Subway Energy Usage and Analysis of Energy Storage System Applications

Final Report | Report Number 23-19 | September 2022

NEW YORK STATE | NYSERDA

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Subway Energy Usage and Analysis of Energy Storage System Applications

Final Report

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Notice

Abstract

The goal of the project is to develop and demonstrate instrumentation on a data collection car to measure potential regenerative braking performance, peak shaving, and energy savings in the New York City Transit subway environment. Data was collected periodically over 15 months from a train in revenue service on the 7-Line. This data was used to determine electrical power and energy consumption, regenerative braking power and energy, on board resistor power and energy dissipation, and total electrical energy available from braking (regenerative or non-regenerative). The results and analysis were used to explore the viability of energy storage system design and opportunities for future development.

Keywords

Regenerative braking, energy storage system, 3rd rail, peak shaving, New York City Transit, subway

Acknowledgement

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Definitions

Energy used is determined when electrical power flows into the train car from the 3rd rail. This energy is used to drive the propulsion system and to carry hotel loads (air conditioning, lighting, etc.).

Regenerative braking (energy returned) occurs when electrical power flows out of the train car into the 3rd rail.

Resistive braking (non-regenerative braking) occurs when electrical power flows to the onboard resistor banks and is dissipated as heat.

Regenerative energy is the measure of regenerative braking power over time.

Resistor energy is the measure of resistor power over time and represents energy currently wasted as well as potentially recoverable with ESS/enhanced receptivity.

Total braking energy is the sum of regenerative and resistor energy, this represents the maximum amount of electrical energy available for use through regenerative or non-regenerative braking.

Friction braking uses brake shoes in physical contact with the wheels to slow the train using friction, generating heat and metal dust. Friction braking is initiated when speeds are too low for the traction motors to provide effective braking energy.

Acronyms and Abbreviations

ConEd	Con Edison
CUNY	City University of New York
DCC	data collection consist
DER	distributed energy resources
ESS	energy storage system
FTA	Federal Transit Administration
GWh	gigawatt-hour
IEEE	Institute of Electrical and Electronics Engineers
KE	kinetic energy
kWh	kilowatt-hour
MTA	Metropolitan Transportation Authority
MW	megawatt
NYCT	New York City Transit
NYISO	New York Independent System Operator
NYPA	New York Power Authority
O&M	operations and maintenance
RFID	radio frequency identification
ROI	return on investment
VDC	volts direct current

Executive Summary

The New York City Transit Subway system consumes approximately 1500 gigawatt-hours (GWh) (2021) of traction energy with demand power of approximately 3,500 megawatts (MW) annually at a cost of about $203 million. Regenerative energy management techniques intended to reduce this usage are being evaluated including onboard energy storage, trackside energy storage, operational enhancements such as start/stop synchronization, and software modifications for train cars to better utilize regenerated energy.

To evaluate these new techniques and technologies, and to develop the associated benefit cost analyses, an understanding of the current energy budget, onboard and 3rd-rail electrical parameters, and operational characteristics is required. Previous efforts in this area have been model oriented or based on single-braking train to single-accelerating train testing on isolated test tracks, which do not represent actual real-world performance in a 3rd-rail distribution grid environment.

In this project electrical energy usage data was collected and analyzed to quantify the energy budget with respect to regenerative braking performance and potential Energy Storage System (ESS) implementation in the New York City Transit Subway system. Electrical parameters including 3rd-rail voltage, rail car line currents, and onboard resistor currents, not available through the onboard propulsion test equipment, were measured by an independent data acquisition system.

Data was collected periodically over 15 months from a train in revenue service on the Flushing Avenue Line (7 Line). This data was used to determine train electrical power and energy consumption, regenerative braking power and energy, onboard resistor power and energy dissipation, and total electrical energy available from braking (regenerative or non-regenerative).

Results of this analysis reveal several key points:

- Sixteen percent (16%) of the mean total electrical energy consumed by traction power is currently returned as regenerative energy to the 3rd rail.
- Five percent (5%) of the mean total electrical energy consumed by traction power is dissipated through the onboard resistors. This represents the maximum energy that could be potentially recoverable by ESS implementation or other energy saving techniques.
- Mean total electrical energy consumed by traction power: 25.8 kWh per stop.
- Mean regenerative energy returned to the 3rd rail: 5.4 kWh per stop.

- Mean energy dissipated into the onboard resistors:1.6 kWh per stop. This represents energy that could be potentially recoverable if 3rd-rail receptivity is increased via the techniques introduced above.
- Mean total braking energy available: 7 kWh per stop.
- Seventy-seven percent (77%) of available braking energy (5.4 kWh regen energy/7.0 kWh total braking energy) is returned as regenerative energy back to the 3rd-rail grid.
- Available braking energy varies stop to stop based on factors such as train speed, track incline, train weight, kinetic energy (KE), track geometry and track receptivity/available load.
- The amount of regenerative energy returned to the 3rd rail varies based on the same factors as the available braking energy as well as the receptivity of the 3rd-rail grid. Receptivity is based on the amount of load drawing power from the 3rd-rail grid when the train is braking.
- Focusing improvements on 3rd-rail receptivity may not result in significantly increased energy savings.

1 Introduction

The New York Metropolitan Transportation Authority (MTA) power use is significant. Traction power alone comprises approximately 2150 gigawatt-hours (GWh) per year, at an electricity cost of approximately $237M annually. In 2021, the New York City Transit Subway system consumed approximately 1,500 GWh of traction energy with a demand of about 3,500 megawatts (MW), costing around $203M.

Subway trains introduced in the past 20 years have included the capability to perform regenerative braking. All new subway car procurements require regenerative braking capability. Regenerative braking utilizes the electric propulsion motors to act as electrical generators while the train is braking, returning electrical energy to the 3rd-rail grid. This energy can be used to power other trains that are drawing power, thereby reducing the overall energy and demand power consumed by the traction system. This capability also reduces electrical power generation, transmission, and distribution requirements as well as the carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxide (NOx) greenhouse gas emissions associated with the system's traction power consumption.

While this regenerative braking capability has been evaluated in test efforts using isolated test tracks and synchronized one-to-one train test techniques (using one train as the braking train and one accelerating train as the load), the real-world performance of regenerative braking in a complex 3rd-rail grid with multiple load and supply trains has never been measured and is not well understood.

Multiple energy storage system solutions, intended to capture, store, and reuse regenerative braking energy have been proposed, typically based on the presumption of significant amounts of unused regenerative braking energy. It is essential that the current state of regenerative braking and the overall 3rd-rail energy budget be quantified to support the design, performance evaluation and benefit cost analysis with respect to any potential solution.

