Electric Power Supply for Commuter Rail: How Are Railroads Keeping Up?

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ABSTRACT:
Electrification offers many advantages for commuter railroads. But to derive the fullest possible benefits from electrification, the traction power supply must meet demand. Aging electrical generation, transmission and distribution systems, new cars with improved amenities and higher acceleration rates, and additional train starts should all cause commuter rail properties to assess their traction power investment needs.

The traction power situation is reviewed on electric commuter railroads in Chicago and elsewhere in North America, and on certain overseas properties where electricity shortfalls have occurred. No North American commuter railroads are immediately at risk of service disruption due to traction power shortfalls, but preventive action may be appropriate on some properties. Strategies for reducing power demand are also discussed. Traction power is vitally important for electrified commuter railroads, because any failure to provide all necessary electricity can have serious consequences for speed and reliability.

Between 1905 and 1933, railroads in Chicago, New York, New Jersey, Connecticut, Philadelphia and Montréal electrified their commuter operations, to the ongoing benefit of riders today.[1] Railroads electrified for reasons including tunnels, the need to reduce engine movements at terminals (in an age before push-pull operations), general operating economy and train throughput, and intensive service in environmentally sensitive areas.

Commuter rail authorities must ensure that there is enough electricity to cover the highest peak demand. Since the 1960s, this has become an increasing concern on several railroads. The principal causes of strain on commuter railroads' power supplies have included:

- High-performance, air-conditioned cars
- Aging of rectifiers (which convert alternating current into direct current), transformers (which increase or reduce voltages), substations, feeder cables, third rail, overhead wires and other components
- Additional train starts
- Historically, disinvestment by financially troubled private railroads
- Insufficient public sector investment in power supply upgrades

On an electrified railroad, traction power is an integral part of the infrastructure. Factors determining the adequacy of a railroad's traction power system include:

- Investment in new and replacement elements
- Age and condition of the physical facilities

[1] For more on the history of and reasons for commuter rail electrification, see Robinson, Myles E., "The Evolution of Steam Railroad Electrification," *The Journal of Land & Public Utility Economics*, Part I, February 1932 and Part II, May 1932; Condit, Carl W., "Railroad Electrification in the United States," *Proceedings of the IEEE*, September 1976; Middleton, William D., *When the Steam Railroads Electrified*, Bloomington: Indiana University Press, 2001; and Allen, John G., "Commuter Rail Electrification: Survey of the Scene," Transit Finance Learning Exchange Workshop on Commuter Rail Electrification, Chicago, March 22, 2011.

- Extent and quality of maintenance
- Power consumption characteristics of equipment
- Maximum number of trains drawing power at any given moment relative to the power supply

Today's traction power situation is better on North American railroads than it was in the 1970s and 80s. But commuter rail authorities need to ensure that supplies remain adequate. Insufficient power can have several consequences for operations:

- Railroads may limit acceleration and/or maximum speed to conserve power
- If traction power issues are localized, it may be necessary to remove and add cars en route
- Too many trains drawing power at once may overload substations, causing power outages

The first two of these difficulties result in slower schedules, but do not detract from operating reliability. The third can lead to unpredictable and possibly lengthy disruptions.

ELECTRIFICATION ALTERNATIVES

Commuter railroads have electrified at various points in history, under different circumstances, and for different reasons. The electrification technologies that railroads have chosen reflect their different needs. Electrified railroads have adopted different systems (direct current, or DC, vs. alternating current, or AC) and different standards, e.g., third rail vs. overhead wire, and lower vs. higher voltages.[2] Although this variety may initially seem confusing, it is helpful to think of railroad electrification as having progressed through three generations between the dawn of the technology in the late 19th century and today.

First-Generation Electrification

The first generation of railroad electrification, lasting roughly from 1895 through about 1910, used third rail to transmit DC at 600 Volts (V) or slightly higher voltages.[3] Figure 1 shows the basics of a first-generation system such as those on the Long Island Rail Road or the New York Central.

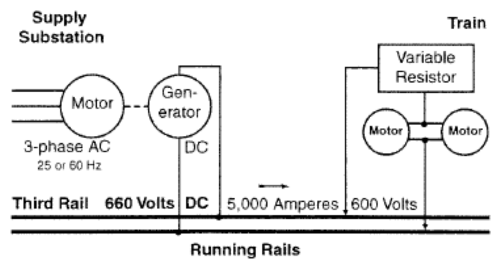

Figure 1. DC Electrification Technology – First Generation, Circa 1910.

First-generation technology was initially introduced to street railways (using overhead wires) and rapid transit (using third rail) in the late 19th century. The first North American railroad to use first-generation electrification technology was the Baltimore & Ohio, which used electric traction through a tunnel beneath downtown Baltimore for freight and intercity passenger trains between 1895 and 1952.

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[2] For more on the technology of railroad electrification, see Oura, Yasu, Yoshifumi Mochinaga, and Hiroki Nagasawa, "Railway Electric Power Feeding Systems," *Japan Railway & Transport Review*, June 1998; Kramer, Jerome, "Developments in catenary design and maintenance," *Railway Track & Structures*, March 1994; Hata, Hiroshi, "What Drives Electric Multiple Units?" *Japan Railway & Transport Review*, September 1998; Middleton, William D., *When the Steam Railroads Electrified*, Bloomington: Indiana University Press, 2001, pp. 434-447; Duffy, Michael C., *Electric Railways 1880-1990*, Stevenage, England: Institution of Electrical Engineers, 2003; Vuchic, Vukan R., *Urban Transit Systems and Technology*, Hoboken, NJ: John Wiley & Sons, 2007, pp. 100-115; Steimel, Andreas, *Electric Traction – Motive Power and Energy Supply*, Munich: Oldenbourg Industrieverlag, 2008; Hillmansen, Stuart, Felix Schmid and Thomas Schmid, "The rise of the permanent-magnet traction motor," *Railway Gazette International*, February 2011; and Allen, John G., John P. Aurelius, and Joseph Black, "Commuter Rail Electrification: Introduction to the Technical Issues," Transit Finance Learning Exchange Workshop on Commuter Rail Electrification, Chicago, March 22, 2011.

[3] For more on first-generation railroad electrifications, see Sloan, David B., "George Gibbs, M.E., D. Eng., E. Rowland Hill, M.E., E.E., Pioneers in Railroad Electrification," New York: Newcomen Society in North America, 1957; Condit, Carl W., "The Pioneer Stage of Railroad Electrification," *Transactions of the American Philosophical Society*, Vol. 67, No. 7, 1977; and the relevant parts of Middleton, William D., *When the Steam Railroads Electrified*, Bloomington: Indiana University Press, 2001. First-generation railroad electrification technology differed little from contemporary electrifications on rapid transit systems; for more on those electrifications, see Middleton, William D., *Metropolitan Railways: Rapid Transit in America*, Bloomington: Indiana University Press, 2003, pp. 228-230.

Long tunnels into central-area terminals led to the 1905 and 1906 electrifications of the Long Island Rail Road and of the New York Central (the suburban service of which was subsequently absorbed into Metro-North Railroad as the Hudson and Harlem Lines). Although the voltages and electric pickup systems on the Long Island Rail Road and Metro-North Railroad are largely the same today as they were when electric service started, both operations now use the latest substation and power delivery technology. For instance, in the early 20th century railroads used rotary converters, also known as motor-generator sets (consisting of an AC motor turning a DC generator) to rectify AC power sources into DC. These rotary converters have long since been replaced with solid-state rectifiers. Therefore, it is not accurate to describe these systems as still being in the first-generation category.

Although first-generation technology was also used in street railway electrifications, only a third rail is able to transmit the large volumes of low-voltage electricity that a busy railroad (or rapid transit operation) requires. Because it is difficult to effectively insulate third rail systems at higher voltages, most such systems have been electrified in the 600- to 750-V range. The low voltage of the electricity used in third-rail systems requires more frequent substations to prevent *voltage drops*, where the voltage falls significantly below nominal levels. This is an important consideration, as train performance begins to suffer if voltages fall more than 10% below the levels at which equipment was designed to operate. Traditional equipment simply operated more slowly under reduced voltages, but on modern equipment the control circuits simply cut out altogether if the voltage is inadequate.

Second-Generation Electrification

Where vertical clearances allowed the use of overhead wire, railroads soon became interested in the higher voltages that overhead-wire systems made possible, as fewer substations were needed for the same distance and electrical losses were lower at higher voltages.[4] All second-generation electrifications have used overhead wire rather than third rail. Railroads adopting DC between the 1910s and the 1930s were using overhead wires energized at 1,200, 1,500, 2,400 or 3,000 V.[5]

Second-generation DC systems differed from their first-generation counterparts in several regards. They used overhead wire rather than third rail, they used somewhat higher voltages, and by 1926, railroads were introducing mercury arc rectifiers (to change AC into DC) where older and less efficient motor-generator sets had previously been used. Figure 2 shows a 1,500-V DC system such as that on the Illinois Central (operated today by Metra). As with earlier third-rail systems, these DC electrifications now use modern substation and power delivery technology, so the second-generation description is no longer accurate.

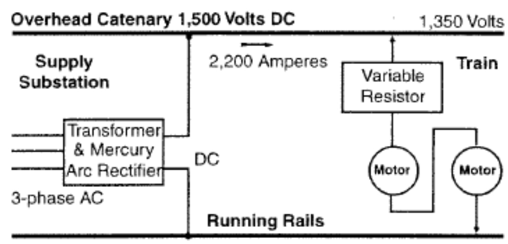

Figure 2. DC Electrification Technology – Second Generation, Circa 1930.

North America's only surviving DC electrifications from the second-generation era are in the Chicago area, on Metra Electric and the Northern Indiana Commuter Transportation District's South Shore Line. Other second-generation DC electrifications in Montréal and New Jersey have switched to third-generation technology.

