulations introducing new standards: Tier 3 and Tier 4, along with stricter emission standards for remanufacturing existing Tier 0, 1, and 2 locomotives. While the 2008 regulations still refer to these standards as Tier 0, 1, and 2, they are commonly referred to with ''plus'' designations to distinguish them from the 1998 standards.[8,9] Federal regulations required locomotive manufacturers to build Tier 4 locomotives starting in 2015. Remanufacturing practices are explained in more detail in Section VII A.

Locomotives are required to meet the emission standards throughout their full useful life. Each U.S. EPA emission standard is the maximum level a locomotive is allowed to emit while operated. Often locomotives are tested and certified at emission levels lower than the most recent standard.

Table 1: U.S. EPA Locomotive Emissions Standards for Line Haul and Passenger Locomotives[8,9]

Emissions Tier	Year of Original Manufacture	NOX Standard (g/bhp-hr)	PM Standard (g/bhp-hr)	HC Standard (g/bhp-hr)	Carbon monoxide (CO) Standard (g/bhp-hr)
Tier 0	2000-2001 (1973-1999 when remanufactured)	9.5	0.60	1.00	5.0
Tier 0+	1973-1992	8.0	0.22	1.00	5.0

[8] U.S. EPA; 40 CFR Part 1033 – Exhaust emission standards, Subpart B; pp16-17. (weblink: https://www.govinfo.gov/content/pkg/CFR-2020-title40-vol36/pdf/CFR-2020-title40-vol36-part1033.pdf).
[9] U.S. EPA; 40 CFR Parts 85, 89 and 92 - Emission Standards for Locomotives and Locomotive Engines; April 16, 1998. (weblink: https://www.govinfo.gov/content/pkg/FR-1998-04-16/pdf/98-7769.pdf).

Emissions Tier	Year of Original Manufacture	NOX Standard (g/bhp-hr)	PM Standard (g/bhp-hr)	HC Standard (g/bhp-hr)	Carbon monoxide (CO) Standard (g/bhp-hr)
Tier 1	2002-2004	7.4	0.45	0.55	2.2
Tier 1+	1993-2004	7.4	0.22	0.55	2.2
Tier 2	2005-2011	5.5	0.20	0.30	1.5
Tier 2+	2005-2011	5.5	0.10	0.30	1.5
Tier 3	2012-2014	5.5	0.10	0.30	1.5
Tier 4	2015 or later	1.3	0.03	0.14	1.5

Table 2: U.S. EPA Locomotive Emissions Standards for Switch Locomotives[10,11]

Emissions Tier	Year of Original Manufacture	NOX Standard (g/bhp-hr)	PM Standard (g/bhp-hr)	HC Standard (g/bhp-hr)	Carbon monoxide (CO) Standard (g/bhp-hr)
Tier 0	2000-2001 (1973-1999 when remanufactured)	14.0	0.72	2.10	8.0
Tier 0+	1973-2001	11.8	0.26	2.10	8.0
Tier 1	2002-2004	11.0	0.54	1.20	2.5
Tier 1+	2002-2004	11.0	0.26	1.20	2.5
Tier 2	2005-2011	8.1	0.24	0.60	2.4
Tier 2+	2005-2010	8.1	0.13	0.60	2.4
Tier 3	2011-2014	5.0	0.10	0.60	2.4

[10] U.S. EPA, 40 CFR Part 1033 – Exhaust emission standards, Subpart B, pp16-17, n.d. (weblink: https://www.govinfo.gov/content/pkg/CFR-2020-title40-vol36/pdf/CFR-2020-title40-vol36-part1033.pdf).
[11] U.S. EPA; 40 CFR Parts 85, 89 and 92 - Emission Standards for Locomotives and Locomotive Engines, April 16, 1999. (weblink: https://www.govinfo.gov/content/pkg/FR-1998-04-16/pdf/98-7769.pdf).

Emissions Tier	Year of Original Manufacture	NOX Standard (g/bhp-hr)	PM Standard (g/bhp-hr)	HC Standard (g/bhp-hr)	Carbon monoxide (CO) Standard (g/bhp-hr)
Tier 4	2015 or later	1.3	0.03	0.14	2.4

Figure 3 and Figure 4 below show the 2020 PM and NOx emission contributions in tons per day (tpd) by locomotive Tier.

Figure 3: 2020 California Locomotive PM Emissions by Tier (tpd)

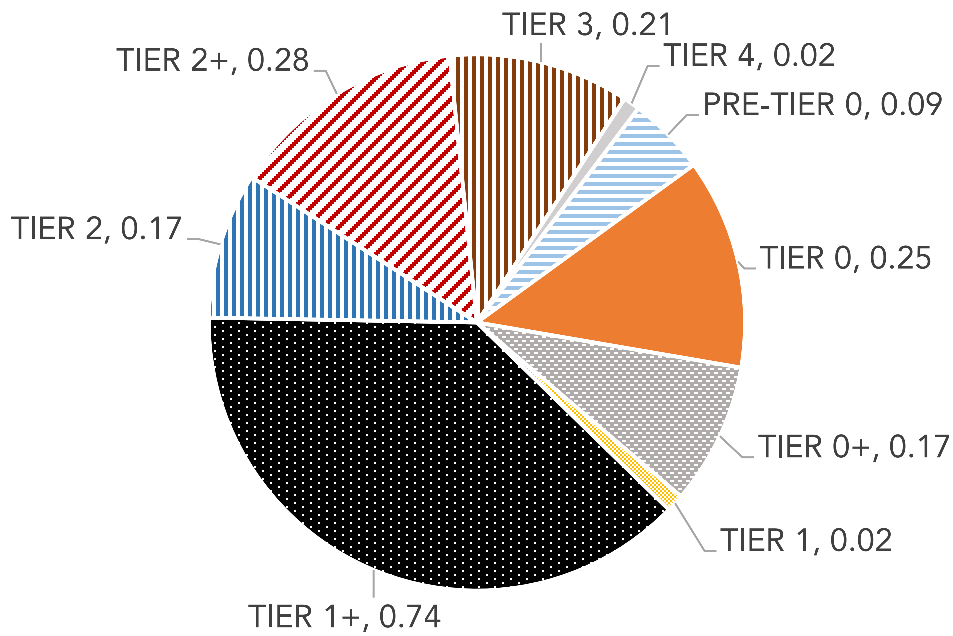
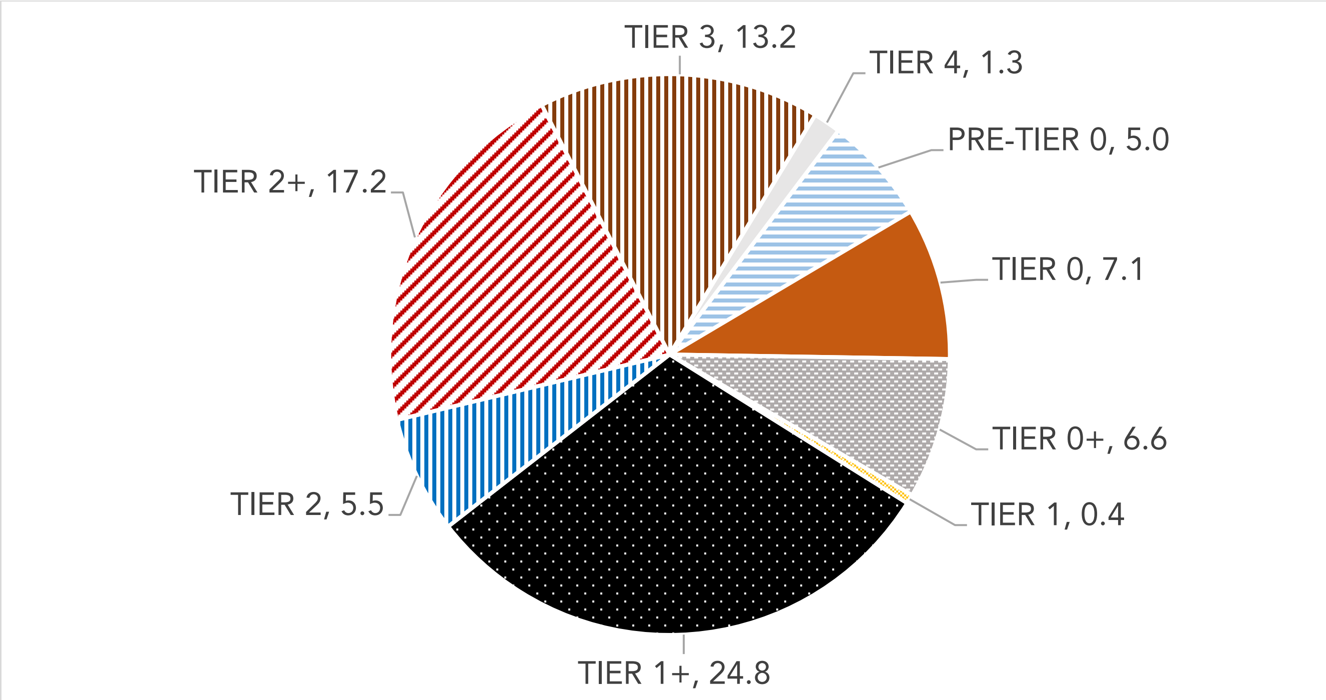


Figure 4: 2020 California Locomotive NOx Emissions by Tier (tpd)

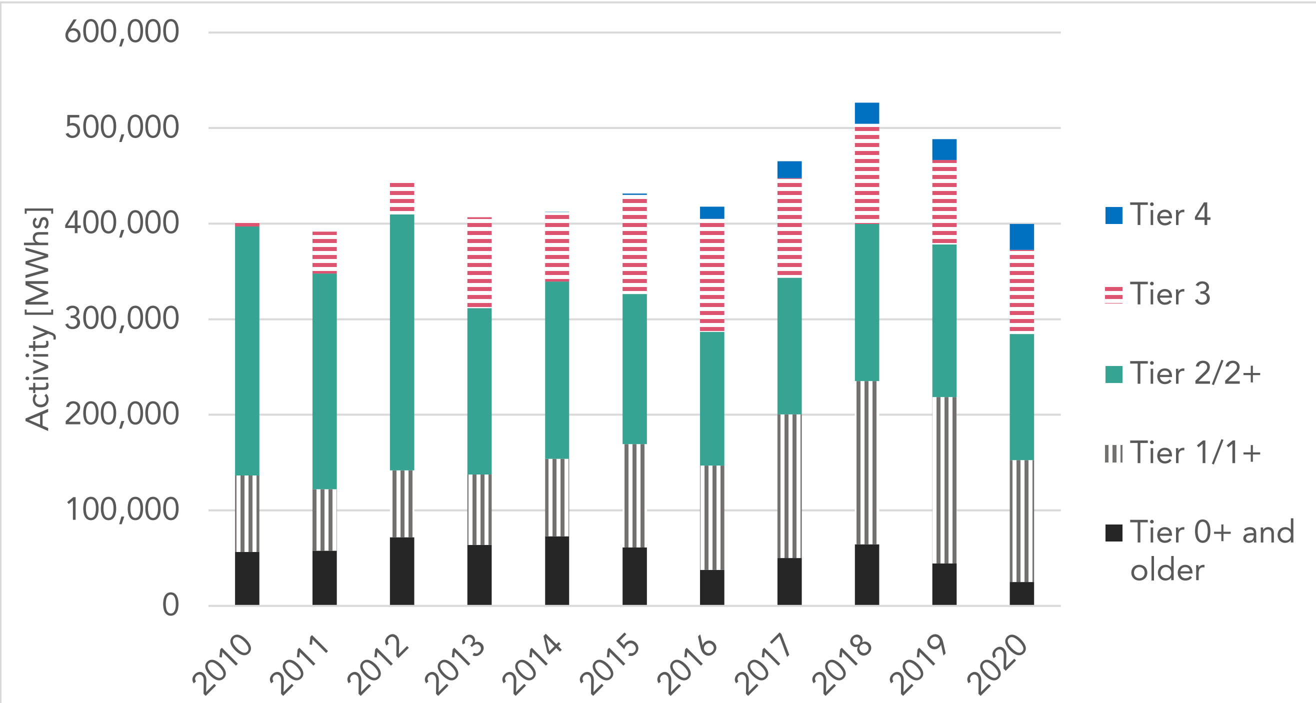


D. California Emission Reduction Agreements

In the 1998 Locomotive NOx Fleet Average Emissions Agreement in the South Coast Air Basin (1998 MOU), UP and BNSF agreed to operate locomotive fleets that on average meet a Tier 2 NOx emission standard, or 5.5 g/bhp-hr by 2010 and through 2030 in the South Coast Air Basin. Since 2010, the average NOx emissions in the South Coast Air Basin have remained at Tier 2 levels.

As can be seen in Figure 5, in 2020, the 1998 MOU data showed, Tier 1 or older locomotives were responsible for over 30 percent of UP and BNSF locomotive activity in the South Coast Air Basin. Most of these Tier 1 or older locomotives were originally manufactured prior to 2004. Tier 4 locomotives accounted for only 6.8 percent of UP and BNSF activity in South Coast in 2020.

Figure 5: 1998 MOU Data 2010 to 2020 Aggregated by Tier



V. Factors Driving Technology Development in Locomotives

A. Remanufacture Practices

Remanufacturing a locomotive can take different forms, but it generally means to replace, or to inspect and qualify power assembly,[12] or to replace an engine with a remanufactured or newly manufactured engine. Because in 40 CFR Part 1033.901 U.S. EPA has defined "new" locomotives to include both newly manufactured locomotives and existing locomotives that are remanufactured or rebuilt, the remanufacturing process can continue with no limit. For a line haul locomotive, remanufacture typically occurs every 7 to 10 years to maintain safety and reliability. For Switch and Passenger locomotives remanufacture intervals can be anywhere from 8 to 20 years or more depending on how often the locomotive is used and its duty cycle.[13]

Remanufactured locomotives are only required to maintain their original build date emissions Tier. For example, a Tier 1 locomotive originally manufactured in 2002 will only need to be

[12] 40CFR1033.901: Inspect and qualify means to determine that a previously used component or system meets all applicable criteria listed for the component or system in a certificate of conformity for remanufacturing (such as to determine that the component or system is functionally equivalent to one that has not been used previously).

[13] A duty-cycle is a representation of an engine usage pattern, based on the percent of time spent at defined loads, speeds or other readily identifiable parameters. Locomotive emission levels vary depending on the duty-cycle used to measure emissions.

remanufactured to Tier 1+ emission standards when it is remanufactured in 2021.[14] Table 1 and Table 2 show the emission standards required by U.S. EPA.[15,16]

Without a mandate to retire or replace old and dirty in-use locomotive engines, railroads continue to operate locomotives with minimum upgrades. For example, in 2019, Class I railroads completed 34 percent of their annual activity in the South Coast using Tier 1+ locomotives,[17] most of which were originally manufactured prior to 2005. Additionally, 74 percent of Class II and III railroads' locomotives were built in 1980 or earlier.[18] Typically, Class III railroads and Industrial operators do not upgrade or remanufacture locomotives because it is not needed due to their low use and duty cycles. Therefore, their emissions level remains uncontrolled or at the level they were originally manufactured. An exception to other locomotive operators, California passenger railroad agencies operate significantly cleaner fleets than freight railroads, with over half of their activity performed by Tier 4 locomotives.

VI. Tier 4 Technologies

A. Technology Description

Tier 4 has been the federal locomotive emission standards since 2015. Tier 4 locomotives are widely available for all types of locomotives. Table 3 shows the number of Tier 4 locomotives in California in 2020.

