TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Article

Transportation Research Record
1–10

DOI: 10.1177/0361198118768532
journals.sagepub.com/home/trr
SAGE

The Life and Death of North American Rail Freight Electrification

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Abstract

Although completely dieselized today aside from certain commuter and intercity passenger routes, U.S. railroads were world leaders in electrification in the early 20th century. The Pennsylvania Railroad and the Milwaukee Road had the most extensive electrifications, but several other railroads electrified largely for freight service. This paper explores the decisions to electrify freight railroads in the U.S., Canada, and Mexico (largely for short tunnels where steam locomotives were not practicable, mountain grades, and busy traffic districts), and why electrifications were discontinued (underpowered installations, aging electric infrastructure, and changes in ownership that made electrification geographically obsolete). Energy shortfalls and price spikes since the 1970s have provoked interest in electrification from freight railroads, but this interest has subsided whenever fuel prices decline. Although it is possible that environmental considerations may lead to electrification in some contexts, as long as fossil fuel prices remain low, electrification is unlikely to play a major role on North American railroads.

The early 21st century finds North American freight railroads using diesel-electric locomotives almost entirely. Experiments have been conducted with gensets (diesel-electric locomotives with multiple engines that can be turned on and off individually to save energy), hybrid locomotives with batteries for temporary energy storage and reuse, and liquefied natural gas, which some conjecture may be more desirable than diesel due to the low price of natural gas brought about through hydraulic fracturing.

One or more of these technologies may yet gain wider acceptance, but thus far no technology shift has occurred in motive power. To inform the consideration of future rail freight power, this paper recounts the history of a once-widespread mode that has received some renewed interest since the 1970s: electric traction.

The capital costs of electrification, particularly of substations, power distribution, electrical contact systems, and electric locomotives, often deterred railroads facing other capital investment needs (*1*). Yet in the early 20th century, the U.S. was a world leader in railroad electrification (*2*). "By 1931, when American railroads were operating nearly 5,000 electrified track-miles, U.S. electrification represented nearly 20 percent of the world total and far more than any other country" (*3*, p. 126). This included freight, intercity passenger, and commuter service alike, and, on two railroads, electric operation of all three train types (*4,5*). But today, no freight operation that is part of North America's general railroad network remains electrified.

Figure 1 shows the maximum extent of significant electrifications on North America's main line railroads installed primarily for freight or otherwise having a significant freight component. Table 1 shows basic data for these operations.

This paper explores the decisions to electrify freight railroads, the experience of electrified lines, and the abandonment of this traction technology – the life and death of North American freight rail electrification – to understand this important chapter in railroading history and glean lessons for future rail development. This study considers the 16 most significant rail freight electrifications in the U.S., Canada, and Mexico shown in Figure 1 and described in Table 1, plus one intercity passenger rail electrification that was similar in its rationale, technology, and history.

Not included are:

- Short operations between coal mines and electric power plants, such as the Black Mesa & Lake Powell or the Navajo Mine Railroad. As these properties electrified because the power generation process made electricity readily available, their experiences

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Figure 1. Location of significant electrifications of main line railroads involving freight in the U.S., Canada, and Mexico.

lack broader applicability to common-carrier railroads.

- The Niagara Junction in Niagara Falls, N.Y., because easily-available hydroelectricity made electrification unusually advantageous. This switching railroad had no line-haul function.
- The New York Central and Illinois Central, which electrified almost entirely for suburban and intercity passenger trains. Their electrified freight service was minimal and very short-distance.
- Electric interurban railways (*6*), which electrified for passenger service and only incidentally had electrified freight service. However, one such line serving a major industrial zone is included because its electrified freight service survived into the 1970s.

Why Railroads Electrified

To appreciate the appeal of electrification for freight railroads during the steam era in which circumstances justified the large capital investment, it is necessary to understand the benefits of electric (and, in the diesel era, diesel-electric) traction. One researcher, discussing the massive post–World War II change from steam to diesel-electric locomotives, explains that

> Diesel-electric locomotives have been the universal choice of North American railroads (and of railways on many other continents) because of the characteristics of their transmissions. Where a mechanical linkage forces a direct relationship between engine speed and track speed, an electric transmission allows for maximum power output at *any* speed, even a dead stop. … In practice this means that a diesel-electric produces maximum

Table 1. Basic Information on Selected North American Rail Freight Electrifications