Second-generation technology also included AC systems which emerged between the 1910s and the 1930s. The "universal" traction motors of the time (so called because they could

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[4] For more on second-generation systems, see Manson, Arthur J., *Railroad Electrification and the Electric Locomotive*, New York: Simmons-Boardman, 1923; *Serial Report: Electrification of Steam Railroads Committee, 1927-1928*, New York: National Electric Light Association, September 1928; Robinson, Myles E., "The Evolution of Steam Railroad Electrification," Part II, *The Journal of Land & Public Utility Economics*, May 1932; *National Power Survey, The Use of Electric Power in Transportation*, Power Series No. 4, Washington: Federal Power Commission, 1936; Thompson, Francis R., *Electric Transportation*, Scranton, Pennsylvania: International Textbook Company, 1940; *Electrification by GE*, Chicago: Central Electric Railfans' Association, 1976; *Westinghouse Electric Railway Transportation*, Chicago: Central Electric Railfans' Association, 1979; and the relevant parts of Middleton, William D., *When the Steam Railroads Electrified*, Bloomington: Indiana University Press, 2001.

[5] Today, only two 1,500-V installations remain in use in North America. The only 1,200-V installation was discontinued in 1941. The single 2,400- and 3,000-V installations were reelectrified at 25,000 V AC, 60 Hz, in 1995 and 1984, respectively.

run on either DC or AC) could not use commercial-frequency AC at 60 Hz. Therefore, second-generation AC electrifications used 25-Hz power, at 11,000 V.

Figure 3 shows the basics of a second-generation AC system, such as the well-known electrification on the Pennsylvania Railroad.[6] As with historically-established DC electrifications, various older components on second-generation AC electrifications have been replaced with more modern technology in recent decades.

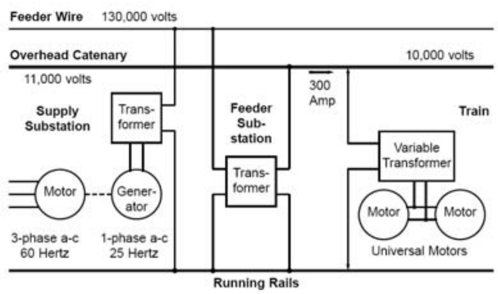

Figure 3. AC Electrification Technology – Second Generation, Circa 1930.

Before the use of electronic controls to regulate train speed, DC systems used variable (tapped) resistors to control the flow of current to the traction motors as the train accelerated. Power was lost and turned to heat in the resistors. Early AC systems could use tapped transformers for this purpose, improving speed control and reducing power loss.

Aside from the larger and more complex substations on AC systems, there are few visible differences between DC and AC installations dating from the early 20th century. Second-generation electrifications all use a *catenary* system, so called because an upper *messenger wire* follows a geometric shape known as a catenary curve as it runs from one overhead wire support structure to the next.

Most second-generation main line tracks feature *compound catenary*, in which vertical wires known as *hangers* connect the messenger wire to an *auxiliary wire*, which is then connected by very short hangers known as *clips* to the *contact wire*, from which cars and locomotives draw current from a *pantograph*. A *simple catenary* system, where the hangers connect the catenary directly with the contact wire, is common for yard tracks and less-busy revenue tracks.

In second-generation systems, both compound and simple catenary, the hangers keep the contact wire nearly flat, eliminating the undulations of the trolley wires used on streetcar systems. However, the contact wires installed for these systems normally run for miles without interruption, so they tend to expand in the summer and contract in the winter (which requires monitoring and re-tensioning on the part of the railroad as the seasons change). For this reason, overhead-wire installations dating from the early 20th century are sometimes described as *variable tension* systems.

Third-Generation Electrification

Modern third-generation electrification systems, using commercial frequency current (60 Hz in North America and 50 Hz in much of the rest of the world), normally at 25,000 V AC, were developed overseas starting in the 1950s and 60s.[7] These systems have become the modern standard both for newly-electrified lines and for reelectrifications of older installations.

Because third-generation systems use commercial-frequency AC, they draw electricity directly from the power grid without the need to convert it to a lower frequency (25 Hz in the US and 16.67 Hz in northern Europe). The develop-

[6] Much of the original Pennsylvania Railroad electrification remains in use today under various owners, at a slightly higher voltage (raised from 11,000 to 12,500 V AC). Amtrak uses 25-Hz AC from Sunnyside Yard in Queens, NY to Washington, DC and Harrisburg, PA, as do the Southeastern Pennsylvania Transportation Authority in the Philadelphia area (which also operates electric commuter service using the same 12,500-V system on lines originally electrified by the Reading Co.) and New Jersey Transit on parts of its North Jersey Coast Line. Frequency converters, both mechanical and electronic, take a balanced 3-phase 60 Hz AC input and convert it into single-phase 25-Hz AC for use by these railroads. The New Haven Line originally used 11,000 V AC, 25 Hz, but switched to 12,500 V AC at the commercial frequency of 60 Hz in 1986.

[7] For a comprehensive technical discussion of early developments in 25,000-V AC electrification, see *British Railways Electrification Conference*, London: British Transport Commission, 1960. More recent discussions may be found in *Railroad Electrification: The Issues*, Special Report 180, Washington: Transportation Research Board, 1977; Weiss, Willard D., H. Ian Hayes and Peter Shaw, "Comparative Catenary Costs—European and U.S. Main Line Electrification," in *Transportation Research Record 939*, Washington: Transportation Research Board, 1983; Kramer, Jerome, "Developments in Catenary Design and Maintenance," *Railway Track & Structures*, Mar. 1994; "Electrification," *Modern Railways*, May 1997; "Electric Traction," *Modern Railways*, Aug. 1998; and Steimel, Andreas, *Electric Traction – Motive Power and Energy Supply*, Munich: Oldenbourg Industrieverlag, 2008.

ment of rectifiers suitable for use aboard multiple-unit cars and locomotives in the 1950s made it possible to power trains drawing commercial-frequency AC because the AC was rectified into DC for use in DC traction motors. For a given power rating, DC traction motors were somewhat lighter in weight than universal motors.

Since the 1990s, the norm for modern equipment using AC traction motors is to rectify single-phase AC from the wire into DC for an inverter to turn into three-phase AC for use in traction motors, but the effect is the same – to power trains with commercial-frequency AC.[8] Also, third-generation systems may use thinner, lighter overhead wire requiring less copper (because the higher voltages involved require less current), and they suffer less from energy losses between substations due to their high voltages.[9] 25,000-V AC systems provide enough power for the busiest commuter railroads, and also meet the needs of high-speed intercity passenger trains.[10]

There is another reason for third-generation systems to use 25,000 V. When railroads adopt high-frequency AC, they must either use a higher voltage (such as 25,000 V), accept a greater voltage drop between substations (which may affect operations), or provide power feeds at more frequent intervals. Figure 4 shows the basic elements of a third-generation system such as Montréal's Deux-Montagnes Line or Amtrak's intercity passenger electrification between Boston and New Haven.

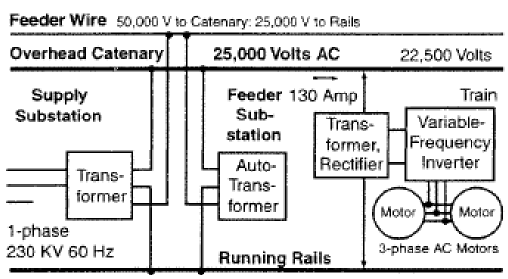

Figure 4. AC Electrification Technology – Third Generation, Circa 1995.

[8] In modern equipment used on DC-powered systems such as Metra Electric and the Long Island Rail Road, DC drawn for the wire or third rail is inverted into three-phase AC for use in the traction motors.
[9] Kaplan, Donald R. "A Revolution in Electrified Service in Montreal," *Passenger Train Journal*, Nov. 1996, pp. 20-21.
[10] Some heavy haul, freight-only electrifications have used 50,000 V AC, but 25,000 V has proved sufficient for most applications.

North America's first 25,000-V installation was the 1984 reelectrification of New Jersey Transit's Morris & Essex Lines, although the existing wires and support structures were used wherever possible. In 1995, Montréal reelectrified its sole electrified commuter rail line, and in 2000 Amtrak electrified its Boston – New Haven Shore Line Route, both also using 25,000 V AC, 60 Hz.[11] Also in the third-generation category is the New Haven Line's 12,500-V installation, which switched from 25 to 60-Hz AC in 1986.

Unless railroads are reusing previously-existing overhead wires (as with the reelectrification of the Morris & Essex Lines on New Jersey Transit), third-generation systems tend to use simple catenary, with the contact wire linked directly to the catenary wire via hangers. These wires are strung in sections of about 1 mi and tensioned at the ends with counterweights. These systems are sometimes termed *constant tension* because the counterweights keep the contact wire at the same tension regardless of the ambient temperature. Some railroads with older electrifications have also installed constant-tension systems because

> in a variable-tension system, slack must be built-in to compensate for temperature-induced changes in tension. In hot conditions … a wave can develop in the slack contact wire ahead of the pantograph, which, at high-enough speeds, can lead to the wire being torn down by the train—a service and maintenance nightmare. Self-tensioning catenary also avoids "hogging" in the wire on cold days, which can cause less-than-ideal contact between the wire and pantograph as the pantograph must extend toward full reach between fixed supports.[12]

Railroads must still monitor and maintain constant-tension catenary systems. However, they do not require as much attention as do variable-tension installations.

[11] As of this writing, no commuter trains operate with electric traction on the Shore Line Route, but the 2011 delivery of multiple-unit cars for the New Haven Line with 25,000-V capability opens the eventual possibility of electric traction on the Shore Line East commuter service between New Haven, Old Saybrook, and New London, Connecticut The Massachusetts Bay Transportation Authority plans to continue using diesel locomotives on its Boston-area commuter rail lines, including service on the electrified Shore Line to Providence, Rhode Island.
[12] Kramer, Jerome, "Developments in catenary design and maintenance," *Railway Track and Structures*, March 1994, p. 35.