Table 3. Number of Tier 4 locomotives Operated in California in 2020

Locomotive Operator Category	Tier 4 Locomotives*	Percentage of Total Fleet
Class I Railroads	530	4 percent of the national fleet of Class I railroads operating in California
Class III Railroads	20	10 percent of the Class III locomotive population in the California
Industrial Operators	3	4 percent of the Industrial locomotive population in California

[14] U.S. EPA, 40 CFR Part 1033 – Exhaust emission standards, Subpart A, p14, n.d. (weblink: https://www.govinfo.gov/content/pkg/CFR-2020-title40-vol36/pdf/CFR-2020-title40-vol36-part1033.pdf).

[15] U.S. EPA; 40 CFR Part 1033 – Exhaust emission standards, Subpart B, pp16-17, n.d. (weblink: https://www.govinfo.gov/content/pkg/CFR-2020-title40-vol36/pdf/CFR-2020-title40-vol36-part1033.pdf).

[16] U.S. EPA, 40 CFR Parts 85, 89 and 92 - Emission Standards for Locomotives and Locomotive Engines, April 16, 1998. (weblink: https://www.govinfo.gov/content/pkg/FR-1998-04-16/pdf/98-7769.pdf).

[17] CARB, Rail Emission Reduction Agreements, accessed June 17, 2022. (weblink: https://ww2.arb.ca.gov/resources/documents/rail-emission-reduction-agreements).

[18] Jo Strang, Shortline Railroad's Perspective - FRA Workshop, September 15, 2021. (weblink: https://www.fra.dot.gov/conference/2021/cleanenergy/pdf/presentations/Jo%20Strang_Shortline%20Railroad's%20Perspective_09.10.2021.pptx).

Locomotive Operator Category	Tier 4 Locomotives*	Percentage of Total Fleet
Passenger Railroads	70	50 percent of the Passenger locomotive population in California

* Tier 4 credit units are not counted as Tier 4 locomotives in this count.

B. Emissions Benefits

Tier 4 locomotives are approximately 80 percent cleaner than Tier 3 locomotives. Emission control technologies can be used to decrease emissions and as of August 2021, various manufacturers offer Tier 4 locomotives for sale that use several various control strategies. More information on the strategies that have been employed and used in Tier 4 locomotives, such as exhaust gas recirculation and diesel particulate filters, can be found in CARB's November 2016 Technology Assessment: Freight Locomotives.[19]

C. Technology Readiness

As mentioned previously, Tier 4 locomotives have been commercially available since 2015. Although uptake of new Tier 4 locomotives has been slow, there are many certified Tier 4 locomotives available for purchase. Table 4 below lists a few examples of Tier 4 freight and passenger locomotives that manufacturers are offering as of August 2021. Some of these locomotives went through CARB verification that included 3,000 hours of in-use testing.[20] Locomotive manufacturer or operator must complete CARB verification process which includes 3,000 hours of in-use testing to receive California incentive funding.

Table 4: Tier 4 Locomotives Offered by Manufacturers*

Type	Manufacturer	Model	US EPA Certification Level (g/bhp-hr) NOx (Tier 4 Standard = 1.3 g/bhp-hr)	US EPA Certification Level (g/bhp-hr) PM (Tier 4 Standard = 0.03 g/bhp-hr)
Line Haul	Caterpillar-Progress Rail	SD70ACe-T4[21]	1.0-1.2	0.01-0.02

[19] CARB, Technology Assessment: Freight Locomotives, 2016, p. IV-4. (weblink: https://ww2.arb.ca.gov/sites/default/files/classic/msprog/tech/techreport/final_rail_tech_assessment_11282016.pdf).
[20] CARB, Locomotive Emission Verifications and Technology Demonstrations, accessed June 17, 2022. (weblink: https://ww2.arb.ca.gov/our-work/programs/reducing-rail-emissions-california/locomotive-emission-verifications-technology).
[21] Progress Rail, EMD® SD70ACe-T4, 2021. (weblink: https://s7d2.scene7.com/is/content/Caterpillar/CM20170915-63120-29009).

Type	Manufacturer	Model	US EPA Certification Level (g/bhp-hr) NOx (Tier 4 Standard = 1.3 g/bhp-hr)	US EPA Certification Level (g/bhp-hr) PM (Tier 4 Standard = 0.03 g/bhp-hr)
Line Haul	General Electric Transportation / Wabtec	Evolution Series ET44AC & ET44C4[22]	1.0-1.2	0.02
Line Haul	Knoxville Locomotive Works	NZE Series[23]	0.1-1.0	0.02-0.03
Switcher	Caterpillar-Progress Rail	EMD24 Repower[24]	0.9-1.0	0.00-0.01
Switcher	General Electric Transportation / Wabtec	ET2325	1.2	0.02
Switcher	Knoxville Locomotive Works	NZE Series[23]	0.2-1.3	0.00-0.03
Passenger	Caterpillar-Progress Rail	F125[26]	1.1-1.2	0.02
Passenger	Siemens	Charger[27]	1.0	0.01

* Partial list intended only as an example of available Tier 4 locomotives.

D. Infrastructure Requirements

Tier 4 locomotives are diesel and operate the same as all other locomotive tiers. Additionally, Tier 4 locomotives do not need any additional infrastructure or modifications to operate on existing rail lines.

[22] Wabtec, Tier 4 Evolution Series Locomotive, May 2021. (weblink: https://www.wabteccorp.com/media/3641/download?inline).

[23] Knoxville Locomotive Works, Quantitative Analysis Unregulated Tier 4 Near Zero Emission Locomotives, December 8, 2021. (weblink: http://www.aqmd.gov/docs/default-source/rule-book/Proposed-Rules/pr-2306/klw_pres_wgm3.pdf).

[24] Progress Rail, Tier 4 EMD24B [RE]powered Locomotive, 2021. (weblink: https://s7d2.scene7.com/is/content/Caterpillar/CM20210512-4b749-edfe7)

[25] CARB, Wabtec ET23 verification letter, December 23, 2020. (weblink: https://ww2.arb.ca.gov/sites/default/files/2020-12/CC.BCC - GE-Wabtec ET23 Switcher Approval Letter Dec 12.23.20.pdf).

[26] Progress Rail, EMD F125 Passenger Locomotive, 2021. (weblink: https://s7d2.scene7.com/is/content/Caterpillar/CM20170915-64297-21822).

[27] Siemens, Charger, Diesel-Electric Passenger Locomotive, America's passenger rail experience, 2021. (weblink: https://assets.new.siemens.com/siemens/assets/api/uuid:1ddf8215-f5a2-4bf4-abd7-6d6118db7718/charger-brochure.pdf).

E. Economics

Tier 4 locomotives economics include the one-time cost to purchase a new locomotive and on-going operating and maintenance costs. Operating costs (diesel fuel), and maintenance costs of a Tier 4 locomotive are comparable to dirtier locomotive Tiers.

Table 5 displays the estimated Tier 4 locomotive one-time and annual maintenance costs for each locomotive type.

Table 5: Tier 4 Locomotive Estimated Costs as of 2021

Locomotive Type	Tier 4 Cost	Estimated Annual Maintenance Cost
Class I Line Haul	$3,100,000	$79,000
Class I and Class III Switcher	$2,700,000	$79,000
Industrial	$2,160,000	$79,000
Passenger	$7,500,000	$79,000

F. Tier 4 Locomotives Outlook

1. Advantages

Tier 4 locomotives are readily available for purchase, and Tier 4 locomotive technologies cut PM emissions by as much as 97 percent and NOx emissions by as much as 90 percent when compared to Tier 1 locomotives.[28] Tier 4 locomotives have been available for purchase since 2015 from several OEMs. Locomotives are ordered and then built. Once an order is in place, production takes approximately a year to complete.

2. Challenges

To successfully reduce emissions and eliminate exposure to diesel toxic emissions from freight sources, locomotives will need to go beyond Tier 4 and towards ZE technologies. CARB staff believes Tier 4 locomotives are a good option to replace older locomotives at the lowest cost but recognize that cleaner and better technologies are already available or will be soon.

[28] US EPA, Emission Factors for Locomotives, April 2009, EPA-420-F-09-025. (weblink: https://nepis.epa.gov/Exe/ZyPDF.cgi/P100500B.PDF?Dockey=P100500B.PDF).

VII. "Tier 5", Hybrid Locomotives and ZE Capable Locomotives

A. Technology Description

In April 2017, CARB petitioned U.S. EPA to update its standards to Tier 5 (see Table 6: CARB Proposed Tier 5 Standards). Since then, locomotive technologies have progressed towards the proposed Tier 5 standards. For purposes of this discussion, "Tier 5" will refer to locomotive engine technology capable of meeting the emission standard set forth in Table 6.

Table 6: CARB Proposed Tier 5 Standards

Tier Level	Proposed Year of Manufacture	NOx		PM		GHG		HC		Proposed Effective Date
		Standard (g/bhp-hr)[1]	Percent Control[2]	Standard (g/bhp-hr)[1]	Percent Control[2]	Standard (g/bhp-hr)[1]	Percent Control[1]	Standard (g/bhp-hr)	Percent Control[2]	
5	2025	0.2	99+	<0.01	99	NA	10-25%	0.02	98	2025
		With capability for zero-emission operation in designated areas.								

1. ARB, Technology Assessment: Freight Locomotives, 2016.[3]
2. Compared with uncontrolled baseline, reflects percent control over line haul baseline for illustrative purposes; ARB staff assumed older pre-Tier 0 line haul and switch locomotives would be able to emit up to the Tier 0 PM emission standards, based on American Association of Railroads in-use emission testing (required to comply with U.S. EPA in-use emission testing requirements) for older switch locomotives with EMD 645 engines.

A locomotive can achieve the proposed PM and NOx Tier 5 emission standards using several different technologies. CARB staff considers a traditional selective catalytic reduction (SCR), diesel oxidation catalyst (DOC), and diesel particulate filter (DPF) combination aftertreatment systems and hybrid technologies as feasible ways to provide greater emission reductions beyond Tier 4 standards. At least one manufacturer, Knoxville Locomotive Works, is offering locomotives with 0.2 g/bhp-hr NOx and 0.00 g/bhp-hr PM.[29] For more detailed information on these technologies, see the November 2016, Technology Assessment: Freight Locomotives.

A locomotive is hybridized when batteries are used together with the main source of propulsion power to reduce locomotive emissions and improve energy efficiency. In the November 2016, Technology Assessment: Freight Locomotives, Staff included hybridization as a technology to enable ZE operation capability required for the Tier 5 emission standards. Manufacturers have focused on hybridization to reduce locomotive emissions and fuel use. Hybrid technologies are available for any of the main sources of propulsion power such as diesel or natural gas (NG) engines, fuel cells, or any other type of power generating system. Hybrid technologies can be used on all locomotive types and Tiers.

Hybrid locomotives have the ability to turn off their internal combustion engines and use batteries in designated areas, such as near disadvantaged communities to maximize the emission reduction benefits. Staff categorized such locomotives with ZE operation capability as ZE capable locomotives. Existing and emerging hybrid technologies are the first step

[29] U.S. EPA, Locomotive CI Engine Certification Data (Model Years: 2007-Present), Engine Family NKLWK35.7XN4, accessed May 31, 2022. (weblink: https://www.epa.gov/system/files/documents/2022-02/locomotive-2007-present.xlsx).

towards achieving full ZE locomotives. Transitioning from a hybrid technology to a full ZE technology is mostly a matter of achieving adequate ZE range so that the operations no longer require a diesel power source and the availability of infrastructure to support the ZE equipment.

A locomotive consist is a group of two or more locomotives used to provide power to a train. Most locomotive consists are currently all diesel locomotives, but a hybrid consist has two or more power sources that propel the locomotives. Diesel locomotives are propelled by electric traction motors by generating electricity from an alternator powered by a diesel engine. Hybrid consist is formed when one or more locomotives use a different source of electricity than the common diesel engine and alternator combination. Combinations of battery electric locomotives, fuel cell locomotives, or internal combustion engine locomotives will form a hybrid consist.

B. Emission Benefits

Hybridization results in reduced fuel use and in turn, reduces emissions and operational costs for locomotive operators. An estimated 10 to 25 percent reduction in fuel consumption can be achieved by using onboard batteries, or hybridization. The initial proof-of-concept and performance testing of a Wabtec batter-electric locomotive FLXdrive was conducted as a hybrid consist with two other Tier 4 diesel locomotives. The demonstration showed fuel consumption was reduced by over 10 percent.[30] The next generation of FLXdrive may be able to reduce fuel consumption by up to 30 percent.[31]

In diesel battery-electric hybrid locomotives, diesel engines augmented by batteries provide main propulsion power. Additionally, the locomotive is equipped with regenerative braking to recapture kinetic energy that would otherwise be lost. This system type reduces fuel consumption and has fewer emissions than typical diesel locomotives.

C. Technology Readiness

Several hybrid locomotives are commercially available and in use and many are being demonstrated. Detailed information on currently available hybrid locomotives is listed below. The information provided is from publicly available sources. Often, manufactures will work directly with stakeholders to provide additional and industry specific information that is not available to public agencies, such as confidential cost information.

As mentioned previously, as part of the Proposed Regulation, CARB staff will conduct two technology assessments, one in 2027 and one in 2032. The assessments will include information that has been made available since the publication of this Technology Feasibility Appendix. The technologies discussed below are meant to serve as examples of the types of technologies that are commercially available in the upcoming years and may be used to comply with the Proposed Regulation.

[30] Wabtec, FLXdrive battery electric locomotive at a glance, accessed November 8, 2021. (weblink: https://www.wabteccorp.com/media/466/download?inline).
[31] Wabtec, CN Advances Sustainability Efforts with Wabtec's Battery-Electric Locomotive, accessed November 4, 2021. (weblink: https://www.wabteccorp.com/media/11296/download?inline).

1. Toshiba HDB 800

Toshiba and DB Cargo cooperated to demonstrate their hybrid HDB 800[32] switch locomotive in Munich, Germany in June 2019. The HDB 800 used for this demonstration project was a four-axle single-cab locomotive equipped with two 471-kilowatt (kW) MAN EU Stage IIIB diesel engines (750kW) with two 61.8kW Toshiba SCiB lithium titanate oxide traction batteries. The HDB 800 is also equipped with permanent magnet synchronous motors.[33] This hybrid switcher locomotive has two diesel engines and one lithium-ion battery. After the success of the locomotive demonstration, DB Cargo has ordered an additional 50 hybrid locomotives. Assembly of the 50 hybrid locomotives was scheduled to start in 2021.[34] Additionally, in January 2022, DB Cargo ordered another 100 Toshiba HDB 800 hybrid locomotives that are expected to be delivered in early 2024.[35] As of 2021, the HDB 800 is under development for operation in Europe but could be adapted for commercial sale in the United States.[36]

2. AMPS Traction GSHX 3380

AMPS Traction, LLC, offers a hybrid locomotive suitable mainly for switcher and short line applications. The 2. AMPS Traction GSHX 3380 can be used in different configurations including Tier 4 Genset only, Genset Dominant Hybrid, Battery Dominant Hybrid, or Battery Only.[37]

3. Siemens Charger Hybrid

Siemens Mobility will begin testing their Charger Hybrid battery locomotive in 2025. In July 2021, Siemens entered into a $3.4 billion dollar agreement with Amtrak for 73 hybrid passenger locomotives.[38] Amtrak plans to operate these locomotives in the Northeast

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[32] Toshiba Hybrid Locomotives and Propulsion Systems, Solutions for Modern Freight Transportation, n.d. (weblink: https://www.toshiba.co.jp/infrastructure/en/railway/assets/pdf/Hybrid%20locomotives%20and%20propulsion%20systems.pdf).