Currently, about 50% of the subway fleet have regenerative braking capability. Enhancements to regenerative braking, including implementation of energy storage systems intended to recover regenerative energy, will only affect 50% of the subway fleet and can only impact 50% of the traction energy budget.

2 Approach

The objective of this project was to provide actual revenue service data and parameters associated with the potential application of energy storage systems (ESS) to the New York City Transit (NYCT) Subway system.

New information regarding available regenerative braking energy, train and system power, and energy usage as well as the basis of demand and energy charges, critical to benefit cost analysis, was developed.

Data was collected on an existing Data Collection Consist (DCC) to provide energy and power usage on a subway train in revenue service. The DCC is an 11 car R188 train (Cars 7501-7510) operating on the IRT Flushing Line (7 Line). The DCC data acquisition system was developed in a previous collaboration between NYCT, Dayton T. Brown, other NYCT Research Partners and the Federal Transit Administration (FTA). In this project, in addition to the existing 3rd-rail voltage and current measurements, the DCC data acquisition system was expanded to add brake resistor current measurement.

The data acquisition system utilized for this project consisted of Dewesoft Krypton A/D converters sampling at 100 samples/second. LEM current transducers were placed on the 600 volts direct current (VDC) bus in each car's Gap Detector box to measure bidirectional current to and from the 3rd rail. Current transducers were also placed on the connections for each resistor bank to measure resistor braking current. Voltage transducers were connected to the DC bus in each car's Gap Detector to measure line (3rd-rail) voltage. A Transcore radio frequency identification (RFID) reader and antenna was installed to read the track RFID tags (associated with the Communications-Based Train Control system) to provide train location. Additional details are provided in the appendix.

The data utilized in this report was collected periodically from July 2020 through October 2021. The impact of COVID-19 on passenger ridership and the number of trains operating may have impacted system regenerative braking performance by reducing 3rd-rail grid receptivity (fewer load trains may reduce regenerative braking performance) and by reducing the average weight of loaded trains. However, the relative relationship of regenerative braking energy and dissipated resistor energy to total available electrical energy should therefore be conservative with respect to ESS evaluation. In other words, with higher ridership and more operating trains, regenerative braking performance should be better and therefore proportionally less energy will be dissipated through the resistors (and potentially available to an ESS solution).

Data was analyzed with respect to regenerative braking performance, available or underutilized energy, impact of peak reduction, load shifting and energy usage reduction approaches on energy savings, peak demand reduction, greenhouse gas emissions reductions, and overall cost reduction.

The data collected in this project can be utilized to properly design, integrate and operate energy storage systems in the NYCT Subway system, leading to reduced energy usage, reduced greenhouse gas emissions, reduced energy costs, and increased infrastructure capacity. Savings in the form of capital development and energy costs could be significant.

It is important to note that energy usage on the 3rd-rail grid was not within this project's scope. It is unclear how much of the energy currently being returned to the 3rd-rail grid is being effectively utilized and results in true energy savings. It is expected that the implementation of ESS coupled with active management of energy utilization could result in savings beyond those presented in this report.

3 Data Collection

The IRT Flushing (7) Line runs between 34 St-Hudson Yards, Manhattan, and Flushing-Main St, Queens. On weekday mornings, some trains operate express toward Manhattan. While on weekday afternoons and evenings, these trains operate as express trains to Queens. There are two main tracks, designated C1 for the Manhattan-bound (or southbound) track and C2 for the Flushing-bound (northbound) track and the express (M) track running between Flushing-Main St and 33 St, Queens.

Figure 1. System Map of New York City Transit Flushing Line

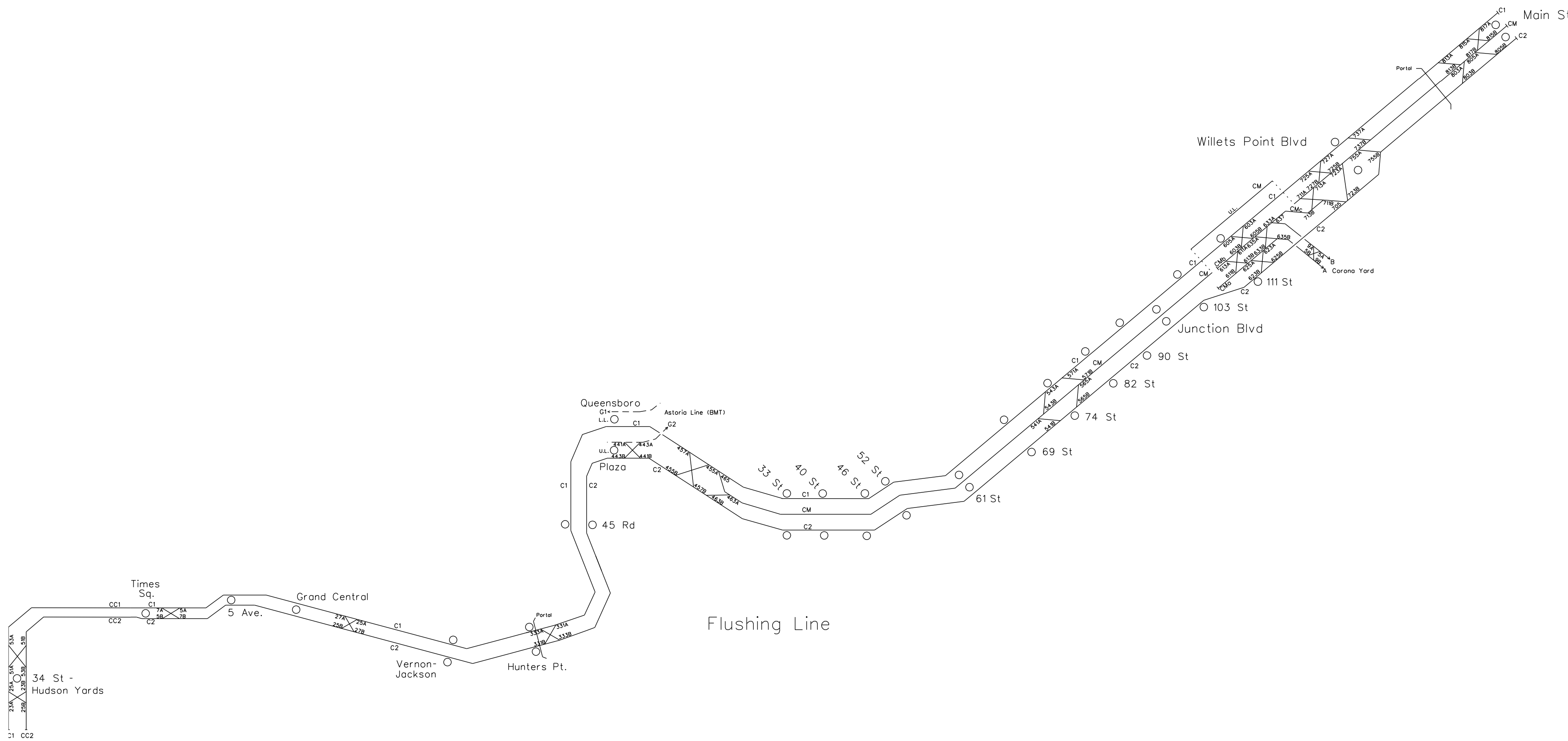
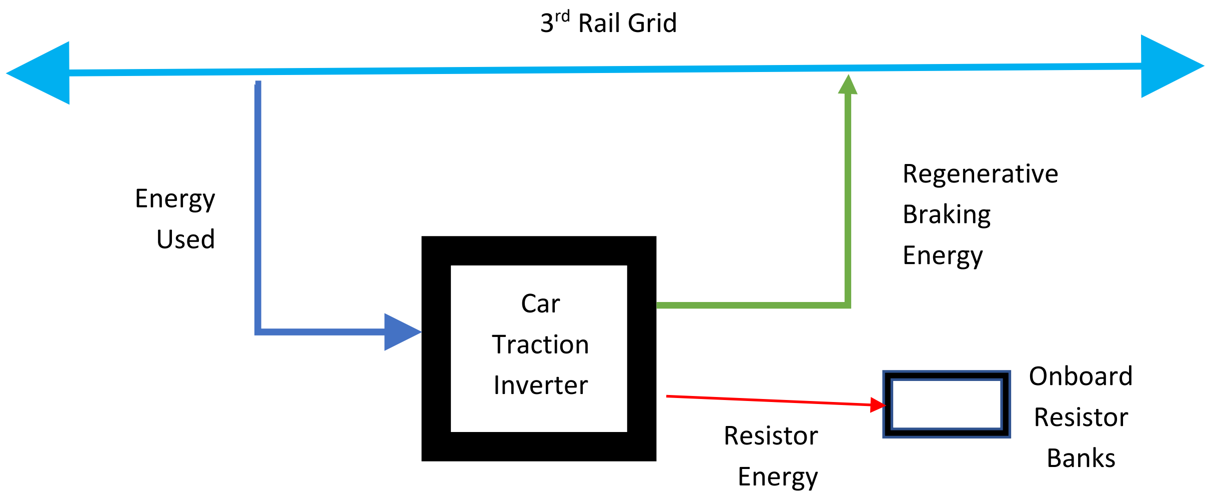