AC and DC Systems

Although 25,000 V AC is the voltage of choice for modern commuter and intercity passenger rail electrification, AC and DC both have their strengths and weaknesses. AC has these characteristics compared to DC:

+ Railroads may space substations at longer intervals

+ AC provides more capacity for the needs of high-speed passenger trains and heavy freights, because the higher AC voltages require less current to do the same work

- AC systems require overhead wire and sufficient clearances for high voltages

- Railroads may need to resignal their lines due to electromagnetic issues, which are more prevalent with AC[13]

- The power load requirements of AC may be more challenging for electric utilities to accommodate

Similarly, DC has these characteristics compared to AC:

+ DC substations are smaller than AC substations and are therefore easier to situate in built-up areas

+ Shorter sections between substations provide greater operating flexibility if parts of the system are de-energized

+ The lower voltages involved with DC require less heavy insulation than AC, and allow third rail (between 600 and 750 V) to be used on lines with low vertical clearances

- The lower voltages involved with DC require higher amperages to deliver equivalent levels of power

- Lower DC voltages also tend to require more frequent substations, larger contact wires, and parallel feeders

Electricity is delivered to the train at a given pressure (voltage). The power that trains draw is measured in Watts (W), basically pressure times current (Volts times Amperes).[14] Thus, the higher the voltage, the less current is required to provide the same level of power. In the 600-750 V range, only a third rail is big enough to transmit large amounts of power.[15] At significantly higher voltages (above, say, 1,000 V) a third rail cannot be effectively insulated from the ground, and overhead wires must be used. (All AC systems involve voltages far higher than the range for which third rail may be used.)

Low-clearance tunnels on the Long Island Rail Road and the New York Central precluded overhead wires, limiting those railroads to DC third-rail systems. Railroads that did not have overhead clearance issues were able to use overhead wires, allowing them to choose between DC and AC. The higher AC voltages allowed railroads to space substations at longer intervals, and resulted in more efficient transmission of power. Railroads soon found that under some circumstances, the operating cost savings of AC more than offset the added weight of transformers aboard AC cars and locomotives.[16] The development of mercury arc rectifiers (first used on the Illinois Central and South Shore Line electrifications starting in 1926) reduced some of the energy losses associated with the use of rotary converters for rectification, a situation that continues with modern solid-state rectifiers. Nevertheless, the electrical losses associated with the lower voltages found in DC systems still differentiates DC from AC installations.

Yet not all railroads chose AC. Generally, railroads electrifying mainly for commuter service during the early 20th century chose DC, and those planning extensive electric freight

[13] The requirement to install Positive Train Control (PTC) on all passenger-carrying lines in the US may change this. PTC communicates by radio at frequencies well removed from that of AC electrification (25 Hz or, for new electrifications, 60 Hz) so is itself unaffected. IF PTC is configured as an overlay to the existing signal system, then track circuits must (as noted above) be immune to the frequency of the current used for propulsion. Alternatively, a new electrification may provide an opportunity to upgrade to a moving-block PTC system without track circuits.

[14] This is literally true for DC, and approximately true for AC. With AC the actual power is Volts times *in-phase* Amperes. Inductance and capacitance in the circuit shift the phase of the current, with the result that the voltage peaks and the current peaks in the waveform do not occur at the same instant. An ammeter shows the amount of current, but does not show phase. If the phase (an angle) is known, it is possible to separate the current into *in-phase* and *out-of-phase* components. This effect is known as the *power factor*, which is unity in a perfectly resistive circuit and somewhat less in most practical situations. If the circuit is inductive (as most circuits are), the power factor is said to be *lagging*; if the circuit is capacitative, the power factor is described as *leading*.

[15] Foreman, Milton J. *et al*., *The Electrification of Railway Terminals as a Cure for the Locomotive Smoke Evil in Chicago: With Special Consideration of the Illinois Central Railroad*, Chicago: R.R. Donnelley & Sons, 1908, p. 105.

[16] Droege, John A., *Passenger Trains and Terminals*, New York: McGraw-Hill, 1916, p. 305.

haulage preferred AC.[17] When planning its electrification, the Illinois Central found that DC

> would require more elaborate equipment on the wayside, but very simple equipment on the trains. The AC systems, on the other hand, required heavier and more expensive equipment on the trains, but minimal equipment along the wayside.
>
> AC electrification … would be a good choice for a long distance electrification involving hundreds of miles of line and relatively few locomotive-hauled or multiple unit (MU) trains. DC … on the other hand, seemed to be the best choice for the [Illinois Central] … , which would involve only a relatively short line, but hundreds of electric MU cars.[18]

Similarly, Canadian National in Montreal and the Delaware, Lackawanna & Western in New Jersey chose DC, although successor agencies converted these lines to AC several decades later, after technological advances had made AC more attractive.

The New York, New Haven & Hartford (New Haven Line) and the Pennsylvania Railroad chose AC because they electrified their extensive through passenger and freight services as well as their commuter trains. The Reading Co. also chose AC for its Philadelphia suburban electrification because it envisioned (even though it never implemented) electric freight operation.

Table 1 summarizes the systems (DC and AC) and standards (voltage, pickup technology) characterizing the three generations of commuter rail electrification. Tables 2 and 3 show the lengths, service levels, voltages, and traction power supply systems of North America's commuter rail electrifications as of 1967 and 2010. Holding other factors equal, higher voltages allow longer distances between substations. On the other hand, extending electrification, adding trains and train starts, and using heavier, faster cars requires more power and usually more substations. On properties where there has been little change in voltage levels, increased demands for power have caused several railroads to add substations, with the result that these are spaced at more frequent intervals.

The situation at North America's electrified commuter railroads is reviewed, starting with those properties with adequate supplies of traction power. Next, those that may need to renew and expand system elements are considered. Finally, historic examples of traction power shortfalls are discussed, along with traction power issues on overseas railways.

MEETING POWER SUPPLY NEEDS

Two New York area commuter railroads are meeting their traction power needs through continued investment. In northern New Jersey, the Delaware, Lackawanna & Western chose a 3,000-V DC overhead wire system for its 1930-31 electrification of what are now known as the Morris & Essex Lines of New Jersey Transit (NJT).[19] This installation was fully adequate then, but faced the prospect of major renewal as it aged.

NJT replaced the original system with a nominal 25,000-V AC, 60-Hz system in 1984.[20] The 25,000-V specification was chosen to facilitate access to New York's Penn Station (through service began in 1996) in anticipation of Amtrak converting its Northeast Corridor to 25,000 V, although that plan was cancelled for cost reasons in 1979, by which point New Jersey's reelectrification work was already underway. The reelectrified system meets NJT's needs, and was extended beyond Bay Street, Montclair to Montclair State University in 2002.

The New York Central began electric operation on its Hudson and Harlem Lines serving Grand Central Terminal in 1906.[21] The railroad adopted an unusual variant of third-rail technology whereby the pickup shoes ran beneath rather than atop the third rail. Although this system was costlier to build and maintain, the railroad sought to avoid the potential effects of icing on third-rail conductivity. The Hudson

[17] The DC vs. AC decision was not entirely clear-cut. Some railroads electrifying their freight operations through difficult mountain grades chose AC (Great Northern, Norfolk & Western, Virginian Railway). Others, however, chose higher DC voltages (Butte, Anaconda & Pacific, Milwaukee Road).

[18] *Metra Electric District Motive Power Study: Evaluation of Traction Power System, Executive Summary*, prepared for Metra, October 22, 2001, p. 1.1.

[19] "Lackawanna Electrification Plans Completed," *Electric Railway Journal*, August 1929; also "Catenary System for the Lackawanna Electrification," *Railway Age*, June 14, 1930.

[20] Allen, John G. and John P. Aurelius. "Commuter Rail Reelectrification: Is It Still Justified?" *Transportation Research Record 1838*, Washington: Transportation Research Board, 2003. In practice, the maximum voltage is 27,500.

[21] Wilgus, William J., "The Electrification of the Suburban Zone of the New York Central and Hudson River Railroad in the Vicinity of New York City," Paper 1079, *Transactions of the American Society of Civil Engineers*, March 18, 1908; reprinted, *Central Headlight* (New York Central System Historical Society), 4th Quarter, 2004 and 2nd Quarter, 2005.

Table 1. Three Generations of Commuter Rail Electrification: Systems and Standards

	DC Systems	*AC Systems*
First Generation (circa 1895-1910)	600 to 660 V (*A*) Third rail (overrunning or underrunning shoes)	(Not applicable)
Second Generation (circa 1907-1938)	1,200, 1,500, 2,400 or 3,000 V (*C*) Overhead wire (variable tension, usually compound catenary)	11,000 V, 25 Hz (*B*) Overhead wire (variable tension, usually compound catenary)
Third Generation (*D*)	(Not applicable)	25,000 V, 60 Hz (*E*) Overhead wire (constant tension, simple catenary)

Notes:
A – Now operated at 700 to 750 V DC.
B – Now operated at 12,500 V AC, 25 Hz.
C – The only remaining second-generation DC systems use 1,500 V today
D – Third-generation systems have been in use since 1950s in Europe, 1960s in Japan, and since 1984 in North America.
E – One installation converted from 11,000 V, 25 Hz to 12,500 V, 60 Hz. Third-generation systems use power at commercial frequency, 60 Hz in North America and 50 Hz in most other parts of the world.

Line operates almost entirely in a riverfront environment, so this concern was understandable.[22]

Because the contact rail was suspended over the roadbed to leave room underneath for the pickup shoes, rather than placing it directly on the roadbed like most such installations, the contact rail had to be lighter than was normal for overrunning third-rail systems (i.e., with the contact shoe atop the third rail). To ensure enough traction power, the railroad installed substations at close intervals. As with other early electrifications, the New York Central had to build its own power generating plants because electric utilities were not yet able to generate electricity on the massive scale that busy railroads needed.[23] (In later decades, the railroad was able to switch to commercial feed and retire its power plants.)

In the decades following World War II, the New York Central became the first railroad to order air-conditioned MU cars, and it provided enough current for their higher power draw. Even during the financially-troubled Penn Central years (1968-1975), power on the Hudson and Harlem Lines remained adequate, although the Metropolitan Transportation Authority (MTA) bought new high-performance cars during that time.

