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Options for Railroad Electrification and Decarbonization

Introduction and Background

Compared with most other modes of freight and passenger transportation, railroads consume energy more efficiently and pollute less. Nevertheless, because most trains rely on diesel engines for power, they can emit harmful air pollutants, especially around rail yards where engines often idle. Reducing emissions from U.S. railroads is of interest to many Members of Congress as part of the nation's overall strategy to reduce air pollution and reach long-term greenhouse gas reduction targets.

The railroad industry has pursued various strategies to reduce emissions. Depending on their operating needs, railroads are considering mature technologies (e.g., wayside electric power) or emerging ones (e.g., battery or hydrogen power) to accomplish this goal.

Wayside Electric Power

Electric railroad technology has existed since the late 19th century. Fully electric trains produce no emissions of their own, generally drawing power from overhead wires (an overhead catenary system, or OCS) or from an electrified third rail running alongside the tracks. Both methods require the construction of electric power substations along the route, adding to up-front infrastructure costs.

Electrification can also provide operational benefits. Electric locomotives have fewer moving parts than diesel locomotives, making them easier to maintain and more reliable, reducing maintenance costs. They also generate more power relative to their weight than diesel engines, enabling higher maximum speeds and faster acceleration and deceleration, potentially reducing travel times. This is especially true when each car in a train contains its own traction motor in what is known as "multiple unit (MU)" configuration, distributing mechanical power to more sets of wheels than those on a single locomotive.

In the United States, electric trains tend to be used primarily for passengers, not for freight. The rapid acceleration and high speeds afforded by electric traction motors are not seen as providing enough benefit to freight traffic to justify the cost of installing or modifying the necessary infrastructure. Freight trains that make use of double-stacked container cars can be compatible with overhead wires, but many existing bridges and tunnels do not have sufficient clearance to accommodate double-stacked containers *and* overhead wires without potentially costly modifications. Furthermore, while diesel locomotives can effectively operate nationwide, electric locomotives would be unusable on unelectrified portions of the network, reducing flexibility. Because most passenger rail routes in the United States share tracks with freight trains, most of the rail system continues to rely on diesel power.

Electric trains can still consume power generated by fossil fuels, and technologies that reduce or eliminate carbon emissions do not necessarily entail full electrification. Carbon emissions, it is argued, can likely be reduced by diverting higher emission highway and airplane traffic to rail without any shift to alternative power sources.

Battery and Battery-Hybrid Power

Rechargeable batteries could be one alternative to electrification. Trains could be entirely battery powered, producing no emissions when operating, or use a configuration known as hybrid diesel-electric battery (HDEB), where a diesel engine also charges a battery similar to that in a gasoline hybrid automobile. Advantages of battery power include minimal need for new or modified infrastructure, though charging stations would be needed for 100% battery operations, and electrical transmission lines may require upgrades. Even with recent advances in chemistry and manufacturing, the added weight of batteries detracts from their ability to efficiently move an entire train.

Several battery-hybrid locomotive models have been built and demonstrated, but comparatively few are in active service. Manufacturers have also introduced pure battery-powered locomotives that can run in tandem with a conventional diesel-electric locomotive, effectively creating an HDEB system across two locomotives. These units can maintain full output exclusively on battery power for 30-40 minutes at a time. Consequently, pure battery operations may be impractical for most long-haul operations owing to the number of chargers that would be needed over the route.

Some commuter rail agencies have begun procuring battery-powered railcars. One application of battery power already deployed in Germany and Japan, and proposed in the United States, is the addition of batteries to conventional electric trains in a battery electric multiple unit (BEMU). BEMUs can charge their batteries while in motion along third rails or overhead wires, then run on battery-only power in non-electrified territory.

Hydrogen Power

Hydrogen fuel cells use either liquid or gaseous hydrogen reacting with oxygen to produce electricity; the reaction produces only heat and water as by-products. Some internal combustion engines can also use hydrogen fuel (instead of diesel), producing no carbon emissions during operation. However, today, the manufacture of almost all industrial hydrogen produces greenhouse gases.

The Federal Railroad Administration (FRA) and Sandia National Laboratories published a study in 2021 that reported, in part, that hydrogen fuel cell power presents many of the same advantages as battery electric power but allows faster refueling compared with batteries. The study

also found that, "[g]iven the need for refueling infrastructure, hydrogen fuel cell powered locomotives would be most useful initially in applications that have limited geographic range." Some California passenger railroads have begun procuring hydrogen-powered railcars, and some freight railroads have successfully converted long-haul diesel locomotives to run on hydrogen power.