Figure 2. Traction Power Flow



Train car traction power flow is shown in Figure 2. When the train is accelerating or cruising the energy used is drawn from the 3rd-rail grid by the traction inverters on each car. When the train is braking the energy generated by the motors goes through the traction inverters and is either returned to the 3rd-rail grid as regenerative braking energy or sent to the onboard resistor banks and dissipated as heat.

When the train operator initiates braking the propulsion controllers on each car initially enter non-regenerative braking and check to see if all of the conditions required for regenerative braking are met. These conditions include track receptivity (determined by 3rd-rail voltage), gap detection (dead rail, no 3rd-rail voltage, no substation ripple), train speed and fault detection. As long as these conditions are met the propulsion controller will switch the traction inverter to send the regenerative power to the 3rd rail. During regenerative braking if any of the conditions are not met the car's propulsion controller will change to non-regenerative braking by directing the braking energy to the onboard resistor banks. After the train speed has sufficiently decreased and there is little to no available electrical energy, the controller will switch to friction braking. The propulsion controller prioritizes regenerative, non-regenerative, and friction braking in that order.

Figure 3. Example of Electric Power Profile over Time

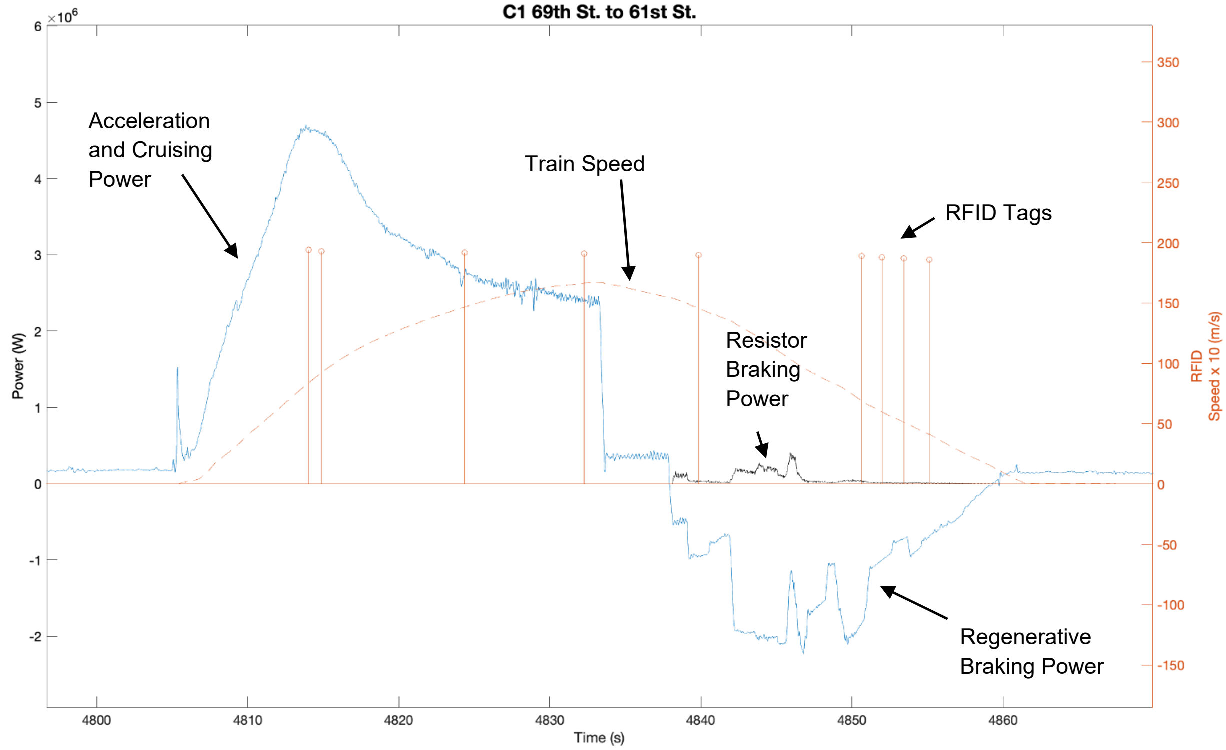


Figure 3 shows an example of the electric power profile as the train moves from a full stop at one station to a full stop at the next station (from 69th St. to 61st St. on the C1 track in this case). The power used increases as the train accelerates from the station (blue line). Once the train reaches speed the power draw drops and varies as the train continues to accelerate, cruise, and decelerate. Power again drops when the train goes into a coast mode. When the operator commands braking effort the resistors take the initial non-regenerative braking current (black line) until regenerative braking is initiated.

