Partial Electrification Strategies for Diesel Commuter Rail's Climate Challenge

John G. Allen (Corresponding Author)
Independent Transportation Consultant
5518 S. Harper Ave.
Chicago, Ill. 60637-1830
(773) 955-1848
Email: jgatransit@2200.com

Alex Lu
P.O. Box 684
Ossining, N.Y. 10562-0684
(978) 361-0528
Email: lexcie@gmail.com

Stuart F. Trout
Independent Transportation Consultant
35 Riverside Avenue
Bedford, Mass. 01730-1528
(781) 275-9145
Email: Stu_TroutCA59@yahoo.com

John P. Aurelius
Independent Transportation Consultant
28 County Walk Lane
East Haven, Conn. 06512-2787
(203) 215-4543
Email: jaurelius28@comcast.net

TRBAM Paper Number #23-01856
TRR Paper Number #22-01193

March 26, 2023

Submitted for publication in Transportation Research Record

ABSTRACT

As societal attitudes toward fossil fuels shifts, commuter railroads may be coming under increased scrutiny for their contribution to greenhouse gas (GHG) emissions. This analysis explores new possibilities created by battery-electric locomotives (BELs) in conjunction with partial electrification for en-route recharging in electrified territory. We propose a systemwide network approach that starts with one or more substations in geographically strategic locations, then electrifying just enough for sufficient electrical charge, with BELs running off the wire in non-electrified areas. As 25,000-Volt alternating-current substations generally have an 18~26-mile reach, considerable possibilities exist for new-start electrifications. This is significantly more cost-effective than a traditional approach that electrifies one corridor at a time. Although BELs are in technical development, and certain implementation challenges remains on commuter railroads, we believe BELs required to enable this type of electrification are within reach of current battery technology.

Drawing on examples in Boston, Philadelphia, Chicago, and Minneapolis, six strategies are outlined: (1) minimizing electrification costs by electrifying radial commuter networks from a centrally-located substation, (2) for systems with longer routes, using BELs to extend the central substation's reach, (3) extending new electric service beyond existing electrifications with BELs, (4) using BELs to create new trans-regional services, (5) co-locating railroad-owned feeder lines with utility infrastructure such as electric transmission rights-of-way to maximize the geographic reach of supply substations, and (6) providing charging pads in certain limited situations. Preliminary ridership, energy sufficiency, and lifecycle cost analyses were performed to show the feasibility of BEL technology in conjunction with a substation-based, supply-side approach to designing electrification projects.

Keywords: Commuter rail, electrification, supply substations, battery-electric locomotives, charge-in-motion.

INTRODUCTION

As societal attitudes move away from fossil fuels in favor of carbon-neutral renewable energy, commuter rail operators are responding to these concerns. In 2021, Metra, northeastern Illinois' commuter railroad, issued a request for proposals for battery-powered locomotives (*1*). The California Department of Transportation has ordered four Stadler hydrogen-powered multiple-units for use on the San Joaquin route (*2*). Although halted in 2022, New York's Long Island Rail Road and Alstom were actively developing a retrofit battery package for existing electric multiple-unit (EMU) cars (*3*).

Electrification, already undergoing a mild renaissance in the early 21st century, merits a closer look, and not just for environmental reasons. Advances in battery technology are leading to a paradigm shift without precedent in the history of railroad electrification that should greatly reduce the capital cost of new installations.

Modern battery-electric locomotives (BELs) with an energy capacity of 7.2 megawatt-hours (MWh) were announced in 2021 (*4*). The authors have previously demonstrated (*5*) that a four-unit consist of these BELs are capable of hauling freight trains of up to 8,000 tons for 230 mainline miles unassisted, potentially enabling discontinuous electrification of major freight lines. When combined with en-route charging on high-voltage alternating-current (AC) catenary, BELs potentially offer a revolutionary technology for commuter railroads looking to reduce diesel train-miles for greenhouse-gas (GHG) emission and climate-related reasons.

Conceptually, BELs resemble existing dual-mode AC electric/diesel locomotives, already operating on one major commuter railroad (Figure 1), except that their off-wire power comes from batteries, which are charged up while under the wire.

Figure 1. NJ Transit dual-mode locomotive entering Convent Station, 2021. Fan Railer photo (CC BY-SA 4.0). **Source:** *https://commons.wikimedia.org/wiki/File:ALP-45DP_Convent_Station.jpg*

Although early 20th-century electrifications used lower voltages, the geographic reach of 25,000-Volt (25kV) AC electrification at 60-Hertz (Hz) commercial frequency creates new possibilities in combination with rapidly-developing BEL technology. Although BELs can work with already-existing electrifications involving lower voltages, the greater reach of 25kV enables longer electrifications to be powered from one single substation, which in turn can reduce infrastructure costs or extend the reach of electric service. BELs themselves further extend the range of electric service by running off-wire beyond electrified trackage.

No BELs have been specifically built for commuter service as of this writing. But given the state-of-art in battery technology—driven by the automotive field (*6*)—and successes of current freight-oriented prototype BELs, vendors should be able to develop BELs suitable for commuter service should an appropriate specification be issued. Several conceptual designs already exist, e.g., (*7*). This paper describes how this technology, when fully proven, could be used.

Our approach to electrification planning is to electrify busier inner-suburban segments, supplemented with BELs or battery EMUs for outer, quieter segments, offering a cost-effective path forward. Preliminary analyses conducted for this effort show that once produced, BELs should have the range needed to extend electric service to exurban areas and beyond.

This concept combines traditional electric operations with BELs, and have been previously discussed at a conceptual level (*8, 9* pp. 168). It had been previously explored with a hydrogen fuel-cell stack in conjunction with a hybrid powertrain (*10*), prior to high-capacity batteries becoming available. Previous work on a concept termed "intermittent electrification" with very short live-wire segments and gaps (*11*) applied to reducing GHG emissions from passenger rail with dual-mode diesel locomotives (*12*) was found to be unworkable because feeder wire and substation-related issues were overlooked (*13*). A recent optimization study examined the location of electrified track necessary to advance such a concept (*14*). Indeed, Deutsche Bahn may be close to implementing such a concept in Schleswig-Holstein (*15*) with minimum electrified segments of several hundred metres at 15kV AC, 16.7 Hz.

This study is distinct from previous work in several significant ways. Our approach keeps the electrified segments contiguous to the maximum extent possible, based on the maximum reach of 25kV supply substations, recognizing that substations are a major part of electrification expense. We utilize BELs in place of diesel dual-mode units to operate through unelectrified territory, thereby achieving 100% GHG elimination at the point of use, rather than a partial solution. Finally, and perhaps most importantly, we sketch out what practical designs on U.S. systems might look like, using case studies on existing and proposed U.S. commuter and regional rail systems, thereby advancing this idea beyond the conceptual stage.

Context of Climate Change

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, which is likely to reach 1.5°C before 2052 (*16*). 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 (*17*).

Diesel locomotives emit GHGs and contribute to climate change. As automobile and bus fleets are hybridized or electrified, today's environmental arguments in favor of diesel-powered commuter rail will become harder to sustain. To reduce diesel train-miles, operators must either cut service or replace diesels with non-GHG-emitting propulsion technologies.

Research Objectives

This paper offers a high-level, first-cut feasibility analysis for BEL-enabled commuter rail electrification. It aims to: (a) identify existing commuter rail services that could be electrified for climate change action; (b) show how single-substation configurations in combination with BELs could make electrification less costly than conventional designs; and (c) show that two 4.8-MWh BELs have the range to perform all but the most demanding duties in typical commuter and inter-regional services, if enough of the core network is electrified.

Limitations of This Research

Our research does not address such implementation issues as upgrading electrical grids for climate-neutral power generation, or infrastructure-based site-specific restrictions (equipment weight, length, special requirements, etc.). Nor does it evaluate mode shift alternatives (e.g., from diesel trains to electric buses), offer ridership forecasts, or address the longstanding debate between locomotives and EMUs (*18*). It also does not determine whether railroads are more GHG-efficient with electrification than with alternate fuels such as hydrogen, nor does it investigate environmental concerns about the fabrication and disposal of batteries or the consequences of mining the necessary semi-precious metals. However, it is worth noting that liquefied natural gas (LNG), "genset" locomotives, and operating diesel locomotives in "hybrid" configurations are not carbon-neutral options (*5*).

Nor is this paper a "business case" for commuter rail electrification. North American commuter and intercity passenger rail services require operating support, and such support is not generally driven by energy costs. From a return-on-investment perspective, the balance of electric power versus diesel largely depends on assumptions about relative energy costs.

Perhaps most importantly, this research does not consider track ownership, jurisdictional issues, or other institutional matters. It is assumed that solutions can be found, as in Massachusetts (*19*), New York, Virginia, Florida, California, and Ontario.

For general background on railroad electrification, readers are referred to the extant literature (*20*-*25*), including research on design alternatives (*26*), electric traction power supply (*27*, *28*), and alternatives to diesel traction (*9* pp. 135-177).

HISTORICAL REVIEW OF NORTH AMERICAN ELECTRIFICATIONS

In the early 20th century, railroads that could afford the substantial expense electrified some or, occasionally, all of their suburban services to solve specific operating issues where steam was unworkable or inadequate (29, *30*). The reasons why they electrified included long tunnels, underground stations, sustained grades, increasing train throughput through faster handling, general economy of operation (particularly in conjunction with intercity passenger and freight trains), and elimination of fossil-fuel locomotive smoke for civic improvement purposes (*31*). Interestingly, these reasons for electrifying remain valid.

The post-World War II emergence of diesel-electric locomotives (*9*, *32*) transformed North American railroads and reduced the operating advantages of electric traction. Mechanical engineers and manufacturers quickly settled on diesel-electrics as the motive power of choice. Diesel-electrics, being essentially electric locomotives with self-contained diesel generators, combined the geographic flexibility of steam with the high torque of electric locomotives (*33*).

Push-pull operation with diesel locomotives and cab cars started on the Chicago & North Western in 1960 (*34*) and quickly spread to other commuter railroads. This made diesel locomotives as easy to use in commuter service as EMUs.

Re-electrifications and other renewals of already-electrified commuter rail lines offered the first tentative signs of reinvestment in electric traction infrastructure. Several re-electrifications switched over from direct current (DC) or low-frequency AC to commercial-frequency, 60-Hz AC (*35*):

- New Jersey Transit, Morris & Essex Lines, from 3,000V DC to 25kV AC, 60 Hz, 1984
- Metro-North Railroad, New Haven Line, from 11kV AC, 25 Hz to 12.5kV AC, 60 Hz, 1986
- Agence Métropolitaine de Transport (Montréal, Québec), Deux-Montagnes Line, from 2,400V DC to 25kV AC, 60 Hz, 1995

First-Wave Electrification Renaissance

Adding to the extent of existing electrifications was a logical follow-on to renewals of older installations. Three New York area commuter railroads added significant extensions to existing electrifications (1982-2002). Several new-start installations, all at 25kV AC, followed:

- Amtrak Shore Line Route, Boston, Massachusetts to New Haven, Connecticut, 2000
- Ferrocarril Suburbano de la Zona Metropolitana del Valle de México, Mexico City, 2008
- Regional Transportation District, Denver, Colorado, 2016

Two other properties are in the process of electrifying at this writing:

- Caltrain, San Francisco to San Jose, California
- GO Transit, multiple lines, Toronto, Ontario, Canada

Figure 2 shows the Caltrain electrification, which uses hardware typical of modern electrifications.

Two unsuccessful proposals and a third yet in play were also part of this first wave:

- In 2012, an otherwise-promising plan to electrify three commuter rail lines in Montréal, Québec, Canada failed when the freight railways, which own the tracks, announced their opposition to electrification.
- In Chicago, Metra, northeastern Illinois' commuter railroad, considered electrifying some or all of the Rock Island District (which Metra owns and operates) in 2018. The interesting aspect was not that Metra found the costs exceeding the benefits, but that this proposal failed to advance by only a small margin.
- Finally, in Boston, as of late 2022 the Massachusetts Bay Transportation Authority (MBTA) appeared to be ready to proceed with electrifying the Fairmount Line, which serves an urban corridor and provides an alternative to the Northeast Corridor mainline between Boston and Readville, Massachusetts (*36*).

This early 21st century renaissance occurred against a backdrop of rising commuter rail ridership between 1983 and the start of the COVID-19 pandemic in 2020 (*37*). At first glance, the pandemic's effects on ridership might imply an end or at least a pause to the present wave of electrification. Recent controversies about electrification costs (*38*) and the applicability of battery-electric traction to rail passenger service (*39*) based on questionable assumptions have further confused matters. But a second wave of interest in electrification may be imminent as ridership recovers, led by increasing unease about GHG emissions and their impact on climate change.

Figure 2. Section of completed Caltrain electrification work at California Avenue, Palo Alto, California, 2022. Dick Lyon photo (CC BY-SA 4.0).
Source: *https://commons.wikimedia.org/File:Caltrain_electric_infrastructure_in_Palo_Alto.jpg*

Current Approaches to Dual-Mode Motive Power

Amtrak is currently procuring Siemens Charger locomotives mated to Auxiliary Power Vehicles (APVs), which draw power from overhead catenary and could optionally be fitted with batteries (*40*). Metro-North's dual-mode procurement (*41*) may include an option for battery tenders that would supply power to adjacent locomotives.

Responding to these market demands, Siemens is reportedly designing a version of the Charger locomotive (designated M42-DMC) with lithium-ion batteries that could operate in battery and diesel modes, recharging from railroad power sources where available. When this locomotive is built, it could provide the capability for a demonstration passenger service that would span existing electrified and non-electrified territories. Although these approaches involve diesel locomotives which might, as an option, be provided with energy storage capacity rather than BELs, this represents a significant first step toward reducing the proportion of diesel train-miles relative to total service.

Further Electrification Renaissance?

Until recently, new standards (Tiers 2, 3, and 4) restricting particulate and noxious emissions from new and rebuilt diesel locomotives (*42*, *9* pp. 123-133) had seemingly raised the threshold for justifying electrification. Now, though, concern about GHG emissions may have the opposite effect of making electrification more desirable.

Current alternative fuels and propulsion technologies have their limitations. Hydrogen lacks the concentrated energy density of fossil fuel, and even under the best of circumstances is likely to underperform relative to diesel or biodiesel (*20* pp. 10-11). Thus, GO Transit considered but rejected hydrogen power as being inadequate for its busy and growing system (*43, 44*). In 2022, Metrolink converted from fossil-fuel diesel to a renewable diesel fuel (RD99) refined entirely from modern carbon (i.e., carbon other than that contained in fossil fuels). To the extent that RD99 production removes CO_2 from the atmosphere, overall net reductions of 65~90% of carbon emissions might be possible (*45*), but it does not entirely eliminate GHG emissions. Today's concern with reducing the carbon footprint of transportation increases the likelihood that the environmental benefits of commuter rail electrification (powered from carbon-neutral sources) will be fully appreciated.

The second-wave electrification renaissance is likely to take two forms. One is conventional electrification using overhead catenary systems (OCS), as in Denver, San Francisco, and Toronto. The second involves the emerging technology of battery-electric locomotives (BELs).

STRATEGIES FOR COMMUTER RAIL ELECTRIFICATION

We propose some strategies and ideas to minimize both capital and operating costs of electrified commuter rail service in the context of reducing GHG emissions, using examples from Boston, Philadelphia, and Chicago. Table 1 summarizes the strategies discussed herein. Because partial electrification requires approaches that differ greatly from those hitherto used for conventional, continuous electrification, these paradigm-shifting strategies are examined first.

Table 1. Summary of partial electrification strategies.

Strategy	Description	Case Study	Opportunities for Use
1	Take Advantage of Commuter Rail's Star Network Topology	Boston Northside	New-start commuter rail electrification where the network has a central terminal and multiple branches extending up to 25 miles from a central yard or station
2	Use Battery-Electric Locomotives to Extend Reach of Central Electric Substation	Boston Northside	Networks with a central terminal where multiple branches extend 25~50 miles out, especially if exurban areas seek new or continued service
3	Extend Service Beyond Existing Electrification with BELs	Philadelphia Reading-side	Existing electrified networks where exurban services were previously discontinued, but localities now seek service restoration or extension

Strategy	Description	Case Study	Opportunities for Use
4	Create Trans-Regional Services Spanning Electrified Zones Using BELs	Mid-Atlantic Regional Network	Connecting two or more electrified commuter rail networks where a "gap" in electrical infrastructure exists in the areas between them
5	Take Advantage of Co-Located Infrastructure	Chicagoland North and West	New-start commuter rail electrification where the network extends more than 50 miles from the downtown, or where ridership density on one or more lines is so high that a straight-electric service is warranted on them, and adjacent branches or extensions are in relatively close proximity
6	Charging Pads	Regional Services Terminating in Smaller Locales	Isolated, very long lines where a single charge from downtown cannot reliably carry the train through to the final destination, and/or shore power may be needed at the outlying yard to maintain charge during weekend layovers

Following descriptions of these strategies is a more technical discussion of the methods used. Evaluating these different strategies and determining the feasible operating ranges of BELs requires data analysis and technical computations using standard industry formulas. Table 2 summarizes the methodologies used and major findings.

Table 2. Summary of methodologies used for evaluating case studies

Methodology	Description	Opportunities for Use	Major Findings
A	Analysis of Cumulative Passenger Loads by Line versus Mileage from Downtown	To determine what fraction of passenger would cross the zone boundary between straight-electric and BEL zones	24% of Boston Northside exurban passengers are in the BEL zone. 14% of Chicagoland North and West riders would require BEL or shuttle service.
B	Energy Assessment for Service Feasibility and Market Scan of Electrification Using Battery Electric Locomotives	To determine if given extension service could operate with BELs using existing electrification, or how much electrification is needed to support a new-start BEL line	Most commuter lines can be operated with BELs if slightly less than half the route-mileage is electrified. Very few services require charging pads at the outer ends, and only under very specific circumstances and assumptions.
C	Life Cycle Cost Analyses of Financial Feasibility of BEL-Enabled Electrification	To compare the cost and performance of BEL-enabled electrification versus more traditional electrification network designs	BEL-enabled electrification represents a 25%~44% lifecycle cost savings over conventional solutions, depending on extent to which service is extended into or curtailed from the surrounding exurbs and countryside.
D	Simplified Battery Charge Level Simulation of an Established Operating Plan	To assess the risk of battery depletion on an individual train basis and determine logistical plans in case of battery depletion and assess shore power requirements	AM peak inbound service has the lowest battery levels due to overnight HEP load, but fleet manipulations to get locomotives with low battery warnings onto daytime charge cycles are not difficult even on lines with relatively sparse service frequency.
E	Infrastructure Efficiency and GHG Reduction Comparative Assessment	To compare cost and effectiveness of different approaches towards GHG reduction	BEL-enabled approaches achieve 100% GHG reduction with 20% to 64% of route-miles electrified, depending on rolling stock utilization goals.

Key to these strategies is a supply-oriented approach to electrification. In a classical service-centric approach, sponsors decided what services should be electrified, and given that scope, railroad engineering departments determined what infrastructure was needed to implement the project. Instead, we stand this logic on its head. Starting with a strategically located substation, we ask how much of the network can be electrified? This might affect such operating matters as storage yards, crew bases, etc., but given the significant range of 25kV electrification from supply substations, designers should have considerable flexibility to identify solutions.

For this analysis, we assumed that on shared freight/passenger corridors, catenary electrification can co-exist with double-stack container trains, or freight trains can be re-routed if necessary. As it should be possible to operate electric locomotives at speeds up to 100 mph with overhead wires dimensioned for double-stack container trains (*46* pp. 2-3), such clearances would not be problematic for commuter rail operations.

Where electrified lines with lower wires have flat junctions with other railroads, short gaps may be needed in the catenary wires to accommodate freight trains, particularly if double-stack container trains use the intersecting line. (This situation already exists on the Northeast Corridor in southwestern Connecticut, where there is a short gap in the wires when crossing the Cob movable bridge over the Mianus River.) We have previously provided (*5*) a list of next steps necessary to prove out that catenary electrification can co-exist with double-stack freight trains in North America.

We now turn to the strategies themselves.