Railroad	Distance	Voltage	Years	Electrification rationale	Why electrification ended
Boston & Maine Hoosac Tunnel	8 mi (13 km)	11 kV AC, 25 Hz	1911–1946	Operation through 4 ¾ mi (7.6 km) Berkshire Mountain tunnel	Diesel locomotives reduced fumes in tunnel to manageable level
New York, New Haven & Hartford (NH)	107 mi (172 km)	11 kV AC, 25 Hz	1907–1969[a]	Electric passenger, suburban and freight operation between New York and New Haven	Conversion to diesel freight reduced power draw on aging, unreliable electrification
Pennsylvania Railroad; subsequently Penn Central, then Conrail	656 mi[b] (1,056 km)	11 kV AC, 25 Hz	1916–1981[c]	General efficiency of operation between northern New Jersey, Harrisburg, Pa., and Washington, D.C. for passenger, freight and commuter trains	Northeast Corridor passed to Amtrak, which raised fees for freights; Conrail responded by shifting trains to other, non-electrified-lines
Baltimore & Ohio (B&O) Baltimore tunnel	3.6 mi (5.8 km)	650 V DC, third rail[d]	1895–1952	Steam traction unworkable in tunnels under central Baltimore	Diesel locomotives reduced fumes in tunnel to manageable level
Virginian Railway (VGN) merged into Norfolk & Western (N&W) in 1959	134.5 mi (216.4 km)	11 kV AC, 25 Hz	1925–1962	Increased throughput for heavy-haul freight through mountains	Merger with N&W resulted in directional running one way on Virginian, other way on N&W line, making electrification difficult to operate
Norfolk & Western (N&W) original electrification	55.9 mi (89.9 km)	11 kV AC, 25 Hz	1915–1950	Increased throughput for heavy-haul freight through mountains	Installation wore out prematurely; railroad replaced part of electrified segment with lower-grade non-electrified-alignment
Cleveland Union Terminals (Cleveland, Ohio)	17.0 mi (27.4 km)	3 kV DC, overhead wire	1930–1953	Steam traction not suited for station below street level; also, office buildings located above tracks as part of station complex	Diesel locomotives reduced fumes in station vicinity to manageable level
Michigan Central (New York Central subsidiary)	4.5 mi (7.2 km)	650 V DC, third rail	1910–1952	Operation through tunnel under Detroit River	Diesel locomotives reduced fumes in tunnel to manageable level
Grand Trunk (Canadian National subsidiary)	4.2 mi (6.8 km)	3.3 kV AC, 25 Hz	1908–1958	Operation through tunnel under St. Clair River	Diesel locomotives reduced fumes in tunnel to manageable level
Detroit, Toledo & Ironton (DT&I)	16.0 mi (25.7 km)	22 kV AC, 25 Hz	1926–1929	Development of high-voltage AC for eventual use on main line between Detroit area and southern Ohio	Railroad sold in 1929; new management not interested in electrification
Chicago, South Shore & South Bend (CSS&SB)	75 mi (121 km)	1.5 V DC, overhead wire	1926–1981[e]	Electrified as passenger-carrying interurban railway; economies of scale with electrified freight operation	Cheaper to replace with diesels as installation aged and traffic shifted toward heavy unit coal trains
Butte, Anaconda & Pacific (BA&P)	37.4 mi (60.2 km)	2.4 kV DC, overhead wire	1913–1967	General economy of operation for Rocky Mountain mining railroad	Cheaper to replace with diesels as traffic declined and installation aged
Chicago, Milwaukee, St. Paul & Pacific (Milwaukee Road)	663.4 mi (1,067.4 km)	3 kV DC, overhead wire	1915–1974[f] 1919–1972[g]	General economy of operation in two mountainous segments, also concern about forest fires with steam locomotives	Installation became physically worn out, cheaper to replace with diesels than to renew electrification
Great Northern (GN), New Cascade Tunnel and approaches	73.5 mi (117.3 km)[h]	11 kV AC, 25 Hz[i]	1927–1956	Increased throughput and general economy of operation through tunnel and associated mountainous segment	Cheaper to operate with diesels than to continue change of motive power
British Columbia Railway (BC Rail)	81.0 mi (130.3 km)	50 kV AC, 60 Hz	1984–2000	New line with two tunnels serving coal mines; concern with diesels stalling out in tunnel moving heavy-haul freight upgrade	Electrification was technically sound, but became uneconomic as coal mines became exhausted
Ferrocarril Mexicano	64 mi (103 km)	3 kV DC, overhead wire	1926–circa 1974	General economy of operation in mountainous territory	Installation became physically worn out, easier to operate with diesels
Ferrocarriles Nacionales de México (FNM)	159 mi (256 km)	25 kV AC, 60 Hz	1994–circa 1996	General economy of operation on busy segment of railroad	Railroad privatized at time when double-stack container service emerging, wires dismantled to provide higher clearances