Figure 3 also shows that some cars are in regenerative braking (negative power blue line), while some cars are in non-regenerative braking (positive black line) until the train comes to a stop. The orange vertical lines show the radio frequency identification (RFID) tags as the train moves down the track. The orange dotted line reflects train velocity.

In this case energy used is 24.2 kilowatt-hour (kWh), regenerative energy returned is 6.75 kWh, resistor energy is 0.34 kWh. The total energy generated from braking is 7.1 kWh. Ninety-five percent (95%) of the available braking energy is returned to the 3rd rail through regenerative braking. Five percent (5%) of the available braking energy goes to the onboard resistor banks. The ratio of energy saved to energy used is 28% and resistor energy to energy used is 1.4%.

Kinetic energy (KE) is calculated from the maximum train velocity and an estimated average mass of 850,000 pounds using the formula $KE=1/2mv^2$. This value is then converted to kWh. In the example maximum velocity is 16.7 meters per second (m/s) and, including energy losses due to the 3% grade approaching the station and the termination of dynamic braking at about 3 mph, KE is 8.2 kWh. This does not account for other energy losses (energy lost due to train aerodynamic drag, wheel/rail interaction, etc.)

Statistical metrics then yield mean, standard deviation, maximum, and minimum performance that can be analyzed with respect to station, date, day of week, etc.

4 Analysis

Figure 4. Total Energy Budget for Subway Train Operating on the 7-Line

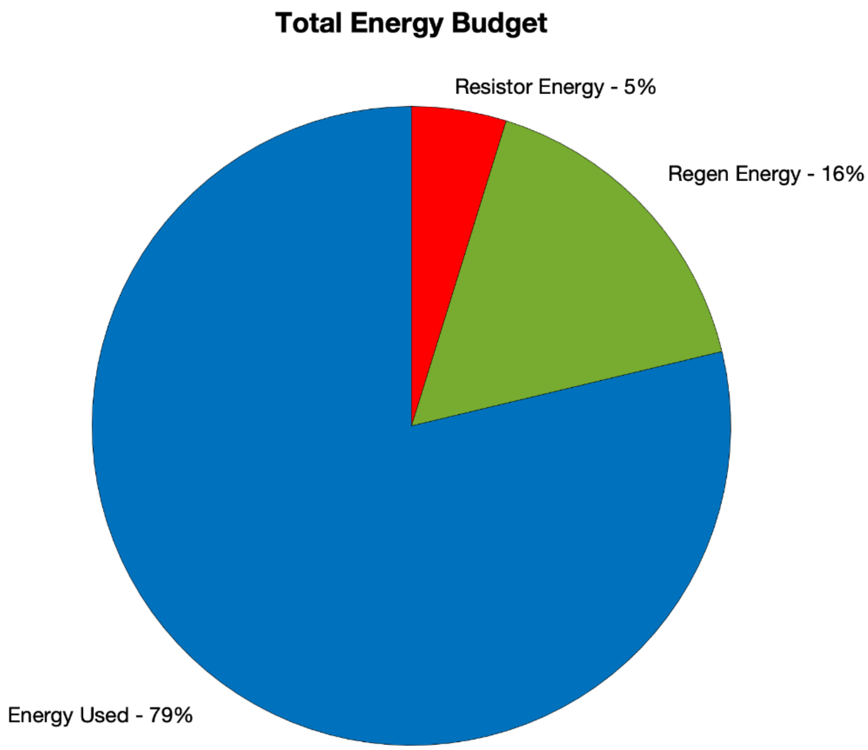


Figure 4 shows the total energy budget for a subway train operating on the 7 Line and gives the breakdown of mean energy used, mean energy returned via regenerative braking and mean energy dissipated through the onboard resistors.

Twenty-one percent (21%) of total energy is available as braking energy, currently recovered via regenerative braking or lost to the onboard resistors.

Sixteen percent (16%) of total energy is returned to 3rd-rail grid via regenerative braking.

Five percent (5%) of total energy is lost to resistors.