Successor Metro-North Railroad (MNR), an MTA operating agency, has invested in its traction power needs, particularly with the 1984 Upper Harlem Line electrification. The MTA's five-year capital plan for 2005-09 included

> $1.38 billion for MNR. About 90% of the commuter agency's funding is slated for normal replacement and state-of-good repair projects. They include … $103 million for traction power …[24]

STAYING AHEAD— FOR NOW

Other railroads are operating electric service with less spare power capacity, although the margin in

[22] Fazio, Alfred E. and Bridget M. Hodgson, *New York City Electrified Railroads in Color, Vol. 1: Lines into Grand Central Terminal*, Scotch Plains, NJ: Morning Sun Books, 2010, pp. 12, 73.

[23] It was not until the Pennsylvania Railroad opened its second-generation electrification in the Philadelphia area in 1915 that a railroad arranged for local electric utilities to meet its entire power supply needs. All subsequent commuter rail electrifications have used power purchased from utilities rather than generated by the railroad.

[24] Luczak, Marybeth, "Going your way," *Railway Age*, July 2005.

Table 2. Basic Characteristics of North American Electrified Commuter Railroads, circa 1967

Historic and Modern Commuter Rail Properties	*Revenue Line-Mi Electrified*	*Weekday Revenue Trains Operated*	*Voltage and Delivery System, Dating From*	*Traction Power Supply Situation (Commercial feed unless otherwise noted*
Illinois Central (now (Metra Electric)	38.7 mi	267	1,500 V DC Variable tension catenary 1926	7 substations (every 5.5 mi)
Chicago, South Shore & South Bend (now NICTD)	76 mi excluding IC trackage rights	49	1,500 V DC Variable tension catenary 1926	9 substations (not including 14.5 mi on Illinois Central; every 8.4 mi)
Canadian National (Montréal, now AMT)	23.5 mi	40	2,400 V DC Variable tension catenary 1918-1925	2 substations (every 11.6 mi)
Pennsylvania Railroad (Wash.-Balto., now MARC)	40.3 mi	2	11,000 V AC, 25 Hz Variable tension catenary 1935	4 substations (every 11.6 mi)
Pennsylvania Railroad (Philadelphia, now SEPTA)	113.1 mi	410	11,000 V AC, 25 Hz Variable tension catenary 1915-1938	14 substations (every 8.1 mi)
Reading Company (now SEPTA)	89.5 mi	376, almost all electrically powered	11,000 V AC, 25 Hz Variable tension catenary 1931-1933	2 substations (every 7.5 mi)
Pennsylvania Railroad (*A*)	68.6 mi	126	11,000 V AC, 25 Hz Variable tension catenary 1931-1933	10 substations (every 6.9 mi)
Delaware, Lackawanna & Western (*B*)	61.7 mi	134, almost all electrically powered	3,000 V DC Variable tension catenary	5 substations (every 12.3 mi)
Long Island Rail Road (now Long Island Rail Road)	106.7 mi	665, most of which electrically powered	660 V DC Third rail, overrunning pickup shoes 1905-1929	31 substations (every 3.4 mi)
New York Central (now MNR Hudson, Harlem)	54.7 mi	288, most of which electrically powered	660 V DC Third rail, underrunning pickup shoes 1906-1913	16 substations (every 3.4 mi)
New Haven Line (now MNR New Haven)	67.1 mi incl. New Canaan branch	143, most of which electrically powered	11,000 V AC, 25 Hz Variable tension catenary 1907-1914	One railroad-owned generating plant plus commercial feed; 15 substations; 2 supply substations (*C*)

Notes:
A – Now New Jersey Transit Northeast Corridor and North Jersey Coast Lines.
B – Now New Jersey Transit Morris & Essex and Montclair Lines.
C – Substations every 4.5 mi; supply substations every 33.6 mi.

Table 3. Basic Characteristics of North American Electrified Commuter Railroads, circa 2011

Modern Commuter Rail Property	*Revenue Line-Mi Electrified*	*Weekday Revenue Trains Operated*	*Voltage and Delivery System, With Reelectrification and Extensions if Applicable*	*Traction Power Supply Situation (Commercial feed on all railroads)*
Metra Electric	40.6 mi	171	1,500 V DC Variable tension catenary Extended 1977	10 substations (every 4.1 mi)
NICTD	75.2 mi excluding Metra trackage rights	43	1,500 V DC Variable and constant tension catenary New outer end of line 1992	10 substations (not including 14.5 mi on Metra Electric; every 7.5 mi)
Agence Métropolitaine de Transport	19.1 mi	49	25,000 V AC, 60 Hz Constant tension catenary Reelectrified and extended 1995	1 substation
MARC, Penn Line (Amtrak)	76.6 mi	47	12,500 V AC, 25 Hz Variable tension catenary	9 substations, incl. 1 under construction (every 8.5 mi)
SEPTA (ex-Pennsylvania Railroad)	130.6 mi	403 (*A*)	12,500 V AC, 25 Hz Variable tension catenary Extended 1983-84	16 substations (every 8.2 mi)
SEPTA (ex-Reading Co.)	92.0 mi	328 (*A*)	12,500 V AC, 25 Hz Variable tension catenary Extended 1974, 1983-84	12 substations (every 7.7 mi)
NJT, NEC and North Jersey Coast Lines	90.9 mi	298 electric (*B*) 308 total (*B*)	12,500 V AC, 25 Hz Variable tension catenary Extended 1982, 1988 partly at 25,000 V AC, 60 Hz Constant tension catenary	12 substations on original lines, incl. non-revenue yard trackage, plus 5 substations on extension (every 5.4 mi)
NJT, Morris-Essex and Montclair	66.6 mi	184 electric 212 total	25,000 V AC, 60 Hz Variable tension catenary Reelectrified 1984 Extended 2001	4 supply substations (every 16.7 mi); 13 transformer stations (every 5.6 mi)
Long Island Rail Road	147.7 mi	715 trains in 2007, mostly electrically powered	750 V DC Third rail, overrunning pickup shoes Extended 1970, 1986	108 substations (every 1.4 mi)
Metro-North RR, Hudson & Harlem Lines	84.3 mi	348, most of which electrically powered	700 V DC Third rail, underrunning pickup shoes Extended 1984	47 substations (every 1.8 mi)
Metro-North RR, New Haven Line	67.1 mi incl. New Canaan Branch	226, most of which electrically powered	12,500 V AC, 60 Hz, Constant tension catenary Reelectrified 1986 (*C*)	4 supply substations (every 3.8 mi); 17 transformer stations (every 3.8 mi)

Notes:
A – Most trains through-routed between former Reading and Pennsylvania Railroad lines; all SEPTA trains are electrically powered. Trains counted only if originating or terminating beyond core segment between Wayne Jct. and 30th St.
B – Includes 84 daily shuttle trains on the Northeast Corridor's Princeton branch and 10 diesel-powered trains between Hoboken and points on ex-Pennsylvania Railroad electrified lines.
C – Also includes 2.1 mi of third rail on the New Haven Line formerly equipped with overhead wire.

Abbreviations for Tables 2 and 3:

NICTD = Northern Indiana Commuter Transportation District.
AMT = Agence Métropolitaine de Transport.
MARC = Maryland Transit Administration commuter rail service.
SEPTA = Southeastern Pennsylvania Transportation Authority.
NJT = New Jersey Transit.
NEC = Northeast Corridor.

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most instances is not close enough to affect service on a regular basis.

Chicago: Metra Electric

Today, Metra's Electric District is meeting its immediate needs for power, but faces the need to add substations to meet future needs. Predecessor railroad Illinois Central (IC) started electric service in 1926.[25] The 1,500-V DC system met the needs of an intensive operation using heavyweight multiple unit cars. "Service requirements were severe; heavy trains were to be moved at high accelerating rates, at relatively high speeds and with frequent stops"[26]

With the replacement of most of the original fleet with the high-performance, air-conditioned, bilevel Highliners in 1971-72, IC added a new substation at Matteson near the outer end of the line (then at Richton Park).[27]

> The new facility was necessary to overcome drops in line voltages, which have been recorded as low as 800 volts DC on the extreme south end of the mainline, significantly below that of the system's nominal 1,500 volts. The major cause for the voltage drop is that the current level of service to … Richton [Park], to which passenger service was extended from Matteson in 1946, is much greater than was anticipated when the electrification was planned in the early 1920s and the area sparsely settled.[28]

A 1972 merger creating the Illinois Central Gulf (ICG) did little to improve the railroad's financial health, and management began to defer maintenance to save money. Fortunately, the Regional Transportation Authority started to provide operating and capital assistance in 1976, before the physical plant became severely run down.

In 1987, ICG sold its electric commuter operation to Metra,[29] which has continued to maintain and modernize the power system:

> The catenary system has undergone major rehabilitation. Contact wire is continuously monitored and significant sections of contact wire have been replaced. Although old, the present system is in a remarkably sound condition. The tensions in the conductors are being monitored and re-tensioning is performed as required. De-wirements are rare and a program of pole foundation repair is ongoing.[30]

Metra has substations at Jackson Blvd. (added in the early 1980s), Weldon (16th St.), Brookdale (69th St.), Front St. (Kensington), Harvey, Vollmer Rd., Matteson (added in anticipation of the original Highliners), and Stuenkel Rd. (added for the 1977 opening of an extension from Matteson to University Park) on the main line; Cheltenham (79th St.) on the South Chicago branch, and Laflin St. on the Blue Island branch. Although Metra Electric runs fewer trains today than the Illinois Central did in 1967, more power

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[25] For more on the history of the Illinois Central's electrification, see Stanford, Paul, "Electric Commuting and a Cleaner Hyde Park," *Hyde Park History No. 1*, Chicago: Hyde Park Historical Society, 1980; Mottier, C.H., "Electrification Work Near End," *Illinois Central Magazine*, June 1926; Lind, Alan R., *Limiteds Along the Lakefront*, Park Forest, IL: Transport History Press, 1986; Lind, Alan R., *From the Lakes to the Gulf: The Illinois Central Railroad Story*, Park Forest, IL: Transport History Press, 1992; and Carlson, Norman, "Train from Randolph Street," *First & Fastest*, Summer 2006. For a technical discussion of the IC's electrification, see the article series about the Illinois Central electrification in the April 1927 issue of *General Electric Review*, reprinted in *Electrification by G.E.*, Chicago: Central Electric Railfans' Association, 1976.