[33] International Rail Journal, Toshiba unveils hybrid locomotive in Munich, June 19, 2021, accessed February 1, 2022. (weblink: https://www.railjournal.com/fleet/toshiba-unveils-hybrid-locomotive-in-munich/)

[34] Toshiba, Battery improves climate footprint: DB Cargo buys 50 Toshiba hybrid locomotives, January 23, 2020, accessed February 1, 2022. (weblink: https://www.toshiba.co.jp/infrastructure/en/news/20200123.htm).

[35] Railtech, DB Cargo orders 200 new dual locomotives, January 18, 2022, accessed July 22, 2022. (weblink: https://www.railtech.com/infrastructure/2022/01/18/db-cargo-orders-200-new-dual-locomotives/)

[36] Toshiba, New Release - Toshiba to showcase Hybrid-Diesel-Battery Locomotive Demonstrator at Transport Logistic 2019, May 2019, accessed August 2, 2021. (weblink: https://www.toshiba.co.jp/infrastructure/en/news/20190528.htm).

[37] AMPS Traction LLC, AMPS Genset Hybrid Locomotive, 2013, accessed July 22, 2022. (weblink: http://ampsonboard.com/amps-genset-hybrid-locomotive).

[38] Reuters, Siemens lands $3.4 billion hybrid train order from U.S. Amtrak, July 7, 2021, accessed February 1, 2022. (weblink: https://www.reuters.com/business/autos-transportation/siemens-lands-34-billion-hybrid-train-order-us-amtrak-2021-07-07/).

Corridors.[39] The hybrid-battery powered locomotives can be charged by either a 480 volt (V) external power source, by regenerative braking, or by the diesel engine.[40]

4. Stadler FLIRT, WINK, and GTW

Stadler offers several passenger train models as diesel-battery electric hybrids. These include, but are not limited to the FLIRT,[41] WINK,[42] and GTW.[43] While Stadler is primarily a European company, they have locomotives that were produced and operate in the United States. Entities in the United States operate Stadler diesel-electric trains; these include Trinity Metro, BART, Caltrain, the San Bernardino County Transportation Authority, and the New Jersey Transit Authority.[44]

In December 2021, the Stadler FLIRT set a world record for Guinness Book of Records with FLIRT for a battery train journey in battery-only mode operating in Germany. The FLIRT travelled exactly 224 kilometers (approximately 139 miles) in battery-only mode without charging its batteries.[45]

5. Wabtec FLXdrive

In January 2021, CARB awarded a $22.6 million grant through the Zero and Near -Zero Emission Freight Facilities Project (ZANZEFF) to the San Joaquin Valley Air Pollution Control District and BNSF to pilot ZE technologies at and near railyards.[46] Using this grant funding, BNSF collaborated with Wabtec to work on a pilot project to develop a battery electric line haul locomotive with 2.4 MWh of battery storage. The battery locomotive worked in a consist between two Tier 4 locomotives from January to March 2021, transporting freight between Barstow and Stockton.

As mentioned previously, a hybrid consist is a group of locomotives using two or more different energy sources, and Wabtec FLXdrive operating with other diesel locomotives

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[39] Siemens, Siemens Mobility awarded historic $3.4 billion in contracts from Amtrak, July 7, 2021, accessed July 22, 2022. (weblink: https://www.mobility.siemens.com/us/en/company/newsroom/press-releases/siemens-mobility-awarded-historic-contracts-from-amtrak.html).

[40] International Railway Journal, Siemens to build 73 trains for Amtrak including first battery-hybrid, July 8, 2021, accessed July 22, 2022. (weblink: https://www.railjournal.com/fleet/siemens-to-build-73-trains-for-amtrak-including-first-battery-hybrid%E2%80%AF%E2%80%AF/).

[41] Stadler, FLIRT, accessed August 16, 2021. (weblink: https://www.stadlerrail.com/en/products/detail-all/flirt160/29/).

[42] Stadler, WINK, accessed August 16, 2021. (weblink: https://www.stadlerrail.com/en/products/detail-all/wink/198/).

[43] Stadler, GTW, accessed August 16, 2021. (weblink: https://www.stadlerrail.com/en/products/detail-all/gtw/27/).

[44] Stadler, Salt Lake City, accessed August 16, 2021. (weblink: https://www.stadlerrail.com/en/about-us/locations/stadler_us_inc/26/).

[45] Stadler, Stadler sets world record for Guinness Book of Records with FLIRT Akku, December 2021. (weblink: https://www.stadlerrail.com/media/pdf/2021_12_22_media%20relase_stadler%20flirt%20akku%20sets%20world%20record%20auf_en.pdf).

[46] BNSF Railway, BNSF and Wabtec commence battery-electric locomotive pilot test in California, January 4, 2021, accessed July 22, 2022. (weblink: https://www.bnsf.com/news-media/news-releases/newsrelease.page?relId=bnsf-and-wabtec-commence-battery-electric-locomotive-pilot-test-in-california).

forms a hybrid consist. The BEL in the consist reduces the overall fuel usage and increases efficiency. BEL can potentially be used with existing diesel locomotives as well as other future ZE locomotives to improve overall energy efficiency. However, as of 2021, BEL has limited range that requires other locomotives in the consist to be practical in line haul applications.

The FLXdrive battery electric locomotive reduced emissions, not just by the replacing a diesel locomotive, but also by increasing the fuel efficiency for the consist by 11 percent.[47] Wabtec plans to develop a second-generation battery-electric locomotive with more than 6 MWh of battery capacity that can reduce fuel consumption by up to 30 percent.[48]

Figure 6: Wabtec FLXdrive from CARB ZANZEFF Project

6. Rail Propulsion Systems ZE Booster Locomotive (ZEBL)

Rail Propulsion Systems offers a ZEBL to supplement existing diesel locomotives for passenger trains.[49] This ZEBL forms a consist with one or more diesel locomotives and provides overall system fuel efficiency increases, which would reduce emissions. The ZEBL is described as having the potential to use wireless power transfer technology with onboard battery management system and the ability to charge with inexpensive wayside power infrastructure.[50]

A. Infrastructure Requirements

Hybrid battery-electric locomotives are built with the capability to be charged by electricity from the grid while stationary using special power cords with multipronged plugs. Or in some cases, such as with the ZEBL, they may be charged using wireless charging systems. To utilize the battery-electric capabilities of hybrid locomotives, charging infrastructure would need to

[47] Luczak, Marybeth, Railway Age, BNSF/Wabtec BEL Pilot- The Results Are In, May 17, 2021, accessed July 22, 2022. (weblink: https://www.railwayage.com/news/bnsf-wabtec-bel-pilot-the-results-are-in/).
[48] Wabtec Corporation, Wabtec's All-Battery Locomotive, FLXdrive, Lowers Freight Train's Fuel Consumption by More Than 11 Percent in California Pilot, May 17, 2021. (weblink: https://www.wabteccorp.com/FLXdrive%20results.pdf).
[49] RPS, Battery Locomotives and Energy Storage Systems, 2021, accessed July 22, 2022. (weblink: https://railpropulsion.com/products/hybrid-energy-storage-systems/).
[50] Wang, Luocheng & Zhao, Tiefu & Chen, Shen-en & Cook, Dave, An Inductive Power Transfer System Design for Rail Applications, 84-89, 10.1109/ITEC.2018.8450168, 2018. (weblink: https://www.researchgate.net/figure/Hybrid-Zero-Emissions-Boost-Locomotive-ZEBL-1_fig1_327519900).

be installed at railyards, passenger stations, maintenance facilities or anywhere locomotives would need to charge.

B. Economics

Hybrid locomotives economics include the one-time cost to purchase a new locomotive and on-going operational and maintenance costs. CARB staff has estimated the cost of a hybrid locomotive, including charging infrastructure to be approximately $4,000,000 for each locomotive, $100,000 for charging infrastructure and $1,000,000 for installation of charging infrastructure.

Operational costs of a "Tier 5" or hybrid locomotive would depend on individual operations. Operational costs would be dependent on the amount of diesel and/or electricity each locomotive used. In some instances, it is possible that hybrid locomotives would be used in only ZE configuration removing all diesel costs.

ZE technologies have fewer moving parts than diesel technologies and as such may require less maintenance. Hybrid locomotives would utilize both conventional diesel technologies combine with ZE capabilities. Therefore, CARB staff assumes maintenance costs would be comparable to other diesel line haul, switch and passenger locomotives.

C. Technology Outlook

1. Advantages

Hybrid locomotives use a combination of combustion and ZE technologies. As discussed previously, these technologies are commercially available and are being adopted by several operators worldwide. By combining ZE technologies such as battery electric power or ZE only capabilities, locomotive fuel consumption and emissions can be reduced from even Tier 4 levels. Fuel savings equates to operational cost savings may help offset the higher initial costs of ZE infrastructure requirements. Additionally, ZE infrastructure may be able to be utilized by additional ZE railyard equipment not just to charge locomotives.

2. Challenges

As mentioned previously, hybrid locomotives use battery technologies in addition to conventional diesel fuel. To utilize the batteries, charging infrastructure must be installed. The location of charging infrastructure is dependent on locomotive operations. In some cases, such as in a railyard, charging infrastructure may be installed near maintenance facilities where the locomotive may charge overnight. In addition to the necessary initial infrastructure investment, finding the time and location for locomotives to charge may be a challenge depending on individual operations. For more details on infrastructure costs see Appendix B: SRIA

Compared to diesel, battery packs currently require larger space and weigh more to provide similar energy storage capacity. Because hybrid locomotives require two separate power sources, such as battery packs and a diesel engine, it may be challenging to fit all components within the locomotive frame.

VIII. Zero Emission Locomotives

The Proposed Regulation would allow Spending Account funds to be used toward ZE locomotives beginning in 2024 and would require ZE locomotives be purchased with Spending Account funds starting in January 2030. Also, Switch, Industrial and Passenger Locomotives with an original engine build date of 2030 and line haul locomotives with an original engine build date of 2035 would be required to be ZE to operate in California. In addition to the requirements of the Proposed Regulation, several railroad and passenger rail agencies have developed and released plans describing pathways to ZE locomotives or are actively working to electrify their locomotive fleets.

As part of Union Pacific's 2022 Climate Action Plan (CAP), UP discusses options to achieve net zero emissions by 2050. One of the ZE technologies UP is considering includes battery-electric locomotive switchers intended to be deployed in railyards. UP recognizes that a battery-electric low-horsepower locomotive prototype exists, and in January 2022, UP announced plans to purchase 20 battery-electric switchers for testing in yard operations.[51] As part of their CAP, UP is looking to the longer-term horizon and preparing for emission reduction targets beyond 2030.[52]

Metrolink released their Climate Action Plan in March 2021. The plan outlines a pathway to aggressively phase out fossil fuel powered vehicles and equipment and reduce their impact on the environment. The plan describes steps Metrolink is taking to help reach the goal of having a locomotive fleet of 100 percent ZE by 2028.[53]

Caltrans released the Caltrans Zero emission Vehicle Action Plan 2.0 in March 2021; the plan includes transitioning to a 100 percent ZE intercity fleet by 2035. The Plan points to hydrogen hybrid dual-mode technologies as the main ZE strategy.[54]

As part of the Caltrain Modernization (CalMod) Program, Caltrain plans to purchase new, high-performance electric trains to replace their diesel locomotive trains that operate on an overhead contact system (OCS) also known as catenary lines. Caltrain expects the first electric locomotives to be in service in 2024.[55]

Often in coordination with locomotive operators and locomotive operations, original equipment manufacturers (OEM) are developing plans and strategies that will get ZE locomotives to commercial availability by the next decade. For example, in mid-2020, Progress Rail developed EMD Joule, a battery electric switcher, working in collaboration with a South American customer, Vale, and signed an agreement with Pacific Harbor Line to

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[51] Union Pacific, Union Pacific Railroad to Assemble World's Largest Carrier-Owned Battery-Electric Locomotive Fleet, Jan 28, 2022, accessed July 22, 2022. (weblink: https://www.up.com/media/releases/battery-electric-locomotive-nr-220128.htm).

[52] Union Pacific, 2021 Climate Action Plan, 2022. (weblink: https://www.up.com/cs/groups/public/@uprr/@corprel/documents/up_pdf_nativedocs/pdf_up_2021_climate_action_pln.pdf).

[53] Metrolink, Climate Action Plan – The Link to a Zero Emissions Future, March 26, 2021. (weblink: https://metrolinktrains.com/globalassets/about/agency/sustainability/climate-action-plan.pdf).

[54] Caltrans, Zero Emission Vehicle Action Plan 2.0, March 1, 2021. (weblink: https://static.business.ca.gov/wp-content/uploads/2021/03/Caltrans_ZEV-Action-Plan_Web_v2.pdf).

[55] Caltrain Electrification Update, June 3, 2021. (weblink: https://www.caltrain.com/files/caltrain/Assets/Caltrain+Electrification+Update+PowerPoint.pdf).

demonstrate EMD Joule in the Ports of Los Angeles and Long Beach.[56, 57] In June 2021, Wabtec and General Motors announced they will collaborate to develop and commercialize General Motor's battery technology and hydrogen fuel cell systems for Wabtec locomotives.[58] In September 2021, Wabtec signed memoranda of understanding with Carnegie Mellon University and Genesee & Wyoming with aim to power locomotive fleets with alternative energy sources, such as batteries, and eventually, hydrogen fuel cells for a ZE freight rail network pilot.[59, 60] In December 2021, Caterpillar signed a memorandum of understanding (MOU) with BNSF and Chevron USA, Inc for a pilot hydrogen-powered locomotive whereby Progress Rail will design and build the prototype hydrogen fuel cell-powered locomotive for line haul and other rail service, Chevron will develop the fueling concept and infrastructure, and BNSF will make its lines available for prototype testing.[61] While the scope of these demonstrations is limited in both number of locomotives and participants compared to the entire rail industry, such joint efforts will make more ZE locomotive options commercially available.

A. Battery Electric and All-Electric Locomotives

1. Technology Description

Battery-electric locomotives house onboard batteries that provide power to an electric motor to drive the locomotive. Battery-electric locomotives take advantage of regenerative braking to recover energy that would otherwise be lost during braking. Directly storing electricity as a fuel source (i.e., battery-electric) has several advantages. Battery-electric locomotives are interchangeable with diesel locomotives in that they do not require specialized systems to operate on existing tracks (e.g., electrified tracks or catenary lines).

Currently battery-electric locomotives have limited operational ranges compared to diesel freight line haul locomotives. Because of this reduced operational range, they are currently mostly being used in hybrid consists. Battery tenders can extend the operation range, but

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[56] Progress Rail, Progress Rail Develops Battery Switcher in Conjunction with Vale, July 28, 2020, accessed July 27, 2022. (weblink: https://www.progressrail.com/en/Company/News/PressReleases/ProgressRailDevelopsBatterySwitcherInConjunctionWithVale.html).

[57] Progress Rail, Progress Rail and Pacific Harbor Line Sign Agreement, November 13, 2020, accessed, July 27, 2022. (weblink: https://www.progressrail.com/en/Company/News/PressReleases/ProgressRailAndPacificHarborLineSignAgreementForBatteryLocomotive.html).