Strategy 1: Take Advantage of Commuter Rail's Star Network Topology

Classic commuter rail networks radiate from a downtown location in all directions, typically with a shared train servicing facility nearby. Modern 25kV AC, utility-frequency, autotransformer-fed systems have a maximum range of 18~26 miles from supply substations (up to 52 miles between substations), depending on such factors as design and power draw. Commuter rail power requirements are on the lower end of theoretical catenary capacity, thereby maximizing substation range. This range allows the network's highest-density segments to be covered from one single, centrally located supply station. This is especially true if a trunk line runs several miles from downtown before splitting into branches, or if the servicing facility is located a few miles out.

Figure 3 shows the hypothetical extent of electrification from one supply substation (with 3 to 5 autotransformer paralleling substations on each branch) for Boston's Northside commuter rail system. All core suburban markets, which encompass line segments serving 83.6% of total ridership—see Figure 4, and Methodology A, below—can be covered from a single substation at the Boston Engine Terminal (B.E.T.), shown in Figure 5. Any operations beyond the electrified zone would require connecting services. Some parts are at the far end of the 25kV transmission range and may experience low-voltage conditions under certain circumstances.

Admittedly, a single-supply configuration has reliability consequences. However, those effects can be mitigated by multiple utility feeds at the central location, and BELs or, as an interim step, electro-diesel dual-mode locomotives for some services. Additional feeder locations might eventually come online for reliability enhancement and as electrified services expand beyond the suburban core. But as a starter electrification system, this is a highly cost-effective configuration.

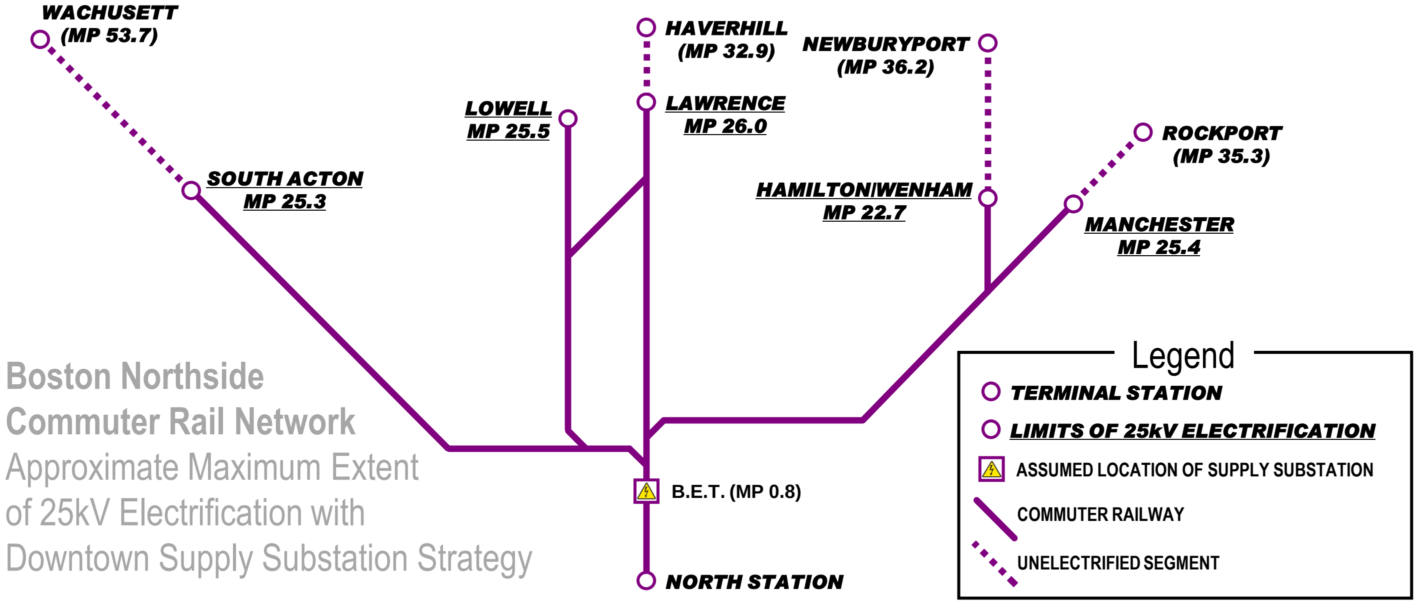
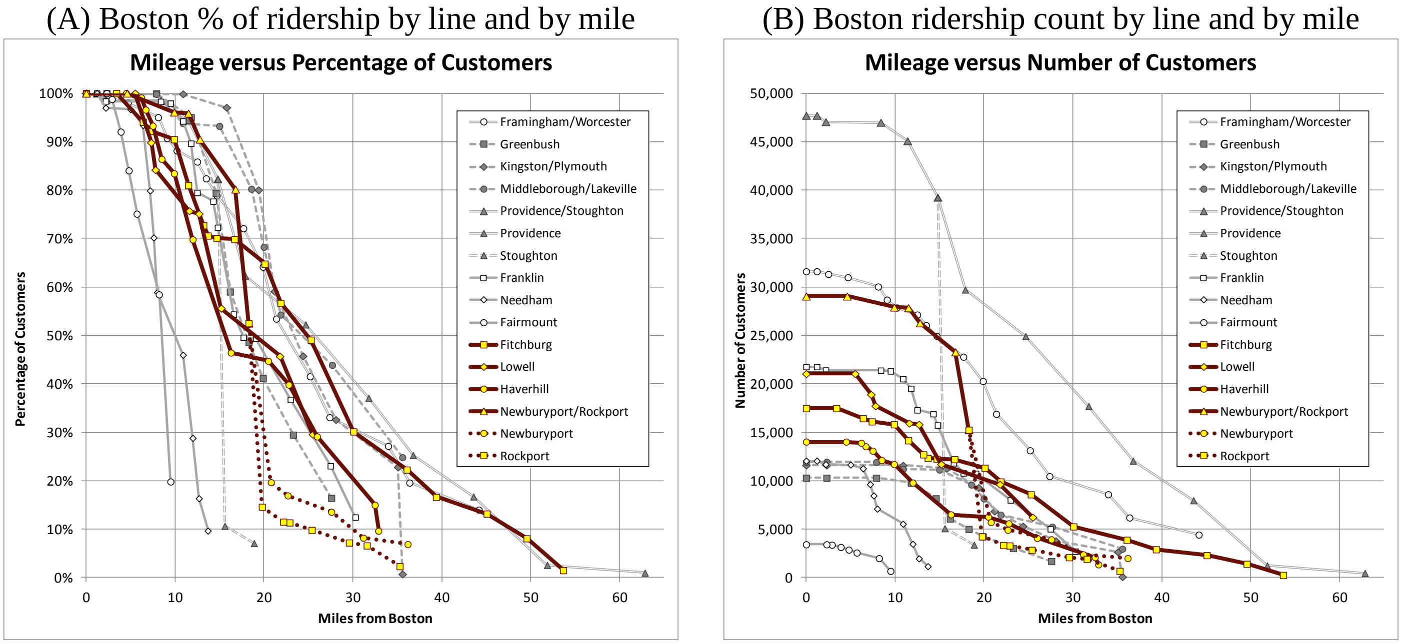


Figure 3. Boston Northside Commuter Rail network case study: central supply substation strategy (Strategy 1), showing maximum feasible electrification at 25kV with one single supply substation at the Boston Engine Terminal.


(A) Boston % of ridership by line and by mile

(B) Boston ridership count by line and by mile

Figure 4. Commuter Rail ridership statistics for Boston showing visualization by line, station, and mileage, emphasizing lines selected for partial electrification case study.
Source: Massachusetts Bay Transportation Authority (*47*).

Figure 5. Boston Engine Terminal, also known as the Commuter Rail Maintenance Facility, a possible site for a 160 MW supply substation. Nick Allen photo (CC BY-SA 4.0).
Source: *https://commons.wikimedia.org/wiki/ File:MBTA_Commuter_Rail_Maintenance_Facility_aerial.jpg*

Strategy 2: Use BELs to Extend the Reach of Basic Electrification

There might be markets beyond the 18~26-mile radius that are important for ridership, operational, or jurisdictional reasons. High-capacity BELs can serve these markets seamlessly, even without 25kV wires reaching important suburban terminals like Haverhill and Fitchburg.

Figure 6 shows the approximate maximum BEL ranges beyond the hypothetical core 25kV network, based on the charging time available between entering the electrified zone inbound and leaving it on the next outbound run—see Methodology B, below. We only need to build the minimum electrification necessary to keep BELs sufficiently charged to reach outlying terminals and return to the electrified zone. Therefore, less electrification is needed than in Figure 3, particularly where we know service on a specific branch is unlikely to extend beyond the current terminal (as with Rockport, at the end of a peninsula).

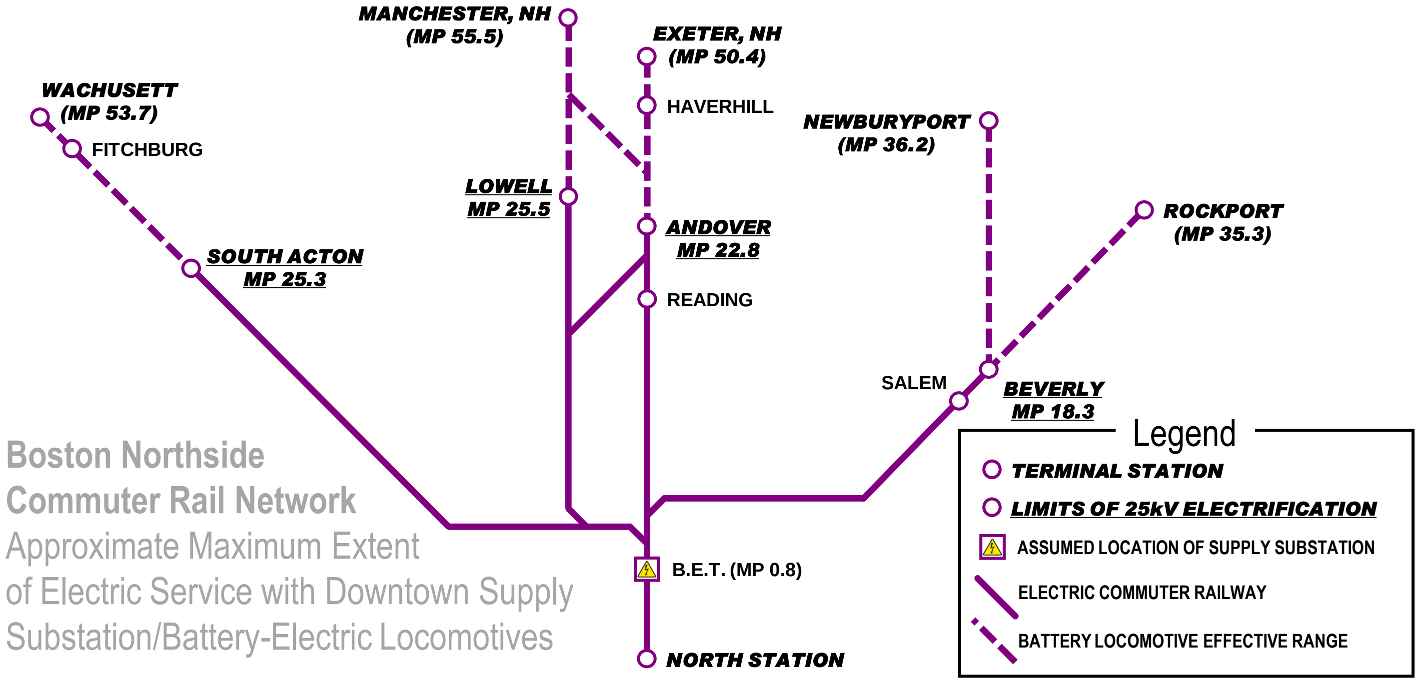


Figure 6. Boston Northside Commuter Rail network case study: central supply substation strategy with battery-electric locomotives (Strategy 2), showing minimum necessary electrification at 25kV with one single supply substation at the Boston Engine Terminal.

Another advantage of this setup is that branching may occur near the maximum range of a single 25kV substation (e.g., Newburyport and Rockport). These branches necessarily increase electrification costs because infrastructure is less cost-effective on lower-density segments. BELs respond to this challenge by serving lower-density areas without having to install and maintain expensive catenary infrastructure.

Some outer terminals, where many communities have sought commuter rail since 1981, extend well beyond the extent of current diesel service. Although funding and governance matters remain yet to be solved, BELs combined with a central supply substation could extend service well beyond boundaries formerly thought possible or desirable. (Because outlying jurisdictions benefit from BEL service extensions, commuter rail agencies may well expect these outer areas to help pay for the core electrification.)

This approach also allows more frequent EMU or electric locomotive service on the highest-density segments, assuming sufficient track and yard capacities. Our operating plan assumptions (Table 3) include 100% electric services to Reading, Lowell, South Acton, and Beverly Depot, supported by new yard tracks at Lowell and near Salem. However, the 9.6 MWh sets of two BELs are effectively drop-in replacements for the current F-40 or GP-40MC locomotives. There is no specific need to replace the existing coaching stock unless additional service is sought. Further study will be needed to definitively establish operating plan alternatives that feasible infrastructure expansion can accommodate.

Table 3. Operating and service plan details for Boston Northside case study (Strategy 2).

Line	Service Plan
Fitchburg	BEL expresses to Wachusett, electric local trains to South Acton. Trains to be crewed from Fitchburg, South Acton, and B.E.T. BEL trains to be stored at Wachusett. Electric South Acton service to be thinned out in the late evening and sets combined with late night outbound EMUs to Lowell for storage. Sets to be deadheaded back to Boston for early AM EMUs to/from Acton.
Lowell	BEL expresses to Manchester NH, electric local trains to Lowell. Trains to be crewed from Manchester, Lowell, and B.E.T. Trains to be stored at Manchester and a new yard at Lowell.
Haverhill	BEL expresses to Exeter, NH to run via Wildcat Branch, electric locals to Andover via Reading. Electric trains will be stored at Reading in an expanded Reading Middle facility. BEL trains continue to be stored at Bradford. Trains to be crewed from Bradford, Reading, and B.E.T. Regional trains to operate with limited stops within the commuter zone.
Newburyport/ Rockport	BEL expresses to Newburyport/Rockport, electric local service to Beverly Depot. Trains to be crewed from Newburyport, Rockport, Beverly Depot, and B.E.T. Trains to be stored at Newburyport, Rockport, and a new yard built within the Salem-Peabody Link right-of-way.

With Strategy 2, most core suburban markets (line segments serving 76% of total ridership—see Table 4, and Methodology A, below)—can be covered from a single substation at the Boston Engine Terminal (B.E.T.). Figure 7 is a zero-origin cumulative ridership chart, visually confirming based on its ballistic-projectile parabolic shape that most ridership density lies within the inner suburban zone which can receive straight-electric service.

Table 4. Electrification performance metrics for Boston Northside case study (Strategy 2).

Line	Weekday Ridership	Ridership Receiving Electric Service	% Electric	% BEL	% Shuttle	Line Length (Miles)	Miles Electrified	% Electrified
Fitchburg	17,480	12,210	70%	30%	0%	53.7	25.3	47%
Lowell**	21,046	21,046	100%	0%	0%	55.5	25.5	46%
Haverhill**	14,026	9,940	71%	29%	0%	50.4	22.8	45%
Newburyport	16,679	10,963	66%	34%	0%	36.2	18.3	51%
Rockport	12,367	8,129	66%	34%	0%	35.3	18.3	52%
Boston North	**81,598**	**62,288**	**76%**	**24%**	**0%**	**231.1**	**110.2**	**48%**

Note: ** The Boston North ridership statistics given here assume Alternative V (Figure 9) with no additional passengers on the New Hampshire extensions. In all likelihood, the ridership counts on the Lowell and Haverhill Lines would be higher by 2,000~3,000 daily trips each due to the increased patronage from the extensions.

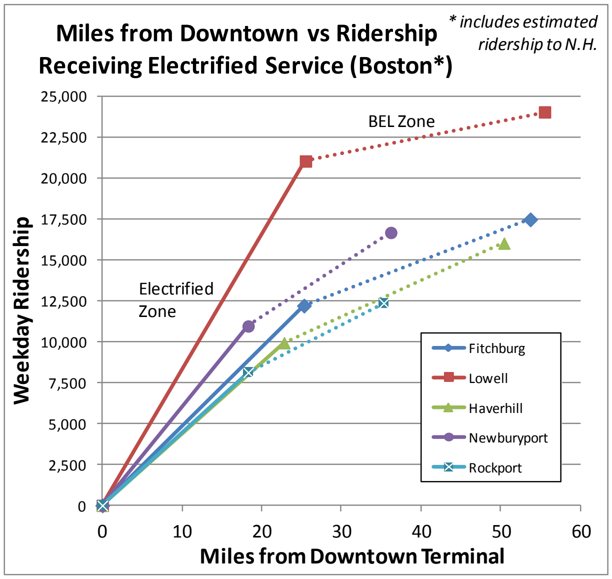


Figure 7. Distance-ridership relationship for Boston Northside case study (Strategy 2).

Figure 8 shows an artist's conception of what commuter BELs operating in charging mode might look like; a BEL-hauled train is passing an electric multiple-unit near the supply substation at B.E.T. The cabless booster behind the locomotive provides necessary additional energy storage.

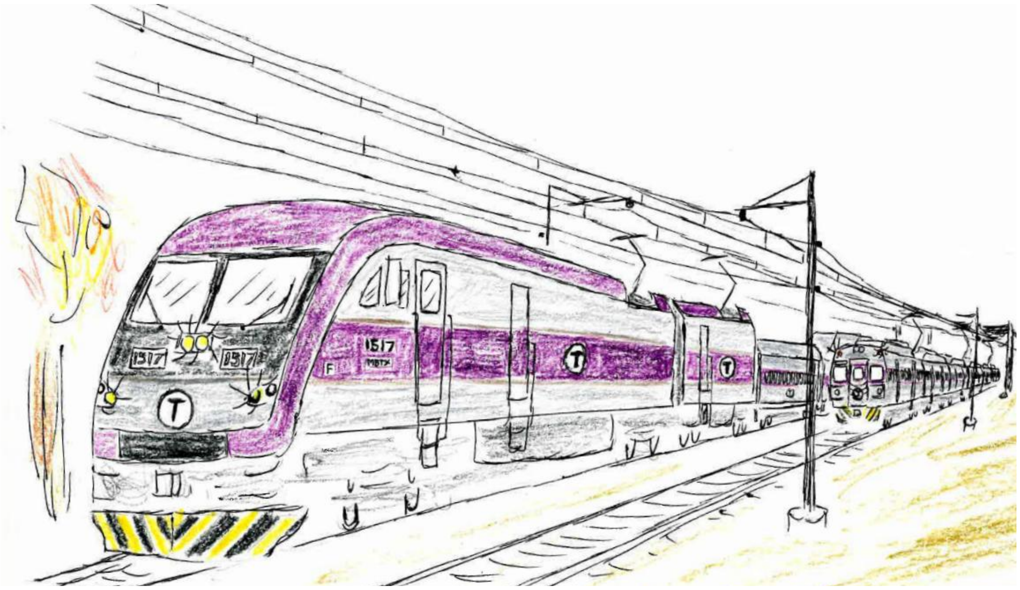


Figure 8. Battery-electrics on the Boston Northside lines; artist's concept by John G. Allen.

Life Cycle Cost Analyses

We performed a hypothetical lifecycle cost analysis of Strategies 1 and 2 (Methodology C, below), compared with a more conventional strategy of electrifying the entire network with straight electric locomotives, to different extents. Based on our assumptions, the results show that the BEL-enabled single-substation design (Strategy 2) saves 25%~44% in total ownership costs, with the range dependent on how far commuter services extend beyond the electrified zone. BELs can extend the range of a single central-city substation from 18~26 miles to about 50 miles from downtown, sufficient for all but the most dispersed regions. Figure 9 summarizes our findings.