[26] "Electrification of I.C. Suburban Service Completed," *Railway Age*, July 24, 1926, p. 130.

[27] "Improve Chicago suburban service," *Illinois Central Magazine*, August 1970.

[28] Benedict, Roy G., "More Power to the Trains," *Headlights*, May-June 1972, p. 12.

[29] "ICG sells commuter lines," *Railway Age*, July 1987.

[30] *Metra Electric District Motive Power Study: Evaluation of Traction Power System*, prepared for Metra, October 22, 2001, p. 1.3.

is needed today because rising passenger comfort standards require faster-accelerating, air-conditioned cars.

Metra and its predecessor ICG have been careful to stay within the limits of the traction power supply. These limits, incidentally, are not entirely within the commuter railroad's control. During electricity consumption peaks, Metra has sometimes been asked to restrict its power use.

In the late 1990s, when Metra was making decisions about specifications for a new set of cars for its Electric District, the agency commissioned a traction power study to assess its needs and examine the possibility of reelectrifying with 60-Hz AC at either 12,500 or 25,000 V AC. Perhaps surprisingly, the study, completed in 2001, recommended that Metra retain its 1,500-V DC system.[31] Although the higher AC voltages offered modest net benefits, these would be more than offset by the implementation costs. Switching to AC would require lowering the tracks at various bridges over the railroad, especially between Monroe St. and Oakwood Blvd. (39th St.), to accommodate the larger insulators needed for a higher voltage. This would cause widespread service disruption, as tracks would have to be removed from service during the undercutting process.

Accordingly, Metra has retained its 1,500-V DC system. The 26 New Highliners (which arrived in 2005) draw 1,500 V DC, as will another 160 such cars under order at this writing. On-board inverters change the direct current into three-phase alternating current for use in the traction motors (as the Chicago Transit Authority's 5000-series rapid transit cars do).

The 2001 study also recommended specific power upgrades. After further considering its power needs, Metra is now seeking funding for five substations with two 3-megawatt rectifiers each, for a total capacity of 30 MW. Of these substations, one (at 31st St.) will be new and the other four (at 51st St., 95th St., Riverdale, and Homewood) will be installed at tie-stations, which house circuit breakers at section insulators (known on Metra Electric as air-gaps). Metra refers to this process as tie-station conversion.

Chicago: NICTD South Shore Line

The South Shore Line is the only electrified commuter railroad that began as an electric interurban railway rather than as a steam railroad. The railroad's 1,500-V DC system dates from 1926 (when it switched from its original 1908 vintage 6,600-V AC, 25-Hz installation for compatibility with the Illinois Central, its route to downtown Chicago).

Electric locomotives had provided all freight service until the construction of a coal-fired electric generating plant en route in the 1960s, when "the heavy unit coal trains were taxing the capacity of the electric substations …"[32] As a result, the railroad added diesel locomotives to its fleet, which later replaced the electrics.

The Northern Indiana Commuter Transportation District (NICTD) was formed in 1977 to preserve South Shore Line service, and developed a plan for modernizing the South Shore Line's physical plant. New cars replaced the 1926 fleet in 1982-83, and officials in both Illinois and Indiana prepared for their increased power needs:

> In addition to the purchase of new cars, NICTD's capital improvement program for the South Shore included major improvements to the railroad's power supply and equipment maintenance capability. To provide needed additional power capability, [Chicago's Regional Transportation Authority] installed new electrical substations at Monroe Street in downtown Chicago and at Hegewisch [on the South Shore Line but in Illinois], while new equipment was installed at all nine of the railroad's existing substations between Hammond and South Bend. Additional feeder cable was installed to better balance the power supply.[33]

Starting in the late 1990s, NICTD rebuilt its 1982-83 cars with on-board inverters and AC traction motors, which provide faster, smoother acceleration. NICTD's power system largely meets today's needs. On the outer portion between Michigan City and South Bend, however, longer distances between substations result in power losses due to electrical resistance. There is enough power for normal operations, although NICTD tries to avoid running longer trains on this lightly patronized segment, and trains of six cars or more are limited to a low acceleration rate. To prevent excessive power consumption, NICTD sometimes adds and removes cars at Car-

[31] *Metra Electric District Motive Power Study: Evaluation of Traction Power System, Executive Summary*, prepared for Metra, October 22, 2001.

[32] Carlson, Norman, ed., *One Hundred Years of Enduring Tradition: South Shore Line*, Lake Forest, IL: Shore Line Interurban Historical Society, 2008, p. 32.

[33] Middleton, William D., *South Shore: The Last Interurban*, Bloomington: Indiana University Press, 1999, pp. 163-164.

roll Ave. (Michigan City Shops), and schedules include the time required for this process.

A more pressing challenge is the old and fatigued overhead wire, which has occasionally led to dewirements when pantograph bounce occurs. NICTD started work on a major program of overhead wire renewal in 2003, and is installing constant-tension catenary for increased service reliability.

Metra's concerns about its Electric District power supply have also affected NICTD, which uses Metra Electric to reach downtown Chicago.

> Until the summer of 1985, the Illinois Central Gulf had refused to let eight-car South Shore trains onto its line, claiming it would be too severe a drain on the ICG electrical substations. Difficult negotiations with the ICG finally ended in success … and ICG fears proved groundless.[34]

More recently, Metra was hesitant to let NICTD run its new double-deck cars, delivered in 2009, on Metra Electric during peak periods for fear of exceeding the power supply at the Brookdale substation (69th St), which is subject to brief yet strong draws of current because it powers a short but steeply-graded section where the South Chicago branch climbs from street level to the raised embankment of the main line. However, subsequent tests of NICTD's latest cars on Metra Electric showed their power consumption was similar to that of Metra's own New Highliners, and Metra has not restricted NICTD's use of the cars in revenue service. Metra has reported no power problems with its own new cars or with NICTD's.

Northeast Corridor: Ex-Pennsylvania Railroad

During the 1910s, 1920s and 1930s, the Pennsylvania Railroad (PRR) was widely acknowledged as the leader in North American railroad electrification.[35] PRR designed its 11,000-V AC, 25-Hz traction power system to handle fast passenger trains with up to 20 heavyweight passenger cars and heavy freight trains. Electric freight service ended in 1982, but electric operation of commuter and Amtrak trains continues (now almost entirely at 12,500 V, 25 Hz) on the Amtrak-owned Northeast Corridor NEC, which includes the ex-PRR New York – Philadelphia – Baltimore – Washington and Philadelphia – Harrisburg lines. Electrified commuter trains also run on ex-PRR branches in Pennsylvania and New Jersey, owned by the Southeastern Pennsylvania Transportation Authority (SEPTA) and NJT.

Amtrak postponed the replacement of older rotating 25-Hz generators until electronic technology became available, and has replaced older components and facilities before failures occurred. Substation capacity has generally met the increasing volumes and speeds of passenger trains since the 1960s, although between the 1970s and 1990s there was little excess power capacity through New York's Penn Station. For this reason, Amtrak required NJT to provide a new 11,000 V, 25 Hz substation at Sunnyside Yard in Queens (where NJT trains lay over between rush hours) in preparation for NJT's 1996 inauguration of Midtown Direct trains from the Morris & Essex Lines. NJT also installed a new substation for its Morrisville, PA yard, adjacent to Trenton, NJ on the NEC.

Today, demands on the power supply in the Northeast Corridor (NEC) are high – and rising. Amtrak introduced Acela service in 2000, with trains running at speeds of up to 135 mph between New York and Washington, DC.[36] Commuter authorities in New Jersey and Maryland are also running more trains. NJT operates at speeds of up to 100 mph on the NEC. SEPTA's Silverliner-V cars (the first of which entered service in 2010) are also designed for 100 mph operation. On MARC's Penn Line between Washington, Baltimore, and Perryville, Maryland, trains with HHP-8 electric locomotives routinely run at speeds of up to 125 mph, as do Amtrak's Northeast Regional trains in much of the ex-PRR NEC. All this fast running requires large amounts of traction power.

Occasionally, low voltage conditions have affected NEC operations, with widespread effects on service. Amtrak is well aware that

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[34] Smerk, George M., Jr., "The Northern Indiana Commuter Transportation District: A Tenth Anniversary Report," *Indiana Business Review*, October 1987, p. 3.

[35] For more on the Pennsylvania Railroad's electrification, see Bezilla, Michael, *Electric Traction on the Pennsylvania Railroad, 1895-1968*, University Park, PA: Pennsylvania State University Press, 1980; Bezilla, Michael, "Pennsylvania Railroad Electrification Strategy," *Business and Economic History*, 2nd series, 1980, pp. 143-151; "Philadelphia – Paoli Electrification," *Electric Railway Journal*, November 13, 1915; "Philadelphia – Chestnut Hill Electrification," *Railway Age*, May 10, 1918; "Pennsylvania Electrification Links Philadelphia and New York City," *Railway Age*, February 25, 1933; and Cudahy, Brian J., *Rails Under the Mighty Hudson*, New York: Fordham University Press, 2002.

[36] This is not to be confused with two 10-mile segments in Massachusetts and Rhode Island, where Acela trains operate at up to 150 mph. These segments are along the Shore Line Route between Boston and New Haven, which Amtrak electrified in 2000 at 25,000 V AC.

these incidents may be harbingers of serious problems in the future, and commissioned a power study in 2005-2006 to examine the state of the traction power system. To address these issues, Amtrak is using federal funds to enhance the Ivy City (Washington, DC) substation, and install new frequency converters (Metuchen, NJ and Lamokin, DE) and upgrade 60-Hz backup power for the signal system. The only other traction power issue now affecting the Northeast Corridor is the age of the ex-PRR variable-tension wires, which Amtrak seeks to rehabilitate.