Note: Data from reference (*5*). Later 20th century short line coal-hauling operations omitted. AC = Alternating current; DC = Direct current; Hz = Hertz; V = Volts.
[a] Electric freight on former NH discontinued in 1969; electrification remains in service for commuter rail and intercity passenger trains.
[b] Includes lines electrified partly, primarily, and in some cases exclusively for suburban and through passenger service.
[c] Some electrification remains in service for commuter rail and intercity passenger trains.
[d] Third rail mounted above and to one side, 1895–1902; repositioned to ground level in 1902.
[e] CSS&SB's predecessor originally electrified at 6.6 kV AC, 25 Hz in 1909; electrified freight service began in 1916 at that voltage, but was poorly developed relative to the situation after 1926.
[f] Rocky Mountain Division.
[g] Coast Division.
[h] Replaced a 1909, 4.0-mi (6.4-km) electrification through the first Cascade Tunnel.
[i] Original 1909 electrification used an unusual three-phase, two-wire system at 6.6 kV AC, 25 Hz.

> tractive effort at zero speed—exactly what a railroad needs to start a heavy train (*7*, p. 411).

This advantage did not apply for steam (or to diesel locomotives with mechanical or hydraulic transmissions). Until diesel-electric locomotives became widespread in freight service after World War II, electrification was the only way for railroads to obtain this significant operating benefit. Steam locomotives commonly needed to be changed at division points, unlike electrics (or diesels).

Only electric motors provide maximum torque from a standstill, and may safely exceed their rated output for brief periods of time without overheating. Diesel-electric locomotives, despite their flexibility, lack one advantage of electrics: the ability—given adequately-powered motors and sufficient electricity—to draw as much remotely-generated power as needed to start and move a train.

Electrification was also advantageous, when justified by its capital costs, to different railroads for different reasons.

Tunnels

First, some roads installed short tunnel electrifications where steam operation was not practicable, as with the Baltimore & Ohio (B&O) beneath downtown Baltimore, Maryland (*8*), the Boston & Maine's Hoosac Tunnel in the Berkshire Mountains of Massachusetts, or under rivers, as with the Michigan Central and the Grand Trunk Western, crossing the Detroit and St. Clair Rivers, respectively.

Grades

Second, railroads sought to facilitate operation on lines with mountain grades. Thus, Norfolk & Western (N&W) and the Virginian Railway (VGN) sought to move long, heavy coal trains more efficiently through long mountainous segments than was practicable with steam locomotives. The Chicago, Milwaukee, St. Paul & Pacific (Milwaukee Road) electrified part of its transcontinental route in two discontinuous segments: one in the Rockies and the other in the Cascade Mountains. In addition to the increased operating efficiency through mountainous terrain, the railroad needed to avoid starting forest fires, particularly in federally owned forests that it traversed.

Intensive Traffic

Third, railroads were concerned with overall efficiency and economy. Unlike the other electrifications analyzed here, freight was not the dominant consideration for the New York, New Haven & Hartford (NH) or the Pennsylvania Railroad (PRR), which also had intensive commuter and busy intercity passenger services at levels too frequent for steam to be optimal. But given electrification for passenger and commuter trains, it made sense during the steam era (and beyond) to operate freights with purpose-designed electric locomotives.

Train Handling

The ability of electric locomotives to start trains more reliably and accelerate faster than steam, particularly for long, heavy trains, was another advantage that in some cases, such as the N&W, helped persuade management of the benefits of electrification.

Multiple Factors

These considerations were not mutually exclusive. For instance, the Great Northern (GN) and British Columbia Railway (BC Rail) were concerned with both grades and tunnels when they electrified. Similarly, although PRR was primarily concerned with overall efficiency, there were operational and safety benefits to electric running through that road's Baltimore tunnels, as had been the case earlier for competitor B&O.

For most of these electrifications, freight was the dominant consideration. However, commuter and intercity passenger trains were important for the NH and PRR electrifications, and passenger service was a lesser but still significant consideration for the Milwaukee Road. Whatever the operating needs of these railroads were, electrification met them—for a time.

Technology Development

Most of these electrifications addressed immediate needs, but one railroad was the exception that proved the rule. The Detroit, Toledo & Ironton (DT&I) was bought by automaker Henry Ford in 1921 (personally, not as a corporate subsidiary). DT&I was important for Ford's supply chain, linking southern Ohio (adjacent to coal mines) with the main Detroit-area manufacturing plant. Far from meeting immediate operating needs, the DT&I electrification was undertaken for reasons of technology development.