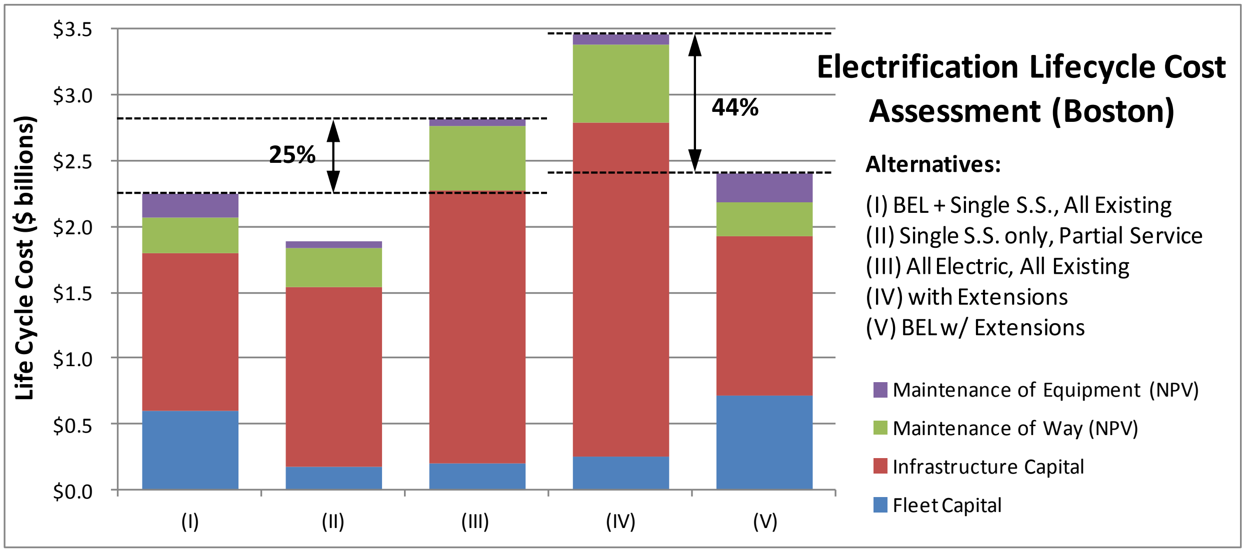


Figure 9. Summary of lifecycle cost analysis findings for Boston Northside case study.
Note: NPV=Net Present Value; S.S.=Supply Substation.

Adapting Battery-Electric Locomotives

Battery prototypes existing in 2022 (*4*) ride on two three-axle radial trucks, weigh 215 tons (36 tons per axle), and store 2.4 MWh of energy. Specification details for next-generation 7.2 MWh BELs are unclear at this writing (*48*), although being designed primarily for freight service, they might be quite heavy. This configuration is not optimal for commuter service, due to weight limitations on some commuter trackage, and because three-axle trucks may not ride well at commuter train speeds.

Commuter operations with BELs normally require locomotives to be charged while operating under catenary. Although most commuter runs do not require 7.2 MWh of energy, it is typically necessary to charge at rates of around 2.4 MW to pick up sufficient charge while power is available. As grid-scale batteries typically have a C/4 charging rate (*49*), enough cells need to be carried to provide charging bandwidth. Future battery technologies might improve on these capabilities (*50*).

With current technology, we expect a 4.8 MWh BEL could be carried on two two-axle trucks using an F-40-type chassis. For our simulations, we have assumed this configuration, with the necessary charging bandwidth being provided by two 4.8 MWh BELs with 1.2 MW of charging capacity each. Where they are situated in the consist does not affect the calculations.

We assumed this hypothetical 4.8-MWh BEL weighs 148 tons, the maximum weight generally allowable on two two-axle trucks, although further design work may result in higher energy capacities or lighter axle loads. These assumptions are intended to show what should be possible assuming current or near-future technology.

Various ideas have been proposed for realizing such a hypothetical 4.8 MWh BEL. One idea that went to the conceptual design stage (*51*) involves reclaiming retired F-40 locomotives and retrofitting batteries within the space formerly occupied by the prime mover. In fact, this appears to be the approach taken by the current Metra procurement (*1*). Another idea involved reclaiming retired AEM-7 locomotives and attaching an adjacent tender for batteries. Validating these proposals, which will require prototyping, lies outside of the scope of this research.

Strategy 3: Extend Service Beyond Existing Electrifications With BELs

The benefits of BELs are not limited to new-start electrifications. They can also serve areas heretofore without commuter rail service due to low ridership density, and expand into new territory without extending electrification.

Diesel service on Philadelphia's commuter rail system ended in 1981 for several reasons, including lack of funding, the need for electric propulsion through the Center City tunnel (which opened in 1984, replacing the above-ground Reading Terminal), and a lack of diesel maintenance facilities due to the institutional disaggregation of commuter and freight services (*52, 53*, *54* p. 63). However, communities formerly served have long expressed a desire for a return of rail service.

Markets Reached

We performed conceptual calculations (described in Methodology B, below) to determine the maximum range for BELs beyond existing electrifications, based on reasonable assumptions about consist size. The key markets of Pottstown and Quakertown, Pennsylvania, and Bound Brook, N.J., for connections to New York, could be served by BELs running round-trip services between these key destinations and Philadelphia 30th Street (Figure 10). However, the extended markets of Reading, Allentown, and Newark (N.J.) could not be reached – not because of insufficient battery capacity, but because trains would not spend enough time under the wire to recharge.

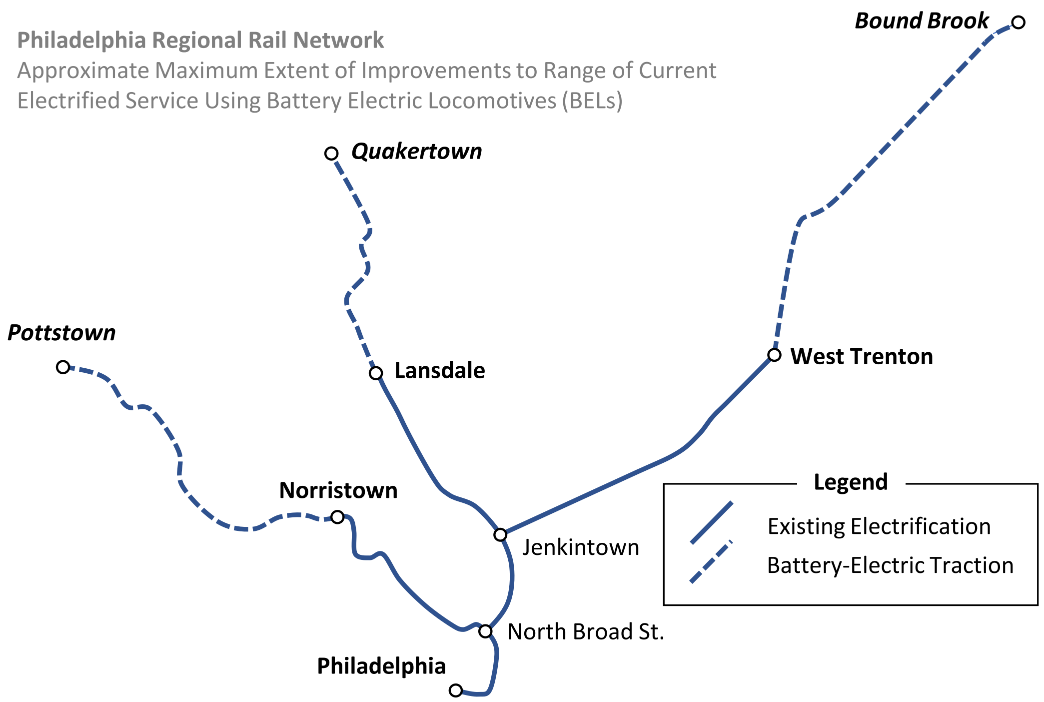


Figure 10. Philadelphia Reading-side case study: extension of existing electrification using BELs (Strategy 3).

Strategy 4: Use BELs to Create Trans-Regional Services Spanning Electrified Zones

Services in Philadelphia have been through-routed between end points on the former Reading and Pennsylvania Railroad (PRR) sides since 1984. PRR's extensive electrification offers BELs additional charging time. We performed further computations (Methodology B) and found that longer charging times would enable BELs to reach other key inter-regional markets beyond the normal commutershed. Regional services such as Harrisburg – West Trenton – Newark (N.J.) (H-W-N), Newark (Del.) to Allentown via Lansdale, and New York to Reading via Norristown are technically feasible (Figure 11).

Admittedly, these services are very speculative. The right-of-way north of Quakertown is today the Bucks County Rail Trail. However, as society works towards reducing GHG emissions, lines now seen as insufficiently promising may come into focus as we look for further ways to divert trips from private automobiles. Recent diesel rail planning studies have been conducted for all these corridors (*55-57*).

Implementation Issues

It might be necessary to reinforce electrical supplies, particularly on the ex-Reading Company (RDG) lines (*28*), to meet the power draw needs of BELs (which could peak at 5.0 MW per pair).

Structural engineering studies would determine if all infrastructure elements, particularly the 1992-1993 replacement for RDG's 9th Street Viaduct in North Philadelphia, can accommodate the weight of BELs as presently envisioned. Similar questions were previously raised regarding dual-mode equipment (*55* p. 4). The weight issue might also involve the elevated structure in Manayunk, between Philadelphia and Norristown. If so, this segment could be bypassed by diverting trains onto a freight line and an industrial track paralleling the elevated structure. Again, further study would establish what might be needed.

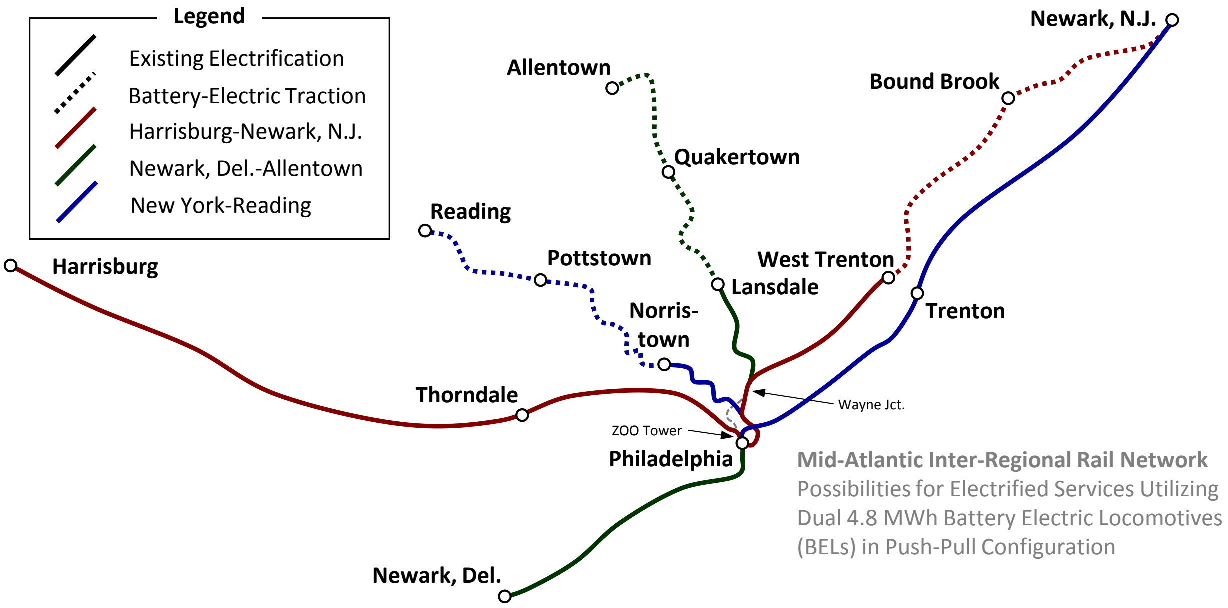


Figure 11. Mid-Atlantic Inter-Regional rail network showing BEL services (Strategy 4).

While RDG's 9th Street Viaduct was being rebuilt, diesel trains were operated via freight lines from Wayne Junction to the lower (Amtrak) level of 30th Street Station, Philadelphia via Zoo interlocking (*54* pp. 76-79). This would not work for commuter service (Strategy 3) because there would not be enough charging time under the wires (although electrifying one of the tracks between Wayne Junction and Belmont for the use of BELs might make this workable). For inter-regional services (Strategy 4), this route could be revived by reinstating a track connection at Zoo (*58*).

Lithium-ion batteries can catch fire due to mechanical abuse like impact and puncture, or electrical abuse such as overcharging (*59*). They can release toxic gases when burned, with the specific compounds released depending on battery chemistry (*60*). Certain chemical reactions in battery fires are not yet fully understood. Batteries are normally designed with redundant cooling systems to prevent chain reactions called "thermal runaways" that can cause fires to burn out of control, and charge management systems to prevent over-voltage conditions (*61*).

Special techniques in firefighting are required to control battery fires, which generally requires a large volume of water to be sprayed over a long period. The New York City Fire Department, through the U.S. Fire Administration, has promulgated guidance on these techniques (*62*). Although this is a relatively new field, experience from the automotive sector suggests that the overall risk of gasoline fires is nearly two orders of magnitude higher than battery fires (*63, 64*). Real-world BEL operating experience is necessary to understand the risks and develop best practices.

The Center City Commuter Connection (like other urban tunnels) has special fire protection requirements. The inadequate ventilation of the original design (based on the assumption that the tunnel would serve electrics only) currently restricts diesel operations. What restrictions might apply to BELs would have yet to be determined, although we assume for this strategy that BELs could be operated through the tunnel.

Matters of this nature are commonly associated with adopting new technologies. With the right incentives, sponsors, operators, and vendors will work together to solve them.

Operational Logistics

In addition to jurisdictional and institutional issues, logistical complications also come into play with trans-regional services. H-W-N service will likely be New York-oriented in market terms, but operationally it must be Philadelphia-based unless the Raritan Valley Line (between Bound Brook and Newark, N.J.) is electrified. Early morning trips to Newark will originate from Philadelphia rather than Harrisburg, which will require a 9.6 MWh BEL set to be fully charged overnight for each train. Advanced operational skills and perhaps computerized dispatching tools are needed for the movement bureau, to keep track of each BEL and its charge levels, ensuring that batteries are not depleted in service (see also Methodology D, below).

Figure 12 shows an artist's conception of inter-regional BELs operating over existing electrified infrastructure at Wayne Junction, hauling existing coaching stock where the BELs are serving as a drop-in replacement for what once might have been envisioned as a diesel service. Existing electric multiple-units will continue to provide most commuter services.

Figure 12. Medium-distance battery-electric trainset operating over existing electrification infrastructure in the Philadelphia area alongside a local electric multiple unit; artist's concept by John G. Allen.

BELs need not charge up only on catenary segments owned by their service sponsors. Trans-regional services transcend jurisdictional boundaries and are conceptually designed for BELs to have enough range to make services feasible. Agreements will be needed for electric power charges, perhaps with auditable net-use meters on BELs that show whose units are consuming how much power on which railroad, where, when, and for what purpose (e.g., propulsion, battery charging, or regenerating power to the wires). Back offices would then settle the charges via billing mechanisms like those for trackage rights, mechanical assistance, and equipment leases.

Strategy 5: Take Advantage of Co-Located Infrastructure

Strategy 2 works well for Boston Northside. But what about larger systems like Chicago's, where the distances between downtown terminals and most outer yards exceed the reach of a downtown substation?

To explore this issue, we first sought to prioritize lines in terms of their 2018 ridership, and then followed the supply-based strategy to situate substations for maximum coverage. Line-level data on ridership and passenger-miles are shown in Figure 14(A-B). Table 5 ranks Chicago's commuter lines by ridership intensity (millions of passenger-miles per route-mile) to identify promising opportunities. For comparison, Table 5 also includes the Electric District (electrified by the Illinois Central).

(A) Chicago % of ridership by line and by mile

(B) Chicago ridership count by line and by mile

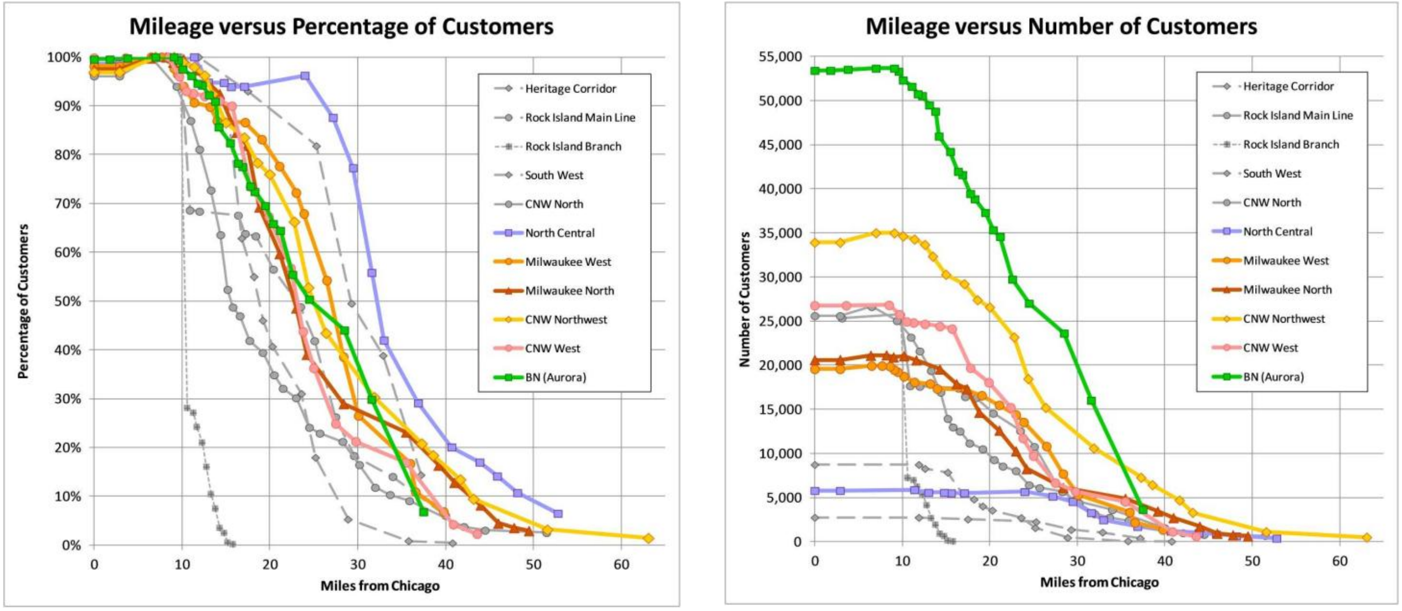


Figure 14. Commuter rail ridership statistics for Chicago showing visualization by line, station, and mileage, emphasizing lines selected for partial electrification case study.
Source: Metra Division of Strategic Capital Planning (*65* pp. 44, 47-49, *66*).

Table 5. Basic 2018-2019 data for evaluating Chicago electrification possibilities.

Line (Outer End)	Million Annual Passenger Trips	Million Annual Passenger Miles	Line-Miles	Average Trip Length (Mi)	Ridership Intensity *(A)*
BN (Aurora)	15.5	363.5	37.5	23.3	9.69
CNW West (Elburn)	8.0	178.2	43.6	22.2	4.09
CNW Northwest (Harvard)	10.5	259.8	70.5 *(B)*	24.7	3.69
Milwaukee West (Elgin)	6.0	145.4	39.8	24.2	3.65
Electric District (University Park) *(C)*	7.4	143.5	40.6 *(D)*	19.3 *(E)*	3.54
Rock Island District (Joliet)	7.4	147.9	46.6 *(F)*	21.2 *(G)*	3.18
Milwaukee North (Fox Lake)	6.5	143.7	49.5	22.8	3.03
CNW North (Kenosha, WI)	8.5	141.5	51.6	16.5	2.74
South West Service (Manhattan)	2.3	44.7	40.8	18.7	1.10
North Central Service (Antioch)	1.6	50.1	52.4	31.2	0.96
Heritage Corridor (Joliet)	0.7	19.7	37.4	27.2	0.53

Notes: BN = Burlington Northern. Milwaukee = ex-Chicago, Milwaukee, St. Paul & Pacific. CNW = Chicago & North Western. A – Millions of annual passenger-miles divided by line-miles. B – Includes 63.1 miles on the main line and 7.0 miles on the McHenry Branch. C – Electrified since 1926. D – Includes the South Chicago and Blue Island branches. E – This average includes shorter trips on the Electric District's two branches as well as the main line. F – Includes the Beverly branch. G – This figure, published by Metra, probably accounts for the average trip length on the main line only, i.e., without the Beverly Branch. With the Beverly Branch, the average trip length is 19.9 miles.
Source: (*65* pp. 44, 47-49)

Burlington Northern (BN)'s Chicago–Aurora line (the first in Table 5) jumps to the fore, not simply because it is Chicago's busiest line, but also because it has the most passenger-miles and stands far above all others in ridership intensity. This 37.5-mi line carries about as many riders as Caltrain does between San Francisco and Tamien, just beyond San Jose, California—a 52-mi line being electrified at this writing with two supply substations. A suburb southwest of Aurora has long sought an extension of service, despite being outside the commuter rail agency's service area.

