The Case for Electrifying Freight Railroads by Half-Measures: Exeunt Diesels, Cue Battery-Electrics

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ABSTRACT

Changing attitudes, regulations, public policy, and international treaties regarding fossil fuels are likely to lead freight railroads towards carbon-neutral technologies, yet only electric traction matches the performance of diesel-electric locomotives. The tremendous power requirements of freight trains make efforts to reduce greenhouse gas (GHG) emissions challenging, but the prospect of 7.2 megawatt-hour (MWh) battery-electric locomotives (BELs) offers promise, and intermittent electrification can facilitate battery charging.

Train performance calculations under simulated real-world conditions show two 14.5 MWh combination BELs can power 8,000-ton trains up to 230 mainline miles unassisted, with average energy consumption of 12.5 watt-hours/ton-mile. This permits discontinuous electrification of major freight lines, leaving "gaps" of up to 200 miles to reduce capital costs, especially in rugged terrain or where the power grid is sparse. Massive onboard battery arrays and intermittent access to the electrical grid for traction power and recharging provide great energy savings through recycling energy now lost when traveling downhill or braking. A case study of a hypothetical Class 1 railroad found intermittent electrification with BELs more than 60% more cost-effective than contiguous electric districts, and dramatically reduced engine changes.

To reduce railroad GHG emissions, governments must support technical development, show that electrification works in various North American settings, and develop institutional-financial frameworks to incentivize intermittent electrification with BELs, all in the context of massive environmental and capacity upgrades to electrical networks. Given proper assistance and incentives, early 21st century railroads may find discontinuous overhead-wire electrification offers great promise in operating terms.

Keywords: Rail freight, electrification, overhead contact system, battery-electric locomotives, charge-in-motion.

INTRODUCTION

As societal attitudes turn away from fossil fuel, environmental regulations are growing more stringent, carbon-limiting international treaties are being considered, and public policy is supporting moves toward non-emitting propulsion technologies, starting with well-publicized advances in the automotive-sector. Until nations overhaul their electric supplies to reduce greenhouse gas (GHG) emissions from power generation, there may simply be shifts in emissions from tailpipes to power plants. But a secular shift in public opinions is bringing creative talent to bear on the engineering challenges of reaching carbon neutrality in transportation – including rail.

Since the mid-1970s, the costs, benefits, and desirability of main line rail freight electrification have been debated (*1*). Credible analysts and experts have reached differing conclusions, and disagreements have even arisen among electrification advocates (*2*,*3*).

These strongly opposing views often rest on very different assumptions. Thus, if diesel fuel costs $50/U.S. gallon and electricity costs $20/megawatt-hour (MWh), electrification might well cover its capital costs. Conversely, if diesel costs $2/gallon and electricity $500/MWh, electrification will not even cover its maintenance costs.

This paper makes no effort to debate the desirability of electrification. Assuming that public policy will eventually move railroads towards carbon-neutral technologies, we provide a preliminary quantitative analysis to demonstrate the feasibility of discontinuous or intermittent electrification in conjunction with recently-announced battery-electric locomotives (BELs) featuring 7.2 MWh of energy (*4*), assuming that those BELs are proven in service and can each be coupled to a cabless booster (or battery tender) providing a further 7.2 MWh of energy storage. This makes electrification less infrastructure-intensive and reduces maintenance costs, thus making it more affordable than continuous 20th century installations.

Climate Change Context

Human activities are estimated to have caused between 0.8°C to 1.2°C (1.4°F to 2.2°F) of global warming above pre-industrial levels, and is likely to reach 1.5°C before 2052 (*5*). Thus, the United Nations Intergovernmental Panel on Climate Change (IPCC) has called for a 40% reduction of GHG emissions by 2030 to avoid climate consequences associated with average warming of greater than 1.5°C. Some industry groups describe zero-carbon rail as a "necessity" by 2050 (*6*).

Diesel locomotives emit GHGs and contribute to climate change. As automobile and truck fleets are hybridized or electrified, today's environmental arguments in favour of diesel-hauled freight trains as an energy-efficient form of transportation will become harder to sustain. As we transition away from a fossil-fuel based economy, some haulage needs will naturally attrit away (such as today's significant tonnages of coal, crude oil, and hydraulic fracturing chemicals.) However, to continue operating in other sectors (general merchandise, intermodal, metals, farm products, and automotive), railroads must replace diesels with non-GHG-emitting propulsion technologies.

HISTORICAL BACKGROUND

The post-World War II appearance of affordable, reliable, mass-produced diesel-electric locomotives transformed railroads, combining steam's go-anywhere flexibility with the tractive force characteristics of electric locomotives. Not always remembered is that diesels in North America supplanted mainline freight electrification. Although electrification peaked at around 1% of total U.S. railroad mileage, served crucial segments across mountains, through tunnels, and in the Northeast Corridor (*7*), the last electric-powered freights ran in 1981 (Figure 1), making diesel power's triumph all but complete.

Yet railroads have not always been confident of the future of diesel traction. During the 1970s, several North American freight railroads, pinched by rising costs and fuel scarcity, seriously considered electrifying their busiest lines (*8* pp. 425-428). But no new installations ensued on common-carrier railroads, other than British Columbia Railway's (BCR) electrification of an isolated coal-mining branch in the Canadian Rockies (Figure 2)—de-electrified in 2000 when steel industry demand for metallurgical coal fell (*9,10*)—and a short-lived electrification of a major freight corridor north of Mexico City. Another oil price spike in 2008 produced renewed interest in electrification (*11*). Then hydraulic fracturing brought about less-expensive, more plentiful oil, and railroads lost interest again.

Even during the 1970s with rapidly rising oil prices, electrification offered few overall cost benefits relative to diesel-electric locomotives. One major railroad held back from electrifying due to uncertainty whether utilities could provide the amounts of power needed (*12*). Oil price spikes were brief, but financing and implementing electrification is long and complex. New standards for locomotives (Tier 2, 3, and 4) came into force for reducing noxious and particulate emissions from railroad operations, and thereby somewhat reduced the relative emission benefits of electrification (*14*), but did not address GHG-related issues.

To put matters in perspective, rail used less energy in 2018 than any other transportation mode: 2.0%, versus 3.1% for pipelines, and 4.3% for water modes (*15* p. 2.12). But railroads today must consider alternatives to diesels, due to growing concerns about GHG emissions. Phasing out fossil fuels will become important for all transportation modes, including railroads (*16*). Examination of how railroads can reduce their carbon footprint should include overhead-wire electrification (*17*), which can be powered from carbon-free generation sources.

RECENT PROGRESS TOWARDS CARBON NEUTRALITY

The diesel era has served railroads well. Diesel provides more energy per pound than any other transportation fuel (*18* p. 151). Recent sustainability efforts have produced various carbon-reduction initiatives, but few alternatives currently under discussion are truly carbon-neutral. We now review some of the technologies currently on offer.

Figure 1. Electric Conrail freight on the Northeast Corridor near the Gunpowder River, Maryland, 1980; Roger Puta photo (CC-PD0). (https://commons.wikimedia.org/wiki/File:Conrail_E44s_--_3_Photos_(33561299960).jpg)

Figure 2. British Columbia Railway coal branch line electrification, Table, B.C., 1987; Roger Puta photo (CC-PD0). (https://commons.wikimedia.org/wiki/File:BCRAIL_6002_at_Table,_BC_on_September_18,_1987_(22446392399).jpg)

"Sustainable" But Not-Quite-Zero-Carbon Experiments

Florida East Coast Railway uses locomotives converted to burn liquefied natural gas (LNG), using fuel tenders (Figure 3). Although this regional railroad found satisfactory results, LNG is not carbon-neutral, particularly due to methane leakage during natural gas production (*19*) and the energy needed to compress and chill natural gas (*18* pp. 149-152). Methane is 25 times more potent as a GHG than CO_2.

Since 2005, several Class I railroads have tested diesel "genset" locomotives for switching service (Figure 4). Instead of a single prime mover, genset locomotives have two or three highway-truck style engines that can be turned on or off individually as power is needed, improving fuel efficiency and thereby reducing overall emissions. But their unique characteristics have confined them to specialized low-power service (*20*) where their duty cycle is efficient. Although gensets reduced particulate emissions significantly relatively to the first-generation diesel locomotives they replaced, this is not a carbon-neutral technology. A genset operating in power-hungry heavy-haul service with all engines firing most of the time can actually be less GHG-efficient overall than one with a larger prime mover.

In 2022, Metrolink, a California commuter rail operator, converted from fossil-fuel diesel to renewable diesel fuel (RD99), which is refined entirely from renewables (*21*). Early indications suggest that renewable diesel has comparable performance to petroleum-based diesel (*22*). To the extent that production of RD99 removes CO_2 from the atmosphere, overall net reductions of 65~90% of carbon emissions might be possible, but it does not entirely eliminate GHG emissions.

Several heavy-haul railroads have recently ordered BELs (*23*), to be operated in conjunction with existing diesel-electric locomotives in a "hybrid" configuration, whereby energy normally lost during braking is recaptured and stored in onboard batteries, which are later used to power the train in conjunction with the diesels (*24*). Although this is a step in the right direction, it is at best an interim solution because the energy losses due to rolling and curving resistance must be replaced by diesel prime movers, which are not carbon-neutral. Elimination of GHG emissions is only complete when all energy expended in transportation can be supplied, at least theoretically, from carbon-neutral sources.

Hydrogen with Fuel Cells

In 2021, a locomotive manufacturer announced a joint venture with an automotive firm to develop fuel cell technology for railroad use (*25*). Because it has only 6.4% of the energy density of diesel (*18* p. 151), hydrogen seems unattractive for heavy freight operations (*26* pp. 10-11). However, at least one major manufacturer (*27*) is fabricating a 200kW fuel cell system for use on passenger multiple units, and believes the underlying technology could be scaled up for heavy-haul applications.

Figure 3. Florida East Coast Locomotive 807 and Liquefied Natural Gas (LNG) Fuel Tender 302 at the Dixie Overpass, Deerfield Beach, Florida. Flickr User BBT609 photo (CC BY 2.0). (https://www.flickr.com/photos/bbt609/30873507632/)

Figure 4. NRE 3GS21B, a popular "genset" locomotive, on Olive St., Anaheim, California, 2007; Matthew "Morven" Brown photo (CC BY-SA 3.0). (https://commons.wikimedia.org/wiki/File:NRE_3GS21B_UPY_2733.jpg)

The majority of commercially available hydrogen today is derived from petroleum products ("blue hydrogen"); it is possible, at least in theory, to produce hydrogen from entirely non-GHG emitting sources (e.g., solar power coupled with electrolysis of water, called "green hydrogen"). If a whole energy ecosystem is built around green hydrogen fuel cells, this would truly be a carbon-neutral technology, as the only combustion product of hydrogen is water. This process has much grid-side potential for capturing otherwise unusable energy sources.