[58] General Motors, Wabtec and GM to Develop Advanced Ultium Battery and HYDROTEC Hydrogen Fuel Cell Solutions for Rail Industry, June 15, 2021, accessed July 27, 2022. (weblink: https://news.gm.com/newsroom.detail.html/Pages/news/us/en/2021/jun/0615-wabtec.html).

[59] Wabtec, Wabtec Signs MOUs with Carnegie Mellon University and Genesee & Wyoming to Decarbonize Freight Rail and Improve Safety, September 10, 2021, accessed July 27, 2022. (weblink: https://www.wabteccorp.com/newsroom/press-releases/wabtec-signs-memoranda-of-understanding-with-carnegie-mellon-university-and-genesee-wyoming-to).

[60] Wabtec, 2021 Sustainability Report, Moving and improving the world. (weblink: https://www.wabteccorp.com/2021_Sustainability_Report).

[61] Progress Rail, Caterpillar, BNSF and Chevron Agree to Pursue Hydrogen Locomotive Demonstration, accessed July 27, 2022. (weblink: https://www.progressrail.com/en/Company/News/PressReleases/CaterpillarBNSFandChevronAgreetoPursueHydrogenLocomotiveDemonstration.html).

the large number of battery tenders required is one of the challenges. OEMs state that battery capacity is highly dependent on the customer and while the early models have small capacity batteries, battery capacity can be increased to meet specific customer operational requirements.

Battery-electric switchers can replace diesel-electric switcher locomotives. Switchers operate within a railyard or within a close distance from a railyard, and have a smaller range and energy demand compared to line haul locomotives. Because switchers operate within or near railyards and have frequent opportunity to charge the batteries, battery-electric locomotives fit switcher operations well.

Passenger locomotive duty cycles can often be predictable. Many passenger locomotives repeat routes on set schedules on a regular basis. Prior to investment in new locomotives, passenger rail agencies can perform modeling to determine whether a battery-electric locomotive can meet their operational requirements. Battery-electric locomotives may work best on short passenger rail routes with long layovers or frequent opportunities to charge the batteries.

All-electric locomotives are powered solely by electrified overhead power lines. Currently, all-electric locomotives operate as passenger multiple units and as passenger and freight line haul locomotives in other parts of the world (e.g., Europe, China, and Russia).

a) Battery Tenders

A locomotive tender car, or "tender" is a specially designed railcar capable of storing fuel. Typically, tenders are used for natural gas or liquid natural gas locomotives. Battery tenders when coupled to another locomotive, can provide additional ZE miles.

Battery tenders are necessary for battery-electric locomotives operating beyond the range provided by the onboard battery. The first-generation Wabtec FLXdrive had energy capacity of 2.4 MWh, and the second generation FLXdrive is planned to have energy capacity of more than 6 MWh. The battery can provide about two hours of energy if the locomotive operates at a full power. Because of the limited range provided by the onboard battery, battery tenders may be necessary for freight line haul and passenger rail operations.

For an average train carrying 7,500 tons of freight, a battery tender with 5 MWh usable electricity provides 21.3 ZE miles.[62] Improved battery technology can provide up to 14 MWh usable electricity per battery tender, and a locomotive paired with a single battery tender can achieve a 150-mile ZE range.[63] Diesel freight line haul locomotives can operate 1,000 miles or more between refueling. To have a similar operation range, the additional battery tenders would be required, or fast-charging infrastructure would need to be installed and available approximately every 150 miles.

[62] CARB, Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System in California: Operational and Economic Considerations, Spring 2016. (weblink: https://www.arb.ca.gov/railyard/docs/uoi_rpt_06222016.pdf).

[63] Popovich, N.D., Rajagopal, D., Tasar, E. et al. Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric. Nat Energy 6, 1017–1025 (2021). (weblink: https://doi.org/10.1038/s41560-021-00915-5).

An alternative to the fast-charging infrastructure is a battery exchange operation. Battery exchange operations would require a fleet of battery tenders charged and ready to be exchanged with empty battery tenders as line haul trains arrive at the battery exchange railyard. CARB estimated in 2016 that UP and BNSF would need a total of up to 1,820 battery tenders for full freight rail operations in and around the South Coast Air Basin.[64]

2. Emission Benefits

Operation of ZE battery-electric locomotives would greatly reduce emissions from locomotives operating in California and the associated negative health impacts of diesel locomotives. For example, an average Tier 0 switcher operating 200 MWh annually will emit 0.13 tpy of PM and 12.6 tpy NOx, which would be eliminated by operation of a ZE battery-electric locomotive not including diesel production emissions.

Battery-electric locomotives would utilize California's electricity grid. Although emissions are associated with the electrical grid, the grid is expected to increase the use of renewable energy sources over the next 10 to 25 years. SB 100 was signed into law in 2018 and requires 60 percent of the State's electricity to come from renewable energy sources by 2030, with a longer-term requirement of sourcing all State's electricity from carbon-free resources by 2045.[65]

3. Technology Readiness

Descriptions of some of the battery electric locomotives in use or under development and detailed is listed below. The information provided is from publicly available sources. Often, manufactures will work directly with stakeholders to provide additional and industry specific information that is not available to public agencies, such as confidential cost information.

As mentioned previously, as part of the Proposed Regulation, CARB staff will conduct two technology assessments, one in 2027 and one in 2032. The assessments will include information that has been made available since the publication of this Locomotive Technology Feasibility Assessment. The technologies discussed below are meant to serve as examples of the types of technologies that will be commercially available in the upcoming years and may be used to comply with the Proposed Regulation.

a) EMD Joule

Progress Rail worked in collaboration with Vale, a Brazilian mining company, to develop and test pilot the EMD Joule battery electric switcher locomotive. The successful pilot took place in 2020 and the EMD Joule became commercially available in early 2021.[66] Progress Rail is

[64] CARB, Technology Assessment: Freight Locomotives, November 2016. (weblink: https://ww2.arb.ca.gov/resources/documents/technology-assessment-freight-locomotives).

[65] SB-100 California Renewables Portfolio Standard Program: emissions of greenhouse gases, accessed July 27, 2022. (2017-2018). (weblink: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB100).

[66] Progress Rail, EMD® Joule BE2.4C Battery Powered Switcher, 2021. (weblink: https://s7d2.scene7.com/is/content/Caterpillar/CM20210414-8d055-15cf8).

also working with Pacific Harbor Line to demonstrate the EMD Joule at the Ports of Los Angeles and Long Beach.[67]

Figure 7: EMD Joule

A lithium iron phosphate battery with capacity up to 2.4 MWh powers the EMD Joule. In addition, this ZE switcher locomotive is equipped with regenerative braking, and can deliver up to 3,000 hp.

Australian mining operation BHP Western Australia Iron Ore ordered two EMD Joule locomotives in January 2022. The locomotives are expected to be delivered in late 2023.[68]

It was announced in January 2022, that Union Pacific would be investing in 10 battery-electric EMD Joule locomotives from Progress Rail. The locomotives will be tested at railyards in California and Nebraska and are expected to arrive onsite in late 2023, with complete delivery anticipated in early 2024.[69]

b) Wabtec FLXdrive

Advancing on the technology from the Wabtec first generation FLXdrive that worked as a hybrid consist, the second generation FLXdrive with a seven MWh power rating has recently been introduced into the ZE market. After the successful demonstration of the first generation FLXdrive for Class I operations in the Unites States, Roy Hill, a mining company located in Australia indicated they were purchasing the upgraded Wabtec FLXdrive in September 2021. The seven MWh FLXdrive locomotive would be delivered in 2023.[70]

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[67] Luczak, Marybeth, Railway Age, PHL to Test Progress Rail EMD® Joule, November 13, 2020, accessed July 27, 2022. (weblink: https://www.railwayage.com/mechanical/locomotives/phl-to-test-progress-rail-emd-joule/).

[68] Progress Rail, BHP Orders Four Battery-Electric Locomotives for WAIO Rail Network, accessed July 27, 2022. (weblink: https://www.progressrail.com/en/Company/News/PressReleases/BHPOrdersFourBatteryElectricLocomotivesForWAIORailNetwork.html).

[69] Progress Rail, Caterpillar to Supply Locomotives to Union Pacific Railroad, Supporting Investment in World's Largest Battery-Electric Locomotive Fleet, January 28, 2022, accessed July 27, 2022. (weblink: https://www.progressrail.com/en/Company/News/PressReleases/CaterpillartoSupplyLocomotivestoUnionPacificRailroadSupportingInvestmentinWorldsLargestBattery-ElectricLocomotiveFleet.html).

[70] Wabtec Corporation, Roy Hill Sets new course with purchase of FLXdrive Battery Locomotive, September 13, 2021. (weblink: https://www.wabteccorp.com/media/10646/download?inline).

Following Roy Hill's lead, another Australian mining operation, BHP Western Australia Iron Ore, ordered two FLXdrive locomotives in January 2022. The FLXdrives are expected to be delivered in 2023.[71]

In November 2021, Canadian National Railway announced purchase of a FLXdrive locomotive for use in Pennsylvania, starting with yard switching activities and potentially performing short haul operations.[72] In January 2022, Union Pacific announced it was purchasing 10 FLXdrive battery-electric locomotives from Wabtec Corporation. UP indicated the FLXdrive locomotives would be used primarily in railyards and not for freight line haul operations. Delivery of the FLXdrive locomotives is expected to be in late 2023.[73]

c) Stadler KISS EMU

The Stadler KISS is a double-decker regional train. The Stadler KISS is an electric multiple unit that operates using overhead contact systems. As part of the Caltrain Modernization project, Stadler is building 19 seven-car trainsets to replace approximately 75 percent of the Caltrain diesel fleet with new electric trains, which would operate between San Francisco and San Jose.

d) Other Projects and Systems

In March 2022, OmniTRAX announced that Newburgh & South Shore has purchased a battery-electric switcher from AMPS Traction.[74] The GP9-based locomotive has 1,700 hp and will operate to serve Cleveland area steel mills.[75]

Rail Propulsion Systems demonstrated two battery electric switchers. One switcher is based on lead-carbon batteries that was previously NS 999 R&D locomotive, and the other switcher is based on repurposed lithium-ion batteries from light duty electric vehicles. Other manufacturers such as Tractive Power offer smaller battery-electric switcher locomotives.

4. Infrastructure Requirements

Battery-electric locomotives are built with the capability to be charged by electricity from the grid while stationary using special power cords with multipronged plugs. Later models will charge using pantograph technology where an arm from the charging system reaches down

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[71] Wabtec Corporation, BHP Group Orders Wabtec's FLXdrive Battery Locomotives, January 17, 2022. (weblink: https://www.wabteccorp.com/BHP-FLXdrive-Order-press-release?inline).

[72] Railway Age, Marybeth Luczak, CN Orders Wabtec FLXdrive (Updated), November 4, 2021. (weblink: https://www.railwayage.com/news/cn-orders-wabtec-flxdrive/).

[73] Wabtec Corporation, Union Pacific Railroad Makes Largest Investment in Wabtec's FLXdrive Battery-Electric Locomotive, January 28, 2022, accessed July 27, 2022. (weblink: https://www.wabteccorp.com/newsroom/press-releases/union-pacific-railroad-makes-largest-investment-in-wabtec-s-flxdrive-battery-electric-locomotive).

[74] AMPS, IS2-70 Zero Emissions Switcher, 2021, accessed August 16, 2021. (weblink: http://ampsonboard.com/projects/amps-electric-rail-switcher).

[75] Trains, OmniTRAX railroad purchases battery locomotive, March 3, 2022, accessed July 27, 2022. (weblink: https://www.trains.com/trn/news-reviews/news-wire/omnitrax-railroad-purchases-battery-locomotive/).

to touch a contact point at the top of the locomotive.[76] Charging infrastructure would need to be installed at railyards, passenger stations, maintenance facilities or anywhere locomotives would charge. Current models of battery-electric locomotives such as the EMD Joule and the FLXdrive also incorporate regenerative braking during operation to recover energy for their batteries.

In some cases, electric locomotives may operate on overhead power lines (catenary lines). In a catenary system, current is supplied at 25 or 50 kV from substations spaced at intervals along the tracks.[77] Depending on the voltage, the substations may be spaced closer or farther apart. Generally, substations are powered through transmission lines from a central power plant, where the voltage supplied depends on the location and distance of the substation. While catenary lines have been an established technology used to power locomotives, there are costly considerations, such as onboarding equipment to accommodate higher voltage supply and servicing long-haul freight. The Caltrain Modernization Program, which is building electric trains, will largely operate their trains using catenary systems.[78]

5. Economics

The price of battery-electric locomotives can vary greatly depending on size and specific requirements needed for each individual operation, including the length of the route and the ability to charge on regular intervals. In addition to the individualized locomotive costs, battery-electric locomotives also have costs associated with operation, maintenance, and infrastructure. Table 7 shows the estimated costs for each locomotive type and annual maintenance cost assumptions.

Table 7: Battery Electric Locomotive Estimated Costs as of 2021

Locomotive Type	Battery Electric Locomotive Cost	Annual Maintenance Costs
Class I Line Haul	NA	$71,100
Class I Road Switcher	$3,400,000	$71,100
Class III Road Switcher	$3,400,000	$71,100
Industrial Yard Switcher	$3,100,000	$71,100
Passenger	NA	$71,100

[76] Wired, Battery-Powered Trains Are Picking Up Speed, February 4, 2022, accessed July 27, 2022. (weblink: https://www.wired.com/story/battery-powered-trains-gather-speed/).
[77] White, R. K., Yabroff, I. W., Dickson, E. M., Zink, R. A., Gray, M. E., and Moon, A. E., Railroad electrification in America's future: an assessment of prospects and impacts. Final report, 1980. (weblink: https://www.osti.gov/servlets/purl/5442946).
[78] Stadler, KISS Double-Decker Electric Multiple Unit EMU, 2020. (weblink: https://www.stadlerrail.com/media/pdf/kcal0220e_us.pdf).

The infrastructure required to support battery-electric locomotives includes equipment costs and installation costs. Installation costs can vary due to site-specific factors, such as the existing electric panel capacity, installation location, and regional labor costs. In addition to installation, the total cost for infrastructure and electricity will vary depending on locomotive operations.

Operating costs of a battery electric locomotive depends on how often it is operated, its speed, grade of the route, and weight of the train. Staff calculated averages for comparison between technologies. Table 8 shows staff estimates of diesel, electricity, and hydrogen fuel cell engine efficiencies. Staff determined the electricity and hydrogen fuel consumed each year using the engine efficiency ratios to account for the improved engine efficiency of ZE locomotives. Table 9 shows diesel fuel costs and electrical power costs.

Table 8: Estimated Diesel, Electricity and Hydrogen Efficiency

Fuel Efficiency	Conversion Value	Engine Efficiency Ratio
Diesel Road Switcher Locomotive Fuel Consumption	73.7 gal/MWh	1
Diesel Line Haul and Passenger Locomotive Fuel Consumption	64.5 gal/MWh	1
ZE Battery-Electric Locomotive Battery Charging	1385 kWh/MWh	2.2
ZE Hydrogen Fuel Cell Line Haul Locomotive Fuel Consumption	1.125 kg hydrogen/gal diesel	1.3
ZE Hydrogen Fuel Cell Passenger Locomotive Fuel Consumption	1.125 kg hydrogen/gal diesel	1.37

Table 9: Price Projections for Ultra-Low Diesel and Commercial Electricity[79]

Year	Diesel (gallon)	Electricity (kWh)
2020	$3.32	$0.18
2030	$4.21	$0.22
2040	$4.38	$0.22
2050	$4.74	$0.21

[79] CARB, Appendix B, Proposed In-Use Locomotive Regulation Standardized Regulatory Impact Assessment (SRIA).