Given the intensive Chicago–Aurora ridership, we sought to electrify the entire line with a single substation, enabling service with electric multiple-units (EMUs). Figure 15 shows an artist's conception of bi-level alternating-current EMUs operating on the Burlington Northern, with long pantographs to support shared-track operations with double-stack container trains.

Figure 15. Bilevel gallery electric MU cars operating on electrified infrastructure with clearances for double-stack container trains in Chicago; artist's concept by John G. Allen.

From there, we looked for other opportunities. Not far away lies the Chicago & North Western (CNW) West Line. Could we power both from the same substation?

As it turns out, the maximum range of 25kV catenary allows one substation to serve both lines. A 138kV transmission line runs parallel to the Tri-State Tollway (Interstate 294) in Elmhurst, Illinois (*67*). Putting a substation on a water-authority property (East Harrison St., Elmhurst) along the transmission line could provide 25kV power to both the Chicago and Aurora ends of the line (Figure 16), for 53,655 weekday trips (Table 6 and Figure 17). Of course, such a strategy would require negotiating an access agreement and lease with the utility company (comparable to a trackage rights agreement between railroads) and an intergovernmental agreement with the water authority. It is a fortuitous coincidence that the CNW West is the second most intensively traveled line in the system, but it was chosen not for its ridership but for its geographic ease of electrification.

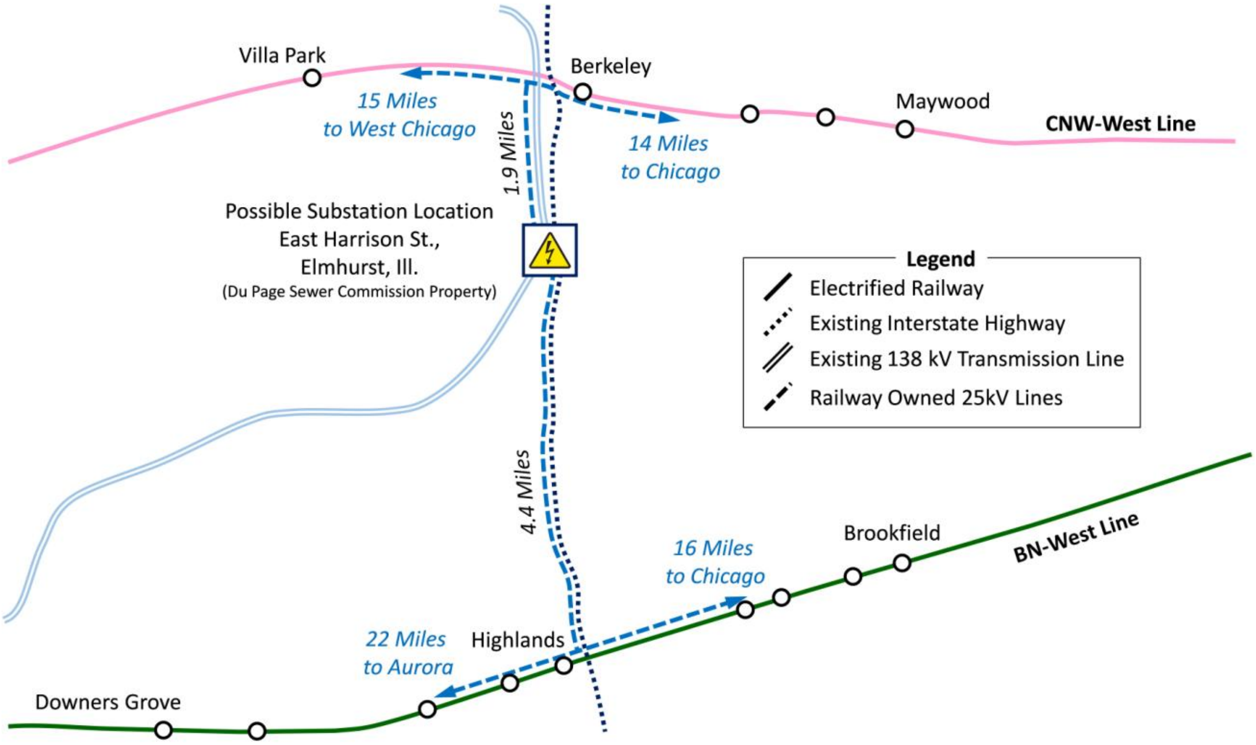


Figure 16. Chicagoland North and West case study, first phase: Elmhurst substation and suburban utility corridors.

Table 6. Electrification performance metrics for Chicagoland North and West case study.

Seq.	Line	Weekday Ridership	Ridership Receiving Electric Service	% Electric	% BEL	% Shuttle	Line Length (Miles)	Miles Electrified	% Electrified
1	BN (Aurora)	53,655	53,655	100%	0%	0%	37.5	37.5	100%
2	CNW West	26,821	22,284	83%	17%	0%	43.6	29.8	68%
3	CNW Northwest	34,993	27,716	79%	21%	0%	63.1	31.9	51%
4	Milwaukee North	21,156	16,259	77%	23%	0%	49.5	32.3	65%
5	Milwaukee West	19,944	18,581	93%	0%	7%	39.8	36.6	92%
6	North Central	5,792	1,334	23%	77%	0%	49.5	32.3	52%
	Total Chicago	**162,361**	**139,829**	**86%**	**13%**	**0.8%**	**286.3**	**195.3**	**68%**

Figure 17. Distance-ridership relationship for Chicago North and West case study.

For the CNW West, electrification could reach beyond West Chicago, but not as far as the next equipment yard at Elburn. Thus, straight electrics would operate as far as West Chicago (22,284 weekday trips, 83% of total ridership) and BELs to Elburn (4,537 trips, 17%). Thanks to existing utility corridors along the highway, it would be relatively straightforward to add an electrical feeder to reach both rail lines. We verified that BELs would have sufficient range to reach Elburn Yard using the energy assessment model noted previously (Methodology B).

Based on this electrification plan, it might be desirable to operate more frequent local service in the electrified zone, with BEL express trains that skip some stops traveling beyond. This is a normal part of schedule re-casting in response to capital investment. BEL trains may carry passengers locally within the electric zone based on ridership needs, much as New York's Wassaic or New Jersey's Bay Head trains do.

Suburban Utility Corridors

Utility corridors are reasonably common throughout North American metropolitan areas, but because they are not rail facilities, they are not always obvious solutions for commuter rail electrification. However, by routing railway-owned power lines within existing utility corridors, rail networks may be electrified at lower cost than by constructing substations for each line separately. The Department of Homeland Security has a geographic dataset showing most high voltage transmission lines and corridors in the United States (*67*).

Expanding on this approach, it may be possible to co-locate a supply substation near Deval, a crossing between CNW's Techny Cutoff freight line, CNW Northwest, and the North Central Service (NCS). The CNW Northwest is the third most intensively used line in the system and lies directly on the proposed Deval substation, making it an obvious candidate for electrification. We propose electrifying the CNW Northwest as far as Barrington, a major equipment storage point. BELs can operate beyond there in battery mode.

Deval is also served by existing 138kV transmission lines and utility corridors (Figure 18). What else can be electrified from Deval? The nearest major line is the Milwaukee North, which can be readily electrified to Rondout, north of Lake Forest, where space is available to site a yard (there is only one existing yard at Fox Lake, the outer end of the line). These core suburban markets on the CNW Northwest and the Milwaukee North would receive straight-electric service (77% and 79% of line ridership respectively), with one-seat rides to the outer suburban areas using BELs. The link between Deval and the Milwaukee-North uses an existing utility corridor that intersects the line in Morton Grove.

Figure 18. Deval Crossing, seen from a North Central Service train just north of the CNW Northwest Line, 1990, David Wilson photo (CC BY 2.0).

Figure 19 shows an artist's concept of a combination of an outer-suburban BEL-hauled train and inner-suburban EMUs operating on the CNW-Northwest Line near downtown Chicago (note the left-hand running characteristic of CNW).

Powering Additional Lines and Improving Resiliency

But the electrification opportunities involving Deval do not end with just those two lines. We can supply the Milwaukee West Line as far as Elgin, including the equipment storage yard, although not necessarily the remaining 3.2 miles to Big Timber. This was unfortunate, as the 7% ridership at Big Timber would have to be served by a battery-EMU shuttle. However, if a future regional service was developed, it might be possible to serve Big Timber with regional BEL trains (see Strategy 6).

Figure 19. Metra BELs pushing a rush-hour outer suburban express on the CNW-Northwest Line, passing an inner suburban EMU; artist's concept by John G. Allen.

We electrified the Milwaukee West aggressively, even though it has less slightly less ridership than the Milwaukee North, because it has no intermediate yards nor an obvious location for adding one. To have any electric service requires electrification to the outer-end yard at Elgin (an important destination in its own right).

Alternatively, depending on the findings of electrical engineering studies, the electrification range might be increased slightly, either by allowing a larger than normal voltage drop or marginally increasing the line voltage. The link from Deval to the Milwaukee West follows the existing Techny Cutoff railroad alignment. The link between the Elmhurst substation and the Milwaukee West uses Interstate 294 and an existing railroad between two major freight yards.

By having the electrification system's two primary substations on a "ring" around the metropolitan area, it provides a level of resiliency unavailable with other designs. Should one supply substation drop out for any reason, it may be feasible to supply all lines from the other substation through a cross-feed, perhaps subject to power reduction orders. This would need to be confirmed by detailed design calculations.

BN and Milwaukee West aside, the other lines have or could readily have intermediate yards, with sufficiently strong ridership beyond there to warrant BEL services directly from downtown. This allowed us to save significant catenary mileage. Because a combination of existing transmission lines and BN's particularly intensive ridership drove the substation location process, there was no obvious way to move the substation outward a few miles to accommodate the Milwaukee West all the way to Big Timber. Further study may suggest other locations that satisfy all other constraints while comfortably powering the entire Milwaukee West.

Having added Milwaukee West, it now makes sense to electrify the North Central Service (even though Table 5 ranks it next to last in ridership intensity) to Wheeling, based on daily diesel train-miles (DDTM) eliminated. From Wheeling, BELs can reach the outer terminal at Antioch. Although the NCS has a lower ridership density than the other lines, it shares tracks with the Milwaukee West between Tower B-12 and downtown, which in fact gives the NCS the highest electrification productivity of the six lines in terms of DDTM eliminated per catenary track-mile (Table 7). With just two substations, we can electrify one line fully, and most of five others, with much greater economy of investment than if we tried to electrify these lines in their entirety.

This demonstrates the network effect, where it becomes cheaper to add light-density branches (which would otherwise never justify electric service) to an existing network, if most lines are already electrified. Indeed, this may be Boston's strategy with the planned Fairmount Line electrification, by connecting new catenary to the Northeast Corridor's existing Sharon, Massachusetts supply substation.

Table 7. Comparative electrification productivity at line level, Chicago North and West.

Seq.	Line	Technology	Catenary Miles (CM)†	2019 Weekday Trains	Daily Diesel Train Miles (DDTM)*	Productivity (DDTM per CM)
1	BN (Aurora)	Straight Electric	113.3	97	3,022	26.7
2	CNW West (Elburn)	Battery-Electric	93.1	59	2,434	26.1
3	CNW Northwest (Harvard)	Battery-Electric	92.5	65	3,047	32.9
4	Milwaukee North (Fox Lake)	Battery-Electric	70.0	63	2,549	36.4
5	Milwaukee West (Elgin)	Straight Electric	70.0	58	1,936	27.7
6	North Central (Antioch)	Battery-Electric	27.5	22	1,162	42.3

Notes: Excludes deadhead mileage. † - Estimated from track charts found at (*68*). Excludes Chicago terminals and equipment storage yards. * - Estimated based on publicly available information.
Source: 2019 weekday trains from (*69*).

Table 8 shows our working service plan assumptions for all six lines in the Chicago North and West case study. At first, electric locomotives in push-pull mode would be used to provide service with existing coaches, but depending on their remaining useful service life, EMUs may eventually replace them on the BN Line and on inner-suburban segments elsewhere with high ridership densities. Figure 20 shows all the lines to be electrified, with supply substation and feeder line locations.

Table 8. Operating and service plan details for Chicago North and West case study.

Line	Service Plan
BN (Aurora)	Replace current diesels with electric locomotives. As coaches becomes life-expired, replace them with EMUs. Recast schedules to take advantage of better capabilities of electric locomotives and/or EMUs.
CNW West (Elburn)	Electric locomotives with existing coaches will be assigned to do the bulk of the work between West Chicago and downtown. Schedules would be regularized as necessary. The remaining demand west of West Chicago will be carried by BEL expresses, with expresses stopping at busier stations within the electric zone as appropriate to optimize use of carrying capacity.
Milwaukee West (Elgin)	All trains replaced by electric locomotive-hauled trains, terminating one stop short at Elgin rather than Big Timber. Trains at Elgin are met by battery-electric multiple-unit shuttles from Big Timber with passengers making cross-platform transfers. No BELs used on this line. Shuttles are charged whilst stabled between runs at Elgin.
CNW Northwest (Harvard)	BELs will provide important express trips from Harvard and McHenry. Electric locomotives will operate local trips as far as Barrington. Electric trains to be stored on the mainline between Palatine and Barrington as diesel trains do at present.
Milwaukee North (Fox Lake)	BEL expresses will provide important express trips from Fox Lake. Electric trains will terminate at Lake Forest and be stored in a new yard at Rondout. If there is insufficient ridership to justify any separate off-peak local service, the BEL trains will make all local stops.
North Central (Antioch)	BEL trains to make all current diesel trips between Antioch and Chicago.

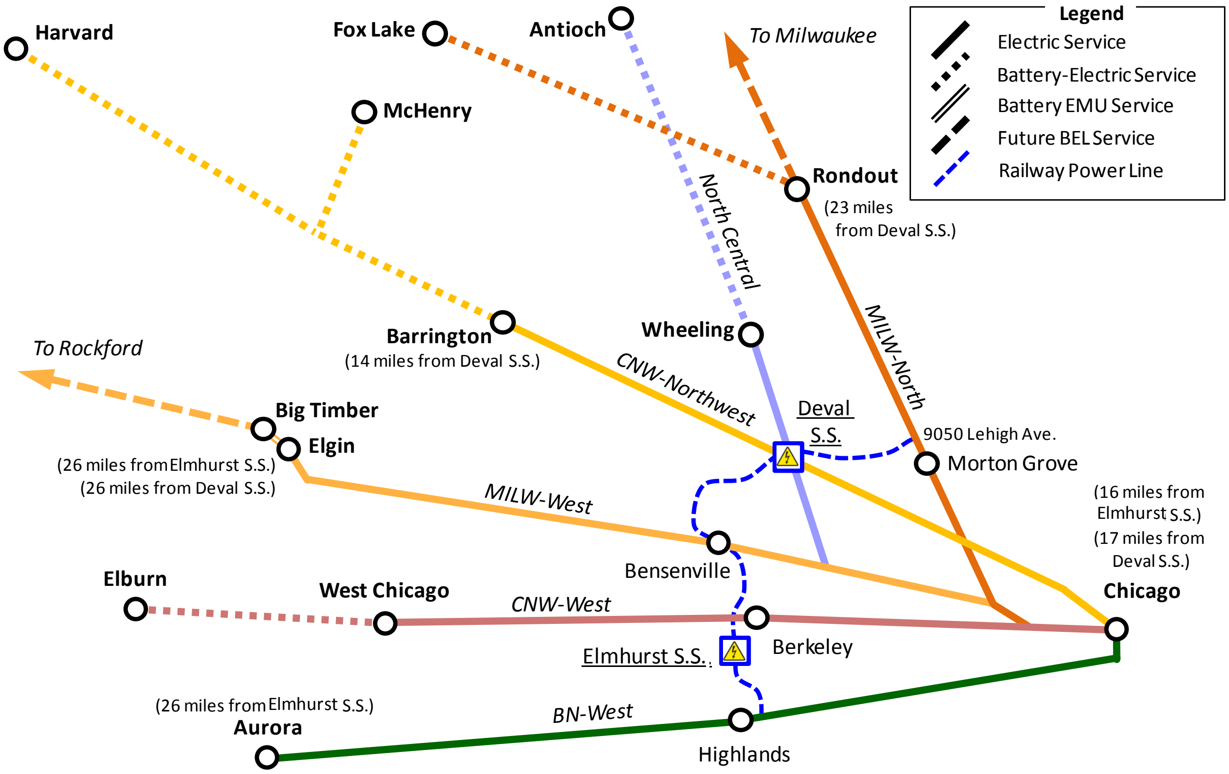


Figure 20. Chicagoland North and West case study, second phase: feasible extent of electrification from two supply substations.

Strategy 6: Charging Pads

Another option is to build "charging pads" at outlying terminals to charge batteries during layover periods, further reducing the track mileage requiring electrification. This makes sense when suitable transmission substations are relatively close to outlying yards, such that one or two dedicated 11.3kV three-phase distribution circuits can be brought in to provide 3.0/6.0 MW of charging capacity. Charging pads can also extend an existing installation's effective range, at the expense of reducing trainset utilization due to the unproductive downtime when sets are held to charge at rest.

One possible use case for a charging pad is where BELs are used on commuter lines with no weekend service. Fairly substantial shore-power supplies would be required to keep head-end power (HEP) on in the coaches during weekend layovers (to avoid draining power from the BEL). In terms of power rating, shore-supplies required for several stabled sets can be comparable to a charging pad. Figure 21 summarizes situations where charging pads are and are not needed for trains worked on a commuter rail service pattern.

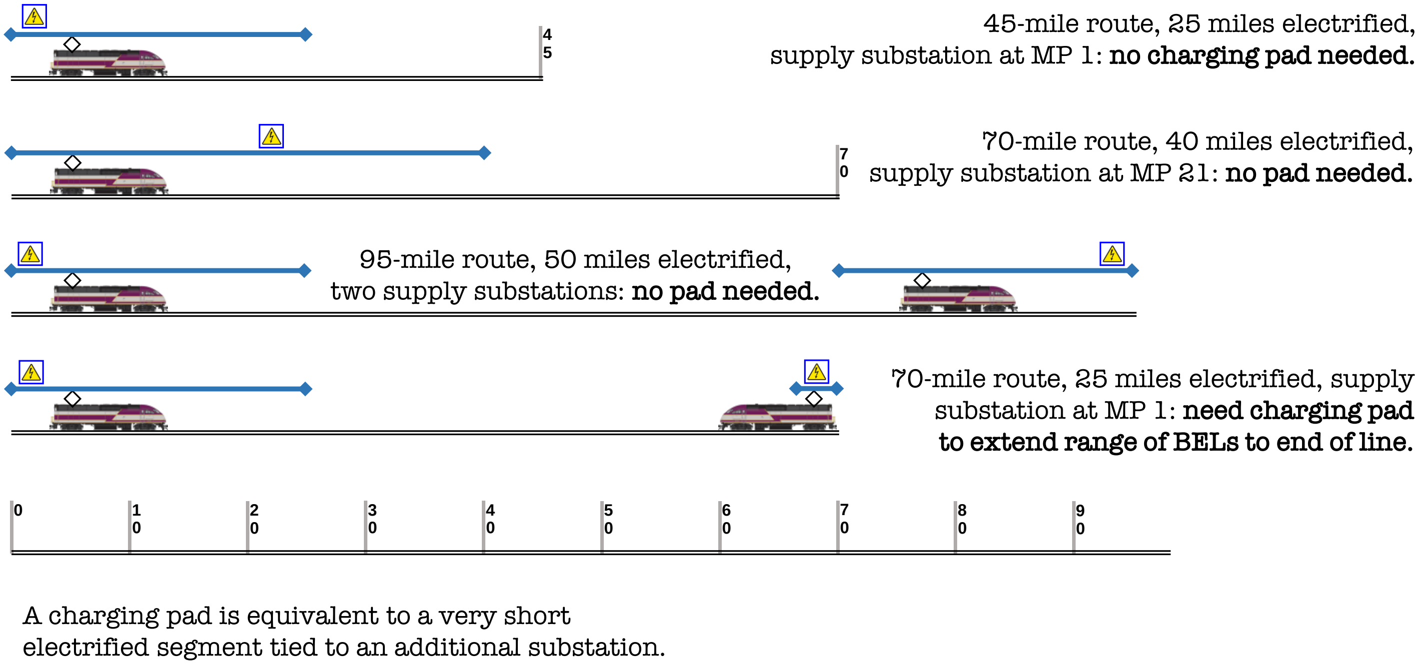


Figure 21. Suitability of charging pads with BELs in commuter service.