Figure 5. Utilization of Braking Energy Generated by a Subway Train

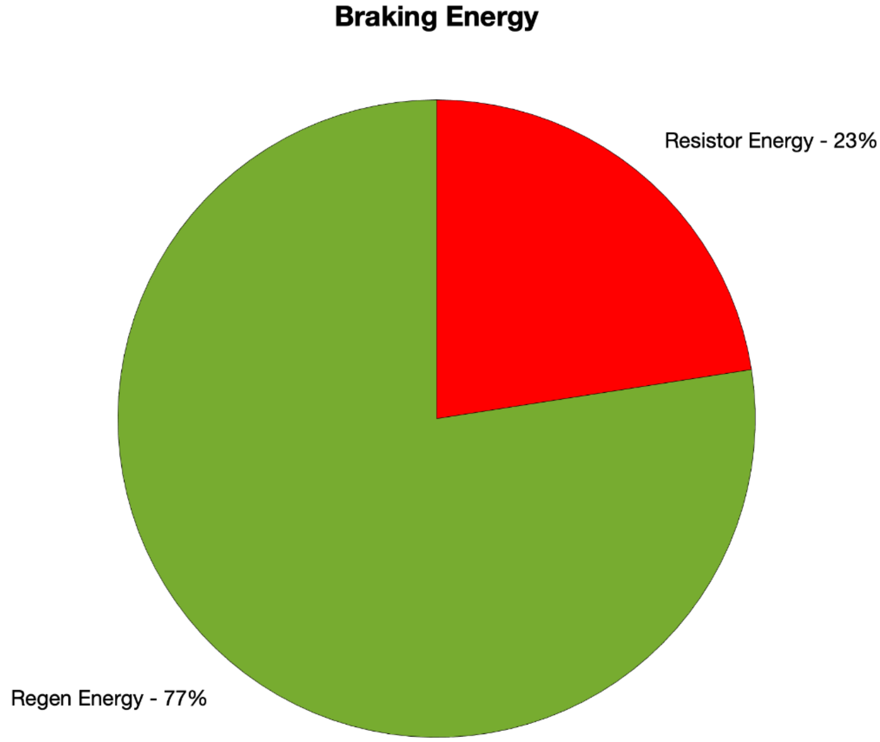


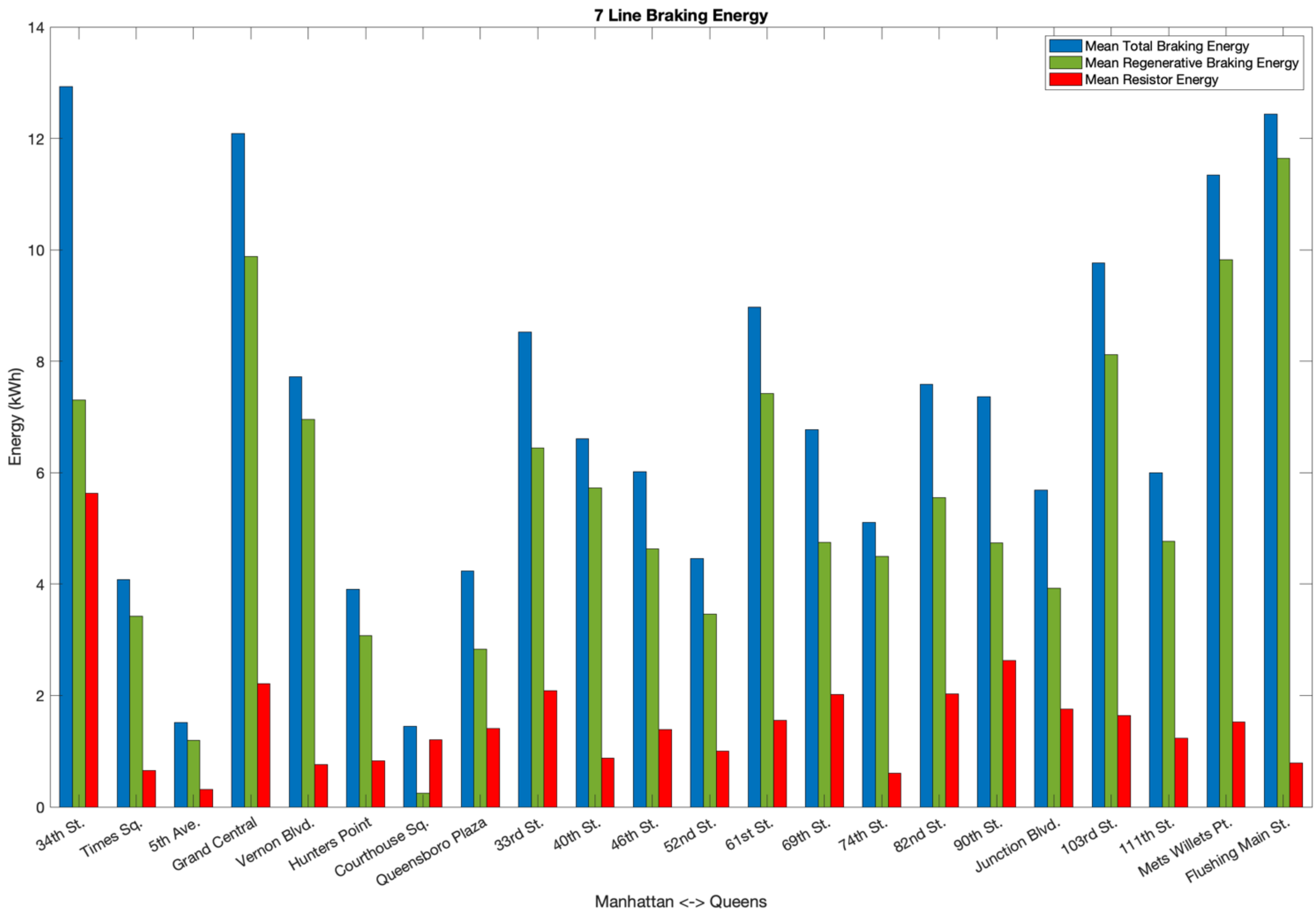
Figure 5 shows the utilization of the braking energy generated by the train.

Seventy-seven percent (77$) of the available braking energy is returned to the 3rd-rail grid via regenerative braking.

Twenty-three percent (23%) of the available braking energy is dissipated through the onboard resisters. This energy is potentially available for recovery using ESS or other energy saving techniques (assumes train can return all available energy via regenerative braking).

The total braking energy, regenerative braking energy, and resistor energy vary significantly from station to station. Figure 6 shows the mean total, regenerative, and resistor braking energy for each stop on the 7 Line.

Figure 6. Mean Total, Regenerative and Braking Energy for Each Stop on the 7-Line

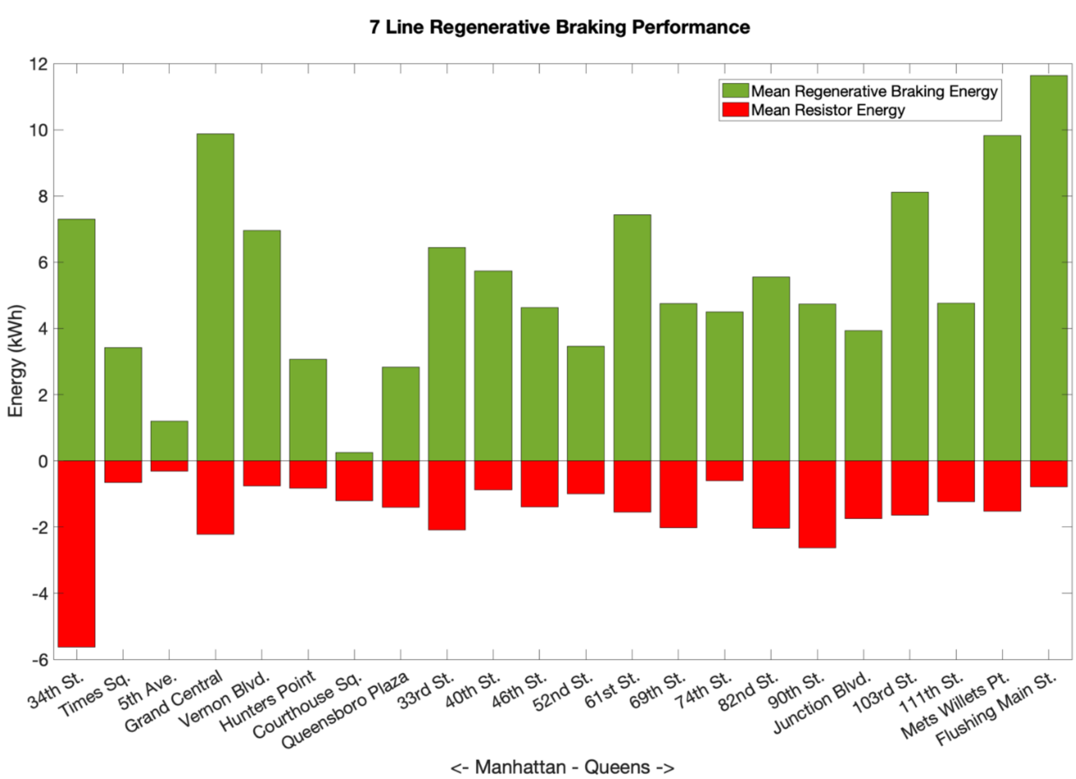


The mean total braking energy generated by a braking train is 6.7 kWh per stop. The amount of total available braking energy for any individual stop is dependent on multiple factors:

- Kinetic energy is the limiting factor and is driven by:
  - train velocity
  - loaded train weight
  - Faster, more heavily loaded trains have higher kinetic energy available when braking, which will generate higher amounts of available electrical energy.
- Track geometry can have a significant effect on kinetic energy:
  - Station approaches with curved tracks or crossovers will limit train speed and therefore available energy.
  - Tracks with uphill grades approaching the station will dissipate energy through gravity which will reduce train velocity and the amount of available electrical energy.
  - Downhill grades approaching the station will enhance available electrical energy.
- Geometry for 3rd rail can also affect regenerative braking performance. Gaps in 3rd rail located in the braking area on approach to the station will inhibit regenerative braking on the train.

Figure 7 shows mean regenerative and non-regenerative (resistor) braking performance per stop for each stop on the 7 Line.

Figure 7. Mean Regenerative and Non-regenerative (Resistor) Braking Performance for Each Stop on the 7-Line



The mean regenerative energy was measured at 5.4 kWh per stop with mean resistor energy at 1.6 kWh per stop. Regenerative braking performance is variable at each stop with a standard deviation of about 2.7 kWh.

It is important to note that the level of energy available for regenerative braking varies greatly from stop to stop and is dependent on many factors, of which track receptivity is only one.

The main factor limiting regenerative braking performance is the total available braking energy available as previously discussed.

Figure 8 shows that the maximum regenerative braking energy correlates to the maximum available braking energy, meaning that in most cases when energy is available it is used for regenerative braking and not resistors.

Figure 8. Maximum Available Braking and Regenerative Braking Energy for Each Stop on the 7-Line

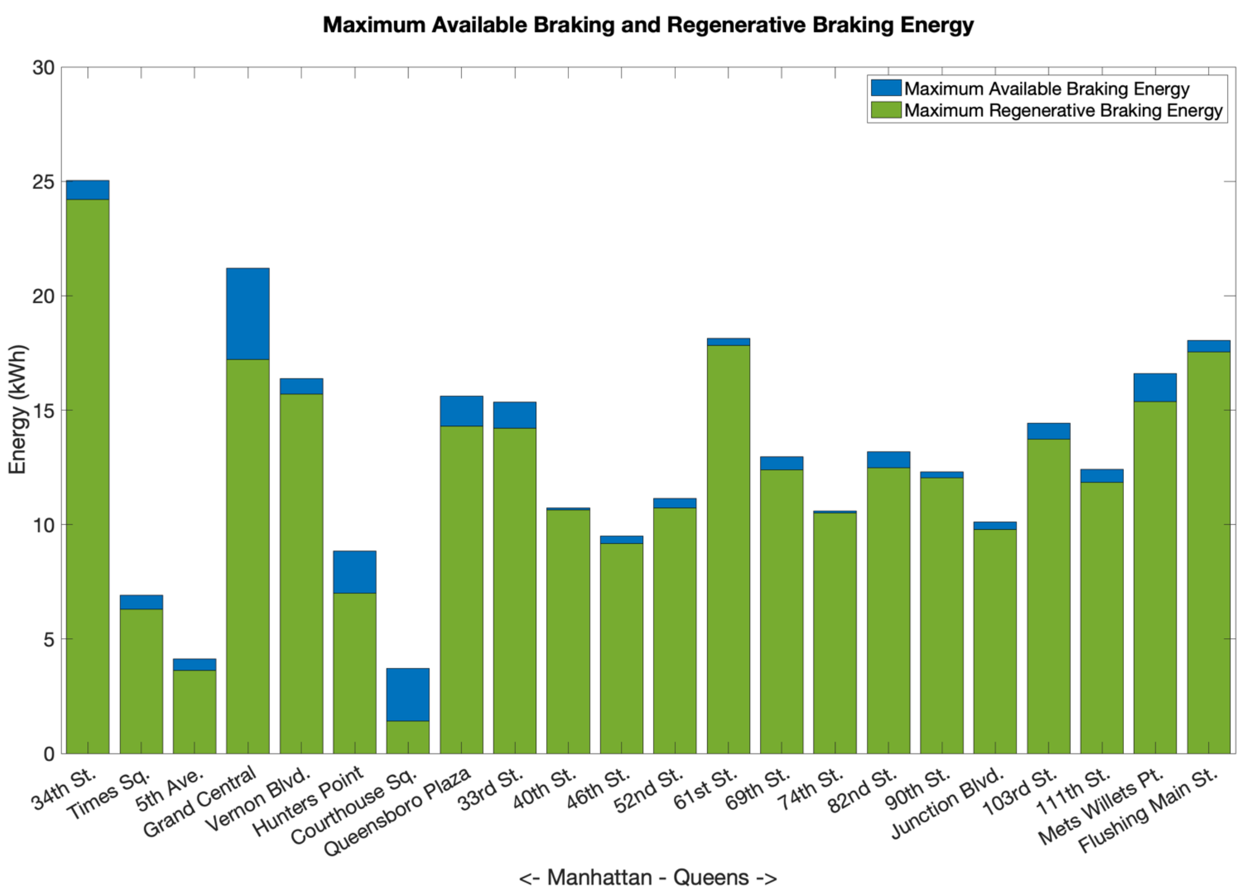


Figure 8 also reveals individual regenerative braking events delivering as much as 24 kWh. This is because in operation the 3rd rail is a complex electrical grid with multiple trains drawing power (and others braking) simultaneously. Regenerative braking performance in real-world operation is not limited to one-to-one train interaction. Substation (or wayside) ESS sizing and performance must be based on 3rd-rail grid parameters while onboard ESS designs can be based on train parameters.

Regenerative braking operation is managed independently by the propulsion controllers in each car. During any individual braking event some cars may perform regenerative braking, while others stay in non-regenerative braking based on the conditions found in each car (refer to Figure 3). The energy sent to the resistors in these cases is not due to track receptivity limits, which are common to all cars in a train, and cannot be recovered by changes external to the train car (improved receptivity, increased kinetic energy, track geometry, etc.). Changes to propulsion control logic and parameters may improve this performance.

Limitations on regenerative braking include:

- Other nearby trains braking in regeneration (causing 3rd-rail voltage to increase, limiting regeneration).
- Slower train speeds (slow speeds due to curves, crossovers, etc.).
- Uphill grades approaching a stop.
- Lighter train loads.
- Limited receptivity (few to no nearby trains accelerating), isolated track/substation sections.
- Gaps in 3rd rail on station approach (Courthouse C2).
- Selected braking effort: minimum, medium, maximum.