In 1923 DT&I announced plans to electrify, starting with a 16-mi segment in southeastern Michigan adjacent to Ford's River Rouge factory. Although the installation never went beyond this initial segment, DT&I envisioned electrifying its entire main line. Furthermore, a link was proposed from southern Ohio to West Virginia, connecting with VGN, which had its own electrification (*9*).

Perhaps presciently, a Westinghouse Electric manager wrote in 1923 that "at present the limit in the United States for the alternating current system is 11,000 volts, but there is no reason why this should not be increased as demands are made for heavier drafts of power" (*10*, p. 292). DT&I electrified at 22,000 Volts (22 kV) alternating current (AC), 25 Hertz (Hz), apparently the highest voltage on any railroad in the world at the time. Although DT&I still used 25 Hz (as lower-frequency AC was then necessary for modulating the speed of electric motors), it anticipated subsequent European development of 25 kV AC electrification at commercial frequency (*11*).

Why Railroads De-Electrified

There were three basic reasons for de-electrifying: diesel locomotives being safer to operate than steam through tunnels, technical limitations, changes in ownership, and maintenance costs.

Diesel in Short Tunnels

These electrifications, implemented to avoid the safety hazards of running steam locomotives through tunnels, were too short to be practical once diesel locomotives replaced steam. With proper ventilation, these tunnels could be safely operated with diesels, at least at the moderate traffic densities prevailing on these segments. Electrification, however, remains important where frequent commuter trains use tunnels, as in New York.

The Cleveland Union Terminals electrification in northern Ohio resembled the shorter tunnel freight electrifications in its technology and history, although it served passenger rather than freight trains and traversed no tunnels. This line was electrified in 1930 for amenity purposes, so that smoke would not pollute the intercity passenger station or office buildings above the tracks. Cleveland's installation was decommissioned in 1953, once the railroads using the station had replaced steam with diesel locomotives (*12*).

Technical Limitations

Several electrifications were ultimately abandoned because they were underpowered, or otherwise aged to the point of becoming liabilities, even though they were considered important when opened in the early 20th century.

Insufficient Power. The NH electrification was North America's first main line AC installation (*13*), but it was inadequately powered for the railroad's eventual needs (which for NH was a financial rather than a technological problem). These problems delayed and limited the use of electric locomotives for freight. NH retired its aging electric freight locomotives and replaced them with diesels in 1959.

However, after reexamining the unavoidable minimum costs of its electrification, NH bought 11 modern freight locomotives from the VGN that were surplus. These entered service in 1963 (*14*). But electrified freight became unsustainable as the power plant (inadequate from the outset) aged and the traction power supply became more brittle. Supplementary power tie-ins from utilities in New York City and Connecticut were both expensive and insufficient.

On December 31, 1968, NH was absorbed into Penn Central (PC), itself formed by merging the New York Central and the Pennsylvania Railroad. PC management ended electric freight service east of New York by mid-January 1969, and the ex-VGN locomotives spent the rest of their service lives on ex-PRR lines (*15*). Power shortages continued until Metro-North Railroad, which inherited the New York–New Haven, Connecticut segment in 1983, overhauled the electrification in 1986 with 12.5 kV AC at commercial frequency drawn directly from the power grid—17 years after electric freight operation had been discontinued.

Other installations used direct current (DC), which subsequently showed itself inadequate for long, heavy freights at any voltage. Among the best-known American electrifications were the Milwaukee Road's two technically identical but separate electrified districts in the Rocky and Cascade Mountains. There was a combined 663 route-miles of electrified track, separated by a 212-mi gap that was never bridged. When the Milwaukee Road electrified in the 1910s, it was not yet understood that even at the high pressure of 3 kV, direct current (DC) might not be adequate for freight service. This, however, became very clear with the longer, heavier trains of the post–World War II era.

To reduce the risk of substation failures or burnouts of electrical wires, longer freights were routinely operated with electric and diesel locomotives on the same train (*16*). Although installing two sets of pickup wires (as has been done on Soviet Railways in 3 kV territory) might have prevented some wire burnouts when trains were drawing power, ultimately the obsolescence and inadequacy of the installation made themselves felt. The financially troubled railroad could not afford the huge capital cost of reelectrification to a higher AC voltage, or even of reinforcing its existing installation for higher levels of power draw. Electric operation through the Cascades ended in 1972 and through the Rockies in 1974 (*17*).