6. Technology Outlook

a) Advantages

Despite larger upfront costs, battery-electric locomotives may be economical for certain routes and operations as they generally have lower maintenance costs in part due to fewer moving components. Additionally, electricity costs are cheaper than diesel fueling costs. For make details on the specific costs of battery-electric locomotives see Appendix B: SRIA

b) Challenges

Battery-electric locomotives have additional costs compared to diesel locomotives such as adding battery charging infrastructure. The initial cost to purchase and install charging infrastructure may pose a challenge. However, the initial costs can be offset with the lower total cost of maintenance, refurbishment and fuel.

Battery-electric locomotive operation capabilities may be limited by the capacity of the battery. The current battery-electric locomotives have limited operation range compared to diesel freight line haul locomotives. Battery tenders can extend the operation range, but the large number of battery tenders required to support a battery exchange operation is a challenge. However, as battery technology develops and larger capacity batteries become available for locomotives, line haul locomotives, that have longer operation ranges may eventually be able to utilize battery electric technologies.

All-electric locomotives require higher initial capital investment compared to diesel locomotives mainly due to high infrastructure cost of overhead catenary system. Caltrain is electrifying 51 miles of its route with the service planned to begin in 2022. The budget for the construction is 848 million dollars, and the total capital budget including new trains and other services is 1.9 billion dollars.[80] Staff believes that electrification of freight railroad in California will cost about two-thirds more per mile than the Caltrain passenger project, due to higher power requirements of freight locomotives.[81]

B. Hydrogen Locomotive (Hydrail)

1. Technology Description

Hydrogen as a locomotive fuel offers many advantages. Hydrogen fuel is lightweight, can be used in conjunction with other technologies, can be scaled to the locomotive energy need and offers fast refueling times. Similar to battery-electric locomotives, hydrogen-powered locomotives are interchangeable with diesel locomotives in that they do not require specialized systems to operate on existing tracks (e.g., electrified tracks or catenary lines).

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[80] Peninsula Corridor Joint Powers Board/Caltrain, Project Monitoring Report (PMR) September 2020, November 3, 2020. (weblink: https://www.caltrain.com/media/679/download?inline).

[81] CARB, 2016, Technology Assessment: Freight Locomotives, November 2016. (weblink: https://ww2.arb.ca.gov/sites/default/files/classic//msprog/tech/techreport/final_rail_tech_assessment_11282016.pdf).

Hydrogen is a non-toxic gas at room temperature that is lighter than air but is highly flammable. Hydrogen fuel tanks are different than the diesel fuel tanks used on diesel locomotives. As seen in Figure 1, diesel locomotive tanks are located under the locomotive body. Hydrogen tanks need to contain high-pressure gaseous hydrogen (up to 700 bar) or a very cold (20 K) supply of liquid hydrogen. If hydrogen leaks, it will generally rise, making it more beneficial for hydrogen fuel tanks to be near the top of rail cars.[82]

Both compressed and liquid hydrogen take more volume compared to diesel. Typical line haul locomotives can carry up to 5,000 gallons of diesel fuel, and operate 1,000 miles without refueling. To provide operation range of line haul locomotives, hydrogen tenders—railcars used to store hydrogen fuel—may be necessary.

Hydrogen locomotives would likely require new hydrogen facilities to support locomotive refueling. However, a single hydrogen refueling facility could support multiple locomotives transiting on various routes.[83] Hydrogen provides refueling times similar to refueling times of diesel.

a) Hydrogen Tenders

A locomotive tender car (tender) is a specially designed railcar capable of storing fuel. Typically, tenders are used for natural gas or liquid natural gas locomotives. However, in some applications, such as for line haul, hydrogen locomotives may be coupled with tender railcars to reduce the need for refueling. Tenders capable of safely and effectively storing hydrogen in ether liquid or gaseous states for use with a locomotive and standards for hydrogen tenders are being developed. Using liquefied natural gas(LNG)powered locomotives and tenders as successful examples, hydrogen tender, hosing, piping, and interface connections are being developed. A 2021 study conducted by the Federal Rail Administration (FRA) on hydrogen fuel technology suggests that, with some revisions, the strategies used for the safe implementation of NG and LNG should be directly applicable for establishing gaseous or liquid hydrogen tenders.[84]

While currently no liquid hydrogen fuel tender is used to power a locomotive, Florida East Coast Railway operates natural gas locomotives with 11,000 gallon liquid natural gas fuel tenders.[85] Assuming same volume, 11,000 gallon liquid hydrogen tender will hold about 3,000 kg of hydrogen, equivalent to about 3,000 gallons of diesel in energy. While this is less than 5,000 gallon capacity of typical diesel freight line haul locomotives, fuel cell locomotives

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[82] United States Department of Transportation – Railroad Administration, Study of Hydrogen Fuel Cell Technology for Rail Propulsion and Review of Relevant Industry Standards, June 2021. (weblink: https://railroads.dot.gov/sites/fra.dot.gov/files/2021-06/Study%20of%20Hydrogen%20Fuel%20Cell%20Tech.pdf).

[83] United States Department of Transportation – Railroad Administration, Study of Hydrogen Fuel Cell Technology for Rail Propulsion and Review of Relevant Industry Standards, June 2021. (weblink: https://railroads.dot.gov/sites/fra.dot.gov/files/2021-06/Study%20of%20Hydrogen%20Fuel%20Cell%20Tech.pdf).

[84] United States Department of Transportation – Railroad Administration, Study of Hydrogen Fuel Cell Technology for Rail Propulsion and Review of Relevant Industry Standards, June 2021. (weblink: https://railroads.dot.gov/sites/fra.dot.gov/files/2021-06/Study%20of%20Hydrogen%20Fuel%20Cell%20Tech.pdf).

[85] Chart Industries, LNG on the Rails- Precursor to LH2 on the Rails? 2018. (weblink: https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-nason-larson.pdf).

have 30 percent or higher efficiency than diesel engine.[86] In addition, refueling times for liquid hydrogen can be similar to refueling times of diesel. Combined, a hydrogen locomotive paired with a single liquid hydrogen tender may be able to meet diesel freight line haul locomotive operation requirements for range and refueling time.

Line haul hydrogen fuel cell locomotives will require further development of a hydrogen fuel tender car. However, some early studies on hydrogen locomotives suggest cryogenic hydrogen storage that can be stored onboard without the need for a dedicated tender may be the preferred option for regional commuter passenger locomotives and may be closer to commercial development than hydrogen locomotives that need tenders.[87]

2. Emission Benefits

Operation of ZE Hydrogen locomotives would greatly reduce emissions from locomotives operating in California and the associated negative health impacts of diesel locomotives. For example, an average Tier 2+ line haul locomotive operating 350 MWh annually will emit 0.04 tpy of PM and 2.6 tpy NOx.

3. Technology Readiness

Descriptions of some of the hydrogen locomotives in use or under development are provided below. The information provided is from publicly available sources. Often, manufactures will work directly with stakeholders to provide additional and industry specific information that is not available to public agencies, such as confidential cost information.

As mentioned previously, as part of the Proposed Regulation, CARB staff will conduct two technology assessments, one in 2027 and one in 2032. The assessments will include information that has been made available since the publication of this Technology Feasibility Appendix. The technologies discussed below are meant to serve as examples of the types of technologies that will be commercially available in the upcoming years and may be used to comply with the Proposed Regulation.

a) Stadler FLIRT H2 Passenger Train

In November 2019, Stadler signed a contract with the San Bernardino County Transportation Authority (SBCTA) to provide a FLIRT H2 passenger train, powered by a hydrogen fuel cell. This train is planned to enter passenger service in 2024, between Redlands and the San Bernardino Metrolink station. The SBCTA contract consists of two passenger cars with a power pack in between that holds the fuel cells and the hydrogen tanks. The train is

[86] R. K. Ahluwalia, D. Papadias, and X. Wang, Rail and Maritime Metrics, U.S. DOE Hydrogen and Fuel Cells Program 2020 Annual Merit Review and Peer Evaluation Meeting, Washington, D.C., May 19 - 21, 2020. (weblink: https://www.hydrogen.energy.gov/pdfs/review20/ta034_ahluwalia_2020_o.pdf).
[87] Sandia Nation Laboratory, H2@RailSM Workshop, August 2019. (weblink: https://energy.sandia.gov/wp-content/uploads/dlm_uploads/2019/09/H2@RailWorkshop_Report_SAND2019-10191R.pdf).

expected to have seating space for 108 passengers and is projected to operate at a maximum speed of up to 79 mph. [88]

b) Alstom Coradia iLint Passenger Train

The Alstom Coradia iLint is a ZE multiple unit fully approved as an alternative to diesel passenger locomotives in Germany and Austria. An onboard hydrogen fuel cell and batteries power an electric traction drive. The train is also equipped with regenerative braking, which converts the kinetic energy of the train to electricity when it brakes, which is then stored in the batteries.

Cummins, the Alstom iLint fuel cell provider for the Coradia iLint claims that hydrail locomotives reduced noise and vibration, have fast refueling (less than 20 minutes), go over 18 hours between fueling, and have lower maintenance and operating expenditures than other conventional locomotives.[89]

Alstom first tested the Coradia iLint in Berlin in 2016 and by 2018 had received approval for passenger operation in Germany. Since then, the trains have covered more than 200,000 kilometers (124,000 miles) of passenger service. In December 2021, the Coradia iLint won the 2022 German Sustainability Design Award. The award recognizes technical and social solutions that are particularly effective in driving the transformation to sustainable products, production, consumption, or lifestyles.[90]

Following the success of the operations in Germany, in 2020, Alstom was in contract with Italian public transport company Ferrovie Nord Milano for six hydrogen fuel cell trains, with the option for eight more. The cost of the six locomotives is approximately €160 million (about $181 million). The first train is expected to be delivered within three years of the order date.[91]

c) Siemens Mireo Plus H Passenger Train

Deutsche Bahn and Siemens Mobility are testing a brand-new hydrogen train system including the development of a new train and a newly designed filling station in Germany. The trial operation planned for service between Tübingen, Horb, and Pforzheim Germany, will begin in 2024 and last for one year. Approximately 120,000 kilometers (74,564 miles) of scheduled rail service are planned to be included in this project. Siemens Mireo Plus H will replace a diesel railcar used on the route and is projected to save about 330 tons of carbon

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[88] Stadler Rail, Green-Tech For the US: Stadler Signs First Ever Contract for Hydrogen-Powered Train, November 14, 2019, accessed July 27, 2022. (weblink: https://www.stadlerrail.com/en/media/article/green-tech-for-the-us-stadler-signs-first-ever-contractfor-hydrogen-powered-train/649/).

[89] Cummins, Trains on the right track, n.d., accessed July 27, 2022. (weblink: https://www.cummins.com/new-power/applications/trains).

[90] Alstom, Alstom's Coradia iLint hydrogen powered train wins German Sustainability Award, December 3, 2021. (weblink: https://www.alstom.com/press-releases-news/2021/12/alstoms-coradia-ilint-hydrogen-powered-train-wins-german-sustainability).

[91] Alstom, Alstom to supply Italy's first hydrogen trains, November 26, 2020, accessed February 2, 2022. (weblink: https://www.alstom.com/press-releases-news/2020/11/alstom-supply-italys-first-hydrogen-trains).

dioxide (CO2). The project's filling station will use green electricity to produce green hydrogen. DB Energie is responsible for its supply.[92]

The Mireo Plus H is a modular commuter train designed to operate on non-electrified rail lines, at speeds up to 160 kilometers per hour (100 miles per hour) over a range of up to 800 kilometers (500 miles). Fuel cells produced and provided by Ballard Power Systems are mounted on the roof of the passenger railcar and work in conjunction with batteries installed beneath the floor. Ballard claims that due to lightweight design, energy-efficient components and intelligent onboard network management, the Mireo Plus H consumes up to 25 percent less energy than other similar passenger trains. The Mireo Plus H is expected to be released in spring 2022 with test runs starting in 2023 and officially enter service in 2024.[93] The Mireo Plus H is expected to cost approximately $5.7 million to $11.4 million when commercially available.[94]

Figure 8: Siemens Mireo Plus H

d) GTI/Sierra Northern Railway Fuel Cell Switcher

In March 2021, the California Energy Commission awarded about $4,000,000 to GTI and Sierra Northern Railway to design and demonstrate a hydrogen fuel cell switcher locomotive.[95] This locomotive is planned to operate at the Port of West Sacramento in

[92] Siemens, Mireo Plus H – the next generation of hydrogen trains, accessed August 3, 2021. (weblink: https://www.mobility.siemens.com/global/en/portfolio/rail/rolling-stock/commuter-and-regional-trains/hybrid-drive-systems/mireo-plus-h.html).

[93] Ballard, Ballard Receives Order for Fuel Cell Modules to Power Trial Operation of Siemens Mireo Plus H Train, July 15, 2021, accessed August 16, 2021. (weblink: https://www.ballard.com/about-ballard/newsroom/news-releases/2021/07/15/ballard-receives-order-for-fuel-cell-modules-to-power-trial-operation-of-siemens-mireo-plus-h-train).

[94] International Railway Journal, DB and Siemens to begin hydrogen train trials in 2024, November 23, 2020, accessed July 27, 2022. (weblink: https://www.railjournal.com/technology/db-to-begin-hydrogen-train-trials-in-2024/).

[95] Sierra Northern, California Energy Commission awards Sierra Northern Railway Team nearly $4,000,000 to build and test Hydrogen Switcher Locomotive, March 20, 2021, accessed August 16, 2021. (weblink: http://sierranorthern.com/news/articles/california-energy-commission-awards-sierra-northern-railway-team-nearly-4-000-000-to-build-and-test-hydrogen-switcher-locomotive/).

2023.[96] Should this demonstration prove successful, commercialization opportunities could follow.

Figure 9: GTI/Sierra Northern Railway hydrogen fuel cell switcher

e) Canadian Pacific H20EL Fuel Cell Line Haul Locomotive

Ballard is working with Canadian Pacific to repower one of their diesel line haul locomotives with hydrogen fuel cell modules in 2021. They will remove the diesel engine and replace it with six 200 kW fuel cell modules to provide 1.2 MW of electrical power (roughly 1,600 hp) to the locomotive's electric traction motors.[97] In January 2022, Ballard announced it had received an order for eight additional 200 kW fuel cell modules to support the expansion of Canadian Pacific's Hydrogen Locomotive Program, ultimately increasing the project from one to three hydrogen locomotives. Ballard expects delivery in 2022.[98]

f) Other Projects and Systems

In December 2021, Caterpillar signed a memorandum of understanding (MOU) with BNSF and Chevron USA, Inc for a pilot hydrogen-powered locomotive whereby Progress Rail will design and build the prototype hydrogen fuel cell-powered locomotive for line haul and/or other rail service, Chevron will develop the fueling concept and infrastructure, and BNSF will make its lines available for prototype testing.[99]

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[96] Ballard Power Systems, Ballard to Power Sierra Northern Railway Switching Locomotive in California, April 19, 2021, accessed August 16, 2021. (weblink: https://www.ballard.com/about-ballard/newsroom/news-releases/2021/04/19/ballard-to-power-sierra-northern-railway-switching-locomotive-in-california).
[97] CP, CP to employ Ballard fuel cells in Hydrogen Locomotive Project, March 9, 2021, accessed July 27, 2022. (weblink: https://www.cpr.ca/en/media/cp-to-employ-ballard-fuel-cells-in-hydrogen-locomotive-project).
[98] Ballard, Ballard Fuel Cells to Power Expansion of Canadian Pacific Hydrogen Locomotive Program, January 19, 2022, accessed February 1, 2022. (weblink: https://www.ballard.com/about-ballard/newsroom/news-releases/2022/01/19/ballard-fuel-cells-to-power-expansion-of-canadian-pacific-hydrogen-locomotive-program).
[99] Progress Rail, Caterpillar, BNSF and Chevron Agree to Pursue Hydrogen Locomotive Demonstration, accessed July 27, 2022. (weblink: https://www.progressrail.com/en/Company/News/PressReleases/CaterpillarBNSFandChevronAgreetoPursueHydrogenLocomotiveDemonstration.html).