Charging pads are most likely to find their ideal applications in regional services that extend beyond the normal daily commutershed, where the distances involved mean that locomotives cannot make an out-and-back trip on one charge, but the service does not terminate in a large metropolis with its own commuter rail system that justifies its own electrification. In busy suburban service, which is the subject of this paper, it is almost always better to extend the electrification marginally beyond the current terminus, to avoid fragmenting the network and avoid having to construct an expensive substation purely for supplying a charging pad, when the budget for that substation could be better invested in incrementally extending the existing electrified network, which will have a higher expected utilization.

Potential Applications to Regional Services

Logistical arrangements from regional services are different from suburban services; it may be necessary to supply fully-charged BELs prior to departure, necessitating extended turnaround times at both the city end and the outer terminus. Two fully-charged 4.8 MWh BELs with 350 tons of trailing load traversing average terrain with average curvature will have a range of about 200 miles, but to avoid stranding passengers the useful range is likely to be capped at 120 miles by operations management.

Table 9 shows some rules-of-thumb for planning purposes as to when charging pads will be needed when planning BEL-hauled services, although because BELs' actual range can be sensitive to terrain, curvature, and payload, plans made based on these criteria should be subject to further verification (using Methodology B, below).

Table 9. Rules of thumb for planning operating ranges of BEL-enabled services

Service Type	**Trainset Utilization Pattern**	**Charging Pad at the Outer End?**	**Miles Operated Under the Wires**	**Maximum Range of BELs Beyond Electrification Limits***	**Maximum Range of Train Service**
Commuter	Trainsets operate in out-and-back service with minimal turnaround time at each terminal	No	*n* Miles	*n* Miles, or 60 Miles, whichever is lower	*2n* Miles, or *n*+60 Miles, whichever is lower
Commuter	Trainsets operate in-and-back-out service with minimal turnaround time at the city terminal, held to charge at the outer end to ensure sufficient energy to reach the limits of electrification	Yes	*n* Miles	*2n* Miles, or 120 Miles, whichever is lower	*3n* Miles, or *n*+120 Miles, whichever is lower
Regional	Sets held at city terminal or utilized in electric shuttle service to provide a full charge (9.6 MWh) when outbound trains leave electrified section, and are turned immediately at the outer end	No	*n* Miles	60 Miles	*n*+60 Miles
Regional	Sets held to provide a full charge (9.6 MWh) upon exiting electrified section and again before leaving charging pad	Yes	*n* Miles	120 Miles	*n*+120 Miles
Inter-Regional*	Sets held or interlined to provide a full charge (9.6 MWh) when leaving both electrified sections	N/A†	*(m+n)* Miles	120 Miles	*(m+n)*+120 Miles

Notes: This table takes a conservative view of energy adequacy, meaning that a passenger train stranded with an out-of-energy BEL is considered a major operating exception. Where the authority desires to take more operating risks, the full-charge range can be extended to 90 miles and 180 miles respectively.

*Applies where there is electrified commuter service at both ends of the route. †A charging pad need not be provided when both urban ends of the service have commuter-based electrification (i.e. Strategy 4). *m*=Applies to inter-regional services with commuter electrifications at both ends, with *m* representing the electrified line-miles at the city not covered by the variable *n*. *n*=Number of electrified line-miles at the city end.

We performed no modelling to verify these use cases, but below are some random examples of potential markets for charging pad-enabled regional services. Charging pads are of limited help for commuter services because of the need for short turnaround times at the termini.

- **New Haven, Connecticut—Greenfield, Massachusetts:** 100 miles—To eliminate the GHGs associated with this existing diesel-operated service (which has been extended north of Springfield, Massachusetts), BELs can be charged on the existing electrification at New Haven and a new charging pad at Greenfield during layovers.
- **Pittsburgh—Greensburg—Altoona, Pennsylvania:** 114 miles—the first 24 of which would be subject to Strategy 2 electrification. Regional trains would run the remaining 90 miles in battery mode and recharge at the Altoona charging pad. BELs would also be used in commuter service to reach Greensburg and Latrobe (31 and 40 miles, respectively, from Pittsburgh).

Chicago North and West Regional Service

In Strategy 5, we electrified the Milwaukee District as far as Rondout and Elgin, the maximum prudent extent based on two supply substations located in suburban Chicago required to support commuter service. If we assumed regional service patterns of trainset utilization, how much further can we push out the service and what other infrastructure would we need to support them?

Figure 22 shows a summary of what services are possible. Rondout is 32 miles from Chicago Union Station (CUS). The remaining 54 miles to Milwaukee can be covered on a round-trip basis by fully charged BELs leaving the electrified district northbound at Rondout. By operating the equipment strictly on an out-and-back basis, we find that the regional service to Milwaukee is possible without any additional infrastructure. However, if service was extended the 70 miles beyond Milwaukee to Fond du Lac, Wisc., it would be necessary to install a charging pad there, because the 124 miles between Rondout and Fond du Lac is at the upper limit of a one-way trip with fully-charged BELs. Similarly, Madison is 107 miles from Rondout. A charging pad at Madison would enable service (artist's concept, Figure 23) to be operated to and from Chicago via Rondout.

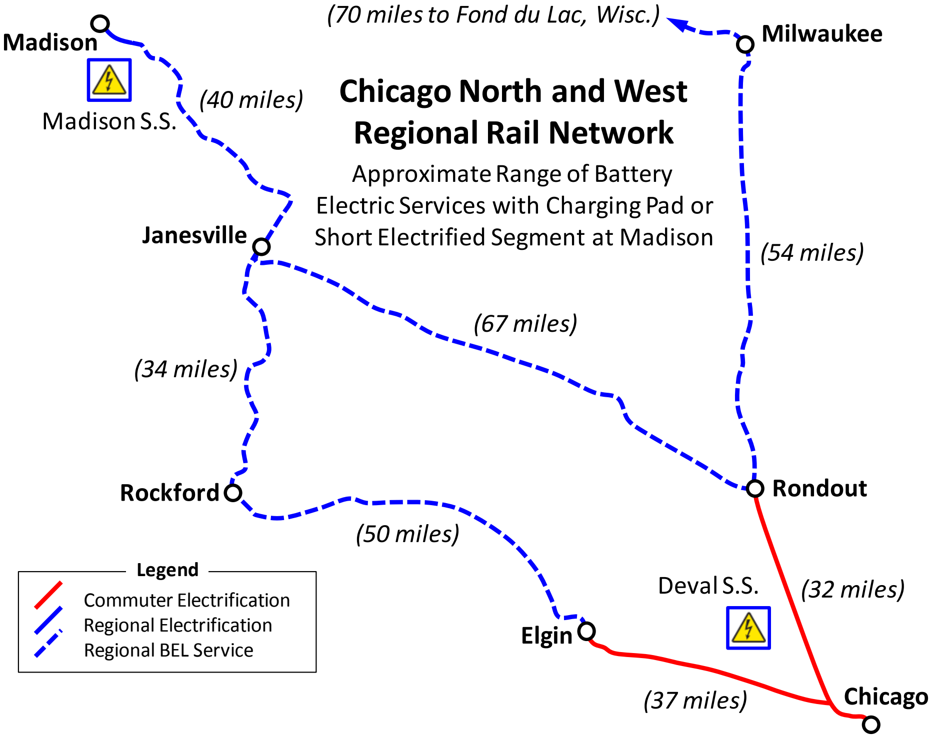


Figure 22. Chicagoland North and West case study, regional rail phase: feasible extent of electrification from existing regional rail electrification and one or two charging pads.

Figure 23. A battery-electric trainset leaves downtown Madison en route to Chicago. Artist's concept by John G. Allen.

Elgin is 37 miles from CUS. The remaining 50 miles to Rockford can also be covered by BELs on a round-trip basis. However, a string of municipalities in the Rock River Valley between Rockford and Janesville may also desire service to Chicago. To provide service on that corridor, it would be necessary to operate the train to Janesville via Rockford. At that point, the train is 85 miles from Elgin and unable to return to Chicago on a round-trip basis. It is therefore necessary to operate the service to Madison, to use the charging pad.

A side effect of the infrastructure design is thus that Madison-Janesville segment receives a higher frequency of service. Based on the ridership patterns, it is quite possible that at least some of the service will short-turn at Rockford (via Elgin). To further improve trainset utilization, we could use the BEL sets to run commuter round trips to/from Elgin or Rondout during the time when they would otherwise be held at CUS for charging.

"Twin Cities to Twin Ports" Regional Service

How far can we really go with the judicious use of charging pads? Minneapolis-St. Paul has a relatively small Metropolitan Statistical Area population (3.69 million as of the 2020 Census), but it does have one commuter rail line between Target Field in downtown Minneapolis and Big Lake, Minnesota. Local plans call for an extension to St. Cloud in the future. If we assume a Strategy 5 electrification in the Twin Cities, what services can we run in conjunction with Strategy 6?

St. Cloud is 59 miles from Coon Rapids, which is 13 miles from Minneapolis. Minneapolis is a further 12 miles from St. Paul. If we treat the St. Cloud service as a regional train, where we ensure the BELs are fully charged before leaving downtown, it is actually possible to run this service out-and-back between St. Paul and St. Cloud. We could also operate every other trip as a Coon Rapids shuttle, which would double the service frequency on the busiest segment of the line between there and St. Paul and, allow the trainset to earn revenue whilst charging.

Duluth is 140 miles from Coon Rapids, which is too far for the current BELs even if we install a charging pad there. However, if we situate the substation required for Strategy 5 electrification in Coon Rapids, we can electrify a further 21 miles between there and Athens, Minn. This would allow the regional BEL service to run the 119 miles to reach the charging pad in Duluth.

Thus, in this case, we will have completely electrified an Eastern Minnesota suburban and regional rail network with just two substations, and 44 miles of catenary (Figure 24): Athens-Coon Rapids (21 miles) for the regional service, Coon Rapids-St. Paul (21 miles) for the commuter service, and a two-mile spur between Minneapolis Junction (Harrison St.) and Target Field. BELs are extremely infrastructure-efficient in low-density areas such as this (see Methodology E, below).

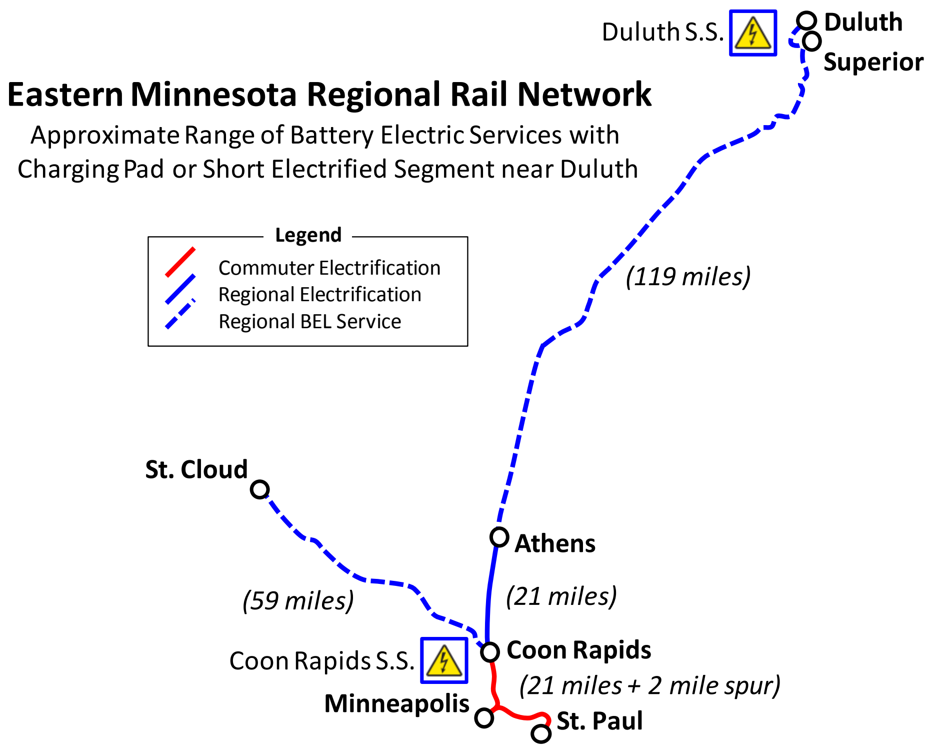


Figure 24. Eastern Minnesota regional rail network: feasible extent of electrification using a single substation at Coon Rapids and a single charging pad at Duluth.

ANALYTICAL METHODOLOGIES AND RESULTS

The following section provides a technical discussion of the analytical methods used to support the analysis of the six strategies.

Methodology A: Ridership Analysis and Visualization

To identify the busiest line segments, we used a visualization technique to plot weekday passenger loads on each line segment against mileages from downtown (Figures 4 and 14). This allows us to visualize how many passengers would travel entirely within the electric zone if we terminated it at a given station, and how many would cross the zone boundary. We also plotted the data in percentage terms, because a small number of customers may still be a substantial fraction of total ridership on a given line.

In each case we plotted the candidate lines for electrification in colour, and other diesel lines in the same metropolitan area in grey, to establish their relative suitability for BEL-enabled electrification (e.g., relatively high ridership density), although by no means was ridership the only consideration for inclusion in the case study schemes.

Operating considerations such as existing yard locations, combined with substation location and 25kV transmission limits, may ultimately dictate the extent of electrification. But this visualization helped us to make decisions about initial substation siting and whether a single centrally-located substation or multiple outlying substations would be best. The key consideration is the distance beyond which demand density falls sharply (if it is within the 25-mile threshold based on 25kV substation reach)—and whether the demand density/distance relationship is linear (e.g. Figure 4, Providence Line; Figure 14, BN-Aurora Line), or significantly non-linear with plots showing either a characteristic S-shape (e.g. Figure 4, Newburyport/Rockport Lines), or a classic L-shape (e.g. Figure 14, CNW-North Line and South West Service). Lines whose travel demands are concentrated in the inner suburban portions are better candidates for partial electrification.

These visualizations also helped with choosing between a local battery EMU shuttle and a direct BEL train from downtown when developing operating plans. If there is substantial ridership beyond electrification limits, then a direct BEL train is considered. Otherwise, the service is relegated to a connecting shuttle.

If the policy goal is to reduce GHG emissions rather than to improve service or reduce costs, ridership density alone should not drive electrification decisions. Electrification productivity, such as daily diesel train miles per catenary mile shown in Table 7, which is ultimately a rough proxy for GHG reduction per dollar invested, is a much more useful indicator with which to evaluate proposals.

Methodology B: Energy Assessment for Service Feasibility and Market Scan

This analysis determines, at a strategic level, how many (existing or proposed) commuter rail corridors could benefit from partial electrification in conjunction with BELs. In selecting corridors to examine, we chose from the following situations:

1. Existing electrified commuter rail corridors where communities have sought to extend services beyond existing electrified zones. This includes situations where services formerly existed.
2. Hypothetical new-start electrifications where diesel services currently exist, but an electrification strategy would reduce GHG emissions.

Based on each corridor's basic service characteristics, we computed the minimum time available for charging the two 4.8 MWh locomotives during a round trip, from entering the (new or existing) electrified zone inbound, to leaving it outbound. Available power leaving electrified territory was based on a combined locomotive capacity of 9.6 MWh (and a C/4 maximum combined charging rate of 2.4 MW). We conservatively assumed that whenever a locomotive was actively accelerating, the battery could not be charged, to avoid exceeding the 4.0 MW substation limit of typical suburban electrifications. It should be possible to configure the circuitry aboard BELs to prevent recharging while drawing power for traction.

Through these calculations, we found BELs to be feasible on 32 distinct services in the Boston, New York, Philadelphia, and Chicago areas. Table 10 shows detailed results in terms of battery power, train ascent and descent, rolling, curving, accelerating and braking requirements, parasitic loads, charging pad requirements at outer endpoints, energy sufficiency, and capacity for degraded operations. The calculations show the feasibility of operating the various proposed services using BELs under conditions of partial electrification. Interestingly, our findings suggest that it should be feasible to use BELs between Boston South Station and Needham, Massachusetts, even though less than half of this route is on the electrified Northeast Corridor.

We made reasonable assumptions about typical worst-case rates of grade, curvature, and other physical characteristics (see notes, Table 10). We normally assumed a worst-case commuter rail consist of two 148-ton locomotives with seven 135,000-lb coaches each drawing a parasitic load of 40 kW, although in some cases we scaled back the consist for particularly curvaceous or long routes. These were fed into aggregate formulas that provide cumulative outputs of a Train Performance Calculator (TPC) without having to simulate each linear foot of track. Trains were generally assumed to run express through the electrified zone, and as locals elsewhere.

We separately computed the energy required to lift trains uphill, overcome rolling and curving resistance, and accelerate from station stops, using industry standard formulas. Additionally, taking maximum battery charging rates and regenerative braking efficiency into account, we calculated energy recoverable from descending grades and braking to station stops.

This was not a true TPC exercise, because it was not feasible to collect detailed physical characteristics for all these lines. This methodology should be understood as predicting what a detailed TPC would likely report in the worst case, based on assumptions informed by the authors' experience. Operators studying given networks should undertake detailed TPC and preliminary engineering analyses, during which they can also examine additional options such as electrifying segments other than immediate approaches to the downtown area and consider alternative supply substation sites.

Operating BELs on Legacy Electrification Infrastructure

Although the Boston and Chicago cases presume 25kV electrification, we found partial electrification to be feasible with the 12.5kV systems used in much of the Northeast Corridor, and potentially even with low-voltage third-rail systems. However, the lower the voltage, the more current is needed to provide the same power. Excessive current draw should be avoided so as not to exceed substation and traction return capacity.

The desirability of 25kV for new-start electrification – with or without BELs – lies in its greater electrical efficiency. The higher voltage allows railroads to electrify more line-miles with fewer substations. Generally, the lower voltages found on legacy installations should not affect the feasibility of using BELs, as the Philadelphia-based examples (Strategies 3 and 4) suggest.