The Ferrocarril Mexicano used the same system as the Milwaukee Road on a mountainous segment between Mexico City and Veracruz, Mexico. Faced with the same issues, successor Ferrocarriles Nacionales de México (FNM) discontinued electric operation by 1974.

Aging Electric Infrastructure. N&W electrified its main coal-carrying line in West Virginia in 1915 at 11 kV AC, then seen as the state-of-the-art voltage, to provide greater operating capability on sustained grades without adding track. The railroad built its own power plant, as rural utilities did not then have the electric capacity the railroad needed. But the installation aged prematurely, and by the end of World War II, modern steam locomotives had become more power-efficient. In 1950, N&W opened a new, non-electrified-segment with lower grades and a new tunnel, replacing the electrics with steam until the dieselization process took effect (*18*, pp. 87–88).

Electric interurban railway Chicago, South Shore & South Bend (CSS&SB) was modernized and reelectrified in 1926 for compatibility with the Illinois Central's suburban electrifications, which CSS&SB used to reach downtown Chicago (*19*). Given its electric status, electric freight locomotives were the obvious choice at the time. Indeed, freight operations in highly industrialized northwest Indiana ensured CSS&SB's survival. But as the railroad focused on unit coal trains starting in the 1970s, with their heavier power draw, and as the locomotives aged and spare parts became unavailable, dieselization made more sense. The last electric-powered freight train ran in 1981 (*20*). Commuter service is still electrified.

Butte, Anaconda & Pacific (BA&P), a Montana copper-mining railroad, electrified largely to more efficiently handle traffic between mines and smelters, using 2.4 kV DC. Although BA&P bought new electric locomotives as late as 1957, its installation was aging and traffic was declining as the mines became increasingly exhausted. A combination of these factors brought electrification to an end in 1967 (*21*).

Changes in Ownership

Other installations, when decommissioned, were fully capable of meeting the demands placed on them, but the fixed nature of electrification made them vulnerable to traffic shifts, particularly those caused by changes in ownership. All these railroads used AC, which if designed properly, provided sufficient power for decades.

The largest electrified freight operation to be dieselized after certain main lines changed hands was the Pennsylvania Railroad's huge installation (large parts of which survive in passenger and commuter service). Starting with a Philadelphia suburban segment in 1915, by the late 1930s it encompassed a large area between New York, Harrisburg, and Washington, D.C. (*22*). PRR apparently influenced decisions by VGN and GN to select 11 kV AC, 25 Hz.

During World War II, PRR's electrification contributed significantly to the war effort by moving freight and personnel reliably. Reexamining the future of electrification in 1958, PRR decided to reinvest in the future of electrified freight and ordered new locomotives in 1959 to replace life-expired units (*23*). Even in bankruptcy in the early 1970s, successor PC continued to operate electric freight locomotives on ex-PRR lines.

The creation of Conrail in 1976 led to a revival of rail freight in Northeastern U.S., but spelled the end of electrified freight operations. Concurrently with Conrail's creation, national passenger operator Amtrak took title to electrified ex-PRR lines between New York and Washington, and between Philadelphia and Harrisburg, used primarily by passenger and commuter trains. Although Conrail had trackage rights on Amtrak, the latter raised its fees to reflect what it believed was the high cost of maintaining tracks to meet the needs of heavy freight as well as fast passenger trains. Conrail responded by upgrading its own nonelectrified ex-Lehigh Valley and Reading Co. lines, where it shifted most of its traffic between northern New Jersey and Harrisburg. Conrail's last electric freights ran in 1982 (*24*).

Although N&W abruptly ended electric operations in 1950, rival VGN's 1925 installation remained efficient and in good condition. VGN bought four new electric locomotives in 1948, and 12 more in 1956. But matters changed drastically in 1958 when N&W acquired Virginian, and sought operating economies as it merged the two railroads in the coal country of Virginia and West Virginia. N&W adopted directional running, operating loaded trains eastbound over VGN, which had lower grades. Rather than shuttle electric locomotives against the current of traffic on VGN, or extend electrification so that it served both lines, N&W decommissioned the VGN installation in 1962 (*18*).

On the DT&I – purchased and electrified by automaker Henry Ford – electric operation began in 1926 (fed from the same power source as the River Rouge factory, where lights dimmed when a locomotive was accelerating). Ford, with his deep pockets, seemed unconcerned that the energy costs of the initial 16-mi electrification were much higher than for steam locomotives, perhaps because contracts with electric utilities might have reduced these costs for a longer electrification. But the Interstate Commerce Commission, uneasy with Ford's maverick role in the railroad industry, ordered a halt to further electrification work shortly after construction started on a further extension. Under anti-trust pressure, Ford sold DT&I in 1929 to a holding company controlled by PRR. Despite parent PRR's large electrification, the new management lacked Ford's interest in electrification, and the locomotives were scrapped (*9*).