Some of the challenges facing the hydrogen economy include the large amount of energy required to produce and compress hydrogen, relative to the energy produced when it is burnt, plus practical issues concerning large-scale storage and fueling (*18*). Whilst practical issues will eventually find engineering solutions, the energy input issue concerns the physical and chemical properties of hydrogen gas itself.

Battery Electric Locomotives with Overhead Catenary Electrification

The remainder of this paper will be concerned with overhead catenary-wire electrification in conjunction with onboard-locomotive battery storage. To be carbon-neutral, this electricity must come from non-emitting sources. In 2022, 38% of U.S. electricity was generated from natural gas, and 22% from coal. In the European Union during 2021, 19% of electrical power was generated from natural gas, 15% from coal, and 4% from other fossil fuels. Thus, at present, electrification must be considered only a partially carbon-neutral option. However, most if not all electric power can theoretically be made carbon-free in conjunction with various form of grid-side energy storage.

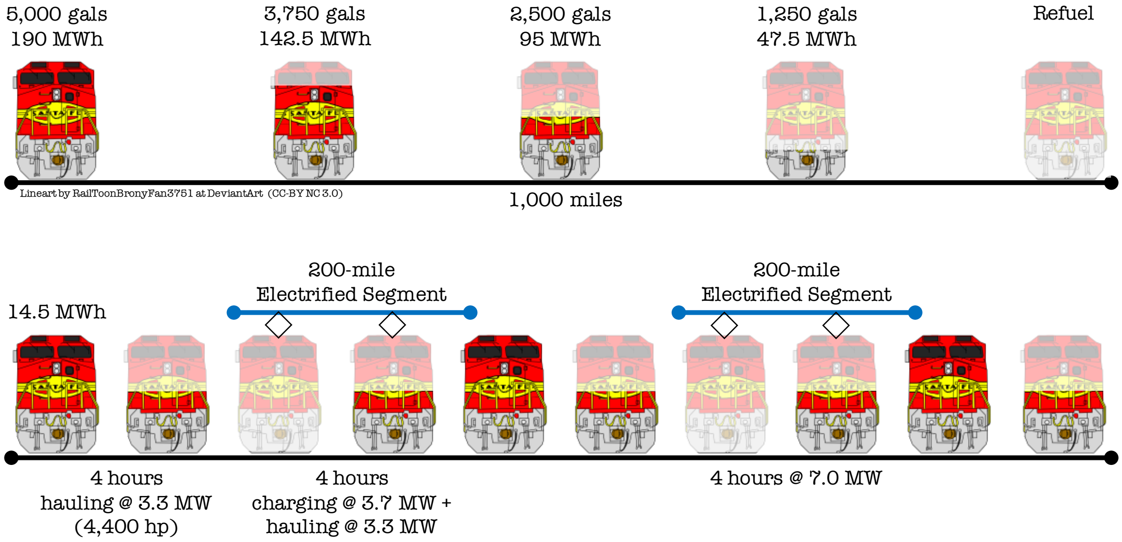
The biggest challenge facing carbon-neutral electricity generation is the fact that grid-scale energy storage solutions are needed to harvest carbon-free energy sources (e.g. wind, solar, tidal, hydro, etc.) where and when naturally occurring and available, and provide it to loads where and when required. The classic solution to this is the pump-storage generating station, but recent advances in battery technologies have made grid-scale battery storage a technically feasible proposition (if not necessarily economically viable at present, e.g. (*28*)). Progress is also being made in applying hydrogen fuel cell technology to energy storage. In our case study, we assume that carbon-neutral power can be purchased on the wholesale electricity market where and when required, in the quantities needed—subject to the usual load planning and peak smoothing constraints—and use BELs solely for hauling trains where there is no catenary wire.

MAKING INTERMITTENT ELECTRIFICATION WORKABLE

Partial electrification by combining traditional electric operations with battery-electric locomotives (BELs) have been previously discussed (*29, 18* pp. 168). Limited battery capacity and low-cost diesel fuel were long seen as impediments. But with high oil prices, the 2021 announcement of 7.2 MWh BELs (*4*), and the possibility of using cabless boosters (or battery tenders) to increase energy capacity and charging bandwidth, we investigated the feasibility of electrifying parts of the network while allowing BELs to run through non-electrified "gap" sections.

Such discontinuous electrification would electrify mainlines: (a) in the highest traffic density areas, (b) where electric power is inexpensive and plentiful, and (c) in strategically placed "charging islands" to reduce "gap" sections to manageable lengths. Charging islands can be located near existing power transmission infrastructure. Gaps would occur where the overhead catenary system (OCS) is hardest to install or maintain, or where insufficient transmission or generation capacity exist.

These gaps must be long enough to produce meaningful infrastructure savings to offset the incremental costs of BELs, and they must fully recharge within islands substantially shorter than the entire route. This example aims for ~200-mile-long islands, with a 50% mark-to-space ratio goal (i.e., on/off ratio or duty cycle) between electrified sections and gaps. This would require BELs with a 200-mile range in normal freight service. Figure 5 illustrates conceptually the difference between current diesel operation and BELs.



Lineart by RailToonBronyFan3751 at DeviantArt (CC-BY NC 3.0)

Figure 5. Concept of Intermittent Electrification with 200-Mile Long Charging Islands and 50% Mark-to-Space Ratio.

Estimating BEL Range via Comparison to Diesel-Electrics

Typically, North American freight diesels carry 5,000 gallons of fuel and run ~1,000 miles between refueling. Diesel's energy density is ~36 megajoules (MJ) per liter, or 37.9 kilowatt-hours (kWh) per U.S. gallon. A full tank therefore contains about 190 megawatt-hours (MWh) of energy. However, diesels are on average about 40% efficient (comparable with typical thermal generating stations), leaving only ~75.7 MWh available at the drawbar. Energy requirements in "average" freight service are therefore around 75.7 kWh per mile.

How many miles can BELs travel with these energy requirements? The 7.2 MWh is delivered to the railhead with around 95% efficiency, leaving 6.8 MWh for traction. However, BELs store some energy now lost through rheostatic braking on diesel-electrics. If 50% of this energy is recaptured (consistent with 30% claimed fuel savings when operated in tandem with diesel-electrics), the 6.8 MWh "virgin" energy plus 3.4 MWh of "recycled" energy produces total outputs of 10.3 MWh before batteries are exhausted, or a 135-mile range at 75.7 kWh/mile.

Can this be extended to a more useful 200+ miles? Attaching a cabless booster containing a further 7.2 MWh would extend the estimated range to 270 miles. Even with the additional weight, this is still comfortably above the target 200-mile range. The 14.5 MWh available from a two-segment locomotive (*23*) is an immense amount of energy, and with intermittent electrification, gives diesels serious competition.

Although these range estimates remain to be proven, a study from a mainline pilot program in California came to broadly consistent conclusions (*30*), predicting that 7,500-ton trains with 14-MWh batteries would have a 150-mile range, implying energy consumption of 93.3 kWh/mile.

Estimating Required Lengths of Charging Islands

North American freight trains average about 20-25 mph. However, this range conceals great variation because of network fluidity and other operating issues. If congestion is low, freights can average 40 mph, taking about five hours to travel 200 miles. Presently, BELs are advertised as achieving full charge after four hours on high-voltage catenary (*4*). This suggests in most cases, BELs can charge fully at service speeds through 200-mile-long charging islands.

Battery Technology Assumptions

Current grid-scale batteries, and batteries for electric cars and aviation applications are typically based on Li-Ion or Ni-Metal-Hydride battery chemistry—similar to batteries used in laptop computers—although there is no shortage of other contenders (e.g., (*31*)). Some creative solutions have been proposed for railroad applications (*32*), indeed a hydrogen fuel cell stack could itself be considered a form of battery. Current grid-scale batteries typically have a C/4 charging rate (*33*). We therefore assumed that whatever the battery chemistry, batteries can be designed to meet those charging rate, capacity, weight, and volume constraints. Certainly, other studies (*30*) have found these generic specifications are feasible within the dimensions and weight limits of railway vehicles.

Estimating BEL Range by Train Performance Simulation

This "average" estimation approach by comparison with diesels leaves some uncertainty that BELs would be suitable for certain duty cycles over specific types of terrain. To show that BELs can handle most traffic types over all types of terrain, we performed Train Performance Calculations (TPC, Table 1) using industry standard formulas (*34,35*).

These estimates, although back-of-the-envelope by nature, show that energy demand per mile varies dramatically by terrain. But it typically averages out about 100 kWh/mile for 8,000-ton trains, consistent with estimates from other calculations above. Most energy is consumed by rolling resistance. Because what goes up must come down, terrain constrains operations only in that BELs must not run out of energy before cresting the summit (Figure 6(a-b)).

							Energy Requirement in Megajoules (MJ)							Megawatt-hours (MWh)			
Line Segment	**(A) MP Start**	**(B) MP End**	**(C) Dist. (Miles)**	**(D) Elev. Gain (ft)**	**(E) Elev. Loss (ft)**	**(F) Wt. Avg. Curve Deg.**	**(G) Lift**	**(H) Descend**	**(J) Rolling Resist.**	**(K) Curve Resist.**	**(L) Accel.**	**(M) Decel.**	**(N) Starting**	**(P) MWh Demand**	**(Q) MWh Recov-erable**	**(R) MWh Total**	**(S) MWh /Mile**
(1)	373.0	394.5	21.5	1,580	0	1.50	34,287	0	2,331	1,469	0	0	0	10.7	-0.2	10.5	0.488
(2)	373.0	394.5	21.5	1,580	0	1.50	34,287	0	2,331	1,469	287	0	2	10.8	-0.2	10.6	0.493
(3)	394.5	454.0	59.5	0	1,425	1.50	0	-30,923	10,217	4,065	860	0	0	4.1	-8.6	-3.8	-0.064
(4)	373.0	454.0	81.0	1,580	1,425	1.50	34,287	-30,923	13,910	5,534	860	0	0	14.8	-8.8	6.7	0.082
(5)	454.0	373.0	81.0	1,425	1,580	1.50	30,923	-34,287	12,365	5,534	591	0	0	13.3	-9.5	9.8	0.121
(6)	55.6	84.0	28.4	169	95	0.87	3,667	-2,062	4,877	1,124	1,021	0	0	2.7	-0.6	2.4	0.085
(7)	155.4	204.2	48.8	533	530	0.33	11,566	-11,501	13,159	734	1,434	0	0	7.1	-3.2	4.4	0.090
(8)	0.0	128.0	128.0	580	610	0.05	12,586	-13,237	31,346	292	9,783	-8,654	0	15.0	-6.1	9.9	0.077