Besides powering commuter trains on the NEC itself, Amtrak supplies power for Philadelphia's Chestnut Hill West and Cynwyd lines directly, and for the ex-PRR Media-Elwyn line and the Airport line through SEPTA's distribution system. SEPTA's older cars run only on 12,500 V, but the Silverliner-V cars were built to accommodate either 12,500 or 25,000 V.[37] This provides greater operating flexibility and allows for future possibilities with regard to the power system serving the NEC.

In New Jersey, Amtrak supplies power to NJT for the first 7.3 mi of the North Jersey Coast line (NJT provides power for the remainder) and the 12,500-V section of the short connecting track between the NEC and the Morris & Essex Lines. In 1982 NJT extended electrification from South Amboy to Matawan at 12,500 V, 25 Hz, and again in 1988 from Matawan to Long Branch at 12,500 V, 60 Hz. To allow increased service without building a new substation, in 2003 NJT raised the voltage on the 60-Hz portion to 25,000 V.

NJT's multiple-units can be configured for either voltage while undergoing routine maintenance, but can only operate on one voltage at a time. Electric locomotives can make the change en route – necessary for service to Penn Station, New York on the Morris & Essex Lines, on the Montclair-Boonton Line since the 2002 inauguration of Midtown Direct service, and for electric service on the North Jersey Coast Line beyond Matawan.

New York: Long Island Rail Road

In 1905, New York's Long Island Rail Road (LIRR) inaugurated its 660-V DC third-rail electrification (now 750 V), becoming the first North American railroad to electrify on a widespread scale.[38] In the late 1960s and early 1970s, LIRR took delivery of high-performance, air-conditioned M-1 cars with higher power consumption. To address the situation, the railroad built new substations, doubling the amount of power available and amply meeting its growing power needs – which included a substantial extension of electric service from Mineola to Huntington. Building a new AC overhead wire system might have cost less, but the tunnels to Brooklyn's Atlantic Terminal lack the clearances needed for overhead wires, and a dual-voltage fleet would have introduced its own complications.

LIRR added power capacity in conjunction with a major electrification extension to Ronkonkoma in 1986. However, various components of many of the substations from the 1960s and earlier have been aging as the railroad took delivery of a new generation of heavier and faster-accelerating M-7 cars between 2002 and 2007. A 2007 inventory of LIRR's physical plant found that major investment may be required to maintain the system in a state of good repair and support planned expansion:

> Fifty-four (54) sub-stations are from the 1969-72 [capital] program. Their design life was 35 years. … A replacement program is required ... and should begin soon. Currently there are 13 older sub-stations, 1940's vintage that are in immediate need of replacement. Seven … will be replaced during the current capital program, leaving six … to be replaced at a later date. The 2005-09 capital program provided $145 million for Power, which requested $250 million. This sub-station replacement program was the big loser.[39]

Although LIRR received less money than requested, management has made power

[37] *Technical Specification for the Purchase of Silverliner V Electric Multiple Unit Commuter Rail Cars*, Philadelphia: Southeastern Pennsylvania Transportation Authority, August 2005, p. 1.23.

[38] Condit, Carl W., "The Pioneer Stage of Railroad Electrification," *Transactions of the American Philosophical Society*, Vol. 67, No. 7, 1977, pp. 32-38; also Sturm, Robert C., "The Sunrise Trail: A Brief History of the Long Island Rail Road," *National Railway Bulletin*, No. 4, 1995. The LIRR was not the first North American railroad to electrify its suburban service; that distinction belonged to the Northwestern Pacific service in Marin County, CA, north of San Francisco. Electrified in 1903, the Northwestern Pacific discontinued its commuter operation in 1941 after completion of the Golden Gate Bridge had drawn much business away from the railroad's train and ferry combination; see Demoro, Harre W., *Electric Railway Pioneer: Commuting on the Northwestern Pacific, 1903-1941*, Glendale, CA.: Interurban Press, 1983.

[39] Nelson, Donald N., *Assessment of the Condition of the MTA Long Island Rail Road*, prepared for the MTA Long Island Rail Road, September 21, 2007, p. 15.

infrastructure renewal a high priority, and power systems have been funded at increasing levels since 1995. In 1995-1999 LIRR allocated $17.1 million for power infrastructure replacement, increasing substantially in 2000-2004 to $77.4 million. This amount further increased to $145 million in 2005-2009, and this has been raised to $190 million under the 2010-2015 capital plan. This reflects a continued commitment to meeting traction power needs despite the challenges of competing infrastructure needs in a fiscally constrained environment. Nine LIRR substations were replaced under the 2005-2009 capital program, and some of the old rectifiers (which change AC into DC) have been reused on the New York City subways. In future capital programs, LIRR will work towards replacing substations from the early 1970s.

The railroad has been investing in other traction power components, including third rail, protection boards, third-rail cable and disconnection switches, and negative reactors. LIRR plans to replace aging conventional third rail with new, more efficient aluminum third rail. The entire power system is considered to be in a state of good repair, although substantial needs remain.

A consultant performed a traction power study in anticipation of the East Side Access project, one of the largest expansion projects in the railroad's history, which will bring the railroad to Grand Central Terminal.[40] This study recommended three new substations in Queens to accommodate additional trains, as well as three other new ones elsewhere on the railroad. LIRR is trying to fund these substations to ensure that power supply continues to meet future needs. LIRR is building its own tracks and platforms at Grand Central, where MNR needs the existing tracks for its own trains. Also, although the two railroads use compatible voltages, LIRR's overrunning third-rail system are not readily compatible with MNR's underrunning pickup shoes.

TRACTION POWER SHORTFALLS

Electrified railroads need a comfortable margin of traction power to prevent voltage drops and electrical overloads leading to service-disrupting power failures. New climate-controlled, rapidly-accelerating equipment may cause electricity shortfalls unless power supplies are increased. Otherwise, trains may have to accelerate and run more slowly, sometimes without lights, heat, or air conditioning.

No electrified commuter railroad in North America has a serious shortage of traction power as of this writing. But this affected Canadian National, and was a serious issue on the Reading Co. and the New York, New Haven & Hartford Railroad. Furthermore, traction power has been a concern on several overseas railways.

Montréal: Canadian National

In Montréal, a 2,400-V DC overhead wire system, inaugurated in 1918, served Canadian National (CN) well for decades.[41] Initially there was just substation at the outer end of the 3.1-mi tunnel under Mt. Royal, which was the reason for the line's electrification in the first place. In 1950, CN replaced the aging original substation with two new ones, one at Central Station downtown and the other in the suburbs. But CN subsequently

> started using diesel-electric [rather than electric] switchers in [Central Station] and the yards, which minimized the [downtown electrical] load … while the load on the [suburban] substation was too large. At the same time, some local trains began using two [electric] locomotives in multiple to increase the acceleration and the speed between stations. The trolley voltage was raised to 2750 volts … but no satisfactory solution to the problem of transferring capacity [between substations] was achieved …[42]

In 1992, transportation officials proceeded to rebuild and re-electrify the line at 25,000 V AC,[43] and this important project was completed in 1995. Power capacity has been fully adequate since then under the Agence Métropolitaine de Transport (AMT).

Philadelphia: Reading Company

The former Reading Company in Philadelphia, electrified its suburban service between 1931 and

[40] Middleton, William D., "Long Island Rail Road Builds for the Future," *Railway Gazette International*, August 2004; also Miller, Luther, "How do you get to Grand Central?" *Railway Age*, April 2005.

[41] Gordon, William G., "Montreal Tunnel Zone Electrification," *Electric Railway Journal*, November 30, 1918.

[42] Clegg, Anthony, *The Mount Royal Tunnel: Canada's First Subway*, Montreal: Railfare DC Books, 2008, p. 61.

[43] "Montreal Commuter Train Regeneration," in Smith, Douglas N.W., ed., *Canadian Rail Passenger Yearbook*, Ottawa: Trackside Canada, 1993; also Allen, John G. and John P. Aurelius. "Commuter Rail Reelectrification: Is It Still Justified?" *Transportation Research Record 1838*, Washington: Transportation Research Board, 2003.

1933.[44] From the outset, the Reading's 11,000-V, 25-Hz AC supply was barely adequate. High power demand charges from the local utility caused the railroad watched its power consumption carefully.

> A very critical cost in electric train operation was power consumption for heating … To further conserve on heating costs, an "Electric Heat Order" was developed as a detailed instruction to train crews on the operation of electric heat and the conservation of energy. … Electric heat would be off on all dead-heading equipment until it was ready to receive passengers …
>
> Next, between the hours of 8:00am and 9:00am, and between 5:00pm and 6:00pm, the enginemen of all … trains were required to cut train heat at designated locations. Trains destined for the Reading Terminal were required to cut heat [as they neared the terminal]. Leaving Philadelphia, trains would cut train heat as they neared their final destination.[45]

The City of Philadelphia and the Southeastern Pennsylvania Transportation Authority (SEPTA) improved service with new cars, known as Silverliners. A small order came in 1963, and more cars arrived in the mid-1970s (replacing most of the Reading's original multiple-unit cars). The air-conditioned, high-performance Silverliners consumed more power, and the 5-mi Fox Chase branch was electrified in 1966, yet the traction power supply was not increased. As one observer noted in 1979,

> power facilities have been plagued by frequent outages. Reserve capacity is slight, and operation at reduced speed, without heat, or with some lines out of service has been necessary when any of the major parts of the electrical system have failed.[46]

In the 1970s, it became clear just how close the Reading was to its traction power limits. Commuter rail ridership rose during strikes on SEPTA's City Transit Division in April 1977 and March 1979. Railroad officials pressed every available multiple-unit car into service, but extra trains were operated with diesel locomotives to avoid overloading the power supply.

Between August 28 and August 30, the main AC frequency converter at Wayne Junction substation overheated, at a time when the backup converter was off-line for maintenance.[47] There was enough electricity available for lighting, but not for traction power. SEPTA leased 19 Conrail diesels to provide a skeleton service, with electric multiple unit cars using their pantographs to draw supplementary power.