The government-owned FNM operated a series of trunk lines between Mexico City and points north on busy routes to northeastern Mexico and the U.S. Seeking greater operating efficiencies, FNM procured electric locomotives in 1982 and built a priority freight corridor between Mexico City and Querétaro with a modern 25 kV AC, 60 Hz electrification. Electric service began in 1994, but lasted just 2 years. Rail freight concessioning, a process started in 1996, led to increased investment in modern diesel-electric locomotives and full adoption of modern operating practices used on U.S. and Canadian railroads. The wires were soon dismantled to accommodate double-stack container trains (*25–27*).

Maintenance Costs

The GN installation began in 1909 as a short electrification through its original Cascade Tunnel in 1909 using an unusual and cumbersome three-phase, twin-wire version of 11 kV AC (most AC electrifications on railroads involve only one phase). But the tunnel and the steep alignment, even with electrification, proved inadequate for the railroad's operating needs. GN therefore built a new 8-mi Cascade Tunnel, with gentler grades and a lower summit, along with a new and longer single-phase

11 kV electrification that opened in 1927 (*28*). These changes made the GN electrification, at 73.5 mi, comparable with the N&W and VGN (at 55.9 mi and 134.5 mi, respectively).

Unlike the better-known Milwaukee Road electrification, GN's installation provided sufficient power. During the steam era, electric haulage through the tunnel was a necessity, but with dieselization, the costs of maintaining electric locomotives, substations, and wires exceeded the benefits. GN ended electric operations in 1956 after making ventilation improvements in the tunnel. Some of GN's locomotives found a second life in freight service on the PRR (*29*).

In the Canadian Rockies, BC Rail electrified its 81-mi Tumbler Ridge Subdivision in 1984. This branch, in an isolated part of the province in the Rocky Mountains, served two coal mines. With two long tunnels involving grades, BC Rail was concerned that diesel locomotives would stall out from a lack of fresh air while straining their engines to maintain speed, and decided on electrification. BC Rail selected 50 kV AC, 60 Hz, largely because at this very high voltage, the railway would need only one substation (*30–32*).

Technologically, BC Rail's electrification had a long future ahead of it, but it closed after only 17 years when one of the two coal mines became exhausted. The railway decided that the remaining mine's production did not warrant the fixed cost of electrification.

Analysis

North American railroads converted almost completely from steam to diesel within about a dozen years from the late 1940s to the late 1950s. It is not that railroads failed to appreciate the advantages of electric traction; instead, this appreciation came in the form of the diesel-electric locomotive, which is essentially an electric locomotive powered by an on-board diesel engine. The flexibility of the diesel-electric has spared railroads the expense of erecting lineside power supplies, even though this comes at the cost of maintaining both diesel engines and electric motors aboard locomotives. For all North American freight railroads, the cost savings from fleet standardization and abandonment of costly electrification infrastructure more than outweighs the marginally better throughput (up to about 15%) that electrification potentially offers.

With the exception of Henry Ford's DT&I, considerations other than immediate operating needs did not enter into decisions to electrify freight railroads. As the case studies show, all other freight railroads electrified because they believed that doing so would make their operations more efficient, or, in some cases, feasible in the first place.

Technical Standards

One factor said to have retarded the growth of electrification was the lack of a technical standard. This was most evident in the so-called battle of the currents, between proponents of DC (led by Thomas Edison and continued by General Electric), and AC advocates (led by George Westinghouse and continued by Westinghouse Electric). Even within the DC camp, there were several alternatives. Third-rail systems tended to use between 600 and 750 V, and different overhead-wire systems used 1.2, 1.5, 2.4 and 3 kV. Although DC remains reasonably well-suited for commuter rail under some circumstances, the amounts of current required for heavy freight trains ultimately exposed its weaknesses, as the Milwaukee Road's experience showed.

On the AC side, early work with 6.6-kV current indicated that a higher voltage was preferable. NH's 1907 installation pioneered the use of 11 kV AC. The state of electric motor technology in the early 20th century was such that lower AC frequencies were needed to provide the level of speed control that railroads required. Therefore, 11 kV AC installations in the U.S. used 25 Hz. This voltage, used on longer electrifications (NH, PRR, N&W, Virginian, GN) other than the Milwaukee Road, paralleled European development of 15 kV AC at 16.67 Hz (still used on national railways in Germany, Switzerland, Austria, Sweden, and Norway).