The National Fuel Cell Research Center at UC Irvine is developing a solid oxide fuel cell and a gas turbine (SOFC-GT) to power a locomotive.[100] In 2018, the Department of Energy awarded the Advanced Research Projects Agency-Energy (ARPA-E) grant to FuelCell Energy to develop stationary solid-oxide fuel cells for use in such hybrid system.[101] If successful, compact stack design can lead to high power suitable for line haul locomotives.

4. Infrastructure Requirements

The use of hydrogen fuel cells to power locomotives requires hydrogen refueling infrastructure. Each refueling infrastructure station (station) has the same functional components that include hydrogen storage vessel(s), high-pressure compressor(s), chiller(s), and dispenser(s). Hydrogen may be created on site or delivered to the site via trucks or trains. Each station will be unique due to the layout of the site, equipment and the dispensing capacity.

Stations or tenders receiving deliveries will receive gaseous or liquid hydrogen. High-pressure gaseous hydrogen delivery is transferred by hose from a specialized delivery trailer into the hydrogen storage vessels, or a station could swap out bulk hydrogen storage containers. Liquid hydrogen is delivered by a tanker truck at cryogenic temperature.

Railyards may consider constructing new or expanding existing heavy-duty refueling stations to serve multi-modal uses that could include locomotives and other railyard equipment.

5. Economics

Fuel cell locomotive costs include fuel cell locomotive capital costs, maintenance costs, operating costs, and infrastructure costs. The costs associated with the purchase and maintenance of fuel cell locomotives is include in Table 10.

Table 10: Hydrogen Fuel Cell Locomotive and Maintenance Costs as of 2021

Locomotive Type	Hydrogen Fuel Cell Locomotive Cost	Annual Maintenance Costs
Class I Line Haul	$4,250,000	$79,000
Class I Road Switcher	NA	$79,000
Class III Road Switcher	NA	$79,000
Industrial Yard Switcher	NA	$79,000

[100] U.S. Department of Transportation, Federal Railroad Administration, Prototype Design and Evaluation of Hybrid Solid Oxide Fuel Cell Gas Turbine Systems for Use in Locomotives, October 2019. (weblink: https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/19086/Prototype%20Design%20and%20Evaluation.pdf).
[101] ARPA-e, Adaptive SOFC for Ultra High Efficiency Power Systems, July 26, 2017, accessed July 27, 2022. (weblink: https://arpa-e.energy.gov/technologies/projects/adaptive-sofc-ultra-high-efficiency-power-systems).

Locomotive Type	Hydrogen Fuel Cell Locomotive Cost	Annual Maintenance Costs
Passenger	$13,000,000	$79,000

Maintenance costs for hydrogen fuel cell locomotives are estimated to be similar to diesel locomotives because at this time there are too few fuel cell locomotives to evaluate. However, fuel cell powered equipment historically has fewer moving parts and should equate to fewer maintenance requirements over time.

The cost of hydrogen infrastructure is included in hydrogen fuel pricing. As can be seen in Table 11, hydrogen fuel cell locomotive operating costs become more cost-effective as the price of diesel increases and the price of hydrogen decreases. The price of hydrogen fuel currently fluctuates depending on several factors such as location, supply, and method of generation due to a developing supply network with currently low throughput. It is expected hydrogen fuel prices will lower as the supply chain matures. Once costs drop, they will offer more competitive value with fossil fuels. Hydrogen costs for locomotive operators that build their own stations will depend on the quantity of hydrogen sold.

Table 11: Price Projections for Ultra-Low Sulfur Diesel and Hydrogen[102]

Year	Diesel (gallon)	Hydrogen (kg)
2020	$3.32	$16.55
2030	$4.21	$12.62
2040	$4.38	$8.08
2050	$4.74	$5.00

6. Technology Outlook

a) Advantages

One of the main advantages of hydrogen fuel cell locomotives is that the operation range between refueling and the refueling time can be comparable to the conventional diesel locomotives. Long operation range and short refueling time make hydrogen fuel cell especially a suitable technology for line haul and passenger locomotives.

Another potential advantage of fuel cell locomotives is lower maintenance cost due to fewer moving parts than internal combustion engines. However, there is no data on fuel cell locomotive maintenance cost.

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[102] CARB, Appendix B, Proposed In-Use Locomotive Regulation Standardized Regulatory Impact Assessment (SRIA).

b) Challenges

Further development is necessary to demonstrate fuel cell locomotives can provide enough power as well as the range for use over long distances. As of 2021, all commercial and demonstration projects use proton exchange membrane fuel cell (PEMFC) technology that is commonly used in fuel cell cars and trucks. Canadian Pacific has plans to build a prototype fuel cell locomotive with 1.2 MW PEMFC. While 1.2 MW is more powerful than any fuel cell that has yet been used in a locomotive, typical Class I freight line haul locomotives have diesel engines rated for 4,400 hp, or 3.3 MW. To make up the additional power needed, onboard batteries or battery-electric locomotives can provide additional power. However, a locomotive using both fuel cell and batteries in a consist will only be able to operate at full power, in this case 3.3 MW, until the battery is fully discharged. Once the battery is discharged, the locomotive will only be able to operate at about a third of the rated power until the batteries are charged again. Freight line haul operations may require PEMFC with higher power to avoid potential scenarios where there is not enough power to fulfill the operation requirements.

One kilogram of hydrogen has roughly equivalent energy content as one gallon of diesel. As of 2022, hydrogen costs more per kg compared to diesel per gallon. Even considering about 30 percent higher energy efficiency of fuel cell locomotives and lower maintenance cost, fuel cell locomotives will cost more to operate for the operators until the hydrogen price decreases. A preliminary study indicates that to break even relative to a cost of $2.25 per gallon for diesel, the cost of delivered hydrogen would potentially need to be $2.20 per kg for freight locomotives and $3.50 per kg for passenger locomotives.[103]

IX. Battery-Electric Rail Equipment

A. Technology Description

Rail equipment performs similar functions as switchers, moving railcars in and around railyards. Rail equipment have tires that enable them to move off the tracks, and because of this, rail equipment is not a locomotive by U.S. EPA definition. However, there are several ZE models commercially available that could potentially perform the duties of switcher locomotives, and a few models are also eligible for the Clean Off-Road Equipment (CORE) Voucher Incentive Project.[104] Rail equipment comes in wide range of tractive effort to meet various customer requirements.

B. Emissions Benefits

Operation of ZE battery-electric rail equipment would greatly reduce emissions from locomotives operating in California and the associated negative health impacts of diesel

[103] Sandia National Laboratories, H2@Rail Workshop, August 2019. (weblink: https://energy.sandia.gov/wp-content/uploads/dlm_uploads/2019/09/H2@RailWorkshop_Report_SAND2019-10191R.pdf).

[104] California Clean Off-Road Equipment Voucher Incentive Project (CORE), 2022, accessed July 27, 2022. (weblink: https://californiacore.org/equipment-category/railcar-movers-switchers/).

locomotives. For example, an average Tier 0 switcher operating 200 MWh annually will emit 0.13 tpy of PM and 12.6 tpy NOx.

Battery-electric rail equipment would utilize California's electricity grid. Although emissions are associated with the electrical grid, the grid is expected to increase the use of renewable energy sources over the next 10 to 25 years. SB 100 was signed into law in 2018 and requires 60 percent of the State's electricity to come from renewable energy sources by 2030, with a longer-term requirement of sourcing all State's electricity from carbon-free resources by 2045.[105]

C. Technology Readiness

Descriptions of some of the ZE rail equipment in use or under development are provided below. The information provided is from publicly available sources. Often, manufactures will work directly with stakeholders to provide additional and industry specific information that is not available to public agencies, such as confidential cost information.

As mentioned previously, as part of the Proposed Regulation, CARB staff will conduct two technology assessments, one in 2027 and one in 2032. The assessments will include information that has been made available since the publication of this Technology Feasibility Appendix. The technologies discussed below are meant to serve as examples of the types of technologies that will be commercially available in the upcoming years and may be used to comply with the Proposed Regulation.

1. Parallel Systems Autonomous Battery-Electric Rail Equipment

Parallel Systems, a startup company based out of California, has developed autonomous battery-electric rail equipment that moves individual shipping containers. Individual shipping containers are placed on rail equipment and then the rail equipment move the individual containers to their destination. To reduce air drag, multiple containers carried by the rail equipment can form a platoon of containers that resembles a conventional train but allows flexibility for any containers to split off to multiple destinations while en route. The rail equipment has up to 500-mile range with less than one hour charge time.[106] At least one Class I railroad operating in California, Union Pacific, showed keen interest in the technology.[107]

Parallel Systems has been testing its first prototype in California since November 2020 and is currently finishing up its second-generation prototype, with plans to begin testing this in

[105] SB-100 California Renewables Portfolio Standard Program: emissions of greenhouse gases (2017-2018), accessed July 27, 2022. (weblink: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB100).

[106] Parallel Systems, Product, accessed July 27, 2022. (weblink: https://moveparallel.com/product/).

[107] Trains, Union Pacific CEO signals interest in autonomous intermodal cars, January 20, 2022, accessed July 27, 2022. (weblink: https://www.trains.com/trn/news-reviews/news-wire/union-pacific-ceo-signals-interest-in-autonomous-intermodal-cars/)

2022.[108] Parallel Systems is not commercially available but has plans to commercialize its third-generation system.[109]

2. Nordco NVX-Electric

The Nordco NVX-Electric is the battery electric version of Nordco's Navigator series of railcar movers. It has an electric drive motor and lithium-ion batteries capable of delivering up to 162 kW of power.[110]

Figure 10: Nordco NVX-Electric railcar mover.

3. Zephir Electric Range

Zephir is an Italian company that designs, manufactures, and sells various railcar movers, including battery electric ones.[111] Their LOK E Line is a family of battery electric railcar movers. These railcar movers have two electric motors, each powering one of the switcher's axles. Their other electric railcar movers include their CRAB Line, the CRAB EVO, and the KUBO Line, all of which have variable maximum towing capacity.

4. Colmar SL160E

The Colmar SL160 E is a battery-operated railcar mover equipped with two 40kW motors running at 55hP per motor, each supplied by 3 battery packs and allows for a minimum of 8 hours of continuous use before needing to recharge. This rail equipment can tow up to 3,200

[108] Fast Company, Former SpaceX engineers raised $50 million to build a Tesla for freight trains, January 19, 2022, accessed July 27, 2022. (weblink: https://www.fastcompany.com/90713785/former-spacex-engineers-raised-50-million-to-build-a-tesla-for-freight-trains)

[109] Grace Donnelly, Emerging Tech, A new startup thinks the future of trains is battery-powered, autonomous, and small, January 19, 2022, accessed July 27, 2022. (weblink: https://www.morningbrew.com/emerging-tech/stories/2022/01/19/a-new-startup-thinks-the-future-of-trains-is-battery-powered-autonomous-and-small)

[110] Nordco, Navigator, Electric, NVX- Electric, 2021, accessed July 27, 2022. (weblink: https://www.nordco.com/Products/mobile-material-handling/Navigator-Series.htm)

[111] Zephir, The Electric Range, 2021, accessed July 27, 2022. (weblink: https://trackmobile.com/electric-railcar-movers/).

tons.[112] In addition to the SL160E Colmar makes several other electric rail equipment including the SL150 which was deployed at the Toronto Transit Commission in Ontario, Canada Leslie Barns Workshop in 2020.[113]

D. Infrastructure Requirements

Battery-electric rail equipment can be charged via onboard chargers or battery-specific charging stations, powered by the electrical grid. At these charging stations, the battery packs can be charged using special power cords with multipronged plugs.

Battery electric rail equipment can be powered by multiple sources, including level 2 and 3 chargers.[114] In addition to the charging infrastructure when stationary, rail equipment can be charged using onboard chargers and multi-tap transformers servicing a variety of voltages. Onboard chargers and transformers allow operators to charge electric equipment using standard industrial power outlets that may already exist in their facilities. The upcoming development of onboard chargers and transformers will eliminate the need for further free-standing charger installations. A battery recharging time from a depleted to full charge varies from 2.5 to 8 hours depending on the battery chemistry and charging infrastructure.[115, 116]

Depending on the rail equipment operators, considerations for charging may include battery pack specifications, compatibility with other railcar movers and equipment, electrical rates, and cost of equipment and infrastructure.

E. Economics

Battery-electric rail equipment has several costs to consider compared to a Tier 4 switcher (Table 12). Compared to a switcher, which operates similarly, battery-electric rail equipment are assumed to have a lower total cost of ownership. The different costs that contribute to total cost of ownership of a battery-electric rail equipment include capital costs, operating costs, maintenance costs, and infrastructure costs. Infrastructure costs for battery-electric rail equipment is based on CARB staff assumptions, largely derived from battery-electric locomotive development.[117]

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[112] Colmar, SL160E – Electric Railcar Mover, accessed March 28, 2022. (weblink: https://www.colmarequipment.com/en/equipment/railway/railcar-movers-electric/sl160e).

[113] Colmar, Railcar Movers in Operation – North America, December 18, 2020, accessed March 28, 2022. (weblink: https://www.colmarequipment.com/en/news/2020/12/18/railcar-movers-in-operation-north-america).

[114] Nordco, Navigator, Electric, NVX- Electric, 2021, accessed August 16, 2021. (weblink: https://www.nordco.com/products-catalog/mobile-rail-car-movers/navigator-series/NVX5025e.htm)

[115] Gordon Russell, LOK 5.5 E – MPV, 2022, accessed July 27, 2022. (weblink: https://www.gordonrussell.com/product-259-lok-55-e---mpv)

[116] Wabtec Corporation, Zero Emission Electric Railcar Movers, December 8, 2021. (weblink: http://www.aqmd.gov/docs/default-source/rule-book/Proposed-Rules/pr-2306/shuttlewagon-presentation.pdf?sfvrsn=6)

[117] California Air Resources Board, Preliminary Cost Document for the In-Use Locomotive Regulation, 2021. (weblink: https://ww2.arb.ca.gov/sites/default/files/2021-03/3.16.21%20Locomotive%20Reg%20-%20Preliminary%20Cost%20Document_Final.pdf).

Table 12: Cost Comparison Between a Battery-Electric Rail Equipment and a Tier 4 Switcher as of 2021

Cost Component	Battery Electric Rail Equipment	Tier 4 Switcher
Capital	$1,175,000[118]	$2,700,000
Battery Pack	$250,000[119]	N/A
Maintenance	$0.75 per locomotive-mile[120]	$1.32 per locomotive-mile
Infrastructure Capital	$1,000,000	N/A

Infrastructure installation costs are dependent on the site location, as well as the capacity of the grid. For models with onboard chargers, the specifications of the battery and chargers can contribute to the total costs. Factors such as battery life, charge cycle, and operation can impact the replacement and maintenance costs as well.