Regenerative braking enhancers include:

- Downhill grade approach to stop.
- Increased train speeds.
- Heavier train loads.
- Multiple simultaneous accelerating trains, quasi-synchronization of braking and accelerating trains.
- Increased train traffic at shared substations.
- Selected braking effort minimum, medium, maximum.

5 Individual Stations

Regenerative braking performance is highly location dependent. Braking energy usage at individual stops varies and is based on multiple factors previously identified.

Figure 9 and Figure 10 show regenerative and non-regenerative braking performance for stops on the 7 Line C1 and C2 tracks respectively.

Figure 9. Regenerative Braking Performance for Each Stop on the 7-Line C1 Track

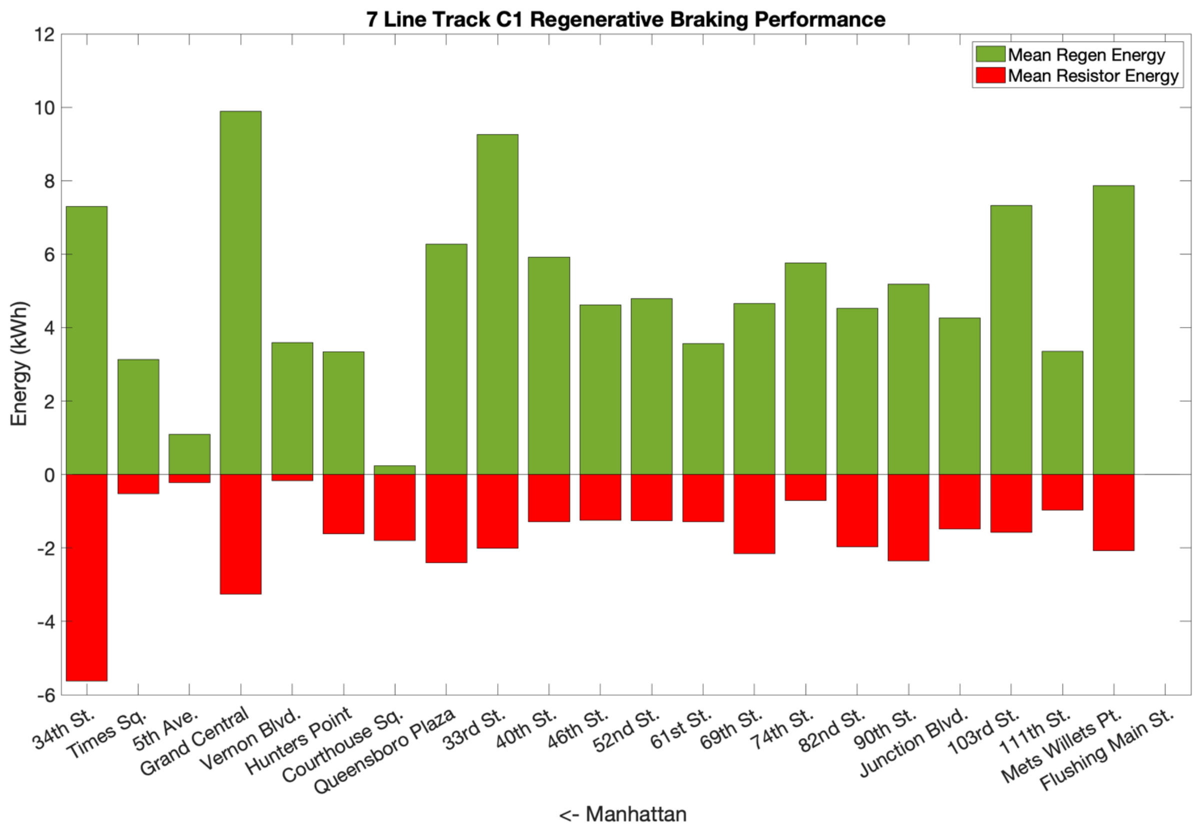
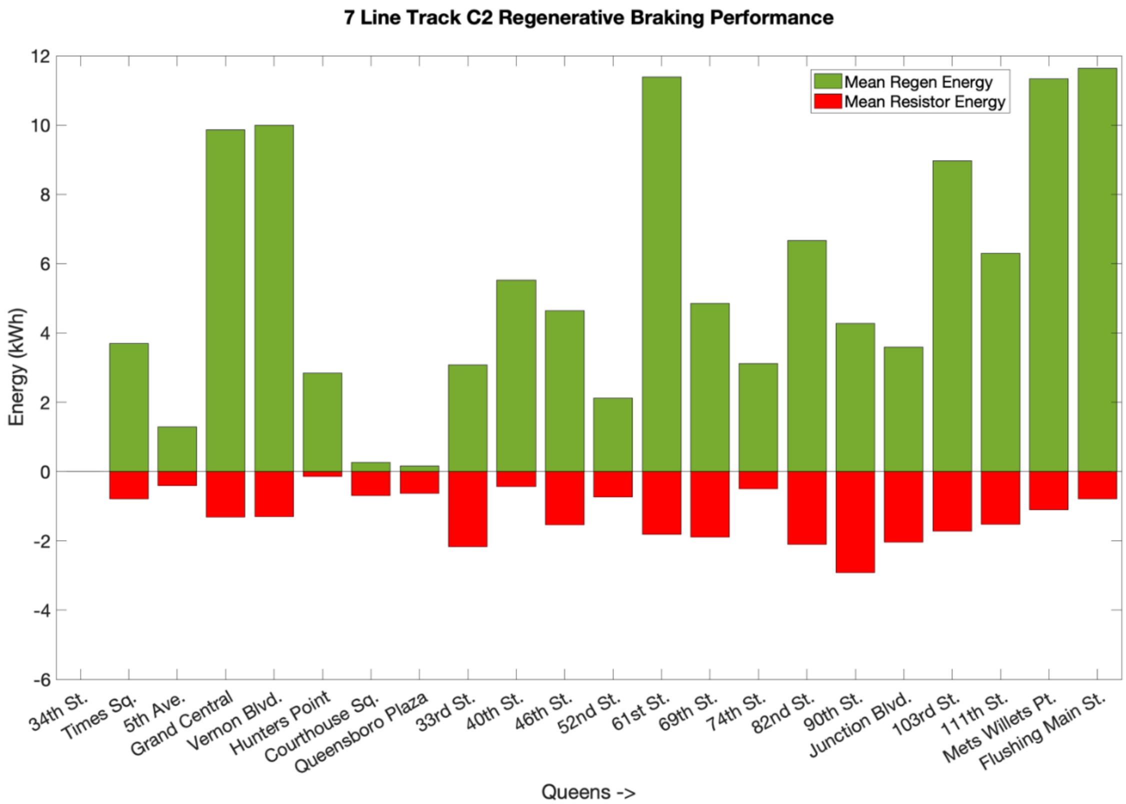