Yet 11 kV AC never emerged as an industry standard. The DC vs. AC issue remained unsettled until the 1950s, when 25 kV AC at commercial frequency (60 Hz in North America and 50 Hz in most other parts of the world) became the universally accepted norm for major new railway electrifications, with certain heavy-haul operations (such as BC Rail) choosing 50 kV. But by then, electrification was in retreat on U.S. railroads, as the diesel-electric locomotive combined the tractive-force benefits of electric traction with the diesel's ability to travel anywhere.

In that sense, electric traction triumphed over steam on North American railroads, but with a self-contained (diesel) generation source aboard the locomotive rather than with external electricity sources.

Even if 11 kV AC had emerged as a standard, resulting in somewhat more electrification, it is difficult to see how this alone would have safeguarded electrification against other factors leading to its removal. Neither has the emergence of 25 kV as the modern industry standard (along with its heavy-haul cousin 50 kV) led to the electrification of any lines other than BC Rail's mining branch and Mexico's freight corridor.

Energy Prices and Interest in Electrification

The 1973–74 energy shortage produced interest in electrification on the part of major freight railroads, including Illinois Central Gulf (*33*), Union Pacific, and Canadian Pacific (*34*). The 1979 energy shortfall led Conrail to study electrification between Harrisburg and Conway Yard west of Pittsburgh, and even settled on 25 kV AC as the preferred voltage despite its existing 11 kV AC, 25 Hz installation further east. But a cost–benefit analysis suggested that there were more productive uses for Conrail's investment capital, and there matters ended (*35*).

Nevertheless, when energy prices were high, interest in rail freight electrification rose. In 1977 the Transportation Research Board published a volume devoted to electrification from a freight railroad perspective (*36*). Even after railroads lost interest in electrification when oil prices fell in the 1980s, other parties continued to investigate the economics and operations of rail freight electrification (*37*). There was renewed interest in electrification in the early 2000s when energy prices spiked (*38*), but no electrification resulted. Then, hydraulic fracturing ushered in a new period of inexpensive oil and natural gas.

There appears to be a fundamental mismatch between the high capital cost, the long lead time for implementation, and the sometimes-volatile nature of energy supplies and prices. The time frame within which energy price spikes have run their course has been shorter than the lead time needed for such a major investment as electrification (particularly in today's procedure-conscious age).

Aging Technology

Even if some of the technologically superior electrifications had survived, experience on Amtrak's Northeast Corridor (NEC) and electrified commuter railroads suggests that freight railroads would have encountered the same difficulties that surviving installations have experienced with maintaining adequate power for the needs of more, longer, and faster Amtrak and commuter trains (*39*).

The ex-PRR portion of the NEC, with the voltage raised from 11 to 12.5 kV but still at 25 Hz, has come under strain as the strong acceleration and high speeds of modern trains raises levels of power draw. Electric freight operation, had it continued, would have placed additional stress on the ex-PRR installation. Similarly, the 11 kV installations on the VGN and the GN would have felt the strain from the rising demands of modern traffic levels had they survived.

Technological Unfamiliarity

Another factor was the loss of momentum among North American railroads and suppliers. As one observer noted in 1984,

> a big part of the problem of making profitable sense out of electrification stems from an American gap in the technology. Our technological heritage … is keyed to the Pennsylvania Railroad's electrification … In the 40 years since then, U.S. technology has waned. European and Far Eastern nations are now leaders (*40*).

Those roads that have electrified have drawn on European experience, where electrification (albeit largely passenger-driven) is widespread and expanding. BC Rail relied heavily on Swedish experience (*30*), and Amtrak's electrification between New Haven and Boston draws on British practice (*41*).

Other Factors

There is a contradiction between increased tonnage per train and the relatively infrequent nature of freights compared with commuter trains and (on the NEC) intercity passenger trains. Unless the operating circumstances clearly require electrification, as with BC Rail, the cost of providing traction power needs to be weighed against how often trains will operate. Additionally, issues of critical mass and high initial investment make electrification a difficult proposition for railroads:

> Operating officials prefer a single, ubiquitous, standardized pool of motorized power that can go anywhere and pull anything. Engineering officials do not want to bother with catenary and substation maintenance. Financial officers do not want the added debt … to fund electrification (*42*, p. 47).