Table 10. Battery-electric locomotive energy assessment model outputs

Basic Service Characteristics

ID	Line Name	Service Origin	End of Electrification	Service Terminus	Basic Service Characteristics					
					(A)	**(B)**	**(C)**	**(D)**	**(E)**	**(F)**
1	Hudson	New York	Harmon	Poughkeepsie	33	39	4	10	60	70
2	Harlem	New York	Brewster	Wassaic	53	30	7	7	60	70
3	Danbury	New York	Norwalk	Danbury	40	24	3	7	70	50
4	Waterbury	Stamford	Devon	Waterbury	28	29	3	6	70	40
5	Greenport	Penn Station	Ronkonkoma	Greenport	49	45	7	6	75	45
6	Montauk	Penn Station	Babylon	Speonk	37	34	2	9	75	60
7	Stoughton	South Station	Canton Jct.	Stoughton	15	4	8	2	70	40
8	Needham	South Station	Forest Hills	Needham	5	9	4	8	70	40
9	Franklin [11]	South Station	Readville	Franklin	9	21	4	10	70	40
10	Quakertown	Philadelphia	Lansdale	Quakertown	24	16	8	6	40	40
11	West Trenton	Philadelphia	West Trenton	Bound Brook	32	27	8	5	50	60
12	Pottstown	Philadelphia	Norristown	Pottstown	18	23	7	6	40	40
14	Harrisburg/Newark	Harrisburg	West Trenton	Newark NJ	135	52	20	8	60	60
15	Newark/Allentown	Newark, Del.	Lansdale	Allentown	63	37	18	10	60	45
16	Reading/New York	Penn Station	Norristown	Reading	108	41	29	9	80	45
17	Hackettstown	Hoboken, N.J.	Dover	Hackettstown	43	17	4	5	60	45
18	Montclair-Boonton	Penn Station	Montclair S.U.	Dover	24	19	7	8	40	40
19	Jersey Coast	Penn Station	Long Branch	Bay Head	51	16	11	9	60	50
20	Lowell/Manchester	North Station	Lowell	Manchester NH	26	30	7	3	55	50
21	Haverhill via Wildcat	North Station	Andover	Exeter NH	23	27	5	7	45	50
22	Newburyport	North Station	Salem	Newburyport	17	19	6	6	45	50
23	Newburyport	North Station	Salem	Rockport	17	19	6	7	45	50
24	Fitchburg	North Station	South Acton	Wachusett	25	28	9	6	40	45
25	Middleboro/Lakeville	South Station	Randolph	Middleborough	15	21	5	10	45	45
26	Plymouth/Kingston [12]	South Station	S. Weymouth	Plymouth	16	21	5	8	45	45
27	Greenbush	South Station	Wey. Landing	Greenbush	12	17	3	9	45	45
28	CNW-West	CNW Station	West Chicago	Elburn	30	14	14	4	60	60
29	CNW-Northwest	CNW Station	Barrington	Harvard	32	31	15	7	60	60
30	CNW-Northwest	CNW Station	Barrington	McHenry	32	19	15	5	60	55
31	MILW-North	Union Station	Lake Forest	Fox Lake	28	21	14	8	60	55
32	North Central Service	Union Station	Wheeling	Antioch	27	26	9	9	60	50

Columns: (A) = Miles Electrified [1]; **(B)** = Miles Diesel [1]; **(C)** = Stations Electrified [2]; **(D)** = Stations Diesel [3]; **(E)** = Speed in Electrified Territory (mph); **(F)** = Speed Diesel Zone (mph);

Assumptions: [1] Electric mileage is always rounded down, and diesel mileage rounded up, to provide a worst-case scenario estimate; [2] Assumes a service pattern that may or may not currently exist, of a skip-stop express in the inner suburban portion of the route; [3] Reasonable assumptions about station stops made in portions of the line currently has no direct service; [11] Assuming service operated via the NEC with appropriate arrangements at Readville; [12] Includes two-way switching movement to and from coach yard.

Geography Key: (1)-(6) = Greater New York; (7)-(9) = Boston Southside Existing Installations; (10)-(12) Philadelphia Regional Rail; (14)-(16) Inter-Regional Rail Northeast; (17)-(19) = New Jersey; (20)-(24) Boston Northside Strategy 2 electrification; (25)-(27) Boston Old Colony Strategy 2 electrification; (28)-(32) Chicago North and West Strategy 5 electrification. CNW = Chicago & North Western.

Table 10. Battery-electric locomotive energy assessment model outputs (continued)

Available Battery Power, Coach Weight, Ascent and Descent Energy Requirement Calculations

	Available Battery Power Calculations						Tons	Climbing and Descent Energy Calculations						
ID	**(G)**	**(H)**	**(J)**	**(K)**	**(L)**	**(M)**	**(N)**	**(P)**	**(Q)**	**(R)**	**(S)**	**(T)**	**(U)**	**(V)**
1	0:39	0:04	0:20	1:47	4.29	N	350	200	350	15.6	802	-1.0	100%	-272
2	1:03	0:07	0:20	2:41	6.45	N	350	475	833	12.0	617	-3.1	76%	-494
3	0:41	0:03	0:20	1:48	4.33	N	350	380	666	9.6	691	-2.2	100%	-517
4	0:28	0:03	0:30	1:33	3.74	N	350	459	805	11.6	1,044	-1.8	100%	-625
5	0:47	0:07	0:20	2:08	5.12	N	338	300	516	18.0	1,440	-0.8	100%	-400
6	0:35	0:02	1:00	2:15	5.40	N	405	200	380	13.6	816	-1.1	100%	-295
7	0:15	0:08	0:20	1:06	2.67	N	473	63	132	1.6	144	-2.1	100%	-102
8	0:05	0:04	0:20	0:38	1.53	N	473	143	297	3.6	324	-2.1	100%	-231
9	0:09	0:04	0:20	0:46	1.86	N	350	333	583	8.4	756	-1.8	100%	-452
10	0:43	0:08	0:20	2:02	4.90	N	473	253	528	6.4	576	-2.1	100%	-410
11	0:46	0:08	0:20	2:08	5.13	N	473	428	892	10.8	648	-3.2	75%	-518
12	0:32	0:07	0:20	1:38	3.95	N	473	364	759	9.2	828	-2.1	100%	-589
14	2:42	0:20	0:05	6:09	9.60	**Y**	350	819	1,435	20.7	1,241	-2.7	89%	-993
15	1:15	0:18	0:05	3:11	7.66	N	350	584	1,024	14.8	1,181	-2.0	100%	-795
16	1:36	0:29	0:05	4:16	9.60	**Y**	350	653	1,144	16.5	1,318	-2.0	100%	-887
17	0:51	0:04	0:30	2:21	5.65	N	473	269	561	6.8	544	-2.4	100%	-435
18	0:43	0:07	0:20	2:00	4.82	N	473	301	627	7.6	684	-2.1	100%	-487
19	1:01	0:11	0:20	2:44	6.58	N	473	75	156	6.4	461	-0.8	100%	-121
20	0:33	0:07	0:20	1:40	4.03	N	350	475	833	12.0	864	-2.2	100%	-646
21	0:36	0:05	0:20	1:43	4.15	N	300	433	700	10.9	787	-2.1	100%	-543
22	0:26	0:06	0:20	1:25	3.43	N	350	307	538	7.8	559	-2.2	100%	-418
23	0:26	0:06	0:20	1:25	3.43	N	350	293	513	7.4	533	-2.2	100%	-398
24	0:45	0:09	0:20	2:09	5.16	N	350	675	1,182	11.4	909	-3.0	79%	-727
25	0:24	0:05	0:20	1:18	3.12	N	350	326	572	8.2	659	-2.0	100%	-444
26	0:25	0:05	0:20	1:20	3.22	N	350	337	591	8.5	682	-2.0	100%	-459
27	0:18	0:03	0:20	1:03	2.55	N	350	274	480	6.9	554	-2.0	100%	-373
28	0:35	0:14	0:20	1:59	4.77	N	424	227	442	5.7	343	-3.0	80%	-275
29	0:37	0:15	0:20	2:05	5.02	N	424	496	968	12.5	751	-3.0	80%	-601
30	0:37	0:15	0:20	2:05	5.02	N	424	295	575	7.4	487	-2.7	87%	-390
31	0:33	0:14	0:20	1:55	4.64	N	424	336	655	8.5	555	-2.7	87%	-444
32	0:32	0:09	0:20	1:43	4.13	N	424	406	791	10.2	737	-2.5	96%	-590

Columns: (G) = One-way run time (hh:mm) in electrified zone at maximum authorized speed [4]; **(H)** = Dwell time (hh:mm) at outlying stations [5]; **(J)** = City terminal minimum equipment dwell time (hh:mm); **(K)** = Available charging time (hh:mm, round trip); **(L)** = Available energy entering non-electrified territory (MWh) [6]; **(M)** = Locomotive capacity 9.6 MWh exceeded? (Y/N); **(N)** = Coach tonnage; **(P)** = Elevation gain to summit (ft) [7]; **(Q)** = MJ of energy to lift train; **(R)** = Miles in descent; **(S)** = Seconds in descent; **(T)** = Energy release rate (MJ/s = MW); **(U)** = % of recapturable energy; **(V)** = MJ of energy recyclable during descent.

Assumptions: [4] Time spent accelerating from each station stop is not available for charging batteries due to concerns about substation loading. Schedule padding = 20%; [5] Dwell time per station = 1 minute; [6] Maximum charging rate = 2.40 MW = C/4 on a 9.6 MWh locomotive (i.e. 4 hours to charge to 100%), for two 4.8 MWh locomotives the charging rate is twice 1.2 MW; [7] Worst case, assumes a steeply-graded route in the diesel segment (assumed average gradient for all uphill segments = 0.30%). This obviously will not be true for every route. Adjusted manually where appropriate; Acceleration due to gravity = 9.81 m/s/s; Dynamic brake efficiency = 97%; Assumed % of mileage in descent = 40%; Gradient variability factor = 3; Assumed cumulative curvature per mile (degrees) = 1.00; Typical achievable braking rate = 1.00 mph/s.

Table 10. Battery-electric locomotive energy assessment model outputs (continued)

Rolling, Curving, Acceleration, Braking, Parasitic Load Energy Calculations

	Rolling	Curving		Acceleration		Braking					Parasitic Load		Charging Pad	
ID	**(W)**	**(X)**	**(Y)**	**(Z)**	**(AA)**	**(AB)**	**(AC)**	**(AD)**	**(AE)**	**(AF)**	**(AG)**	**(AH)**	**(AJ)**	**(AK)**
1	1,363	15	2,152	284	2,836	-2,751	70	-4.1	59%	-1,630	2:36	0.73	**Y**	1.6
2	1,049	20	2,207	284	1,985	-1,926	70	-4.1	59%	-1,141	2:06	0.59	N	0
3	536	24	2,119	145	1,013	-983	50	-2.9	83%	-815	2:12	0.62	N	0
4	508	29	3,093	93	556	-539	40	-2.3	100%	-539	2:37	0.73	**Y**	1.6
5	737	20	3,246	115	690	-669	45	-2.6	94%	-629	3:10	0.63	N	0
6	888	20	2,714	226	2,035	-1,974	60	-3.8	64%	-1,257	2:33	0.61	N	0
7	74	4	70	110	220	-214	40	-2.8	87%	-186	1:02	0.29	N	0
8	165	9	354	110	881	-855	40	-2.8	87%	-745	1:47	0.50	N	0
9	368	21	1,622	93	926	-898	40	-2.3	100%	-898	2:33	0.71	**Y**	1.6
10	294	16	1,120	110	661	-641	40	-2.8	87%	-559	1:58	0.55	N	0
11	789	20	2,363	248	1,239	-1,202	60	-4.1	58%	-698	1:59	0.56	N	0
12	423	23	2,315	110	661	-641	40	-2.8	87%	-559	2:19	0.65	N	0
14	1,456	30	5,705	208	1,667	-1,617	60	-3.5	69%	-1,117	3:03	0.86	N	0
15	731	37	5,008	117	1,172	-1,137	45	-2.6	92%	-1,048	3:08	0.88	N	0
16	816	41	6,243	117	1,055	-1,023	45	-2.6	92%	-943	3:14	0.91	N	0
17	352	17	1,265	139	697	-676	45	-3.1	77%	-524	1:50	0.51	N	0
18	349	19	1,580	110	881	-855	40	-2.8	87%	-745	2:17	0.64	N	0
19	373	16	1,120	172	1,549	-1,503	50	-3.4	70%	-1,048	2:03	0.58	N	0
20	671	20	2,207	145	434	-421	50	-2.9	83%	-349	2:07	0.59	N	0
21	548	27	2,535	134	935	-906	50	-2.7	90%	-815	2:20	0.56	N	0
22	434	19	1,384	145	868	-842	50	-2.9	83%	-698	1:56	0.54	N	0
23	414	19	1,259	145	1,013	-983	50	-2.9	83%	-815	1:59	0.56	N	0
24	563	43	4,450	117	703	-682	45	-2.6	92%	-629	2:25	0.68	**Y**	1.6
25	408	21	1,561	117	1,172	-1,137	45	-2.6	92%	-1,048	2:24	0.68	N	0
26	422	21	1,669	117	938	-910	45	-2.6	92%	-838	2:16	0.64	N	0
27	343	17	1,101	117	1,055	-1,023	45	-2.6	92%	-943	2:11	0.61	N	0
28	412	14	838	232	928	-900	60	-3.9	62%	-559	1:28	0.41	N	0
29	901	10	1,282	232	1,625	-1,576	60	-3.9	62%	-978	2:17	0.64	N	0
30	479	15	1,143	195	975	-946	55	-3.5	68%	-640	1:45	0.49	N	0
31	546	21	1,841	195	1,560	-1,513	55	-3.5	68%	-1,024	2:06	0.59	N	0
32	587	20	2,097	161	1,450	-1,407	50	-3.2	74%	-1,048	2:26	0.68	N	0

Columns: (W) = Rolling resistance (MJ) in diesel zone [8]; **(X)** = Worst case cumulative route curvature (degrees) [9]; **(Y)** = Curving resistance (MJ) in diesel zone [10]; **(Z)** = MJ of energy expended per station stop; **(AA)** = Total MJ of energy expended for acceleration; **(AB)** = Total MJ of energy released during braking; **(AC)** = Duration of braking action per stop (seconds); **(AD)** = Energy release rate (MJ/s = MW); **(AE)** = % of energy recapturable; **(AF)** = MJ of energy recyclable during braking; **(AG)** = Round trip time off-wire; **(AH)** = Round-trip energy consumed by parasitic loads (MWh); **(AJ)** = Outer terminal charging pad needed? (Y/N); **(AK)** = Energy transferred at charging pad (MWh).

Assumptions: [8] Modified Davis formula (1970); Defaults: Tons per coach = 67.5 tons; Coach tonnage = 473 tons; Locomotive tonnage = 296 tons (two locomotives); Axles per train = 36; [9] Manually adjusted where significant differences from typical assumptions are known; Parasitic load per car = 40 kW; Acceleration/deceleration time per station = 1.5 Mins; [10] AREMA (0.8 lbs per ton per degree);

Table 10. Battery-electric locomotive energy assessment model outputs (concluded)

Charging Pad, Energy Sufficiency, and Degraded Operations Assessments

	Energy Sufficiency Assessment							**Degraded Operations**		
ID	**(AL)**	**(AM)**	**(AN)**	**(AP)**	**(AQ)**	**(AR)**	**(AS)**	**(AT)**	**(AU)**	**(AV)**
1	4.5	-1.0	3.4	2.1	5.49	5.89	Y	4.5	4.3	**N**
2	4.0	-0.9	3.1	1.9	4.94	6.45	Y	4.0	6.4	Y
3	3.0	-0.7	2.3	1.4	3.70	4.33	Y	3.0	4.3	Y
4	3.5	-0.6	2.9	1.7	4.58	5.34	Y	3.5	3.7	Y
5	3.5	-0.6	3.0	1.8	4.74	5.12	Y	3.5	5.1	Y
6	4.0	-0.8	3.1	1.9	4.99	5.40	Y	4.0	5.4	Y
7	0.6	-0.2	0.4	0.2	0.65	2.67	Y	0.6	2.7	Y
8	1.4	-0.5	0.9	0.6	1.47	1.53	Y	1.4	1.5	Y
9	2.7	-0.7	1.9	1.2	3.09	3.46	Y	2.7	1.9	**N**
10	2.0	-0.5	1.5	0.9	2.36	4.90	Y	2.0	4.9	Y
11	3.5	-0.7	2.8	1.7	4.54	5.13	Y	3.5	5.1	Y
12	3.0	-0.6	2.3	1.4	3.75	3.95	Y	3.0	4.0	Y
14	6.6	-1.1	5.4	3.3	8.68	9.60	Y	6.6	9.6	Y
15	5.3	-1.0	4.3	2.6	6.88	7.66	Y	5.3	7.7	Y
16	6.1	-1.0	5.1	3.0	8.11	9.60	Y	6.1	9.6	Y
17	2.1	-0.5	1.6	1.0	2.55	5.65	Y	2.1	5.6	Y
18	2.6	-0.7	1.9	1.1	3.02	4.82	Y	2.6	4.8	Y
19	2.4	-0.6	1.7	1.0	2.76	6.58	Y	2.4	6.6	Y
20	2.9	-0.5	2.4	1.4	3.78	4.03	Y	2.9	4.0	Y
21	3.2	-0.7	2.5	1.5	3.92	4.15	Y	3.2	4.2	Y
22	2.3	-0.6	1.7	1.0	2.78	3.43	Y	2.3	3.4	Y
23	2.3	-0.7	1.7	1.0	2.69	3.43	Y	2.3	3.4	Y
24	4.5	-0.7	3.8	2.3	6.06	6.76	Y	4.5	5.2	Y
25	2.7	-0.8	1.9	1.2	3.10	3.12	Y	2.7	3.1	Y
26	2.7	-0.7	2.0	1.2	3.12	3.22	Y	2.7	3.2	Y
27	2.3	-0.7	1.6	0.9	2.49	2.55	Y	2.3	2.6	Y
28	1.9	-0.4	1.4	0.9	2.27	4.77	Y	1.9	4.8	Y
29	3.3	-0.9	2.4	1.5	3.91	5.02	Y	3.3	5.0	Y
30	2.3	-0.6	1.7	1.0	2.72	5.02	Y	2.3	5.0	Y
31	3.1	-0.8	2.4	1.4	3.77	4.64	Y	3.1	4.6	Y
32	3.4	-0.9	2.5	1.5	4.06	4.13	Y	3.4	4.1	Y

Columns: (AL) = Round Trip Energy Demand (MWh); **(AM)** = Round trip recoverable energy (MWh); **(AN)** = (AL) + (AM) = Net energy requirement (MWh); **(AP)** = Reserve energy requirement (MWh); **(AQ)** = Total energy requirement (MWh); **(AR)** = (L) + (AK) = Available battery power (MWh); **(AS)** = Is service feasible? (Y/N); **(AT)** = Energy demand without regeneration (MWh); **(AU)** = (L) = Energy supply leaving electrified district (MWh); **(AV)** = Reserves sufficient for degraded operations? (Y/N)

Assumptions: Battery efficiency = 97%; Battery power reserve requirement factor = 60% (This assumption is a fleet management decision; different operators may have different policies regarding minimum reserve fuel requirements.)

Perhaps counterintuitively, our calculations show BEL operation is feasible on some legacy low-voltage third-rail lines for services where slightly less than half of the distance is electrified. However, in some cases there is a need for either a charging pad at the outer end of the line, or short extensions of existing electrification. These cases exemplify the tradeoff for longer non-electrified portions where additional infrastructure would be built. Studying the specific operating needs and infrastructure costs on a given line would determine what form this should take.

BELs will need to recharge when coming into the electrified zone. As this need will be the greatest when returning to the outer end of the electrified zone after operating in battery mode, rail operators will have to pay particular attention to ratings of their existing power supplies in these outer areas.

These increased power requirements will need to be recognized and planned for. Existing substations may have to be enhanced and/or new ones built to provide the necessary power. Some commuter railroads experienced power shortages when they introduced new, high-performance equipment in the late 20th century without improving power supplies (*28*). Likewise, operating power-hungry BELs on unimproved legacy electrifications could have reliability consequences unless power needs are addressed.

On some branch lines, there was not enough charging time under the wires for off-peak services to be operated as shuttles from the branch junction. However, various solutions are possible, such as originating the shuttles from a point further down the mainline, or to provide layover charging facilities near the branch junction.

Methodology C: Lifecycle Cost Analyses for Financial Feasibility

The five Boston Northside alternatives (Table 11(a)) analyzed in the lifecycle cost analysis represent different strategies for how electrification might be addressed. Alternatives (I) and (V) use BELs to provide service beyond a core electrified territory representing the minimum electrification necessary to reach the entire service area, with Alternative (I) representing the existing network and Alternative (V) including long-proposed extensions to New Hampshire. Alternatives (II) through (IV) are conventional electrification solutions that vary in scope, with Alternative (II) not quite covering the entire existing service area due to the maximum feeding distance of 25kV substations.

We determined the track-miles of catenary required based on the current track map and determined the number of autotransformer substations required based on their maximum feeding distances. Because interlockings require special catenary work, and may require signal interference immunization, we provided extra scopes of work to account for this. We assume a large supply substation at the Boston Engine Terminal, and other smaller supply substations in outlying areas as needed to meet electrical demands. We made no attempt to determine site-specific conditions or connections to the electrical grid. Eastern Massachusetts has a comparatively dense transmission grid, and suitable supplies should be available close to where they are required.