Federal Support

No federal statute or regulation prioritizes or promotes railway electrification or decarbonization, and freight railroads typically do not receive federal funding as they are financially self-sufficient private businesses. Projects to electrify or decarbonize rail lines may be eligible for several federal grant programs, but no federal funds have been explicitly directed toward rail electrification since the New Haven-Boston segment of Amtrak's Northeast Corridor was electrified in 2000. Other federal programs to support deployment of battery charging infrastructure or hydrogen fuel, such as those funded by the Infrastructure Investment and Jobs Act of 2021 (P.L. 117-58) or the unofficially named Inflation Reduction Act of 2022 (P.L. 117-169), have generally been targeted to highway uses, not railroads. Recent examples of federal support for rail electrification or alternative fuels include the following:

- Congress appropriated $2.5 million in FY2023 FRA funding to "continue ongoing research, development, and testing on innovative technologies and solutions for low- or no-emission alternative fuels for locomotives, engine improvements, and motive power technologies."
- FRA selected 10 projects to receive a total of $171 million in Consolidated Rail Infrastructure and Safety Improvements grants for the procurement of 16 new battery-electric locomotives, 19 diesel-to-battery (or battery-hybrid) conversions, one hydrogen locomotive, and two hydrogen research and development projects.
- Amtrak plans to use federal funds to replace some of its railcars and locomotives with new trainsets, some of which will be equipped with dual-mode diesel-electric and diesel/battery-hybrid locomotives.
- A December 2024 Department of Energy report contained a "rail decarbonization strategy" designed to reach net zero greenhouse gas emissions by 2050.

The California Air Resources Board In-Use Locomotive Rule Proposal

Since 2015, newly manufactured or remanufactured locomotives have had to comply with "Tier 4" federal emissions rules set by the U.S. Environmental Protection Agency (EPA); these primarily apply to air pollutants, such as particulate matter (PM) and nitrogen oxides (NOx), not greenhouse gases, such as carbon dioxide (CO_2). In April 2023, the California Air Resources Board (CARB) approved regulations that would have directed railroads to accelerate their adoption of zero-emission propulsion technology. The California approach differed from federal requirements in that it would have regulated the operators of existing locomotives (as states are blocked from regulating new locomotives by federal law), and it would also have applied to greenhouse gases.

The rule required a waiver from the EPA before it could go into effect. CARB withdrew its request for a waiver in January 2025 before the EPA issued its decision. At the time, the rule had already been challenged in court. Opponents argued, among other points, that federal law vests exclusive jurisdiction over interstate rail transportation with the Surface Transportation Board, preempting state laws. Under the proposed rule,

- locomotives would not have been permitted to idle for longer than 30 minutes (subject to exceptions);
- starting in 2030, only locomotives with an original engine build date less than 23 years old would have been allowed to operate in California, excepting those that met EPA Tier 4 emission standards, that were operated in a zero-emission configuration while in California, or that had primary engines that had not yet reached a specified output in megawatt-hours (MWh);
- all passenger and switcher locomotives built in 2030 or beyond, and all line-haul freight locomotives built in 2035 or beyond, would have been required to operate in a zero-emission configuration while in California; and
- all operators of non-zero-emission locomotives would have been required to make payments into escrow accounts, in amounts calculated using their emissions rates, with those funds designated for the acquisition of zero-emission locomotives and infrastructure (or EPA Tier 4 locomotives before 2030).

Operators could have adopted alternative compliance plans with state approval, including the "alternative fleet milestone option," where 100% of fleet usage in California would have been from Tier 4 or cleaner locomotives by 2035 and 100% from zero-emission locomotives or rail equipment by 2047. The rule included conditions for exemptions or extensions and would have directed CARB to reevaluate the feasibility of these requirements in 2027 and 2032 and adjust if necessary.

Because railroads routinely dispatch their locomotives anywhere on their systems and interchange them with other railroads, the California requirements could have had implications that reached beyond the state. The largest railroads may have needed to replace, rebuild, or redeploy thousands of locomotives to achieve compliance at a time when the industry customarily acquires or remanufactures perhaps a few dozen locomotives per year. CARB had estimated that the rule would cost $15.9 billion in equipment and labor over 25 years, and these costs could have been passed on in higher shipping rates. (CARB also estimated the value of the rule's health benefits at $32 billion.) Furthermore, because smaller "short-line" railroads generally purchase older, used locomotives to save on costs, they may not have had the financial wherewithal to make the requisite escrow payments and purchase new locomotives if they wished to stay financially solvent (there were 26 such railroads operating in California in 2021).

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