SEPTA addressed the traction power situation on the Reading by installing a new converter at Wayne Junction in 1985 (the first electronic frequency converter in US railroad service) and two more at the same site in 1990. With the 1984 opening of the Center City tunnel connecting the former Reading and Pennsylvania lines into a single operation, SEPTA accommodated the two separate power supplies with a phase break on the Reading side shortly beyond the tunnel. The Reading power enhancements have reduced electricity-related operating restrictions, although an additional substation on the West Trenton Line and another on the Norristown-Manayunk line would improve operations. SEPTA is now using 90% of its continuous load capacity during peak periods.

Subsequent ridership growth on the former Reading lines shows the importance of addressing power supply issues. Between 1994 and 2007, SEPTA's commuter rail ridership grew by 31.3% overall, but growth on the former Pennsylvania Railroad lines amounted to only 17.0%. On the former Reading lines, ridership increased by 52.7%, largely due to residential growth patterns.[48]

New York: New Haven Line

From 1907 to 1914, the New York, New Haven & Hartford Railroad inaugurated its 11,000-V AC system between New York and New Haven.[49] At that time, power companies were reluctant to sell single-phase power in quantity for fear of unbal-

[44] Wright, G.I., "Reading Installs Electric Traction," *Railway Age*, March 29, 1930.

[45] Coates, Wes, *Electric Trains to Reading Terminal*, Flanders, NJ: Railroad Avenue Enterprises, 1990, p. 46.

[46] Pawson, John R., *Delaware Valley Rails*, Willow Grove, PA: privately published, 1979, pp. 48-49.

[47] Frequency converters on the former Reading Company, as on the former Pennsylvania Railroad, turn 60-Hz power from the utility company into 25-Hz power for the railroad's use.

[48] DeGraw, Ronald, "Regional Rail: The Philadelphia Story," *Transportation Research Record 1433*, Washington: Transportation Research Board, 1994, p. 108; also *Fiscal Year 2009 Annual Service Plan*., Philadelphia: Southeastern Pennsylvania Transportation Authority, April 2008, p. 109.

[49] McHenry, E.H., "Electrification of New York New Haven & Hartford," *Railway Age*, August 6, 1907. and "Alternating-Current Electrification of the New York, New Haven & Hartford Railroad, 1907," New York: American Society of Mechanical Engineers and Institute of Electrical and Electronics Engineers, 1982.

ancing their loads.[50] Alternating current is generated with three phases, but railroads prefer single-phase AC because three-phase AC requires a complex two-wire electric pickup system. (Three-phase motors existed, but did not then provide the speed control that most railroads needed.)

To ensure sufficient supplies of single-phase AC, the New Haven built its own coal-fired power generating plant at Cos Cob, Conn., assisted by a motor-generator substation at an electric utility power plant at Devon, near Stratford, Conn. The generating plant, supplemented by power bought from local utilities, was more or less adequate for the New Haven's needs for many decades (although the electrification was marginally underpowered even by the 1910s).

In the early 1950s, the New Haven acquired dual-mode electric/diesel locomotives for its outer-zone suburban and intercity trains, and considered cutting back the outer end of electric service from New Haven to Stamford.[51] But the dual-mode locomotives that the railroad envisioned taking over these duties were less powerful than its electric locomotives, and it could not afford additional dual-mode locomotives.[52]

In the 1970s, new cars on the New Haven Line led to difficulties with the power supply:

> The new M-2 multiple-unit commuter cars that began arriving in 1973 required much more power than the older equipment, and during peak periods, load dispatchers were obliged to regularly cut power to sections of the line to avoid overtaxing the Cos Cob plant or exceeding limits on the … [utility] supply. Sometimes more than a dozen trains would coast to a stop waiting for power to be restored. On-time performance hit rock bottom.[53]

Planning capital improvements on a line owned first by the bankrupt Penn Central and then by successor freight railroad Conrail was difficult for public authorities in two states. The 1983 formation of Metro-North Railroad (MNR) placed the suburban services of the ex-New Haven and the ex-New York Central under one management. MNR addressed the power problem by retiring the Cos Cob power plant in 1986 and switching to utility-supplied 60-Hz (commercial frequency) power with a slight increase of voltage to 12,500~13,000 V AC. (All New Haven Line and Amtrak equipment not able to run on 60-Hz current had already been retired.)

There was one complication, however. On AC systems, higher frequencies work better with higher voltages. With 60-Hz power, it became necessary to either raise the voltage (such as to 25,000 V AC) or provide more frequent feeds to the contact wire (via substations powered from the utility grid or transformer stations using the high-voltage lines along the railroad). As converting the fleet to 25,000 V would have required removing cars from service on MNR's busiest line, it was simpler to provide more feeds to the overhead wire. Despite some initial difficulties, today's power system works for a line where trains do not exceed 90 mph. Between the early 1990s and the mid-2000s, MNR replaced the aging variable tension catenary with new constant tension wires.

The New Haven Line is well prepared for the arrival of new M-8 cars (which have regenerative braking for use in AC territory) in 2011 to replace the oldest M-2 equipment, though future growth will have to be met. A 2007 study for the Connecticut Department of Transportation explored the possibility of using fuel cells to even out voltage levels along the railroad and make the power system more robust.[54] Once LIRR serves Grand Central Terminal and vacates some slots at Penn Station, MNR may wish to institute New Haven Line service to Penn Station, implying the need for substation enhancement on the Amtrak-owned Hell Gate Route.[55]

Trenes de Buenos Aires

Traction power issues have not been limited to North America. In Buenos Aires, private concessionaires inherited a deteriorated physical plant when they took over commuter trains from the

[50] These objections soon subsided as utilities began producing much larger amounts of power. When the Pennsylvania Railroad planned the first phase of its electrification between Center City Philadelphia and the western suburbs, opening in 1915, it was able to purchase all the current it needed from local utilities.

[51] Frattasio, Marc J., *The New Haven Railroad in the McGinnis Era*, Hart, MO: White River Productions, 2003, pp. 58, 105.

[52] For more on the state of the New Haven's power system and the railroad's motive power strategies during the 1950s and early 1960s, see Pinkepank, Jerry A., "Why N.H. re-electrified," *Trains*, August 1964.

[53] Middleton, William D., "Super Railroad," *Trains*, March 2003, pp. 44-45.

[54] "A Study of the Feasibility of Utilizing Fuel Cells to Generate Power for the New Haven Rail Line," prepared for the Connecticut Department of Transportation, August 2007.

[55] *The Northeast Corridor Infrastructure Master Plan*, Northeast Corridor Working Group, n.p., May 2010, pp. 20-22.

former national railways in the 1990s. In 1995, Trenes de Buenos Aires (TBA) took over two heavily-traveled 800-V DC third-rail commuter operations, and found that

> One of the most frequent causes of delay are power shortages, so TBA has allocated top priority to repair of the power distribution plant. It has already signed a … contract … for renewal and maintenance of the equipment. Most money is destined for repair and uprating of … substations … and to third rail renewal …[56]

London – Southern Region

London's Southern Region 750-V DC third-rail electrification, largely dating from the early 20th century, had long met the needs of a huge and complex operation serving commuter rail and some intercity runs.[57] The Southern Region electrification even accommodated Eurostar trains using the Channel Tunnel for two decades until a dedicated high-speed line was built. But traction power became an issue when train operators faced a December 31, 2004 deadline for replacing antiquated multiple-units with swinging "slam doors" operated manually by passengers.

Track owner Network Rail undertook a crash program to provide more electricity for the new, more power-hungry multiple-units being ordered to replace the slam-door cars. Britain's passenger rail franchising and separation of infrastructure from operations further complicated matters. "The strengthening of the traction power supply on Network Rail's Southern Region is claimed to be Europe's largest ongoing electrical engineering project."[58]

Netherlands Railways

Traction power became an issue on the Netherlands' normally well-regarded railway system, about two-thirds of which is electrified at 1,500 V DC.[59] Rail officials increased service substantially in the 1980s without providing the traction power upgrades these additional trains needed. As a result, trains sometimes ran at reduced speeds to save electricity, and if several trains accelerated simultaneously, there might be a localized voltage decrease of almost one-third.

> In 1921 a government appointed commission recommended … that [1,500 V] DC be adopted … Much destruction was wreaked on the Dutch network in the Second World War, and in the aftermath NS pondered a change to [3,000 V]. The choice rested unhappily with [1,500 V] …
>
> Today, what seemed a reasonable choice 80 years ago with EMUs [i.e., electric multiple units] using 750 V DC traction motors is a major anachronism with locomotives rated at 4.8 MW hauling relatively fast trains at 5 min intervals. A seven-car EMU in 1927 had an hourly rating of 1.8 MW, but in 1996 a seven-car double-deck EMU was rated at 3.2 MW. … Not only that, but 60 additional substations are being built in the short term simply to maintain the minimum catenary voltage.[60]

The new substations have alleviated matters somewhat. For the longer run, rail officials in the Netherlands are moving towards the modern European standard of 25,000 V AC, 50 Hz, starting with new lines for high-speed passenger trains and freight.

Other Railways

Sydney's large CityRail commuter system faced the need for various capital investment projects as the 21st century opened, including "the upgrade of the [1,500-V] DC traction power supply to facilitate an all air-conditioned fleet."[61] CityRail's 2006 outer suburban cars have 25,000-V, 50-Hz capability if the system adopts AC.[62]

In Wellington, New Zealand, railway authorities augmented the 1,500-V DC power supply in order to extend electric service and to meet the needs of a new generation of cars, although these efforts may be barely sufficient:

> KiwiRail Network has installed 10 new rectifier substations across the network, and insu-

[56] Garibotto, Enrique, "TBA takes over last BA suburban trains," *Railway Gazette International*, August 1995, p. 485.

[57] For a comprehensive history of the electrified suburban service of the Southern Railway / British Rail Southern Region, see Moody, G.T., *Southern Electric, 1909-1979: the history of the world's largest suburban electric system*, London: Ian Allan, 1979.