Line Segments

(1) Sand Patch Grade, Westbound on East Slope (ES)
(2) Sand Patch Grade, WB on ES w/ Restart Mid-Grade
(3) Sand Patch Grade, Westbound on West Slope
(4) Sand Patch Grade, Westbound (Both Slopes)
(5) Sand Patch Grade, Eastbound (Both Slopes)
(6) Akron Mainline, New Castle Jct. PA to Niles OH
(7) Akron Mainline, Sterling OH to Willard OH
(8) Chicago East Subdivision, Willard OH to Garrett IN

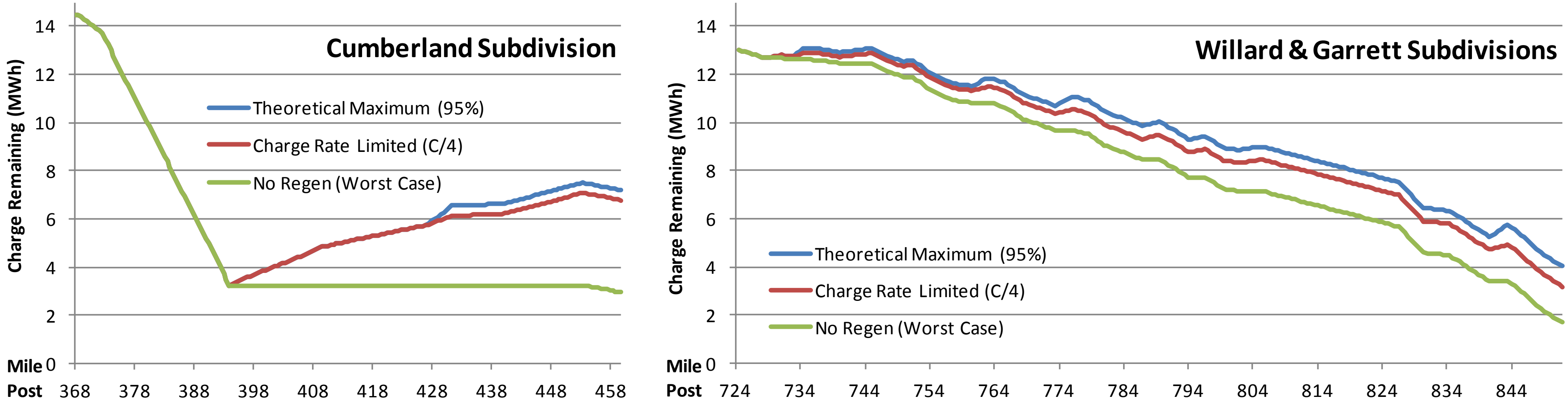
Assumptions:

- 8,000 ton train with 80 cars and 25 ton axle load.
- Average speed of 20 mph ascending/40 mph descending Sand Patch Grade EB, and 20/35 mph Westbound; 40 mph on Segment (6), and 60 mph on Segments (7) and (8).

Curvature data is from a Chessie System Track Chart of 03-22-1985. Some curvature values were estimated from Google Maps for track segments not covered by the track chart. Speed restriction data are from CSX System Employee Timetables (2005).

Column	**Explanation**
(D),(E)	Total gain/loss in elevation within the line segment, in feet.
(F)	Weighted average curvature in degrees. This is the sum of (degrees of curvature × curve length) for all curves, divided by the total line segment mileage. Useful in calculating curving resistance.
(G)	Energy expended in lifting the train through the elevation change. P.E. = mgh (g = 9.81 m/s/s)
(H)	Energy released in allowing the train to descend through the elevation loss.
(J)	Energy expended in overcoming rolling resistance. Modified Davis Formula (1970), see (*35*). The output is in lbf (Pound-Force) per U.S. ton, converted to energy using W.D. = force × distance.
(K)	Energy to overcome curving resistance. 0.8 lbf per trailing ton per degree of curvature (*34*).
(L)	Energy expended in accelerating train to desired speed, including for observance of any speed restrictions. K.E. = $\frac{1}{2}mv^2$, energy required in accelerating is the difference in K.E. between current speed and target speed. Segment (7) included seven 40 mph permanent speed restrictions (PSR) and one 50 mph PSR with a general line speed of 60 mph. Segment (3) and (4) accounts for acceleration at the summit from 20 mph to 40 mph.
(M)	Energy generated in braking train to desired speed, assuming 100% regenerative braking.
(N)	Energy expended in starting the train from a standing stop. 5 lbf per training ton, moved one foot.
(P)	Total energy required to move the train through the line segment.
(Q)	Theoretical maximum energy potentially recoverable from regenerative braking.
(R)	Practical total net energy required to move train through the line segment after accounting for normal 95% regenerative braking efficiency, and maximum battery charging rate (linear) of C/4 (3.6MW).
(S)	Average energy consumption in MWh per mile travelled.

Table 1. Train Performance Computations for Selected Line Segments between Baltimore and Chicago.


(a) Projected Battery Charge Level Westbound Unelectrified from Cumberland, Md. to Connellsville, Penn. (Initial Charge = 100%)

(b) Projected Battery Charge Level Westbound Unelectrified from Willard, O. to Garrett, Ind. (Initial Charge = 90%)

(c) Grade Profile for Main Line from Chicago, Illinois to Baltimore, Maryland via Sand Patch, Pennsylvania

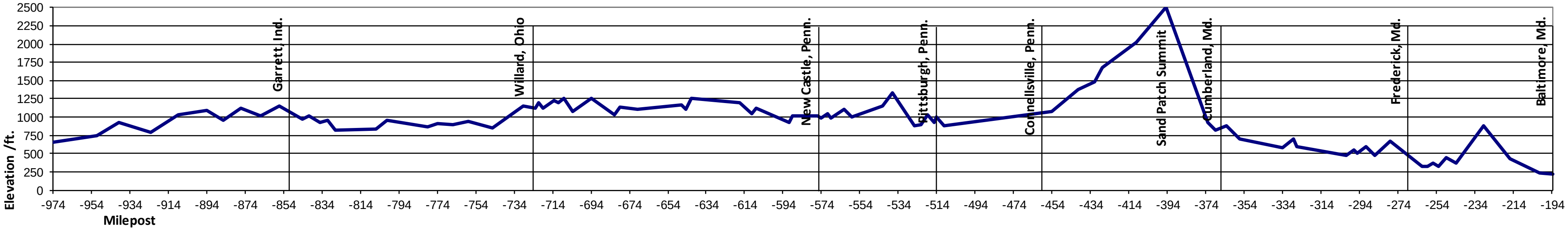


Figure 6. Train Performance Computation Results for 14.5-MWh BEL-Booster Combinations Hauling 8,000 Trailing Tons over Selected Line Segments

Early 20th century railroad electrification schemes focused on providing consistent power in mountainous terrain to reduce or eliminate pusher locomotive requirements (and steam locomotive firemen's workloads). In a BEL world, intermittent electrifications should be planned on a network-wide basis while ensuring each locomotive has sufficient energy reserves to crest the summit. This might concentrate electric supply needs in foothill areas, where electrification is cheaper to install than building OCS through rugged terrain (*36*).

Sand Patch Grade in southwestern Pennsylvania's Laurel Highlands (Figure 6(c) and 7), is one of the longest and highest such east of the Mississippi River. Its energy requirement is only 10.7 MWh, well within the capability of a 14.5 MWh locomotive-booster combination (Table 1). However, descending very steep grades (like Sand Patch eastbound) generates energy faster than onboard batteries can recharge at 3.6 MW, which leads to incomplete energy recapture, reducing the travel range for the remainder of that move.

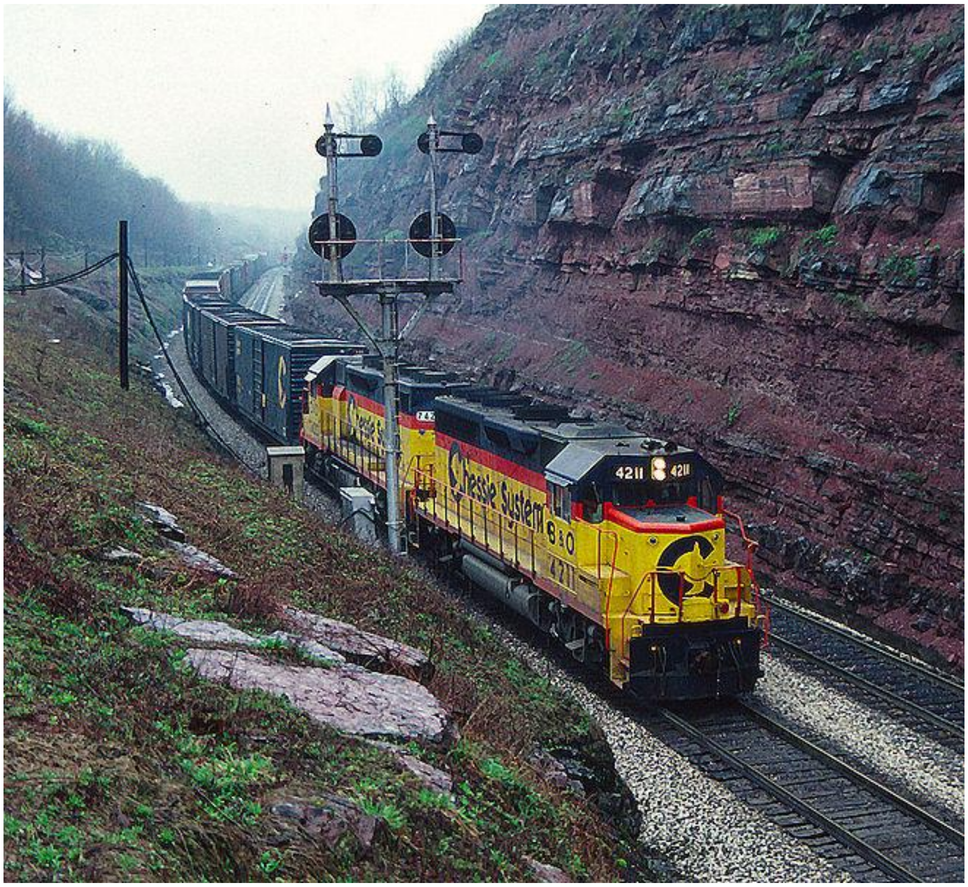


Figure 7. Eastbound Chessie System freight train about to enter former tunnel on Sand Patch grade, 1987; Bruce Fingerhood photo (CC-BY 2.0). (https://commons.wikimedia.org/wiki/File:West_portal_sand_patch.jpg)

To the extent that railroads with steep downhill grades generate more power than onboard batteries can absorb, they can be used as sources of electric power generation. As with hydroelectric generating stations, they produce electricity through gravity. Where sufficient train densities exist, such locations could be connected to the grid via catenary wires, to allow energy to be captured and utilized elsewhere.