Table 11. Hypothetical life cycle cost assessment of commuter rail electrification strategies.

(a) Infrastructure Characteristics

Alt.	**Description**	**Electrified Track Miles**	**Electrically Operated Track Miles**	**% Operated Under Wire**	**% Operated on Batteries**	**Autotrans-former Subs Required**	**Supply Subs Required**
(I)	Electrification of Existing Service Using BELs and One Supply Substation	173.8	291.1	60%	40%	13	1
(II)	Maximum Extent of Electrification Using One Supply Substation (Figure 3)*	198.4	198.4	100%	0%	15	1
(III)	Electrification of all Existing Services w/ Straight Electrics	291.1	291.1	100%	0%	23	4
(IV)	Electrification of all Existing Services plus NH Extensions	348.1	348.1	100%	0%	31	5
(V)	Electrification of Existing Services & NH Extensions Using BELs (Figure 6)	173.8	348.1	50%	50%	13	1

(b) Capital and Maintenance Cost Assessment

Alt.	**Fleet Required**	**Fleet Type**	**Fleet Cost ($m)**	**Infra-structure Cost ($m)**	**Capital Cost ($m)**	**Electric Traction Dept. Headcount**	**NPV of Ongoing Maint.-of-Way Cost ($m)**	**NPV of Ongoing Loco. Maint. Cost ($m)**	**Total System Cost ($m)**	**Ratio vs Alternative (V) Cost**
(I)	60	BELs	$600	$1,204	$1,804	69	$265	$180	$2,250	94%
(II)	24	Electrics	$180	$1,359	$1,539	76	$293	$55	$1,887	78%
(III)	27	Electrics	$203	$2,071	$2,274	125	$485	$62	$2,821	117%
(IV)	33	Electrics	$248	$2,537	$2,785	153	$594	$76	$3,455	144%
(V)	72	BELs	$720	$1,204	$1,924	69	$265	$216	$2,406	100%

(c) Unit Cost and Labor Productivity Assumptions

Item	**Cost ($m)**
Master Supply Substation	75
Outlying Supply Sub	30
Autotransformer Sub	15
Catenary Cost per Track Mile	3
Catenary Work Cost per Interlocking	7.5
Soft Costs	30%
Battery Electric Locomotive Purchase	10
Straight Electric Locomotive Purchase	7.5
Electric Locomotive Midlife Overhaul	0.3
Battery Locomotive Midlife Overhaul	0.5
Battery Locomotive Five-Year Campaign	0.25

Item	**Value**
Substations Assigned per Gang	3
Supply Subs Assigned per Gang	0.5
Catenary Miles Assigned per Gang	20
Additional Catenary Miles per Interlocking	1
Employees per Gang	3
Linemen Hourly Rate	$40.00
Overtime %	20%
Fringe & Benefits Overhead %	80%
Effective Annual Rate	$194,688
Discount Rate (for NPV)	5%
Vacation/Sick Relief Ratio	20%

Notes: NPV = Net Present Value
* Alternative (II) assumes that no commuter rail service will be provided to some outlying communities that currently receive service. It also requires new storage yards to be constructed. This would not be acceptable in reality, but is included here for cost comparison purposes and to demonstrate the pure application of Strategy 1. This strategy is similar to that applied in Philadelphia in 1981 when most diesel service was discontinued as the Center City rail tunnel was nearing completion.

Based on these asset counts, we used our estimates of unit costs (Table 11(c)) to determine investment needs. These are based on industry experience and reviews of typical projects and are broadly consistent with available industry data (*38*, *70*). Some costs might seem high at first glance, but one railroad recently spent almost $50 million rebuilding a single AC supply substation that provides power from a 138kV source. A significant portion of the construction costs of 25kV AC electrification is associated with substations, including the utility-side costs of bringing in high-tension lines.

Maintenance of Way costing (Table 11(b)) follows established zero-based methodologies (*71*) based on previously-determined asset counts, with assumptions about headcount budgeting methods, labor rates, and line gang productivity (Table 11(c)) consistent with typical commuter rail practice. OCS installation (*72*), inspection, and maintenance, even with constant-tension catenary, will require significant track time and will affect costs.

Locomotive cost estimates (Table 11(b)) are based on recent procurements. New BEL costs were not available; however, we made the conservative assumption that they would be significantly more expensive than freight locomotives, because North American passenger locomotives are a specialty low-production item. One operator paid $8.8 million per unit for dual-mode electric/diesel locomotives in 2020; another paid $12.4 million. We assumed a passenger BEL would cost $10 million. Shop margins for locomotives were set higher for BELs (20%) than for straight electrics (10%). We estimated locomotive maintenance costs from recent experience (*73*), with five-yearly battery overhauls added to BEL maintenance regimes.

The results of this analysis are summarized in Figure 9 above.

Electrification and Legacy Infrastructure Constraints

Even where partial electrification and BEL operation do not involve legacy electrification, other legacy infrastructure issues may arise. Railroads will have to examine their track and yard capacities (perhaps with simulation studies) and decide what limitations can be worked around versus committing to infrastructure expansions. Signal systems and track circuits will need to be immunized against interference from traction return current. Electric or BEL maintenance shops will need to be constructed or existing shops updated with new tooling. Shore power may be needed where weekend layovers are planned.

Overhead clearances need to be analyzed at low bridges and at downtown terminals and their approaches (e.g., Chicago Union Station, Boston North Station) which were not initially designed for electrified operation. This may not be as much of an issue as generally thought. The British Standards used on Network Rail are based on extensive operating experience with 25kV, and suggest that with proper design, trains may operate safely under bridges with as little as 10½" between the train's maximum height and the overhead wire (*20* p. 55). This implies that 25kV electrification is possible with a 14'6" static height double-deck car if the structure has at least 16'10" of vertical clearance. For structures that are a little lower than that, other techniques have been developed, notably in Scotland, where Clyde Electric trains coast through short neutral sections under bridges having some very restrictive vertical clearances.

There are various options for improving clearances in restricted-space settings. Undercutting the roadbed or installing slab track can provide additional room overhead. Other options include retrofitting or replacing structures, or even using lower voltages (although the latter will, at best, provide a few extra inches).

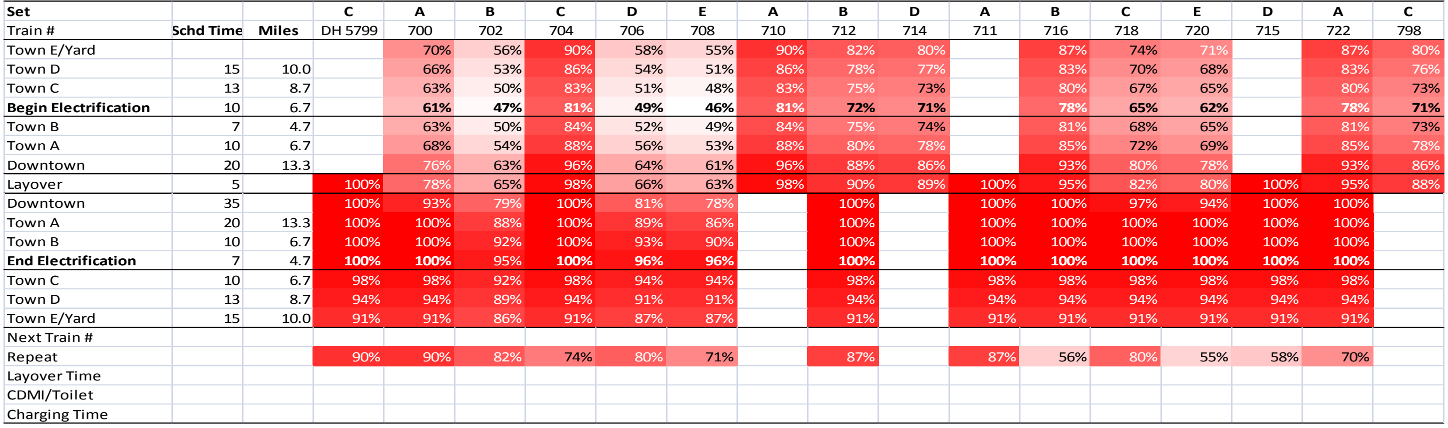
Methodology D: Simplified Battery Charge Level Simulation

To assess the risk of battery depletion on an individual train basis, assess shore power requirements, and determine logistical plans in case of an unexpectedly flat battery, we worked out a sample operating plan (Figure 25(A)) for a fairly sparse hypothetical commuter service on a 50-mile line, half of which is electrified. Sparse services are logistically most challenging because there are few opportunities for swapping out equipment when problems arise.

(A) Sample operating plan for sparse service

Set			C	A	B	C	D	E	A	B	D	A	B	C	E	D	A	C
Train #	**Schd Time**	**Miles**	DH 5799	700	702	704	706	708	710	712	714	711	716	718	720	715	722	798
Town E/Yard				**5:30**	**6:05**	**6:35**	**7:05**	**7:35**	**9:00**	**10:35**	**12:35**		**15:05**	**15:35**	**16:05**		**19:05**	**22:35**
Town D	15	10.0		5:45	6:20	6:50	7:20	7:50	9:15	10:50	12:50		15:20	15:50	16:20		19:20	22:50
Town C	13	8.7		5:58	6:33	7:03	7:33	8:03	9:28	11:03	13:03		15:33	16:03	16:33		19:33	23:03
Begin Electrification	10	6.7		6:08	6:43	7:13	7:43	8:13	9:38	11:13	13:13		15:43	16:13	16:43		19:43	23:13
Town B	7	4.7		6:15	6:50	7:20	7:50	8:20	9:45	11:20	13:20		15:50	16:20	16:50		19:50	23:20
Town A	10	6.7		6:25	7:00	7:30	8:00	8:30	9:55	11:30	13:30		16:00	16:30	17:00		20:00	23:30
Downtown	20	13.3		**6:45**	**7:20**	**7:50**	**8:20**	**8:50**	**10:15**	**11:50**	**13:50**		**16:20**	**16:50**	**17:20**		**20:20**	**23:50**
Layover	**5**		4:25	6:50	7:25	7:55	8:25	8:55	10:20	11:55	13:55	15:55	16:25	16:55	17:25	17:55	20:25	23:55
Downtown	**35**		**5:00**	**7:25**	**8:00**	**8:30**	**9:00**	**9:30**		**12:30**		**16:30**	**17:00**	**17:30**	**18:00**	**18:30**	**21:00**	
Town A	20	13.3	5:20	7:45	8:20	8:50	9:20	9:50		12:50		16:50	17:20	17:50	18:20	18:50	21:20	
Town B	10	6.7	5:30	7:55	8:30	9:00	9:30	10:00		13:00		17:00	17:30	18:00	18:30	19:00	21:30	
End Electrification	7	4.7	5:37	8:02	8:37	9:07	9:37	10:07		13:07		17:07	17:37	18:07	18:37	19:07	21:37	
Town C	10	6.7	5:47	8:12	8:47	9:17	9:47	10:17		13:17		17:17	17:47	18:17	18:47	19:17	21:47	
Town D	13	8.7	6:00	8:25	9:00	9:30	10:00	10:30		13:30		17:30	18:00	18:30	19:00	19:30	22:00	
Town E/Yard	**15**	**10.0**	**6:15**	**8:40**	**9:15**	**9:45**	**10:15**	**10:45**		**13:45**		**17:45**	**18:15**	**18:45**	**19:15**	**19:45**	**22:15**	
Next Train #			704	710	712	718	714	720		716		722	702	798	708	706	700	
Repeat			6:35	9:00	10:35	15:35	12:35	16:05		15:05		19:05	6:05	22:35	7:35	7:05	5:30	
Layover Time			0:20	0:20	1:20	5:50	2:20	5:20		1:20		1:20	11:50	3:50	12:20	11:20	7:15	
CDMI/Toilet						X		X					X			X	X	
Charging Time			6:24	1:54	1:54	1:54	1:54	1:54		1:54		7:29	1:54	1:54	1:54	5:54	1:54	

(B) Battery level forecast for sample operating plan



Set			C	A	B	C	D	E	A	B	D	A	B	C	E	D	A	C
Train #	**Schd Time**	**Miles**	DH 5799	700	702	704	706	708	710	712	714	711	716	718	720	715	722	798
Town E/Yard				70%	56%	90%	58%	55%	90%	82%	80%		87%	74%	71%		87%	80%
Town D	15	10.0		66%	53%	86%	54%	51%	86%	78%	77%		83%	70%	68%		83%	76%
Town C	13	8.7		63%	50%	83%	51%	48%	83%	75%	73%		80%	67%	65%		80%	73%
Begin Electrification	10	6.7		**61%**	**47%**	**81%**	**49%**	**46%**	**81%**	**72%**	**71%**		**78%**	**65%**	**62%**		**78%**	**71%**
Town B	7	4.7		63%	50%	84%	52%	49%	84%	75%	74%		81%	68%	65%		81%	73%
Town A	10	6.7		68%	54%	88%	56%	53%	88%	80%	78%		85%	72%	69%		85%	78%
Downtown	20	13.3		76%	63%	96%	64%	61%	96%	88%	86%		93%	80%	78%		93%	86%
Layover	5		100%	78%	65%	98%	66%	63%	98%	90%	89%	100%	95%	82%	80%	100%	95%	88%
Downtown	35		100%	93%	79%	100%	81%	78%		100%		100%	100%	97%	94%	100%	100%	
Town A	20	13.3	100%	100%	88%	100%	89%	86%		100%		100%	100%	100%	100%	100%	100%	
Town B	10	6.7	100%	100%	92%	100%	93%	90%		100%		100%	100%	100%	100%	100%	100%	
End Electrification	7	4.7	**100%**	**100%**	95%	**100%**	**96%**	**96%**		**100%**		**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	
Town C	10	6.7	98%	98%	92%	98%	94%	94%		98%		98%	98%	98%	98%	98%	98%	
Town D	13	8.7	94%	94%	89%	94%	91%	91%		94%		94%	94%	94%	94%	94%	94%	
Town E/Yard	15	10.0	91%	91%	86%	91%	87%	87%		91%		91%	91%	91%	91%	91%	91%	
Next Train #																		
Repeat			90%	90%	82%	74%	80%	71%		87%		87%	56%	80%	55%	58%	70%	
Layover Time																		
CDMI/Toilet																		
Charging Time																		

Figure 25. Outputs from simplified battery charge level simulation based on sample operating plan for sparse service

Our battery-level simulations based on energy consumption calculations (Figure 25(B)) show that the AM peak inbound service has the lowest battery levels due to overnight HEP loads. Nevertheless, at no point did any trains begin a run with less than 55% charge after laying over for the night, nor enter the electrified zone with less than 49%. This is true even if the outlying yard was not provided with shore power. But if the service does not operate during the weekends, it would be necessary either to deadhead back to the electrified zone, or to provide shore power at the outer end. Operating a weekend service would have higher operating costs but could lead to infrastructure savings.

This sample operating plan also proved out that it was possible to provide extra "charging cycles" in the operating plan in case battery levels becomes unexpectedly depleted for any reason. Sets A, C, and D have extra layover time downtown in the electrified zone in case of an unplanned low-charge condition. Plenty of opportunities exist for set swaps at the outer yard in case a specific set needs to be moved onto a recharge cycle, and set step-ups are possible at the downtown terminal for emergency manipulations. Fleet manipulations to get locomotives with "low battery warnings" onto daytime charge cycles are not difficult even on lines with relatively sparse service frequency.

These are typical concerns an operations manager would have about operating this new type of equipment with energy-based distance constraints that are more restrictive than a diesel. We show that it is possible to work with this through operating plan design. Obviously, plans for each proposed service would need to be worked out individually, through proper consultation between the capital design and operations disciplines. However, we believe additional risks introduced by the range constraint can be mitigated to an acceptable level.

Methodology E: Infrastructure Efficiency Comparison

Implicit in these strategies is a goal of achieving the maximum carbon-reduction from commuter rail operations whilst minimizing fixed infrastructure investment needs, a theme that was explored in (*5*). This methodology provides a high-level assessment of new infrastructure requirements (route-miles electrified) versus GHG reductions achieved compared to other approaches, such as the diesel dual-mode intermittent electrification proposed in (*12*), and a hypothetical full-electrification scenario. The Philadelphia case studies (Strategies 3 and 4) were not included because they use existing electrifications.

Table 12 shows the results of this analysis. As can be seen, the BEL-enabled approaches are incredibly infrastructure-efficient, although Strategy 6 approaches sacrifices rolling stock utilization to achieve this result in very low traffic density areas. As for GHG performance, the BEL-enabled approaches offer far superior reduction to diesel dual-mode based intermittent electrification, whilst providing substantial infrastructure savings over full electrification. The performance of the diesel dual-mode strategy proposed elsewhere (*12*) is shown at the end of Table 12 for comparison with the more environmentally effective strategies proposed in this research.

Table 12. Infrastructure efficiency and greenhouse gas reduction: comparative assessment.

Case Study	Line	(A)	(B)	(C)	(D)	(E)	% Route Miles Electrified	% GHG Reduction
Boston North (Strategy 2)	Fitchburg	25.3	0.0	25.3	53.7	28.4		
	Lowell	25.5	0.8	24.7	55.5	30.0		
	Haverhill	22.8	0.8	22.0	50.4	27.6		
	Newburyport	18.3	0.8	17.5	36.2	17.9		
	Rockport	0.0	18.3	0.0	35.3	17.0		
	Total			**89.5**		**120.9**	**43%**	**100%***
Chicago North and West	BN (Aurora)	38.4	0.0	38.4	38.4	0.0		
	CNW-W (Elburn)	29.7	0.0	29.7	44.0	14.3		

Case Study	Line	(A)	(B)	(C)	(D)	(E)	% Route Miles Electrified	% GHG Reduction
(Strategy 5)	CNW-NW (Harvard)	31.5	0.0	31.5	62.8	31.3		
	McHenry Spur	0.0	0.0	0.0	65.8	7.6		
	MD-North (Fox Lake)	32.3	2.9	29.4	49.5	17.2		
	MD-West (Elgin)	36.6	5.4	31.2	39.8	3.2		
	NCS (Antioch)	29.9	12.7	17.2	55.7	25.8		
	Total			**177.4**		**99.4**	**64%**	**100%***
Chicago North and West Regional (Strategy 6)	Madison via Rockford	41		41	161	120		
	Janesville via Rondout	32		32	99	67		
	Fond du Lac/Milwaukee	36	32	4	156	120		
	Total			**77**		**307**	**20%**	**100%***
Minnesota (Strategy 6)	St. Paul-St. Cloud	23		23	82	59		
	Coon Rapids-Duluth	44	23	21	140	119		
	Total			**44**		**178**	**20%**	**100%***
Hypothetical Full Electrification								
	Total						**100%**	**100%**
Diesel Dual-Mode Intermittent	London Paddington to Plymouth and Paignton							
	Total, Reference (*12*)						**50%**	**54%**

Notes: (A) = Electrified route miles; (B) = Electrified route miles shared with other routes; (C) = Net electrified route mile; (D) = Limits of service (i.e., mileage from downtown); (E) = Non-electrified route miles. *All diesel locomotives were eliminated in revenue service, thus achieving a 100% reduction in GHG emissions; the only non-electric locomotives remaining are emergency back-up locomotives, and those needed for work train service during power outages.

CONCLUSIONS

As concern mounts about GHG emissions, commuter railroads should explore electrification and battery technology. Although no BEL has been designed for commuter service as of 2022, it should now be possible to develop a BEL specifically for commuter rail where a market exists. This should be an area for further research, prototyping, and proving out, with research and development funding from government climate action/energy research grants. Combined with judicious electrification based on maximizing each substation's network reach, BELs offer considerable promise for commuter rail both in operating convenience and environmental sustainability.