There are various incentive programs, including the Carl Moyer Program and Clean Off-Road Equipment Voucher Incentive Project (CORE), to help cover the different costs of battery electric railcar movers and encourage the utilization of advanced technologies.

F. Technology Outlook

1. Advantages

Battery electric-rail equipment can support rail routes and duty cycles that can return to substations and recharge, while also recharging during operations. Compared to diesel-powered locomotives, battery-electric rail equipment is cleaner and quieter. Battery packs are also more efficient than diesel engines. Between specific battery packs, the efficiency of a battery can be attributed to fast charging times, longer battery life, and increased charging cycles. As ZE technology, batteries also eliminate PM and NOx pollution, which can otherwise be emitted by diesel-powered locomotives.

Continued development of battery-electric rail equipment may result in lower maintenance and operating costs. Depending on battery replacement life, the total costs of operation and maintenance for battery packs are lower compared to diesel-powered locomotives.

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[118] Wabtec Corporation, Zero Emission Electric Railcar Movers, December 8, 2021. (weblink: http://www.aqmd.gov/docs/default-source/rule-book/Proposed-Rules/pr-2306/shuttlewagon-presentation.pdf?sfvrsn=6).

[119] California Air Resources Board, Preliminary Cost Document for the In-Use Locomotive Regulation, 2021. (weblink: https://ww2.arb.ca.gov/sites/default/files/2021-03/3.16.21%20Locomotive%20Reg%20-%20Preliminary%20Cost%20Document_Final.pdf).

[120] CARB, Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System in California: Operational and Economic Considerations, Spring 2016. (weblink: https://www.arb.ca.gov/railyard/docs/uoi_rpt_06222016.pdf).

2. Challenges

Compared to diesel locomotives, battery-electric rail equipment has additional initial costs because of their battery packs, which includes infrastructure and battery capital costs. While these may have higher initial costs, the total cost of ownership for battery-electric rail equipment is assumed to be lower than that of diesel locomotives, due to diesel fuel cost savings and lower maintenance costs.

Concerns over battery pack capacity and reliability for these battery-electric rail equipment are considerations that current development may address. Recent models of battery-electric rail equipment have included battery management systems to monitor battery health, which will advance utilization and commercialization of this technology.

While some rail equipment can replace small switchers, they may not be suitable for all switcher applications due to lower power.

X. Other Emission Reduction Technologies

A. Wayside Power

Any of the previously described fully ZE locomotive technologies would satisfy the Proposed regulation's idling requirements. In addition, hybrid systems, such as diesel-electric hybrid locomotives could rely on their ZE components to power the locomotive while stationary, eliminating the need for the diesel engine to operate while the locomotive is stationary.

Wayside power (also known as "ground power" or "yard power") is a temporary plug-in power system that can be used to power trains when the locomotive engines have been shut down. Passenger locomotives may remain at a station or a maintenance facility for many hours or overnight between scheduled routes, called "layover." During layovers, passenger locomotives require power for service and inspection activities or for providing acceptable air temperature in passenger cars before departure. Wayside power eliminates the need for locomotives to run engines during these activities. This technology can also be used in almost anywhere locomotive idling is necessary.

It takes approximately 10-20 minutes to connect a passenger locomotive to wayside power. Passenger locomotive operators in California use wayside power to reduce emissions from idling, and some operators have plans to expand wayside power utilization.[121,122,123,124,125]

[121] Caltrans, Caltrans Intercity Passenger Rail, October 28, 2020. (weblink: https://ww2.arb.ca.gov/sites/default/files/2020-10/Day%201%20Ext%205%20Caltrans%2020201026.pdf).
[122] Metrolink, Climate Action Plan, March 26, 2021. (weblink: https://metrolinktrains.com/globalassets/about/agency/sustainability/climate-action-plan.pdf).
[123] Capitol Corridor Joint Powers Authority, Performance Report FY19. (weblink: https://images.capitolcorridor.org/wp-content/uploads/2020/02/CCJPA_Report2019_Pages.pdf).
[124] Caltrain, Sustainability in Action, accessed July 27, 2022. (weblink: https://www.caltrain.com/about/Sustainability/SustainabilityInAction.html).
[125] Altamont Corridor Express, ACE and the Environment, accessed July 27, 2022. (weblink: https://acerail.com/ace-and-the-environment/).

B. Renewable Diesel and Biodiesel

Renewable diesel (RD) is a diesel alternative that is nearly chemically identical to petroleum-based diesel. Using RD in a diesel engine does not require any engine modifications, and it can be blended into traditional diesel fuel at any ratio up to 100 percent.[126] RD is a promising diesel substitute in many applications, particularly those that are likely to rely on liquid fuels until 2030. RD is currently produced from feedstocks like vegetable oil or animal tallow, through the same technological process used in petroleum refineries. Different feedstocks have different environmental impacts. Depending on the feedstock, RD can offer significant greenhouse gas and criteria pollutant reductions. Preliminary test results show that RD may potentially reduce PM emissions by up to 30 percent and NOx emissions by up to 10 percent.[127] Because RD can be used in traditional diesel engines, it could be deployed quickly to achieve immediate reductions for both GHG and criteria pollutants. Because of low carbon intensity, RD can generate credits in the Low Carbon Fuel Standard (LCFS).

Biodiesel is a diesel substitute made from fats, oils, and greases. Biodiesel is relatively simple to make and has been commercially available for decades. Both Biodiesel and RD are diesel alternatives, and can be made from similar feedstocks[128], but the production processes and finished fuels differ substantially. Biodiesel is a fatty-acid-methyl-ether, not a pure hydrocarbon, and has its own ASTM specification.

Under the 2021 Union Pacific Climate Action Plan, UP committed to increasing the use of renewable diesel and biodiesel fuels. According to the plan, UP is working to increase the percentage of low-carbon fuels consumed to 10 percent of their total diesel consumption by 2025 and 20 percent by 2030.[129]

In August 2021, Progress Rail approved the use of up to 20 percent biodiesel blend in the vast majority of ElectroMotive Diesel (EMD®) locomotives operated.[130] Previously, the locomotives were approved to operate using only up to a 5 percent biodiesel blend.

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[126] CARB, Renewable Diesel Joint Statement, July 31, 2013. (weblink: https://ww2.arb.ca.gov/sites/default/files/2018-08/Renewable_Diesel_Joint_Statement_7-31-13.pdf).

[127] University of California Riverside, For the CE-CERT Engine Testing Portion for the CARB Assessment of the Emissions from the Use of Biodiesel as a Motor Vehicle Fuel in California "Biodiesel Characterization and NOx Mitigation Study", August 2009. (weblink: https://www.arb.ca.gov/fuels/diesel/altdiesel/090923engine-test2006cummins-ism.pdf).

[128] Renewable diesel can be made from a wider range of feedstocks than biodiesel. Biodiesel can only be made with fats, oils, and greases, while renewable diesel can be made from other lignocellulosic feedstocks such as energy crops, algae, municipal solid waste, and others. The technology to produce renewable diesel from lignocellulosic feedstocks is in its early commercial stages.

[129] Union Pacific, 2021, Climate Action Plan. (weblink: https://www.up.com/aboutup/esg/climate-action-plan/index.htm).

[130] Progress Rail, Progress Rail Approves B20 Biodiesel Fuel for Use in EMD® Engines, August 26, 2021, accessed July 27, 2022. (weblink: https://www.progressrail.com/en/Company/News/PressReleases/ProgressRailApprovesB20BiodieselFuelforUseinEMDEngines.html).

In the Caltrans Zero emission Vehicle Action Plan 2.0, Caltrans identifies using renewable diesel in existing locomotives as a strategy to reduce emissions during the transition to ZE technology.[131]

C. Natural Gas

Natural gas (NG) engines and diesel dual-fuel engines can also meet Tier 4 emissions standards. NG engines can be used as a single prime mover or in a genset unit, and typically emit less PM and NOx than equivalent diesel engines. The Gas Technology Institute, partnering with Optifuel received $2.6 million[132] to develop and demonstrate a 4,300 hp diesel dual-fuel locomotive. Tractive Power Corporation, a locomotive manufacturer based out of North Vancouver, BC, Canada, offers to repower or upgrade older locomotives to NG or NG-hybrids.[133]

Railroads may be supportive of natural gas as a locomotive fuel because of its potentially favorable economics as compared with diesel fuel.[134] Only two Class III railroads, Florida East Coast Railway and Indiana Harbor Belt Railroad have adopted either natural gas locomotives or natural gas-diesel dual fuel locomotives.

While renewable natural gas (RNG) can generate credits in the LCFS for use in most on-road vehicles, in the long-term RNG may be better used to replace fossil fuels in sectors that cannot readily electrify. The 2022 AB 32 Climate Change Scoping Plan Update will provide direction on use of RNG in the transportation sector. At this time, CARB staff do not consider RNG as a feasible option for compliance with the Proposed Regulation.

D. Hydrogen Internal Combustion Engines

Hydrogen can be used in internal combustion engines alone or mixed with carbon-based fuels such as diesel, gasoline, or natural gas at various levels. Hydrogen can lower PM and NOx emissions when used in internal combustion engines with carbon-based fuels and has no PM emission when used by itself. A hydrogen internal combustion engine cannot achieve ZE even if 100 percent hydrogen was used due to combustion process producing NOx. The technology is not available commercially for locomotive applications but may be an interim technology towards ZE locomotives.

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[131] Caltrans, Zero Emission Vehicle Action Plan 2.0, March 1, 2021. (weblink: https://static.business.ca.gov/wp-content/uploads/2021/03/Caltrans_ZEV-Action-Plan_Web_v2.pdf).

[132] U.S. Department of Energy, Clean Cities Coalition Network, accessed July 27, 2022. (weblink: https://cleancities.energy.gov/partnerships/search?project_search=Field%20Demonstration%20of%20a%20Near-Zero,%20Tier%205%20Compliant,%20Natural%20Gas%20Hybrid%20Line-Haul%20Locomotive#natural-gas-locomotive).

[133] Tractive Power Corporation, Other Products, 2021, accessed August 16, 2021. (weblink: www.tractivepowercorp.com/our_technology/other-products/).

[134] CARB, Technology Assessment: Freight Locomotive, November, 2016. (weblink: https://ww2.arb.ca.gov/sites/default/files/2020-06/final_rail_tech_assessment_11282016%20-%20ADA%2020200117.pdf).

XI. Locomotive Tracking and Monitoring

The Proposed Regulation requires locomotive activity in California to be reported annually by Air District. Additionally, before 2030, a railroad could gain additional credits for use of a ZE locomotive in disadvantaged communities as defined by the California Communities Environmental Health Screening Tool: CalEnviroScreen.[135] In that case, the railroad would need to report locomotive activity by community boundaries. For full reporting requirements, see Appendix A. The Proposed Regulation would not require real-time reporting, but as discussed below, industry has been already been moving towards real-time reporting.

As of December 1994, The American Association of Railroads has required Automated Equipment Identification (AEI) tracking on locomotives, this allows locomotives passing reader equipment to be identified. An additional layer of tracking was added with the Federal Rail Safety Improvement Act of 2008[136] which required implementation of positive train control (PTC) on railroads. PTC is a communication and signaling system capable of preventing incidents caused by train operator or dispatcher error, it uses signals and sensors along the track to communicate train location. Locomotive operators chose various compliance strategies.[137]

In addition to tracking equipment already required on all locomotives, freight operators may employ additional locomotive tracking to better manage routes and fuel consumption. Within the freight industry, cargo owners, shippers, and logistic firms often already track and measure what is happening with their freight. Demand for such tracking has increased, and shippers often want exact locations of cargo, cargo weight, container or cargo temperatures, and humidity. For passenger lines, operators are concerned with monitoring the interiors of passenger trains to aid in a better experience for riders. And of course, railroad operators want to know the status of their locomotives for near-real-time planning purposes. As a result, many locomotives operating in California and across the United States are already equipped with the technology needed to report locomotive activity and location in real-time.

To achieve real-time locomotive monitoring and tracking, sensors and other tracking systems can be installed either on locomotives or trackside (also referred to as “wayside”). Onboard systems such as Global Positioning Satellite tracking (GPS), and Onboard Diagnostic (OBD) transmitters may be more expensive per locomotive but require less infrastructure and set-up costs. If technologies are dependent on wayside infrastructure, such as AEI tracking, there is a higher infrastructure cost but lower cost per locomotive.[138] Either system would be suitable for the reporting requirements of the Proposed Regulation. In either case, railroads have

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[135] Office of Environmental Health Hazard Assessment (OEHHA), California Communities Environmental Health Screening Tool: CalEnviroScreen 4.0. (weblink: https://oehha.ca.gov/media/downloads/calenviroscreen/report/calenviroscreen40reportf2021.pdf).
[136] Federal Rail Safety Improvement Act, 2008. (weblink: https://crsreports.congress.gov/product/pdf/R/R42637#:~:text=The%20Rail%20Safety%20Improvement%20Act%20of%202008%20%28RSIA08%29,freight%20traffic%20with%20toxic-%20or%20poisonous-by-inhalation%20hazardous%20materials).
[137] Positive Train Control Implementation by Railroad, 2018, accessed July 27, 2022. (weblink: https://railroads.dot.gov/train-control/ptc/positive-train-control-app).
[138] Cristian Ulianov, Paul Hyde and Ramy Shaltout, Railway Applications for Monitoring and Tracking Systems, 2018.

many other business reasons, as discussed, to monitor and track their locomotive activity and location, and therefore staff do not expect substantial changes from business-as-usual due to these reporting requirements.

XII. Class I, Class III, and Industrial Switch Locomotives

Switchers or "switch" locomotives are used to assemble or breakdown trains or move railcars between railyards and industrial facilities. Switchers tend to travel only short distances, typically within or near a railyard. Class I railroads, Class III railroads and industrial facilities operate switchers. Class I railroads operate switchers 24 hours 7 days a week in their railyards, whereas Class III and industrial operators typically use their switchers less frequently.

Class III railroads and industrial operators often purchase used locomotives for their operations. Generally, the used locomotive market consists of locomotives that have been retired by Class I railroads. The practice of cascading old Class I locomotives down to Class III and Industrial operators results in the oldest and dirtiest locomotives operating in railyards and facilities near sensitive communities. Therefore, transitioning Class III and industrial locomotive switchers to ZE equipment will result in immediate and impactful benefit to the most heavily impacted communities.

Switcher operation typically includes multiple short jobs per day with locomotives idling in between jobs. This results in long idling times for the typical switcher duty cycle. Switchers may idle for safety related or operational reasons such as to maintain air pressure at the brakes, for air conditioning or heating, or to keep engine from freezing. While unnecessary idling is reduced with automatic engine start stop (AESS) devices and the Federal U.S. EPA idling rule, idling due to safety related and operational reasons are allowed, which results in longer idling in switchers.

Figure 11: Switch Locomotive

A. Switch Locomotive Technologies

The duty cycle of a switcher is well suited for transitioning to battery-electric or fuel cell ZE locomotives. Battery-electric locomotives have short operational ranges and require more frequent charging compared to diesel-electric locomotives refueling frequency. Fuel cell technology can provide longer range compared to battery-electric locomotives, but still shorter than diesel-electric locomotives. Because switcher operational ranges are shorter, both battery-electric and fuel cell technologies can provide one or more days of operation before needing to charge or refuel. In addition, switcher duty cycles have fewer occurrences of long continuous operation at a high power like line haul duty cycles. Because switchers typically need only short burst of power, batteries can provide the extra power as needed, and the fuel cell system can be less powerful than the maximum power requirement of the locomotive. Fuel cell system only needs to be powerful enough to charge the batteries while the locomotive is idling or working at a low power between high power operations. Additionally, some switcher locomotives may also be replaced by ZE rail equipment. Multiple types of ZE rail equipment are already commercially available and in service.