Significantly, and contrary to conventional wisdom, this result indicates that gently undulating terrain in much of the eastern United States or the Great Plains would have virtually no impact on the operating range of BELs. However, in rugged terrain where gradients exceed about 0.4% (1-in-250), the energy generated by descending trains could exceed battery re-charging bandwidth, resulting in lost energy through rheostatic braking and therefore in reduced BEL range. This issue can be addressed at an operational level by adding extra BELs to the consist within that "mountain district", or by providing additional segments of electric catenary where needed, either to provide supplementary power uphill or to absorb excess power downhill.

Motive Power Assignment

Assuming 200-mile gaps between 200-mile-long electric districts, motive power desks would need to develop locomotive assignment rules, much as fleet offices keep track of locomotive mileages, diesel fuel levels, and minimum horsepower per ton today. Based on a 12.5 watt-hour (Wh)/ton-mile consumption rate, plus a 25% "protect" factor to account for unscheduled stops, and 5% efficiency losses, each 2,000 tons would require just under 7.2 MWh of battery capacity.

Typical 8,000-ton trains might operate with two 4,400 hp units, each carrying 5,000 gallons of diesel fuel. This train would need four 7.2 MWh units (or two 14.5 MWh, dual-segment BELs). The 200-mile mark-to-space (i.e., on-off) ratio for intermittent electrification is thus within reach, assuming typical power desk practices, and that the 14.5-MWh combination is proven in service.

When EMD FT diesels were built between 1939 and 1945, they had 1,350 hp of installed power. Then, the most powerful steam locomotives developed 4,000-6,000 hp, thus diesel consists of four units in A-B-B-A configuration (Figure 8) were often necessary to replace a single steam locomotive. Multiple units were necessary for power reasons in the steam-diesel transition and will be needed for range reasons in diesel-BEL substitution. Higher future cell energy densities will doubtless improve this.

Railroads carrying very heavy commodities such as aggregates, ore, lumber, or paper, or with specific operating philosophies preferring very long trains, require operation of land barges weighing up to 15,000-tons. Movement bureaux would obviously need to assign additional power to these specific trains, potentially requiring up to eight 7.2 MWh units to make the 200-mile range. Railroads may need to adjust their operating strategies, as discussed below.

Locomotive Design Assumptions

Implied in these calculations are certain design assumptions about the BELs. The available information suggests that 7.2 MWh can be carried on two standard three-axle trucks, but based on current battery technology, 14.5 MWh would require a two-segment design for space or weight reasons, or both. This assumption suggests various form factors may be possible to achieve the desired 200-mile range, as shown in Table 2.

Figure 8. Great Northern Railway EMD FT Locomotives, 1943; courtesy of the Minneapolis Tribune. (https://commons.wikimedia.org/wiki/File:Great_Northern_EMD_FT_locomotive_1943.jpg)

Name	Description	Frames	Cabs	Panto-graphs	Trans-formers	Trucks	Traction Motors
Articulated	Single locomotive with two articulated parts	2	1	1	1	3× 3-axles	9
Two-Segment	One locomotive with a cabless booster, similar to EMD FT-A and FT-B	2	1	2	2	4× 3-axles	12
Two Separate Locomotives	Two 7.2 MWh locomotives can be utilized separately	2	2	2	2	4× 3-axles	12
Extra Long Frame	Single locomotive, like EMD DDA40X	1	1	1	1	2× 4-axles	8
Permanently Coupled	Two locomotives permanently joined	2	1	1	1	4× 3-axles	12
Double-Ended	Single articulated locomotive with two cabs, like an articulated version of EMD ML2	2	2	1	1	3× 3-axles	9

Table 2. Possible Form Factors for 14.5 MWh Freight Service BELs.

The precise form factor that balances operating convenience and cost is a matter of electrical and mechanical engineering and is outside the scope of this paper. The detailed design of locomotives is unimportant to this research; the point is that 14.5 MWh is sufficient to power an 8,000-ton train for more than 200 miles under typical operating conditions.

Estimating Required Substation Ratings

Based on parameters sketched out for the 200-mile charging islands, we might expect that where the traffic is moderately busy, on a multi-track mainline there might be eight trains per hour. Assuming industry standard 25kV electrification, each supply substation may cover about ~40 route-miles of territory, so five supply substations would be needed per charging island. At eight trains per hour, each train taking an hour to traverse the territory at 40 mph, all eight might be drawing power simultaneously within the segment. Assuming that each train carries on average 12,000 tons, or is equipped with six 7.2 MWh units that charge at C/4 rates (i.e., taking four hours to charge to 100% capacity), the total power draw due to battery charging alone is 10.8 MW per train, or 86 MW total. If we assume two of these eight trains are actively accelerating, and another four are maintaining speed at half power, the power draw due to real-time energy use is another 40 MW. This potentially calls for a 125 MW substation rating, which is actually only slightly larger than supply substations (Figure 9) currently in use for heavy duty 25 kV passenger railway electrification, which are in the 50 MW to 80 MW range.

Figure 9. Passenger Railway Supply Substation on the Northeast Corridor.

Although BEL technology scales well, in that a heavier train can always be hauled by adding extra locomotives in the consist which results in negligible changes to the locomotives' (thus the train's) total mileage range between need to recharge, supply substations do not necessarily scale well, as it becomes very expensive to provide for that peak power load. For that reason, when railroads are transitioning to electrified operations (with or without BELs), it may be necessary to make operating plan changes and/or invest in energy management systems as to spread out or limit the load that is drawn from the power grid at any given moment. Diesel electrics get around this problem by essentially being mobile power plants that are operated in parallel as needed.

Based on typical carrying capacities of high-voltage distribution circuits, about two-thirds of the capacity of a three-phase 132 kV circuit would be needed to fully supply one such 125 MW substation. With five ±25kV supply substations within a 200-mile-long charging island, it should be understood that the substations would most likely need to be connected to the 275 kV or 345 kV supergrid, requiring substantial coordinated planning with electric utilities, and possibly dedicated generation capacity. The only other alternative would be to limit the average number of trains or average tonnage that is permissible over that segment. The power requirements of charging multiple units in parallel will have implications for substation ratings and cost. This would have significant implications on the optimal train lengths to be carried on an electrified network compared to a diesel one, possibly requiring shorter, more frequent freight trains.

Current and Voltage Choice

Electrifying railroads on a continent-wide scale involves some issues that may not arise with smaller projects. Given the different geographies where electrification would occur, no single voltage will suit all needs. 25kV 60Hz alternating current (AC) is the industry default standard, but 50kV AC may be more suitable for rural areas with sparse supply. Locomotives needing to operate on the Northeast Corridor will need 11kV 25Hz capability. Different transmission and feeder architectures may also be required, with consequences in resiliency, signal interference, and maximum substation spacing, as discussed in prior studies (*37* pp. 6.1-6.5).

The 7.2 MWh BEL, if allowed to accelerate whilst charging, can draw up to 4.5 MW of power, which lower electrification voltages would have difficulty supplying. At 750V DC, this translates to 6,000 Amperes (A), or 1,200~1,500A per shoe, which is near the upper limit of what is reasonable. Assuming that railroads would occasionally need to operate 15,000-ton trains, eight such BELs would be required to achieve the 200-mile range, and the total power draw would be 36 MW. 750V or 1.5 kV DC substations are typically limited to about 10~15 MW, which means medium-voltage DC electrification is not a realistic proposition for modern BEL-enabled freight electrification. Even if the substations could be uprated, the sheer magnitude of negative return current would be prohibitive.

Higher Voltage for Heavy-Haul or Rural Applications

At ±25kV AC electrification, this translates to 180A at the pantograph (and half of that in the rails for traction return), which is quite reasonable. With eight units online simultaneously, the potential traction return current is 720A, which is still within the acceptable range. However, some railroads that have considered electrification found 25kV AC restrictive for their requirements. When power of 10,000hp and upwards is necessary, even with 25kV, substations might have to be located comparatively close together, which is neither desirable nor even possible in some locales. 50kV offers much greater flexibility, providing there are not too many low bridges (*38* p, 202). If heavy haul operations are anticipated with the routine use of six- or eight-BEL consists, then ±50kV AC electrification could be considered, to reduce the current required (and secondarily to allow potentially higher substation spacing, although, at high power consumption it would not be electrically efficient to push substation spacing close to its practical limits.)

Illinois Central Gulf considered 50kV between Chicago and New Orleans. With their power requirements, the substations would be located at 30-40 mile intervals. Over much of the route the electric utilities have adjacent power lines, thereby eliminating the need for feeders to be erected specifically for the railway's use (*39* p. 199). Similarly, British Columbia Railway chose 50kV in the Canadian Rockies for electrical efficiency (*9* p. 14), allowing it to power the entire installation with just one substation.

NETWORK PERFORMANCE ANALYSIS

We used a simple project evaluation model to examine a hypothetical rail freight network, including practical issues facing Class One railroads, such as interline traffic, varying terrain, etc.

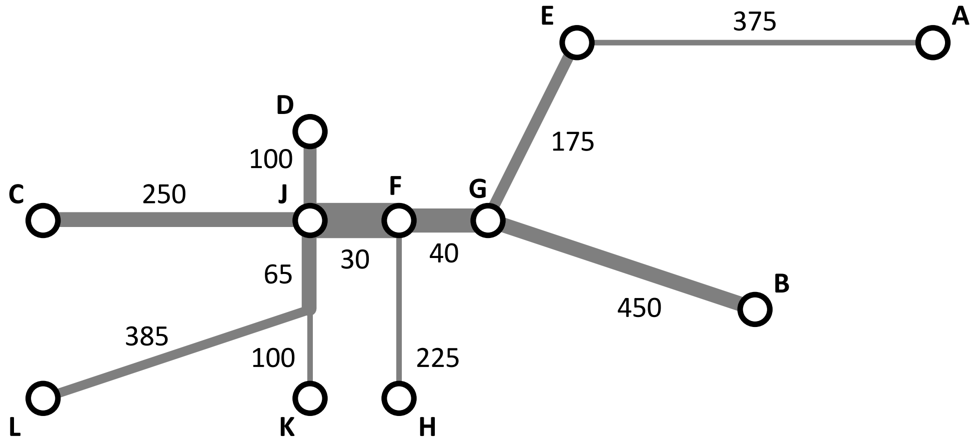
Although recent literature argues that converting diesels to battery locomotives without electrification would save money based on off-peak recharging on the wholesale electricity spot market (*30*), industry reception has been unenthusiastic (*40*). When externality costs are removed, even that study showed $5.85 million in diesel locomotive costs versus $6.47 million for BELs. Yet others argue that the underlying business cases may be sound in certain corridors, warranting further investigation (*41*). Because of sunk investments in diesel locomotives, shops, and workforce skills, change will occur incrementally. We accommodate this incremental approach and show how intermittent electrification makes good use of BELs' practical advantages.