[58] Ford, Robert, "Power supply upgrade highlights the perils of fragmentation," *Railway Gazette International*, April 2004, p. 209.

[59] For more on the choice of 1,500 V DC, see Bearce, W.D., "An Abstract of the Report of the Commission Appointed to Consider the Choice of a System of Electrification for the Netherlands," *General Electric Review*, May 1922.

[60] Hondius, Harry, "Two railways grapple with rolling stock modernization," *Railway Gazette International*, February 2000, p. 113.

[61] Garnham, Barry, "Mapping out a long-term future," *Railway Gazette International*, Metro Report issue, 2007, p. 49.

[62] Downs, Chris, "New South Wales Electrification Report," *Australian Railway Enthusiast*, March 2003, p. 6.

> lated the signalling to prevent electromagnetic interference from the AC drives. Nevertheless, the power supply limits will not permit the [new] sets to operate in formations of more than six cars under normal circumstances.[63]

Sometimes, an older power system is inadequate for rising demand. Italy's 3,000-V DC system, long adequate for most needs, came under strain from the demands of high-speed passenger service, forcing the national railway system to adopt 25,000 V AC for new high-speed segments.[64] In 2007, Indian Railways began switching Mumbai's extremely busy and overcrowded suburban service to 25,000 V AC.[65] The original 1,500-V DC installation was unable to accommodate the power needs of more trains with faster-accelerating cars.

MANAGING TRACTION POWER

Electrified commuter railroads need a systems approach. It is vitally important to anticipate, not just react to, new, higher-performance equipment, higher speeds, and more frequent service. Traction power upgrades need to precede or accompany these events—not just follow them after power shortages have disrupted operations.

Immediate Measures

Some measures are immediate adaptations to power shortfalls and have negative impacts on the speed of service, at least at the margin:

- *Add and remove cars*, if power limitations are confined to outer sections of a railroad. NICTD does this on some trains between Michigan City and South Bend, Ind.
- *Reduce acceleration rates and/or maximum speeds*. Metra Electric limits trains of more than six cars to series (as opposed to parallel) settings, and NICTD restricts acceleration rates of trains of six cars or more on the outer part of its line. When New Jersey Transit re-electrified its Morris & Essex Lines in 1984, the local utility supplied the Bernardsville substation on the Gladstone branch from a 34,000-V power line. Sometimes, accelerating a single 8-car train affected residential electric customers. Train engineers were instructed to use a low acceleration setting until the utility installed a more robust 220,000-V line in the early 21st century. Similarly, on Metro-North,

> The M3a … [MNR's standard multiple unit car at the time] was field-tested, based on its existing conditions. … MNR equipment engineers … recognized that the peak current demand … was excessive under existing settings. Such high current demand has the tendency to pull train voltage down. A new setting was proposed by reconfiguring the control circuitry. The new setting was then field-tested again. …
>
> As a result of the modification, the peak current demand is reduced from 1180 … to 980 Amps per car, a 17% reduction. … With the same electric network in service, the modified fleet would result in a reduction of low voltage occurrences by 28% in the morning peak hours.
>
> Subsequently, MNR decided to modify the control circuits of the whole M3a fleet. The cost of reconfiguring the vehicle's control circuits is insignificant compared with upgrading the traction power system [to] achieve the same performance.[66]

This did, of course, affect running times at the margin, but MNR has sufficient power for the needs of a reasonably fast service.

- *Use diesel locomotives* to supplement electric traction, if the route does not include long tunnels without ventilation. For reasons of operating flexibility, MARC uses diesels on some Penn Line trains, even though that line is fully electrified. NJT uses diesels on some Morris & Essex Line and Montclair-Boonton trains to/from Hoboken (largely for through service to non-electrified portions), and allows sufficient time in its schedules for the lesser acceleration rates of diesel locomotives. NJT and Montréal's Agence Métropolitaine de Transport are buying dual-mode electric/diesel locomotives for service through electrified tunnels to non-electrified lines.

Intermediate Steps

Other efforts to manage power demand can be undertaken with less impact on running times:

[63] MacIntyre, Iain, "Matangi Moves Wellington Commuters," *Railway Gazette International*, January 2011, p. 36.

[64] Fumi, Alvaro, Fabrizio Caracciolo and Vittorio Salvatori, "Commissioning of the 25 kv energy subsystem in Italy," *Railway Engineering*, March 2011.

[65] Jackson, Chris, "Essential upgrade underway on busy suburban network," *Railway Gazette International*, Indian Railways in Transition supplement, October 2007, p. 22.

[66] Yu, J. Gordon, "Traction Power System Study for Metro-North Railroad," presented at the International Conference on Computer Modeling for Rail Operations, Orlando, FL, February 2004, pp. 8-9.

- *Marginally increase voltages* to reduce the amount of voltage drops between substations and/or when several trains are drawing power at once. By increasing actual voltages around 10% above their nominal levels, Metro-North (both third rail and overhead wire), LIRR, Amtrak New Jersey Transit and SEPTA have reduced the risk of low voltages affecting service. Of course, all insulation must be fully effective at the increased voltage.
- *Adjust schedules* so that fewer trains are drawing power in the same vicinity. Zone or skip-stop schedules require fewer train starts and thus reduce overall power draw, holding other factors equal. When the New York Central initiated zone schedules starting in 1965,

> … In the morning peak hour, … [before zone scheduling on the Harlem Line] trains were scheduled to depart 8:04 from Bronxville, 8:05 from Tuckahoe, and 8:05 from Crestwood, … placing three accelerating trains within a two-mile area. [T]he new zone schedules … show that these simultaneous accelerating points are spread over a much greater area. The instantaneous demand on any one substation is reduced substantially. [67]

The New Haven Line, LIRR, and Illinois Central subsequently adopted zone schedules, as did some diesel operations. All these railroads chose zone schedules for reasons of overall operating efficiency, but reduced electricity consumption (on electrified properties) was an additional benefit.

Lasting Resolutions

There are various ways to handle power demand on an electrified railroad, and these should be pursued where feasible. But when the impacts of growing demand (or an aging traction power system) cannot be readily managed, investing in power upgrades and associated measures may be desirable before reliability or throughput are affected.

- *Renew overhead wire*. NICTD has been replacing its older overhead wire to avoid dewirements and the service disruptions they cause. Similarly, Metro-North has replaced much (although, at this writing, not all) of the original overhead wires on its New Haven Line with new wires tensioned by counterweights.
- *Renew third rail*. LIRR has been replacing its original steel third rail with a better-conducting composite aluminum-and-steel version. MNR inherited 70 lb/yard third rail from the New York Central, which was suitable for use with underrunning pickup shoes, but offers insufficient conductivity for modern needs. MNR has adopted New York City Transit's 150 lb/yd subway third rail with modified brackets to accommodate underrunning shoes, as LIRR's third rail was too bulky for MNR's needs. In Grand Central Terminal, where clearances are limited and curves have tight radii, MNR uses a very highly-conducting lightweight aluminum rail with a stainless steel contact surface. These improvements have helped MNR accommodate its higher-performing M-7a cars since 2004.
- *Install new substations and/or increase the capacity of existing substations*. There are several examples of railroads adding substations. The Northwestern Pacific (NWP) electrified its Marin County, Calif. suburban service in 1903, using wooden-bodied cars. These were supplemented with heavier steel-aluminum cars in 1929-30, and NWP added two new substations to meet their greater power requirements.[68] More recently, the Long Island Rail Road and the Illinois Central made vitally necessary power upgrades when they introduced new cars in the late 1960s and early 1970s. In the early 21st century, SEPTA invested in substation upgrades, particularly for the heavily-used trunk line through Center City Philadelphia, before new Silverliner-V cars started arriving in 2010. Occasionally, though, investment in electrical substations and other traction power components has lagged behind the introduction of new cars or more frequent service.
- *Replace aging transformers, DC rectifiers* (Metra, NICTD) *and AC frequency converters* (Amtrak, SEPTA).
- *Replace other aging electrical gear* (LIRR).
- If other measures are insufficient, *reelectrify the system at a higher voltage* (Mumbai).

There are various ways to handle power demand on an electrified railroad, and these should be pursued where feasible. But when the impacts of growing demand (or an aging traction power system) cannot be readily managed, investing in power upgrades may be desirable be-

[67] Eisele, Donald O., "Application of Zone Theory to a Suburban Rail Transit Network," *Traffic Quarterly*, January 1968, p. 58.

[68] Demoro, Harre W., *Electric Railway Pioneer: Commuting on the Northwestern Pacific, 1903-1941*, Glendale, CA: Interurban Press, 1983, pp. 45-46. The railroad abandoned its suburban service in 1941 for commercial reasons, but, the NWP electrification fully met its operating needs while it was in service.

fore reliability or throughput are affected. Even when railroads are not experiencing power outages, inadequate power results in slower operations, either because cars must be added and removed to avoid excessive power draw, or because trains must travel more slowly to limit power consumption.

CONCLUSION

Traction power supply is a vital part of a properly functioning electric commuter railroad. When traction power falls short of requirements, the results undermine much of the benefit that electrification provides.

Commuter rail customers suffer when the supply of traction power fails to keep up with demand. Trains may have to travel more slowly to limit power consumption, perhaps without the full benefit of heating, lights, ventilation or air conditioning. In some instances, cars may be added and removed. If the demand for power exceeds the supply, the result may not be limited to lower voltage levels, but may cause a power outage—halting service on much of the railroad.

Although electric traction power lacks the high visibility of new cars or service extensions, today's commuter railroads recognize its importance. As electrical system components age, electric service is expanded or extended, and cars with higher power consumption are ordered, commuter rail authorities must add and renew substations and other power distribution elements. Readily taken for granted under normal circumstances, electric power supply may become a high-profile issue if it falls short of requirements. Neglecting this vitally important function may be tempting from a short-term budgetary standpoint, but it can lead to consequences which do not promote commuter rail as a fast and reliable form of transportation.

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