1. Class I, Class III and Industrial Switch Technology Outlook

It was announced in January 2022, that Union Pacific would be investing in 10 EMD Joule battery-electric locomotives from Progress Rail and 10 FLXdrive battery-electric locomotives from Wabtec Corporation.[139, 140] In March 2022, OmniTRAX announced that Newburgh & South Shore has purchased a 1,700 hp battery electric switcher from AMPS Traction to serve Cleveland area steel mills.[141, 142] In March 2021, the California Energy Commission awarded about $4,000,000 to GTI and Sierra Northern Railway to design and demonstrate a hydrogen fuel cell switcher locomotive.[143] Staff estimates that by 2025, multiple ZE switchers will be available for purchase in limited volumes, and they will be commercially available by 2030.

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[139] Progress Rail, Caterpillar to Supply Locomotives to Union Pacific Railroad, Supporting Investment in World's Largest Battery-Electric Locomotive Fleet, January 28, 2022, accessed July 27, 2022. (weblink: https://www.progressrail.com/en/Company/News/PressReleases/CaterpillartoSupplyLocomotivestoUnionPacificRailroadSupportingInvestmentinWorldsLargestBattery-ElectricLocomotiveFleet.html).

[140] Wabtec Corporation, Union Pacific Railroad Makes Largest Investment in Wabtec's FLXdrive Battery-Electric Locomotive, January 28, 2022, accessed February 2, 2022. (weblink: https://www.wabteccorp.com/newsroom/press-releases/union-pacific-railroad-makes-largest-investment-in-wabtec-s-flxdrive-battery-electric-locomotive).

[141] AMPS, IS2-70 Zero Emissions Switcher, 2021, accessed August 16, 2021. (weblink: http://ampsonboard.com/projects/amps-electric-rail-switcher).

[142] Trains, OmniTRAX railroad purchases battery locomotive, March 3, 2022, accessed July 27, 2022. (weblink: https://www.trains.com/trn/news-reviews/news-wire/omnitrax-railroad-purchases-battery-locomotive/).

[143] Sierra Northern, California Energy Commission awards Sierra Northern Railway Team nearly $4,000,000 to build and test Hydrogen Switcher Locomotive , March 20, 2021, accessed July 27, 2022. (weblink: http://sierranorthern.com/news/articles/california-energy-commission-awards-sierra-northern-railway-team-nearly-4-000-000-to-build-and-test-hydrogen-switcher-locomotive/).

XIII. Passenger Locomotives

CARB staff estimates about 150 locomotives operate California passenger rail routes. As of 2022, passenger locomotives are overall the cleanest locomotives in California with over 50 percent of operations done by Tier 4 locomotives.

In comparison to other locomotive types, passenger locomotives pull lighter loads at higher speeds. They also need to power the lights, air conditioning, and other material comforts to connected passenger railcars, known as hotel power. Hotel power is provided by a separate head end power engine or the prime mover engine depending on the model. Passenger locomotives have longer operation ranges and require additional hotel power arrangements compared to switchers. However, overall power and range requirements are less than freight line haul locomotives. Therefore, after switchers, it is likely that passenger locomotives would be the next locomotive type to replace diesel locomotives with ZE technologies.

A. Passenger Locomotive Technologies

The duty cycle of a passenger locomotive is well suited for transitioning to battery-electric or fuel cell locomotives. Battery-electric may be best suited for shorter passenger locomotives routes and fuel cell technologies could accommodate longer passenger rail routes. In addition, passenger railroads may choose to operate multiple units (MUs) rather than passenger locomotives.

MUs smaller power requirements poses less technical challenges when switching to ZE, and ZE MUs are further developed than ZE passenger locomotives. Major OEMs such as Stadler, Alstom and Siemens offer battery and fuel cell ZE multiple units.[144, 145, 146] The San Bernardino County Transportation Authority plans to begin use of fuel cell MUs in 2024, which will be the first fuel cell MU in the U.S. While MUs may not be feasible for all routes, they could be a viable solution in some cases.

B. Passenger Locomotive Technology Outlook

As a passenger locomotive leaves a station, it accelerates to reach cruising speed, maintains that speed until it's near the next station, and brakes as it approaches the next station. This pattern is repeated between the stations. The initial acceleration to reach cruising speed requires the most power. Once the desired speed is reached, less power is required to maintain the speed. The locomotive will be in idle or brake as it reduces speed approaching the next station. This repeating pattern of high power followed by low power and braking can work well for fuel cell systems.

Common passenger Tier 4 locomotives have a 4,400 hp engine and fitting an equivalent size 3.3 MW fuel cell system in a locomotive remains a technical challenge. A less powerful fuel

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[144] Stadler, Products, accessed July 27, 2022. (weblink: https://www.stadlerrail.com/en/products/).
[145] Alstom, Regional and intercity: Rapid connections to suit all operators, accessed July 27, 2022. (weblink: https://www.alstom.com/solutions/rolling-stock/regional-and-intercity-rapid-connections-suit-all-operators).
[146] Siemens, Mireo, accessed July 27, 2022. (weblink: https://www.mobility.siemens.com/global/en/portfolio/rail/rolling-stock/commuter-and-regional-trains/mireo.html).

cell system can satisfy the operation if the locomotive is augmented with batteries. Fuel cell-battery electric hybrid locomotives use batteries when maximum power is needed. However, the locomotive can only maintain the maximum power output as long as the batteries last. The batteries of a fuel cell-battery electric hybrid locomotive are recharged by the fuel cell while the locomotive is cruising and from regenerative braking. The batteries and fuel cell can be sized optimally by modeling the route that the locomotive will be running. That is, a manufacturer can simulate the route to determine the optimal fuel cell power and battery capacity such that the locomotive can complete the route without experiencing loss of performance.

Because passenger locomotives typically operate in predictable routes and schedules, it may be possible to use battery-electric technology for select routes that are shorter and provide opportunities for charging. Fuel cell technology may provide more flexibility to passenger railroad agencies, as they can operate longer routes with faster and less frequent refueling. Caltrans identified hydrogen locomotives as the most suitable ZE technology for Amtrak intercity operations, and developed a strategy to transition its rail fleet to 100 percent ZE by 2035.[147, 148] Building on the technological successes of ZE switch locomotives, staff estimates that ZE multiple units as well as ZE passenger locomotives will be commercially available by 2030.

Figure 12: Passenger Locomotive

XIV. Class I Line Haul Locomotives

Class I line haul locomotives typically operate 24 hours a day, 7 days a week, pulling heavy freight. Often, line haul locomotives travel nationwide and are pulling 100 or more railcars. Class I line haul locomotives require high power output for extended periods time, and may

[147] Caltrans, Caltrans Intercity Passenger Rail, Our strategy towards zero emission (Draft), October 28, 2022. (weblink: https://ww2.arb.ca.gov/sites/default/files/2020-10/Day%201%20Ext%205%20Caltrans%2020201026.pdf).
[148] Caltrans, Zero Emission Vehicle Action Plan 2.0, March 1, 2021. (weblink: https://static.business.ca.gov/wp-content/uploads/2021/03/Caltrans_ZEV-Action-Plan_Web_v2.pdf).

have a range of 1,000 miles or more between refueling, making this category of locomotive one of the most challenging to transition to full ZE.

Figure 13: Class I line haul locomotives. Five line haul locomotives are working as a locomotive consist in this train

A. Class I Line Haul Zero Emission Technologies

The most promising ZE technologies, capable of producing the power and range Class I line haul locomotives require, are fuel cell technologies. While battery technology has progressed, the number of battery tenders (railcars to provide additional fuel to connected locomotives) required to provide enough energy for a line haul locomotive operation may be too great to be practical. The latest battery-electric locomotive from Wabtec in 2021 has a six MWh capacity that may supply less than two hours of operation at full power. For line haul locomotives, recharging batteries frequently is impractical due to long charging time, and swapping out battery tenders may also be impractical due to the total number of battery tenders required and the additional time delay from swapping out battery tenders.

While battery-electric technology by itself cannot meet the Class I line haul locomotive range requirements, it is a critical component of fuel cell locomotives. Fuel cell technologies need further development to provide necessary power for line haul locomotives, but as battery capacity grows, power required from fuel cell system will also decrease.

Wabtec and General Motors are collaborating to develop and commercialize GM's battery technology and hydrogen fuel cell systems for Wabtec locomotives.[149] Fuel cell technologies are advancing through locomotive demonstrations (GTI-Sierra Northern Fuel Cell Switcher, Canadian Pacific Fuel Cell Line Haul locomotive, SBCTA Fuel Cell MU), on-road heavy duty truck applications, and stationary applications. As battery technology also develops, staff

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[149] Wabtec, Wabtec and GM to Develop Advanced Ultium Battery and HYDROTEC Hydrogen Fuel Cell Solutions for Rail Industry, June 15, 2021, accessed July 27, 2022. (weblink: https://www.wabteccorp.com/newsroom/press-releases/wabtec-and-gm-to-develop-advanced-ultium-battery-and-hydrotec-hydrogen-fuel-cell-solutions-for-rail).

estimates that by 2035, ZE line haul locomotives that meet the operational requirements of Class I railroads will be commercially available.

As described in the Technology Assessment: Freight Locomotives, development for new technology includes research and design prior to commercial production of ZE freight locomotives and can take 8 to 12 years following the steps below:

- Research and Design: 2 to 3 years;
- Build and Test Prototype: 1 to 2 Years;
- Build and Field Test Small Scale Demo (3 to 5 units): 2 to 3 years;
- Full Scale Demo (10 to 20 units): 3 to 4 years;
- Commercial Production.

While locomotive manufacturers or researchers can complete research and design step, a partnership with a locomotive operator is necessary to complete prototype test to full scale demo. For Class I line haul locomotive development, testing and demonstration by Class I railroad is ideal. Class I railroads are the largest customer as well as crucial component of the ZE line haul locomotive development process. Because of the role of Class I railroads in the development process, Class I railroads influence both the market and the technology.

B. Class I Locomotive Technology Outlook

Class I line haul locomotives operate long distances between refueling, and large energy storage is required to satisfy the range requirement. In some routes, Class I line haul locomotives operate at their maximum power for extended periods when the train is pulling heavy loads such as over mountains. Unlike passenger locomotives that have fixed routes, Class I railroads use line haul locomotives throughout their national network. Due to these operational requirements, Class I line haul locomotives require both long range and high power.

Currently, battery-electric locomotives have the ability to replace one or two diesel locomotives in a consist of four or five locomotives. The battery-electric locomotives reduce fuel consumption, emissions, and can provide ZE operation in specific areas such as when operating in and near communities. The battery-electric and diesel hybrid consist was demonstrated by BNSF in 2021. Battery-electric locomotives operating in a hybrid consist can satisfy the need for emission reduction as well as Class I railroads' operational requirements. However, unless diesel locomotives in the hybrid consist are replaced with ZE locomotives, locomotives will continue to emit PM and NOx.

As technology advanced, operational ranges of battery-electric locomotives increase. Currently the range of a battery-electric locomotive with a battery tender is estimated to be about 150 miles when operating without other power sources such as diesel-powered locomotives or fuel cell locomotives.[150] Battery-electric locomotives may be able to replace diesel-powered locomotives entirely in short regional routes. However, ZE fuel cell locomotives may be more feasible to for line haul locomotives for longer distances or for

[150] Popovich, N.D., Rajagopal, D., Tasar, E. et al. Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric. Nat Energy 6, 1017–1025 (2021). (weblink: https://doi.org/10.1038/s41560-021-00915-5).

routes requiring higher power demands. In 2022, Canadian Pacific built a prototype hydrogen fuel cell locomotive with 1.2 MW of electrical power (roughly 1,600 hp). Unfortunately, at this power level alone, the fuel cell cannot provide the level of power a line haul locomotive may require. Typical diesel line haul locomotives have rated power of 4,000 to 4,400 hp, and full power is necessary for acceleration and pulling heavy loads uphill. For additional power, onboard battery packs are used to augment the fuel cell power output as needed, and are recharged when the fuel cell has excess power or through regenerative braking. This means that the continuous time the locomotive can operate at full power is limited by the battery energy storage capacity. To match both the range and power of diesel-powered line haul locomotives with fuel cells, the fuel cell systems need to be almost three times more powerful (around 3.0-3.3 MW), or an accompanying battery will need to have the capacity to provide continuous full power.

Class I ZE line haul may consist of both battery-electric locomotives and fuel cell locomotives. Battery-electric locomotives are technologically closer to commercialization, and can operate as full ZE locomotives in regional routes or operate as a part of a hybrid consist in longer routes. As fuel cell locomotives become available, they can replace diesel-powered locomotives for longer routes. Existing battery-electric locomotives can also be used with fuel cell locomotives, and provide additional battery augmentation to the fuel cell locomotives. This will extend the range the fuel cell locomotive can operate continuously at the full power.

Higher power fuel cell locomotives and higher capacity battery electric locomotives will be developed through current demonstrations of fuel cell locomotives and battery-electric locomotives. With advanced fuel cell locomotives alone, or with combination of battery electric locomotives in the consist, staff estimates that ZE line haul operation will be feasible by 2035.

XV. Conclusion

Tier 4 locomotives are commercially available for all locomotive categories and can provide immediate emission reduction of 80 percent or more compared to the next cleanest emission Tier. However, to successfully reduce emissions from freight sources, locomotives will need to go beyond Tier 4 to ZE technologies. CARB staff believes Tier 4 locomotives are a good option to replace older locomotives at the lowest cost but recognize that ZE technologies are already available.

As mentioned throughout this document, different ZE technologies are suitable for different locomotive categories. Industrial locomotives have the smallest operation range and power requirements and battery-electric rail equipment and small ZE switchers, some of which are commercially available as of 2021, can likely replace diesel industrial locomotives. Class I and III switchers have longer operation ranges and higher power requirements, and staff expects that battery-electric switchers and fuel cell switchers that are in demonstration phase can meet their requirements.

Passenger locomotives have longer operation ranges and higher power requirements than switchers or industrial locomotives. However, because passenger locomotives have fixed routes and more frequent opportunities to charge or refuel, different pathways to zero emission exist. For the least stringent routes, battery-electric multiple units or passenger locomotives may work well. If longer operation range is required, fuel cells with appropriately sized battery combination could meet the requirements.

Line haul locomotives have the longest operation range and the highest power requirements. Battery-electric locomotives can replace diesel locomotives in short regional routes, and operate with diesel locomotives as hybrid consists in near term. For full ZE line haul operation, fuel cell locomotives with hydrogen tenders is the most promising technology to meet the operation range requirement. However, the latest fuel cell locomotive prototype Canadian Pacific is developing is still less powerful than the typical diesel line haul locomotive. Staff estimates that ZE line haul operation is feasible through development of higher power fuel cells and using battery electric locomotives in a consist.

Based on development timeline for new technology from research and design to commercial production, staff estimates that ZE switcher and industrial locomotives will be available for purchase in limited volume by 2025, ZE passenger locomotives by 2030, and ZE line haul locomotives by 2035.