Hypothetical Electrification Case Study

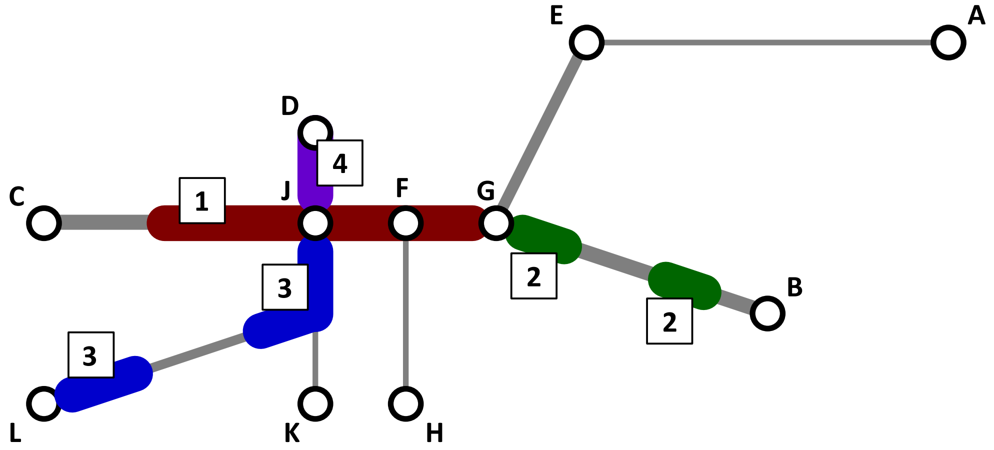
The case study network (Figure 10(a)) is a hypothetical east-west Class I railroad with 2,195 route miles, whose predominant traffic patterns form an approximate "X", but also with significant north-south flows that do not pass through the middle of the "X". This railroad has 60 daily train starts between important origins and destinations (Table 3(a)), with up to four pairs of daily departures in the busiest corridors, and one daily departure in quieter service lanes. Two strategies are examined: intermittent (discontinuous) electrification (Figure 10(b)) and contiguous electrification (Figure 10(c)). Both strategies cost 50% less than full electrification when completely built out.

Trains of 8,000 tons are assumed. These can be reliably handled by two diesels, or two 14.5 MWh combo-BELs. No attempts were made to model this railroad for specific commodities. Local pick-ups and deliveries were not considered.

(a) Network Map with Nodes and Mileages



(b) Four Phases of Intermittent Electrification



(c) Three Phases of Contiguous Electrification

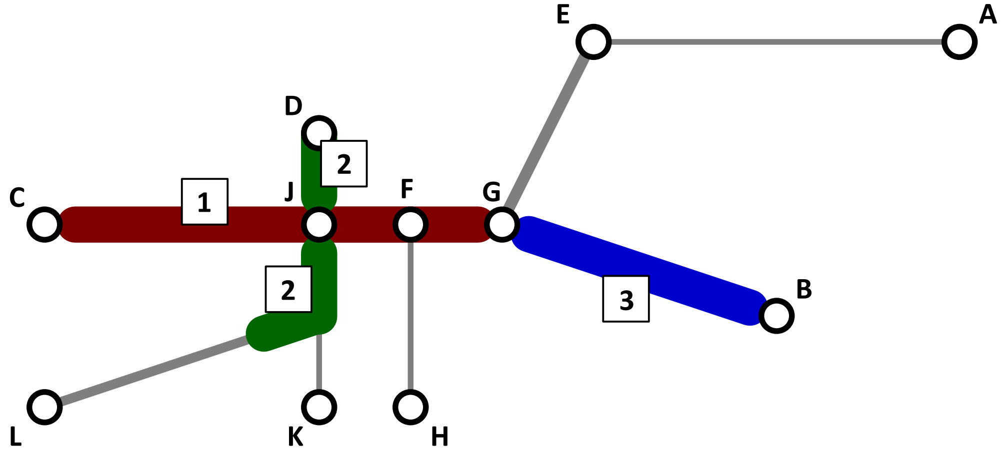


Figure 10. Maps for Hypothetical North American Class I Electrification Case Study.

(a) Traffic Dept. Assumptions (Daily Trains)

		Origin								
		A	**B**	**C**	**D**	**E**	**H**	**K**	**L**	**Ttl**
Destination	**A**		0	2	1	0	1	0	1	**5**
	B	0		4	2	0	0	2	4	**12**
	C	2	4		2	2	2	0	0	**12**
	D	1	2	2		1	1	2	1	**10**
	E	0	0	2	1		0	0	1	**4**
	H	1	0	2	1	0		0	1	**5**
	K	0	2	0	2	0	0		0	**4**
	L	1	4	0	1	1	1	0		**8**
	Ttl	**5**	**12**	**12**	**10**	**4**	**5**	**4**	**8**	

(c) Mechanical Department Assumptions

	Locomotive Type		
	Battery Electric	**Straight Electric**	**Diesel Electric**
Capability detail	Catenary operation and recharging capability, 14.5 MWh including integral battery tender	Medium horsepower freight type unit, 5,500 peak hp, 75 mph speed limit	High-horsepower AC traction unit, 4,400 hp
Purchase cost (per unit)	$10 million	$6 million	$5 million
Shop margin for maintenance	20%	10%	15%

(b) Engineering Department Assumptions

			Equipment Counts					**Infrastructure Costs ($ millions)**				
(A) Line	**(B) District**	**(C) Character**	**(D) Route Miles**	**(E) # CPs**	**(F) # // Subs**	**(G) # Supply Subs**	**(H) # Radio Bases**	**(J) $ Cat.**	**(K) $ Elec. CP**	**(L) $ // Stn**	**(M) $ Supply**	**(N) $ Total**
CJ	CJ-1	Metropolitan	55	6	6	1	6	$550	$60	$150	$75	$835
CJ	CJ-2	Rural	135	7	14	3	14	$540	$28	$140	$90	$798
CJ	CJFG-1	Rural	60	3	6	2	6	$240	$12	$60	$60	$372
JF	CJFG-2	Industrial	30	3	3	1	3	$180	$18	$45	$45	$288
FG	CJFG-3	Industrial	40	4	4	1	4	$240	$24	$60	$45	$369
DJ	DJ-1	Industrial	100	5	10	3	10	$600	$30	$150	$135	$915
LJ	LJ-1	Rural	175	9	12	3	18	$700	$36	$120	$90	$946
LJ	LJ-2	Rural**	150	8	10	3	15	$750	$40	$125	$113	$1,028
LJ	LKJ-1	Rural	60	3	4	1	6	$240	$12	$40	$30	$322
LJ	LKJ-2	Rural	65	4	5	1	7	$260	$16	$50	$30	$356
KJ	LKJ-3	Rural	100	4	5	2	10	$400	$56	$50	$60	$566
GE	GE-1	Lakeside	175	6	18	4	18	$875	$30	$225	$150	$1,280
EA	EA-1	Industrial	200	10	20	5	20	$1,200	$60	$300	$225	$1,785
EA	EA-2	Industrial	175	6	12	3	18	$1,050	$36	$180	$135	$1,401
GB	GB-1	Rural	170	9	17	4	17	$680	$36	$170	$120	$1,006
GB	GB-2	Mountainous	150	8	15	4	15	$1,200	$64	$300	$240	$1,804
GB	GB-3	Exurban	90	5	9	2	9	$540	$30	$135	$90	$795
GB	GB-4	Metropolitan	40	4	4	1	4	$400	$40	$100	$75	$615
FH	FH-1	Rural	225	8	12	4	23	$900	$120	$120	$120	$1,260
Total	**19**		**2,195**	**112**	**186**	**48**	**223**	**$11,545**	**$748**	**$2,520**	**$1,928**	**$16,741**

Notes: ** This District contains a short Metropolitan segment.
Column (E) = Count of Interlockings (CPs); (F) = Count of Paralleling Substations; (G) Count of Supply Substations; (H) Count of Radio Bases; (J) Electric catenary construction costs; (K) Special catenary work at Interlockings. Costs are factored based on Column (C), includes all Civil/Right-of-Way work, and excludes land acquisition/cost of leasing staging areas. Columns (D) through (H) used in estimation of Maintenance of Way costs.

Other Key Assumptions: Electrification with ±25kV 60Hz architecture. Diesel price = $6.00 per gallon; Electricity price = $110 per MWh. Fringe & benefits overhead = 80%; Pay Rates: Linemen, Signalmen, Welder $35/hr; Trackman $25/hr; Dispatcher/Supervisor $40/hr; Train & Engine Crews = $375 daily; Crew District Size = 300 miles; Crew Overhead Ratio (Absence/Vacation/Training) = 30%; Crew Size = 2; Discount Rate = 5%. All costs are strategic estimates, actual costs will depend on designs, labor agreements, and other factors.

Table 3. Assumptions for Hypothetical North American Class I Electrification Case Study

On the engineering side, 2,195 route-miles were divided into 15 districts, and each was assigned cost factors based on terrain and proximity to large metropolitan areas (Table 3(b)). Electrification unit cost assumptions are broadly consistent with currently available industry data (*42*,*43*). Table 3(c) shows assumptions about locomotive price and availability.

Maintenance-of-way and train crew costing follows established zero-based methodology (*44*) with assumptions about infrastructure (substation counts, interlockings, etc.), labour rates, gang productivity, and crewing methods consistent with typical Class I practice. Note that electrification has an effect on Signal, Communications, and Track & Structures Maintenance of Way costs because additional infrastructure is needed to support electrification, as well as the increased complexity in coordinating work due to the need for power isolations (see e.g. (*45*)), impedance bond disconnections, and working within restricted overhead clearances on tasks such as rail replacement and track production (see e.g. (*46*)).

System costs were allocated proportionately. We were unable to estimate locomotive maintenance costs, as BEL maintenance costs are necessarily speculative. Batteries will eventually decline in usable capacity and must be replaced. BEL units are likely to need five-yearly battery overhauls, much as diesels need prime mover rehabilitation (although on somewhat longer intervals). One significant unknown here is the costs and environmental impacts of battery fabrication and disposal, and the consequences of mining the necessary semi-precious metals.

We outlined multiple stages for project implementation for both intermittent electrification (Figure 10(b)) and contiguous electrification (Figure 10(c)). For each stage, we estimated performance metrics, including electrically powered train-miles, daily engine changes required, investment cost-effectiveness, and transportation, maintenance, and fuel cost impacts.