Ultimately, rail freight electrifications became vulnerable to technological deterioration (NH, N&W, Milwaukee Road) or changes in traffic and operating patterns (PRR, VGN, BC Rail, FNM). Technological improvements, driven by environmental legislation, continue to lower emissions from diesel locomotives. But fossil fuels are unlikely to remain inexpensive indefinitely. At some point, supplies may tighten due to international events, environmental impacts of hydraulic fracturing, eventual exhaustion of reserves, or even shortages of water (a key component of today's fuel extraction). More localized electrification might conceivably result from air quality concerns, e.g., in southern California (*43*), although these issues may also be manageable through improvements in diesel engine emissions. The environmental balance of any possible electrification would, of course, depend on the original electric power sources.

Recommendations

The most recent cost–benefit analysis of rail freight electrification in the U.S. context appears to have been published in 1983, proposing electrification of 10,000–29,000 route-miles (*44,45*). Much has changed since then. Hydraulic fracturing has driven the price of fossil fuels down (at least for the immediate foreseeable future), and advances in diesel engine technology have reduced emissions greatly. These factors do not favor electrification.

However, freight railroads are busier today, and there is greater concern about fossil fuel emissions. Furthermore, electrified lines would not necessarily rely on any one original energy source. There may also be some complementarity with wind and solar energy, especially in rural areas. Thus, a new analysis may be appropriate.

Railroads face many investment needs, one of the most pressing of which is positive train control, mandated by the U.S. Congress. The emphasis on short-term financial performance makes it difficult for companies in any industry to justify long-term investments. Therefore, public–private partnerships might be needed, such as that between the U.S. Reconstruction Finance Corporation and PRR enabling electrification between Wilmington, Delaware, and Washington, D.C., to proceed in the 1930s. Some of the benefits of electrification accrue more to society than to the railroads. This would suggest a cost-sharing role in rail freight electrification for those state and federal levels of government reflecting these benefits. At the same time, railroads seeking the operating benefits of electrification should be expected to participate in the costs.

Future Directions

The early 21st century finds electrification for rail freight essentially nonexistent in North America, the world leader a century earlier. Inexpensive fossil fuel, brought about by hydraulic fracturing, has minimized the likelihood of freight railroads investing in electrification, which requires large upfront costs before operating savings can be obtained. The low energy prices of the late 2010s emerge against a background of increased concern about greenhouse gas emissions generally and emissions from mobile sources in particular, although great progress continues to be made in reducing diesel emissions (*46*).

Electrification advocates between the 1910s and 1940s were concerned about the different voltages and power delivery systems then in use, and pled for standardization. Settling on a basic specification has served the North American railroad industry excellently in other regards. Adoption of high-voltage, industrial-frequency AC, such as 25 kV AC, 60 Hz, would enable railroads to use a more robust electrification technology than any available in the first half of the 20th century.

Nor is it clear that any future installations would be modeled on those of the late 20th century. In 2011, during an oil price spike, one large railroad was considering a

> lineside storage and energy transfer system where helpers are used in train operations. Discontinuous electrification, with overhead line installed on short sections of steeply-graded route, would enable downhill trains to "export" regenerated dynamic braking energy for use by other trains heading uphill, for lineside storage or for sale to a third party (*47*, p. 48).

Whatever motive power technologies North American freight railroads pursue in the future will, in all likelihood, be profoundly influenced by today's almost-universal use of diesel-electric traction. To the extent that there is a motive power debate within the industry, for the time being it involves liquefied natural gas (LNG) rather than electrification (*48*).

Electrification may yet have a role to play, particularly in emissions-conscious jurisdictions such as in California. Similarly, technological breakthroughs in battery technology may well make electrification more desirable, particularly in specialized contexts such as helper districts. But barring a large cost differential in favor of electricity as opposed to diesel fuel and natural gas, or a future policy shift away from fossil fuels in favor of other energy sources, that role is unlikely to be a large one.

Future development of battery technology could conceivably result in battery-powered locomotives. If issues of cost and charging time can be resolved, electric operation may take a new technological form.

More immediately, the life and death of freight electrification on North America's railroads may be relevant for the debate over diesel vs. LNG as a locomotive fuel. Even though LNG may be less expensive in operating terms, the savings may not be enough to justify the necessary capital costs of fueling and maintenance facilities for LNG locomotives. If LNG does not revolutionize North American freight railroading, the dead hand of rail freight electrification may help explain why not.

Acknowledgments

The authors are grateful to John P. Aurelius for his insights on electrification technology, to Jay Guarneri for preparing the map in Figure 1, and to the reviewers for their helpful ideas.

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The Standing Committee on Freight Rail Transportation peer-reviewed this paper (18-02855).