We examined six strategies for electrification of traditional commuter rail systems assuming that BELs suitable for commuter service was developed (based on specifications described briefly in this paper). Of these strategies:

- Strategies 1 and 2 are suitable for more compact metropolitan areas where commuter lines radiate from a central station in different directions. Strategy 1 is suitable for cities where the commutershed extends out less than 25 miles and does not require the use of BELs. Strategy 2 is suitable for cities with commutersheds up to 50 miles and utilizes BELs.
- Strategy 3 is for electric commuter rail cities that are looking to extend electric service beyond existing electrification infrastructure using BELs.

- Strategy 4 can be used to provide a regional service to connect two or more commuter rail cities each with existing or future electrified commuter rail systems.
- Strategy 5 is suitable for megaregions whose commutersheds extend more than 50 miles from the downtown that do not currently have electrified commuter rail. It may also be suitable for supporting regional services in sparse regions where local desires exist for such service to be electric (rather than operated with alternate fuels).
- Strategy 6 can be used to provide regional services beyond the typical commutershed to smaller cities or remote parking facilities that extend up to 120 miles beyond the limits of electrification. Operating more than 120 miles in non-electrified territory is currently a challenge for BELs because their range is not as long as diesel locomotives.

Some practical implementation matters remain to be worked out. But this analysis shows that given current technological progress, a modern electrified network operated with a mixture of straight electrics (locomotives and/or multiple-unit cars) and BELs should be cheaper than a conventional electric solution and would have a wider geographic reach. Thus, service sponsors should start to examine expanding electric service now, whether by new-start electrification, BEL extensions of existing electrified systems, or new regional or interregional travel opportunities.

ACKNOWLEDGEMENTS

The authors thank J.E. Kesich, Jim Heimbuecher, Walter Simpson, Lew Hoens, Adam Otsuka, Bob Newhouser, David Mangold, and M.J. Shiffer for useful discussions. The authors are also grateful to the anonymous reviewers at both the Transportation Research Board and the American Society of Mechanical Engineers' Joint Rail Conference who provided useful feedback on all previous draft manuscripts from this project. The views are those of the authors and do not necessarily reflect the official policy of any railroads, manufacturers, government bodies, or other organizations. Any errors are the sole responsibility of the authors.

REFERENCES

(1) Metra. *Metra to Create Battery-Powered Locomotives*. August 17, 2022. *https://metra.com/newsroom/metra-create-battery-powered-locomotives/* Accessed Nov. 3, 2022.
(2) Tamaoki, M. Caltrans Intercity Passenger Rail: Our Strategy Towards Zero-Emission. Presented at *CARB ZE Seminar*, Sacramento, Calif., October 29, 2020. *https://ww2.arb.ca.gov/sites/default/files/2020-10/Day%201%20Ext%205%20Caltrans%2020201026.pdf* Accessed Nov. 3, 2022.
(3) Castillo, A.A. LIRR: Can't Add Batteries to Power Existing Trains Where Tracks Not Electrified. *Newsday Long Island*. *https://www.newsday.com/long-island/transportation/lirrs-diesel-trains-kdcsks6w* Accessed Jul. 31, 2022.
(4) Vantuono, W.C. FLXdrive 'Electrifies' Pittsburgh. *Railway Age*. *https://www.railwayage.com/news/flxdrive-electrifies-pittsburgh/* Accessed Jun. 23, 2022.
(5) Lu, A. and J.G. Allen. The Case for Electrifying Freight Railroads by Half-Measures: Exeunt Diesels, Cue Battery-Electrics. *Engineering Archive* **2665**. *https://doi.org/10.31224/2665*

(6) Hayes, J.G., and G.A. Goodarzi. *Electric Powertrain: Energy Systems, Power Electronics and Drives for Hybrid, Electric and Fuel Cell Vehicles*. Wiley & Sons, Hoboken, N.J., 2018.

(7) Cook, D., P. Eggleton, and I. Stewart. Concept Definition of a Zero Emissions Boost Locomotive for Regional Passenger Rail. *ASME/IEEE Joint Rail Conference* **JRC2015-5743**. https://doi.org/10.1115/JRC2015-5743

(8) Iden, M.E. Battery Electric Locomotives & Battery Tenders: Operational & Infrastructure Challenges to Widespread Adoption. *ASME/IEEE Joint Rail Conference* **84775**, 2021. https://doi.org/10.1115/JRC2021-58378

(9) Simpson, W. *Diesel-Electric Locomotives*. Simmons-Boardman, Omaha, Nebraska, 2020.

(10) Kent, Stephen. Wire-Free Electrification. *IEEE Transportation Electrification Community Newsletter*, December 2016. https://tec.ieee.org/newsletter/december-2016/wire-free-electrification/ Accessed Jan. 15, 2023.

(11) Kluth, Andrew. Rail Industry Decarbonisation Task Force and Rail Safety and Standards Board—Final Report to the Minister for Rail, July 2019. https://www.rssb.co.uk/Research-and-Technology/Sustainability/-/media/4617FB13CB78457A97AD028E3287D1F5.ashx Accessed Jan. 15, 2023.

(12) Abdurahman, B.M., T. Harrison, C.P. Ward, and W.J.B. Midgley. An Investigation into Intermittent Electrification Strategies and an Analysis of Resulting CO_2 Emissions Using a High-Fidelity Train Model. *Railway Engineering Science* **29**, 314–326, 2021. https://doi.org/10.1007/s40534-021-00248-9

(13) Wordsworth, N., and R.E. Writer. Routes to Zero Carbon Rail. *Rail Engineer*, 16 December, 2020. https://www.railengineer.co.uk/routes-to-zero-carbon-rail/ Accessed Jan. 15, 2023.

(14) Kapetanović, M., N. Bešinović, A. Núñez, N. van Oort, and R.M.P. Goverde. Optimal Network Electrification Plan for Operation of Battery-Electric Multiple Unit Regional Trains. Presented at the *11th Triennial Symposium on Transportation Analysis Conference, Mauritius*. https://research.tudelft.nl/en/publications/optimal-network-electrification-plan-for-operation-of-battery-ele Accessed Jan. 15, 2023.

(15) Cordero Sapién, Josephine. Deutsche Bahn has Announced it will be Building Overhead Line 'Islands' for Regional Battery Trains. *Railway News*, 15 March, 2022. https://railway-news.com/deutsche-bahn-is-building-overhead-line-islands-for-battery-trains/ Accessed Jan. 15, 2023.

(16) Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. *Global Warming of 1.5°C*, Cambridge University Press, 2018. https://doi.org/10.1017/9781009157940.001

(17) International Energy Agency and Union Internationale des Chemins de Fer. *The Future of Rail–Opportunities for Energy and the Environment*, 2019. https://www.iea.org/reports/the-future-of-rail/ Accessed Nov. 3, 2022.

(18) Bowen, D.J. Multiple-Unit or Locomotive-Hauled? *Railway Age*, Jun. 2009, pp. 17–20.

(19) Kochansky, P. Negotiating Passenger Rail Operating Rights: Lessons Learned in Massachusetts. Presented at the *American Public Transportation Association Rail Conference*, 2011.

(20) Keenor, G. *Overhead Line Electrification for Railways*. https://ocs4rail.com/downloads/ Accessed Jan. 26, 2022.

(21) *Railroad Electrification: The Issues*. Transportation Research Board Special Report 180, National Academy of Sciences, Washington, D.C., 1977

(22) American Railway Engineering & Maintenance-of-Way Association (AREMA). Chapter 9: Railway Electrification. *Practical Guide to Railway Engineering*, 3rd Edition, 2019. *https://publications.arema.org/Publication/PRAC_001* Accessed Jul. 12, 2022.

(23) Morris, B., F. Foiadelli, and D. Zaninelli. *Electrical Railway Transportation Systems,* 1st Edition, 2018. IEEE Press Series on Power and Energy Systems.

(24) Kiesling, F., R. Puschmann, A. Schmieder, and E. Schmieder. *Contact Lines for Electric Railways, 3rd Edition*. John Wiley & Sons, Hoboken, N.J., 2018.

(25) Steimel, A. *Electric Traction – Motive Power and Energy Supply: Basics and Practical Experience*. Deutscher Industrieverlag, Munich, Germany, 2014.

(26) Schwarm, E.G. Summary and Generalization of the Conrail Electrification Study Results for Application to Other Railroads. U.S. Department of Transportation, Transportation Systems Center, Cambridge, Massachusetts. *https://railroads.dot.gov/elibrary/summary-and-generalization-conrail-electrification-study-results-application-other* Accessed May 15, 2021.

(27) Oura, Y., Y. Mochinaga, and H. Nagasawa. Railway Electric Power Feeding Systems. *Japan Railway & Transport Review* **16**, Jun. 1998, pp. 48–58. *https://www.ejrcf.or.jp/jrtr/jrtr16/pdf/f48_technology.pdf* Accessed Nov. 6, 2022.

(28) Allen, J.G., J.P. Aurelius, and J. Black. Electric Power Supply for Commuter Rail: Are Railroads Keeping Up? *Transportation Research Record* **2219**, 2011, pp. 88–96. *https://doi.org/10.3141/2219-11*

(29) Condit, W.W. Railroad Electrification in the United States. *Proceedings of the IEEE* **64**(9), 1976, pp. 1350-1360. *https://ieeexplore.ieee.org/abstract/document/1454595*

(30) Hay, W.W. Electrification. In *Railroad Engineering*. John Wiley & Sons, New York, 1982, pp. 119-139.

(31) Allen, J.G. Reasons for Commuter Rail Electrification: Early 20th Century and Since 2000. *Transportation Research Record* **2673**, 2019, pp. 227–238. *https://doi.org/10.1177/0361198119840621*

(32) Lamb, J.P. *Evolution of the American Diesel Locomotive*. Indiana University Press, Bloomington, Indiana, 2007.

(33) Resor, R.R. Innovation and Competition in Locomotive Manufacturing, 1950-2000. *36th Annual Meeting of the Transportation Research Forum*, Vol. 1, 1994, pp. 407–419.

(34) Lamb, J.P. Push-Pulls for Profit. *Trains*, **20**(8), 1960, pp. 42–44.

(35) Allen, J.G., and J.P. Aurelius. Commuter Rail Reelectrification: Is It Still Justified? *Transportation Research Record* **1838**, 2003, pp. 11–18. *https://doi.org/10.3141/1838-02*

(36) Allen, J.G. and G.L. Newmark. Commuter Rail Electrifications That Never Were and What They Teach Us. *Transportation Research Record* (forthcoming), 2022. *https://doi.org/10.1177/03611981221101028*

(37) Allen, J.G., and H.S. Levinson. Accommodation of Long-Term Growth on North America's Commuter Railroads. *Transportation Research Record* **2419**, 2014, pp. 40–49. *https://doi.org/10.3141/2410-05*

(38) Levy, A. Construction Costs: Electrification. *Pedestrian Observations*, May 22, 2018. *https://pedestrianobservations.com/2018/05/22/construction-costs-electrification/* Accessed Nov. 3, 2022.

(39) Levy, A. In-Motion Charging is Not for Trains. *Pedestrian Observations*, Jul. 13, 2022. *https://pedestrianobservations.com/2022/07/13/in-motion-charging-is-not-for-trains/* Accessed Nov. 3, 2022.

(40) PRIIA Section 305 Next Generation Corridor Equipment Pool Committee (NGEC). *Update on Acquisitions And Capital Programs*. 12th Annual Meeting, 2022. https://www.highspeed-rail.org/Pages/Section305Committee.aspx Accessed Nov. 3, 2022.

(41) Next Generation Corridor Equipment Pool Committee. *Metro-North Railroad Siemens Dual Mode Locomotives*. 11th Annual Meeting, 2021. https://www.highspeed-rail.org/Pages/Section305Committee.aspx Accessed Nov. 3, 2022.

(42) Jackson, C. Emissions Regulations Tightened Again. *Railway Gazette International* **167**(2), 2011, pp. 35–37.

(43) Marin, G.D., G.F. Naterer, and K. Gabriel. Rail Transportation by Hydrogen Vs. Electrification–Case Study for Ontario Canada, I: Propulsion and Storage. *International Journal of Hydrogen Energy* **35**(12), 2010, pp. 6084–6096.

(44) Marin, G.D., G.F. Naterer, and K. Gabriel. Rail Transportation by Hydrogen Vs. Electrification–Case Study for Ontario, Canada, II: Energy Supply and Distribution. *International Journal of Hydrogen Energy* **35**(12), 2010, pp. 6097–6107.

(45) McCormick, R., and T. Alleman. *Renewable Diesel Fuel.* National Renewable Energy Laboratory, July 18, 2016. https://cleancities.energy.gov/files/u/news_events/document/document_url/182/McCormick___Alleman_RD_Overview_2016_07_18.pdf Accessed Nov. 11, 2022.

(46) Bay Area Regional Rail Plan. *Technical Memorandum, Electrification of the Bay Area Regional Rail System: Cost, Issues and Potential*. Prepared for Metropolitan Transportation Commission, Bay Area Rapid Transit, Caltrain, and California High-Speed Rail Authority, 2007.

(47) Massachusetts Department of Transportation. MBTA Blue Book Open Data Portal. https://mbta-massdot.opendata.arcgis.com/ Accessed Jul. 22, 2022.

(48) Progress Rail. *New Milestone for Fortescue's Decarbonization Strategy With Purchase of Two New Battery Electric Locomotives.* https://www.progressrail.com/en/Company/News/PressReleases/NewMilestoneforFortescuesDecarbonizationStrategyWithPurchaseofTwoNewBatteryElectricLocomotives.html Accessed Jun. 27, 2022.

(49) Bender, D., R. Byrne, and D. Borneo. *ARRA Energy Storage Demonstration Projects: Lessons Learned and Recommendations.* Report SAND2015-5242. Sandia National Laboratories, Albuquerque, N.M, July 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-5242.pdf Accessed Nov. 4, 2022.

(50) Wang, C.Y. et al. Fast Charging of Energy-Dense Lithium-Ion Batteries. *Nature*, **611**, pp. 485–490. https://www.nature.com/articles/s41586-022-05281-0 Accessed Jan. 4, 2023.

(51) Trout, S.F. *Proposal for Locomotive Conversion of F40PH to Full Electric*. Unpublished Manuscript, SFTrout Mechanical Engineering LLC, Bedford, Massachusetts, 2016.

(52) Allen, J.G. and A. Lu. Organizational Regimes for Commuter Rail: Improving Train Service Worldwide. *Transportation Research Record* **2146**, 2010, pp 100-108. https://doi.org/10.3141/2146-13

(53) Allen, J.G. and G.L. Newmark. Access Protocols for Railroads: Reframing the Infrastructure Separation Debate. Research in Transportation Economics, 2021. https://doi.org/10.1016/j.retrec.2021.101136

(54) Woodland, D.W. *The Reading in the Conrail Era, 1976-1998, Book Two*. Silver Brook Junction Publishing, Telford, Pennsylvania 1999.

(55) Pennsylvania Department of Transportation. *Reading to Philadelphia Passenger Rail Analysis*, Final Report, December 2020. https://www.montcopa.org/DocumentCenter/View/

34180/PennDOT-study__Reading-Philadelphia-Rail-Study---Final-Report Accessed Nov. 4, 2022.

(56) Parsons Brinckerhoff. *Quakertown-Stony Creek Rail Restoration Study*. Bucks County Planning Commission, July 2000. *https://www.buckscounty.gov/DocumentCenter/View/2024/2000-Quakertown-Stony-Creek-Rail-Restoration-Study-PDF* Accessed Nov. 4, 2022.

(57) New Jersey Transit Corporation. *Proposed Restoration of Passenger Rail Service on the West Trenton Line*. Newark, New Jersey, 2007.

(58) Hay, J. White Elephants and Darwinism at Zoo. *The Delaware Valley Railroad Passenger*, Jan. 1996, pp. 6–7.

(59) Teague, Chris. How Much Should You Worry About EV Fires? *Autoweek*, 3 October, 2022. *https://www.autoweek.com/news/a38225037/how-much-you-should-worry-about-ev-fires/* Accessed 15 Jan., 2023.

(60) Larsson, F., P. Andersson, P. Blomqvist, et al. Toxic Fluoride Gas Emissions from Lithium-Ion Battery Fires. *Scientific Reports* **7**, 10018 (2017). *https://doi.org/10.1038/s41598-017-09784-z*

(61) Rielage, Robert. What Firefighters Need to Know About Electric Car Batteries. *Fire Rescue 1*, 19 July, 2020. *https://www.firerescue1.com/firefighter-training/articles/what-firefighters-need-to-know-about-electric-car-batteries-omiDv8vd87oZ9ZKs/* Accessed 15 Jan., 2023.

(62) U.S. Fire Administration. Guidance on Responding to Lithium-Ion Battery Fires in Mobility Devices. *Infogram*, 28 April, 2022. *https://www.usfa.fema.gov/blog/ig-042822.html* Accessed Jan. 15., 2023.

(63) National Transportation Safety Board. Safety Risks to Emergency Responders from Lithium-Ion Battery Fires in Electric Vehicles. Special Report SR-20-01, Adopted 13 November, 2020. *https://www.ntsb.gov/safety/safety-studies/Pages/HWY19SP002.aspx* Accessed Jan. 15, 2023.

(64) Bodine, Rachel. Gas Versus Electric Car Fires. *AutoinsuranceEZ*, 11 November, 2022. *https://www.autoinsuranceez.com/gas-vs-electric-car-fires/* Accessed Jan. 15, 2023.

(65) Commuter Rail Division of the Regional Transportation Authority. *Metra Operating & Capital Program & Budget 2020*. Metra, Chicago, Illinois, 2019. *https://metra.com/reports-documents/2020-operating-capital-program-and-budget-book/* Accessed Nov. 4, 2022.

(66) Metra Division of Strategic Capital Planning. *Metra Commuter Rail System Station Boarding/Alighting Count: Summary Results, Fall 2018*. Metra, Chicago, Ill., April 2019. *https://metra.com/sites/default/files/assets/planning/ridership/2018_summary_results_report_final.pdf* Accessed Nov. 4, 2022.

(67) U.S. Department of Homeland Security. *Homeland Infrastructure Foundation Level Database—Electric Power Transmission Lines*. *https://hifld-geoplatform.opendata.arcgis.com/datasets/468e9601b9b7407396e5c4f59772f1ff_0/explore* Accessed Jul. 18, 2022.

(68) Chicago Transit and Railfan. Metra Railfan Tips. *http://chicagorailfan.com/tipmetra.html* Accessed Nov. 29, 2022.

(69) Metra. *Metra State of the System Report*. *https://metra.com/state-system-report/* Accessed Jul. 23, 2022.

(70) Marsh, J. Is Electrifying the Freight Rail Network Cost Prohibitive? *FreightWaves*. *https://www.freightwaves.com/news/is-electrifying-the-freight-rail-network-cost-prohibitive* Accessed Jun. 28, 2022.

(71) Lu, A., Z. Zhong, T. Barger, and M. Brotzman. Rightsizing the Railway Signal Workforce: A Zero-Based Resourcing Approach Towards Asset Management. *arXiv Preprint*. March 2021. *https://doi.org/10.48550/arXiv.2103.02025*

(72) Lu, A., A. Lukatskiy, Z. Zhong, and J.G. Allen. Power Off! Challenges in Planning and Executing Power Isolations on Shared-Use Electrified Railways. *arXiv Preprint*. 2021. *https://doi.org/10.48550/arXiv.2102.04517*

(73) Ahluwalia, R.K., D. Papadias, and J.-K. Peng. Total Cost of Ownership for Line Haul, Yard Switchers and Regional Passenger Locomotives – Preliminary Results. *H2@Rail Workshop*, Lansing, Mich., 2019. *https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-ahluwalia.pdf* Accessed Nov. 5, 2022.

AUTHOR CONTRIBUTIONS

The authors confirm contributions to the paper as follows: study conception and design: A. Lu, J.G. Allen, S.F. Trout, and J.P. Aurelius; data collection: A. Lu and J.G. Allen; analysis and interpretation of results: A. Lu, J.G. Allen, and S.F. Trout; draft manuscript preparation, J.G. Allen, A. Lu, S.F. Trout, and J.P. Aurelius. All authors reviewed the results and approved the final version of the manuscript.

DECLARATION OF CONFLICTING INTERESTS

The authors have no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. A. Lu is an employee of a commuter railroad but is not acting in his official capacity.

FUNDING

The authors received no financial support for the research, authorship, and/or publication of this article.