Findings

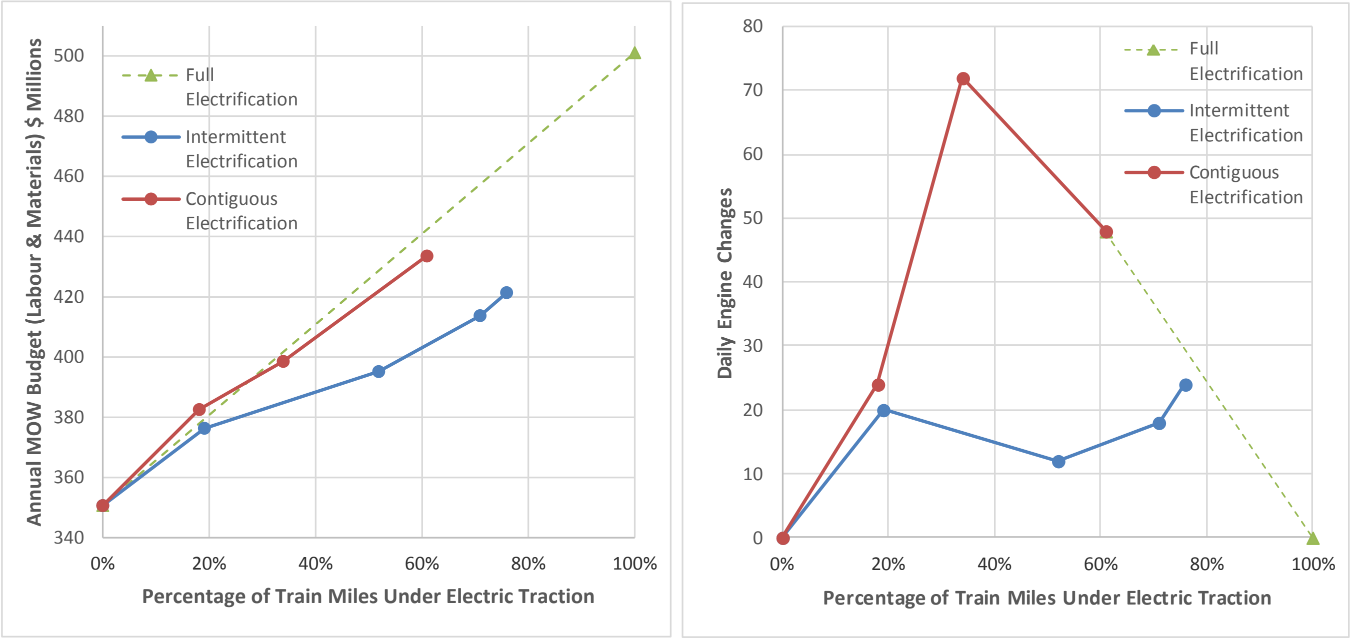
This case study clearly shows that substantial investment is needed for any rail network electrification. It is not clear at all where the financial savings would come from to repay that investment, as electrified railroads are more expensive to operate and maintain than non-electrified ones (Figure 11(a)), due to their increased fixed plant, higher complexity, and interaction between different maintenance groups.

Under current conditions, the anticipated energy cost savings do not offset the investment and maintenance costs of electrification in any scenario. Table 4 shows the shortfall. However, obviously these costs could easily change based on relative prices of diesel versus electric power and are sensitive to electrification cost estimates.

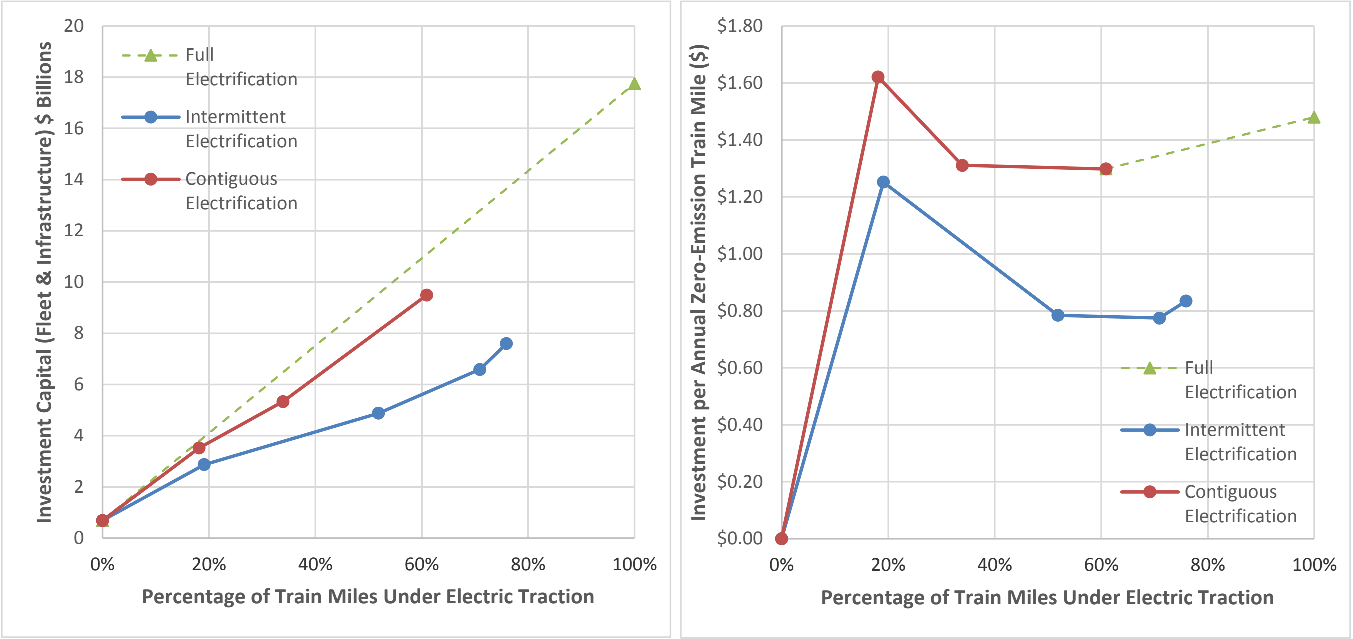
So long as less than 100% of the rail network is electrified, any electrification imposes an efficiency penalty, as locomotive changes tend to reduce fleet utilization, require larger fleets, and increase service disruption risks (Figure 11(b)). All these reasons explain the industry's current reluctance to embrace electrification.

Scenario	**Base**	**Intermittent**		**Electrification**		**Continuous**		**Electrification**	
Performance Measure	**Case**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 1**	**Phase 2**	**Phase 3**	**Full**
Daily Train Miles:									
Electrified	0	5,920	13,280	18,680	21,280	7,240	13,560	24,360	39,990
Battery	0	1,720	7,460	9,680	9,080	0	0	0	0
Diesel	39,990	32,350	19,250	11,630	9,630	32,750	26,430	15,630	0
Total	**39,990**	**39,990**	**39,990**	**39,990**	**39,990**	**39,990**	**39,990**	**39,990**	**39,990**
(Diesel Operated Under the Wires)	0	1,880	760	680	80	1,880	80	80	0
Percentage of Train Miles:									
Electrified	0%	15%	33%	47%	53%	18%	34%	61%	100%
Battery	0%	4%	19%	24%	23%	0%	0%	0%	0%
Diesel	100%	81%	48%	29%	24%	82%	66%	39%	0%
(% Electric Traction)	0%	19%	52%	71%	76%	18%	34%	61%	100%
Active Fleet Requirements:									
Battery Electric	0	46	82	104	114	0	0	0	0
Straight Electric	0	0	0	0	10	40	98	105	132
Diesel	138	117	87	59	46	124	98	77	0
Total	**138**	**163**	**169**	**163**	**170**	**164**	**196**	**182**	**132**
Daily Engine Changes	0	20	12	18	24	24	72	48	0
Route Miles:									
Electrified	0	265	525	825	925	320	545	995	2,195
Not Electrified	2,195	1,930	1,670	1,370	1,270	1,875	1,650	1,200	0
Total	**2,195**	**2,195**	**2,195**	**2,195**	**2,195**	**2,195**	**2,195**	**2,195**	**2,195**
(% Electrified)	0%	12%	24%	38%	42%	15%	25%	45%	100%
Investment Cost Estimate ($bn):	.								
Electrification Infrastructure	$0.00	$1.83	$3.63	$5.25	$6.17	$2.66	$4.26	$8.48	$16.74
Rolling Stock:									
Battery Electric	$0.00	$0.46	$0.82	$1.04	$1.14	$0.00	$0.00	$0.00	$0.00
Straight Electric	$0.00	$0.00	$0.00	$0.00	$0.06	$0.24	$0.59	$0.63	$1.01
Diesel	$0.69	$0.59	$0.44	$0.29	$0.23	$0.62	$0.49	$0.39	$0.00
Total Locomotives	$0.69	$1.04	$1.25	$1.34	$1.43	$0.86	$1.08	$1.01	$1.01
Total Investment	**$0.69**	**$2.87**	**$4.88**	**$6.59**	**$7.60**	**$3.52**	**$5.33**	**$9.49**	**$17.75**
Cost Effectiveness:									
$ Investment per Annual Zero-Emission Train Mile	**N/A**	**$1.25**	**$0.78**	**$0.77**	**$0.83**	**$1.62**	**$1.31**	**$1.30**	**$1.48**
Annual Operating Costs ($m/annum):									
Maintenance of Way (Labor+Mat.):									
Signal Dept.	*$142.6*	*$147.1*	*$149.3*	*$151.7*	*$152.6*	*$148.2*	*$150.6*	*$155.3*	*$161.6*
Communications Dept.	*$46.5*	*$46.8*	*$46.9*	*$47.1*	*$47.1*	*$46.8*	*$46.8*	*$47.2*	*$48.2*
Electric Traction Dept.	*$0.0*	*$18.3*	*$32.9*	*$46.6*	*$52.3*	*$22.4*	*$34.2*	*$60.4*	*$112.5*
Track & Structures Dept.	*$161.6*	*$164.2*	*$166.0*	*$168.3*	*$169.3*	*$165.2*	*$167.0*	*$170.6*	*$178.8*
Total Maintenance of Way	$350.7	$376.3	$395.2	$413.7	$421.4	$382.6	$398.6	$433.6	$501.1
Train & Engine (Road Crews)	$66.4	$71.1	$69.3	$70.7	$72.1	$72.1	$83.4	$77.8	$66.4
Fuel:									
Electric Power ($0.11/kWh)	*$0.0*	*$21.2*	*$57.6*	*$78.8*	*$85.0*	*$25.1*	*$47.1*	*$84.6*	*$138.9*
Diesel ($6.00/gal)	*$569.8*	*$460.9*	*$274.3*	*$165.7*	*$137.2*	*$466.6*	*$376.6*	*$222.7*	*$0.0*
Total Energy Cost	$569.8	$482.2	$331.9	$244.5	$222.2	$491.8	$423.7	$307.3	$138.9
Affected Operating Expenses	**$986.9**	**$929.6**	**$796.4**	**$728.9**	**$715.7**	**$946.4**	**$905.7**	**$818.6**	**$706.5**
Annual Savings versus Base Case	$0.0	-$57.3	-$190.5	-$258.0	-$271.2	-$40.4	-$81.2	-$168.2	-$280.4
Net Present Value ($bn at 5%)	$0.0	-$1.1	-$3.8	-$5.2	-$5.4	-$0.8	-$1.6	-$3.4	-$5.6
Shortfall vs. Base Case ($bn)	**N/A**	**$1.7**	**$1.1**	**$1.4**	**$2.2**	**$2.7**	**$3.7**	**$6.1**	**$12.1**

Table 4. Hypothetical North American Class I Case Study: Network Performance Metrics


(a) Relationship to Maintenance of Way Budget

(b) Relationship to Operational Complexity


(c) Relationship to Investment Capital

(d) Relationship to Investment Cost Effectiveness

Figure 11. Hypothetical North American Class I Electrification Case Study: Findings

However, if public policy moves railroads into a post-diesel world, the intermittent electrification approach phases out diesels quicker and at lower cost (Figure 11(c)). This produces more train-miles under electric traction and does so sooner than a contiguous “electric district” approach. It has the additional advantage of substantially reducing operating complexity by reducing engine changes.

The fleet impacts have a more complex, nonlinear relationship with electrification levels and strategies, as do diesel-train-miles operated “under the wires”. But, if we examine the investment cost effectiveness measure of dollar investment per annual zero-emission train mile, the intermittent electrification strategy outperforms a contiguous electric district in all project stages (Figure 11(d)), being usually over 60% more cost effective. Even a contiguous district can still be 20% more cost-effective than full mainline electrification.

Life Cycle Cost Analysis

Figure 12 shows the total life cycle cost of for all scenarios outlined in Table 4. For all electrification scenarios, compared to a base scenario of diesel-only operations, the Net Present Value (NPV) of capital, operating, and maintenance costs are always higher in the electrification scenario under the current assumptions of energy costs. This explains why there has been little interest in electrification from the for-profit U.S. railroad industry.

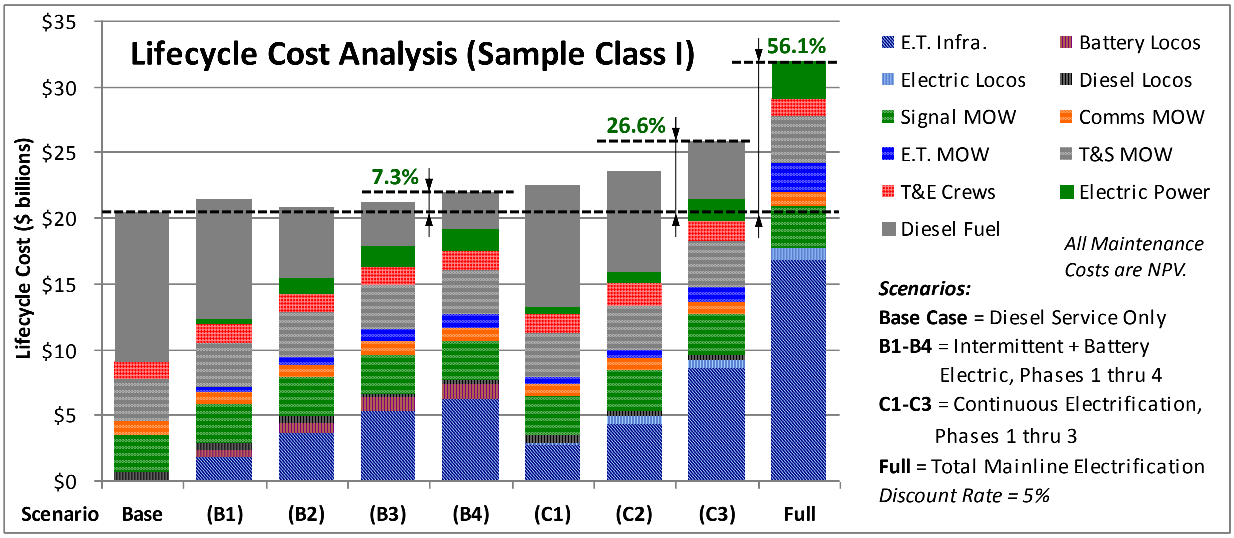


Figure 12. Life Cycle Cost Analysis for a Hypothetical North American Class I Railway

The interesting finding here is that even with 76% of train-miles operated under electric traction in Scenario (B4) of intermittent electrification, the increase in lifecycle costs is only a modest 7.3%. However, the corresponding Scenario (C3) of continuous electrification delivers only 61% of electric train-miles for a cost increase of 26.6%, while the Full Electrification Scenario results in a lifecycle cost increase of 56.1%. This further underscores the cost-effectiveness of BEL-enabled freight railroad electrification.

SHORT TERM ACTIONS TOWARDS AN ELECTRIC FUTURE

North American freight railroads have challenging operating environments with no recent electrification experience. To show Class I railroads that electrification is a mature technology, multiple areas need attention.

Proving High-Capacity BELs

Although 7.2-MWh BELs have been announced, no prototypes exist as of this writing. 14.5 MWh combo-BELs are still at the concept stage. 2.4-MWh BELs have proved out under service conditions (*30*). This development process should continue for high-capacity BELs. This work would include identifying battery chemistry alternatives and validating design assumptions, including those used in the present study. Perhaps a grant request for design, development, and construction of a small fleet of BELs using FRA Consolidated Rail Infrastructure and Safety Improvements (CRISI) Program funding could be considered.

Demonstration Service on Existing Infrastructure

For a demonstration in freight service once high-capacity BELs are available, the industry could consider one route from Harrisburg, Pennsylvania east to Perryville, Maryland, then north or south on the Northeast Corridor. This service is currently operated with diesel-electric locomotives with trains of less than 8,000 gross tons, with significant train-miles operated “under the wires”. Substituting BELs for diesel locomotives on such a service would initially take care of concerns regarding signal system and electric traction infrastructure compatibility, as the signal system and PTC are already in place.

Clearances for Double-Stack Container Trains

Electrification must accommodate American Association of Railroads (AAR) Plate H clearances, which apply to the tallest freights, double-stack container trains. India’s dedicated freight corridors (Figure 14) accommodate double-stack container trains under electric catenary (*47*), but differences in well-car designs, dynamic envelopes, wind parameters, and overpass/tunnel clearances require the technology to be proven locally.

Demonstration programs are needed on high-volume intermodal corridors to gain operating and maintenance experience. Pantograph sway under freight operating conditions, with resulting dewirement risks, should be addressed and average reliability estimated based on such factors as prevailing wind speed, catenary design, support structure spacing, wire composition, pantograph specifications, wave propagation, speed and number of locomotives, track curvature, etc. Maximum safe speeds should also be established for different track classes. Pantograph sway issues at Plate H wire height could make operation with OCS problematic at speeds over 100 mph (*48* pp. 2-3), potentially impacting nascent higher-speed passenger rail efforts.

Figure 14. On Indian Railways, the Western Railway operates this electrified double-stack container train from Palanpur to Botad in Gujarat, June 10, 2020; Piyush Goyal photo (Government of India Open Data License via http://indianrailways.gov.in/).

High and Wide Loads

North American railroads pride themselves in supporting out-of-gauge dimensional loads such as aircraft fuselages, electrical components, and defense logistics items directly between rail-connected sites (*49*). Any electrification plans must take these needs into account, so that the necessary clearance profiles are provided (*50*, p. 14). Non-electrified routes or tracks must be identified if OCS would restrict this very useful network capability. In areas with dense rail networks, a strategic set of lines could be designated for oversize loads. In some cases, additional-clearance OCS or parallel non-electrified tracks might be provided for high and wide loads.

Analysis of Service Strategies: Tonnage & Terrain

Due to the multiple-unit and remote-control capabilities of diesel-electric locomotives, and the substantial strength of AAR couplers, the train tonnage and horsepower required to move each train has grown virtually without limits over the past 30 years. This has led to increasing returns to scale within the industry, but the limits of AAR couplers have already been reached and that operational strategy may be approaching a point of diminishing returns, where the risk of derailments or other incidents may exceed the cost of operating smaller trains. The financially feasible or fiscally prudent limits to supply substations power ratings may impose further restrictions on maximum train sizes, or indeed reduce the optimal average train size. To allow BEL-enabled electrification to be adopted on an industry-wide basis, an analysis of service strategies would be necessary to understand how or whether the industry may benefit from operating smaller trains more frequently. An understanding of this fundamental issue may lead to increased acceptance and buy-in for arbitrary maximum train length or tonnage limits for siding-length, substation-rating, and physical characteristics (terrain) related reasons.

Feasibility Assessment & Operations Analysis by Market Segment: Commodities & Speed

One limitation of this current research is that although we estimated many variables using averages at a high level, we did not evaluate the effect of market segments on BEL requirements or length of "electric districts". Intermodal trains operate with significantly higher speeds and lighter loads than unit trains of bulk commodities, which may change the calculus regarding the fraction of route-miles needing electrification and the BEL specifications required. This analysis would be a logical next step to establish parameters for railroad franchises focused on different commodities.

Effects of North American Climate

North American climate conditions and geographical features challenge catenary maintenance:

- Extreme cold, especially in Western Canada and the northern U.S. Plains states, where winter temperatures can occasionally be as low as –30°F, causes catenary wires to freeze (requiring deicing trains) or snap (insufficient slack to account for thermal contraction).
- Extreme heat in the Southwest, where summer daytime temperatures reach 110°F, causing catenary wires to droop, and substation equipment to overheat.
- Western wildfires may close segments of mainlines and force trains to be diverted onto other routes. This risk might be substantially mitigated through electrical grid improvements, as overheating is a significant cause of wildfires.
- Atlantic Seaboard and Gulf Coast hurricanes, where since 2010 an average of 7.8 hurricanes have occurred annually with sustained winds over 74 mph. These damage electrification infrastructure because of debris (trees, building components, etc.) falling on OCS.
- Tornadoes, particularly in the Central U.S., are usually geographically limited in their impacts but can cause extreme damage.
- Remote geography of the Rocky Mountains, high desert, and high plains, where routine maintenance access to railroad rights-of-way can be challenging.

Although technological solutions exist for these conditions, large-scale North American experience is insufficient to understand the maintenance cost implications of electrification. Demonstration programs in representative locales would provide this necessary experience.

Consequences of Electrification on Signal Systems

Signal installations on most North American mainlines make no provision for future electrification. Current return on AC electrifications could cause interference with existing Signals and Communications circuits, due to ground leakage, negative return, and electromagnetic interference issues (see, e.g. (*37*)). Pilot projects working with different signal and control technologies could determine the likely impacts and help develop mitigations.

Potential Changes in Maintenance Practices

Many maintenance-of-way processes would be impacted by electric catenary poles and wires. Aside from adding Electric Traction Departments and catenary inspection vehicles, some track maintenance methods would require modification, (e.g., cranes in switch replacement jobs, grapple trucks in tie jobs, signal inspections on overhead gantries, track and power outage procedures, etc.) Track time is already at a premium in very busy corridors, and the maintenance productivity impacts of working in an OCS environment must be addressed (*45*). High-clearance OCS may mitigate, but not eliminate these challenges.

Demonstration projects will help develop safety procedures, and gain information and operating experience. It would also be useful to review experience with electrifications, past and present, involving heavy freight service to determine what elements of their construction (choice of design and materials) and maintenance might inform railroads going forward.

Catenary Zigzag

Early 20th century electrifications generally sought to keep overhead wires at or near track centerline. Most railroads used short tangent sections on curves to prevent pantographs from dewiring and fouling hanger wires (*51* p. 179-183). The Pennsylvania Railroad superelevated much of its catenary work to keep contact wires centered relative to pantographs (*52* pp. 26-29).

With the increased use of constant-tension catenary involving sections about a mile long, held taut with counterweights or springs, it is accepted that OCS zigzag is necessary and even desirable to distribute wear more evenly along pantograph contact strips. But North American experience with OCS zigzag is based on passenger experience. Tolerances for freight operations will need to be established.

Opportunities for Federal Assistance

These challenges should be addressed with suitably funded Federal demonstration programs covering operating and maintenance experience, best practices in design, construction, and maintenance, and cost implications. Demonstration programs should cover multiple sites in various geographies.

The U.S. federal government has historically been heavily involved in railroad electrification. The largest U.S. electrification project to date (the Pennsylvania Railroad's electrification from Wilmington, Delaware to Washington, D.C. and from Paoli to Harrisburg, Pennsylvania) was funded by Works Progress Administration loans during the Depression (*53* pp. 141-165). Indeed, the seminal Gibbs & Hill Conrail electrification feasibility study, discussed in (*37,53* pp. 30-35), was completed in response to the 1976 Railroad Revitalization and Regulatory Reform (4R) Act's Section 606(i) requirements.

Railroad, electric utility, and public officials could use updated guidance similar to that offered in 1977 with TRB Special Report 180, *Railroad Electrification: The Issues* (*55*). Similarly, British Railways hosted a conference in 1960 to promote 25kV commercial-frequency AC electrification (*56*), hitherto implemented only in France.

Industry-Driven Legislative Guide

From the private sector perspective, there may be a need to produce a legislative guide. With a public works project of this magnitude and expected benefits shared between privately owned railroads and the public realm, the industry should define the terms of engagement and the types of government grant programmes or incentives that it would like to see. Such a study could elicit reasons why railroads might resist such programs, and possible roadblocks (e.g., additional social, unrelated political requirements), that if included in legislation, might hinder industry involvement and buy-in. This could aid lawmakers in developing funding, requirements, and legislation.

LONGER TERM IMPLEMENTATION ANALYSIS AND PLANNING

In parallel with short-term actions, steps could be taken to determine how a catenary electrification system might be built out:

Commodity Flow Analysis: Where to Build

Planning future electrification requires more than simply looking at present-day traffic flows (*57*). Dominant freight traffic flows would change with future reductions in fossil fuel use and trends towards re-shoring manufacturing. Traffic flow data are needed to determine engineering parameters and lines to electrify. Thus, full future commodity flow studies should be undertaken. Such strategic analyses were last conducted in earnest for parts of the U.S., funded by the 1973 Regional Rail Reorganization Act (*58,59*). This function has passed onto state rail plans, but these rarely address systemwide issues, which must be considered when deciding where to electrify, with what technology, with which operating strategy, in what sequence.

Analyses using such data sources as the STB Rail Waybill Sample, U.S. Census Commodity Flow Survey, their Canadian equivalents, private databases of commodity-level truck traffic forecasts, and nationwide economic forecast models with multiple industrial development scenarios are needed to inform preferred locations for electrification pilot projects. Such commodity flow analyses would also identify industrial segments potentially benefitting from federal investments and could generate or identify constituencies favouring demonstration projects. Similar methods have been applied to publicly funded rail freight investment projects (*60*).

Business Case Analysis: Why Build

The North American rail industry has multiple stakeholders with competing interests. Electrification programs must show benefits from each stakeholder’s perspective, including electric utilities, freight railroads, intercity passenger carriers, commuter railroads, and the public interest. Business case analyses can show anticipated benefits accruing to all stakeholders and may offer guidance for cost allocation so the project investment burden can be shared equitably.

Methods used by the Northeast Corridor Commission show that, with the right legislative framework, Federal quangos (quasi non-governmental organizations) can implement arrangements to distribute investment burdens among competing interests, and account for non-monetary contributions (*61*). Federal demonstration programs could include a National Rail Electrification Planning Commission to perform business case analyses and ensure investment program areas are sustainable with good cost-benefit ratios. It could also spearhead strategic system planning and coordinate demonstration projects.

Electrification System Strategic Planning: What to Build

Switching from fossil fuel-powered to electric vehicles will require enormous upgrades to electrical grids. Policymakers and utility officials must take freight railroads' needs into account when planning these upgrades.

An electrified railroad has peaky single-phase loads. Joint planning must take place with local utilities to manage their impacts. However, the linear nature of rail lines means that railroads can acquire power from cheaper sources enroute with transmission or even co-located generation investments like solar farms, wind farms, and hydroelectricity, although load balancing with local grids will still be needed. Here, BELs provide another advantage by buffering peaky loads, a goal which electrified railroads have long pursued (*62*).

Smaller electrification projects can involve cost minimization whilst meeting specifications. But here, strategic railroad-and-transmission grid interconnection points can be identified, and high traffic-density electrified corridors grown organically outwards as far as train traffic and power transmission limits justify. This also identifies "power gaps" for planning future generation or transmission capacity, together with interim "diesel plans" or hydrogen alternatives for line segments deemed uneconomical to electrify at present, even with the infrastructure savings available from BELs.

Unlike straight electrics, BELs can traverse such elements as truss bridges, movable bridges, tunnels, and constricted-clearance overpasses in battery mode, making it unnecessary to electrify there (with consequent capital savings from not having to raise clearances). These geographical barriers often form natural boundaries for electricity distribution zones. By leaving them unelectrified, complex electrical switching arrangements can be avoided.

System plans identifying line segments worth electrifying from both traffic and power availability perspectives also allows utilities to plan generation and transmission capacity by identifying future electrified railway demands, providing valuable information including load size, characteristics, and grid connection points.

In addition to the direct costs, an OCS imposes indirect costs by constraining track geometry, which raises curve realignment and track superelevation costs for higher speeds. Several lines are being studied for incremental higher-speed passenger services at up to 125 mph. Such investments should be considered together with freight needs and sequenced appropriately.

Federal demonstration programs could include nationwide planning studies, divided into regions, using results from technological proof-of-concept, operations strategy, and commodity flow analysis to provide long-term blueprints for North American mainline railroad electrification.

Institutional Mechanisms: How to Pay

The Association of American Railroads is opposed to electrification, particularly because of the capital cost (*63*). If moving toward carbon-neutral transportation is an important policy goal, governments should be prepared to finance non-emitting technologies, and help railroads make the transition. Several ideas follow:

- A Class One railroad president suggested in 2008 that electrification might be funded through tax credits (*64*). This could incentivize railroads to make large, socially desirable investments based on enlightened self-interest.
- Railroads might consider joint ventures with consortia, perhaps "a mix of financial institutions, including insurance companies, banks, and pension funds. Depending on the location of the proposed project, … a development authority might also be pursued" (*65* p. 50).
- For smaller railroads, governments could make infrastructure improvement loans (like Railroad Rehabilitation and Improvement Financing) or grants, using evaluation criteria like the Federal Transit Administration's for evaluating trips carried per amount invested, and allowing local matches. Thus, railroads would state how many ton-miles would be electrically hauled and how much GHG emissions eliminated (including electric generation), using models like Canada's GHGenius.
- In 2009, responding to the Great Recession, U.S. Congress instituted the Car Allowance Rebate System, better known as the "cash-for-clunkers" program, which reduced emissions from private automobiles. Similar programs could help railroads afford non-emitting locomotives. Where traffic levels are too low to justify electrification, it could incentivize railroads to convert to battery or hydrogen power.
- Under a cap-and-trade regime, firms in industries that cannot shift to GHG-free activities seek to buy GHG emission rights from other firms—potentially including railroads. This could provide funds to reduce railroad emissions. Obviously, it should be priced correctly so that electric utilities would not purchase credits to operate coal-fired plants to generate power for railroad electrification.
- Closing inter-line electrification "gaps" at major gateways was formerly a concern for electrification planning. With BELs, though, this is less important, as locomotives can switch readily between electric and battery modes (assuming sufficient electrical charge). Nevertheless, since battery recharging is time-dependent, installing OCS on busier parts of major terminal railroads (e.g., Conrail Shared Assets, Belt Railway of Chicago, Indiana Harbor Belt, Terminal Railroad Association of St. Louis) might provide operating efficiencies by allowing BELs to recharge while waiting for clearance to proceed through congested areas.
- AAR has standards on how railroads may charge each other for working on each other's rolling stock, whether out of necessity or for mutual benefit. A similar system would be needed for electric power charges, perhaps like the norms for wholesale purchase of electricity by one utility company from another. Auditable net-use meters on BELs could show whose units are consuming how much power on which railroad, when, and for what purpose (e.g., propulsion, battery charging, regeneration). This information would also be internally useful as railroads deploy real-time throttle optimization tools.

Differences From Prior Efforts

Rail freight electrification for carbon neutrality will differ in two significant ways from earlier proposals based on attaining energy independence (*66,67*). First, those proposals envisioned electrification from the Powder River Basin in eastern Wyoming (North America's leading source of coal) and may have also presumed electric haulage of Appalachian coal traffic. Those priorities are no longer in keeping with public policy.

North American free trade and cross-border railway mergers and acquisitions will create a cross-border electrified network, and Canadian systems may well center on Chicago like their U.S. counterparts. Mexican railroads may eventually become part of this electrified network.

CONCLUSION

Freight railroads are understandably concerned about the cost of finding alternatives to diesel-electric traction. But if public policy (and lasting changes in the price and supply of petroleum) move North America's railroads towards non-emitting propulsion technologies, this research shows discontinuous or intermittent electrification with BELs supplemented with cableless boosters for energy storage, alternating approximately every 200 miles between powered and unpowered segments, is a doable approach with technological promise and high cost-effectiveness, provided that the energy capacity, charging rate, weight characteristics, and reliability of BELs are proven in practical service conditions.

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