Figure 10. Regenerative Braking Performance for Each Stop on the 7-Line C2 Track



The stop at 61st St. is an example of track geometry affecting available braking energy and regenerative braking performance. Kinetic energy approaching the station on the C1 track is typically about 16–17 kwh. Kinetic energy on the C2 track is typically about 3 kWh higher (at about 20 kWh). However, the available braking energy is about 6 kWh more on the C2 track. This is because the approach to the station on the C1 is a 3% uphill grade while the C2 track approach has a -3% downhill grade. The resultant mean regenerative braking energy is about 4kWh on C1 compared to more than 11 kWh on C2. Meanwhile the energy dissipated through the resistors remains similar at about 1.3 kWh and 1.8 kWh for C1 and C2 respectively.

At 34th St. Hudson Yards the C1 track may be a good candidate location where the implementation of ESS to improve receptivity would be beneficial. While the C1 track approaching the station is curved, it has a downhill grade that varies from -2.4 to -3.8%. The terminal station is relatively low-train traffic and is an isolated substation at 34th St. In this case, regenerative braking is typically load limited, as can be seen in Figure 9 as high (almost 6 kWh) resistor energy along with high (more than 7 kWh) regenerative energy. An ESS could enhance receptivity in this area and capture the energy dissipated in the resistor banks.

Conversely, regenerative braking performance at the Queens end of the line is quite good (Figure 10). The C2 track at Flushing–Main St. is on a downhill grade that varies from -3.9 to -2%. Despite a local crossover the available energy at this stop is more than 12 kWh with mean regenerative braking energy at 11.8 kWh and resistor energy less than 1 kWh. The high level of regenerative braking performance at this terminal station, and at the adjacent Mets–Willets Pt. station, may be explained by the proximity to the Corona Yard substation which has a lot of train traffic providing consistent load.

The 5th Avenue stop has uphill grade approaches on both C1 and C2 tracks. This results in low available energy and poor regenerative braking performance on both tracks. On the plus side, the system should also be saving energy during the acceleration phase of train operations since the exit tracks from the station are downhill in both directions.

At Times Square the C1 track approaches on a downhill grade but due to the short distance from Grand Central and a crossover just before the station the train stays at a slower speed so kinetic energy is low. Trains on the C2 track approach with much higher speed and kinetic energy, but since it is an uphill grade the difference in available energy and regenerative braking performance between the two tracks is insignificant.

Analysis of other stations like Courthouse Square and Vernon Blvd. reveal similar track geometry characteristics that contribute to lower available braking energy and lower regenerative braking performance. Some characteristics (e.g., location of 3rd-rail gaps with respect to train braking location) could possibly be modified to improve regenerative braking performance.

The M track carries express trains toward Manhattan in the morning and toward Queens in the afternoon. While regenerative braking performance is very good, averaging 12.5 kWh, with mean resistor energy of 5.8 kWh, analysis of ESS implementation here was not analyzed since there are only 2 stations and daily train traffic is limited.

In general, as discussed in the ESS Applications section, implementing ESS to increase the available electrical load with the intent of improving regenerative braking performance will not result in significant regenerative braking improvement and energy savings.

6 Energy Storage System Applications

The implementation of ESS into the NYCT subway system will need to be guided by a performance-based approach like that provided in the Institute of Electrical and Electronics Engineers (IEEE) Guide for Wayside Energy Storage Systems for DC Traction Applications, IEEE Std 1887–2017.

Common applications of energy storage in traction power systems include the following:

- Energy recovery
- Voltage regulation
- Emergency backup
- Peak shaving
- Load shifting
- Frequency regulation

The cost of electrical energy and demand power for the NYCT subway traction system are comprised of New York Power Authority (NYPA) Supply Charges and Con Edison (ConEd) Delivery Charges. The 2021 consolidated costs of Traction Power for NYCT are:

- Energy ($/kWh) $ 0.0559
- Demand Power ($/kW) $ 27.41
- Composite Rate ($/kWh) $ 0.14

The following application analyses are intended to identify important parameters and to provide a framework for the evaluation of any particular ESS project. This analysis uses the 2021 cost of energy and does not account for any future fluctuations in energy costs.

6.1 Energy Recovery

In energy recovery applications, energy storage is used to reduce energy consumption through the capture and release of regenerated energy from rolling stock. Typically, energy produced by the train during braking is consumed by other trains operating in the vicinity.

In the circumstance where there are no other trains available (insufficient electrical load), the excess energy is dissipated as heat by onboard resistor banks.

Energy storage can be used to store energy that would otherwise have been consumed by the resistor banks, and then released back into the traction power system when there is sufficient electrical load.

If all resistor energy could be recovered using ESS the total annual savings for the 7 Line would be 6,335,164 kWh or about $886,923.

Successful energy recovery is also dependent on accurate, reliable ESS charge/discharge control which will require careful selection of control parameters. (See ESS Control on page 27).

The regenerative braking system currently shows healthy regenerative braking performance with respect to total available braking energy. Benefits cost analysis indicates diminishing returns on ESS as available braking energy decreases at individual locations.

A minimum service life of 20 years and a break-even target of 10 years for an ESS would be a reasonable assumption. This would provide for recovery of capital costs plus about 10 years of net savings. It is expected that annual operating and maintenance costs would increase beyond this 10-year timeframe, reducing annual net savings.

Energy recovery analysis assumptions:

- All resistor energy is recoverable as regenerative energy with the installation of ESS in proximity to a station.
- Proportional reduction of both energy and demand power.
- ESS service life of 20 years.
- Break even at 10 years.

Improved potential at specific stations indicates that the best ESS benefit cost would be installation at stations with more resistor energy available.

Table 1 shows the 7 stations with the highest mean resistor energy available at each stop and the total annual energy savings, based on recovery of that mean resistor energy. The total annual energy savings for this scenario would be about 3,166,877 kWh representing 3% of annual traction energy consumption on the 7 Line at a value of $443,363.

Table 1. Potentially Recoverable Braking Energy

Station	C1 Mean Resistor kWh/stop	C2 Mean Resistor kWh/stop	Total Saved kWh/year	Annual Energy Cost Savings
34th St.	5.6	0	570,256	$79,836
90th St.	2.4	2.6	533,412	$74,678
Grand Central	3.3	1.3	463,073	$64,830
33rd St.	2.0	2.2	423,336	$59,267
69th St.	2.2	1.9	412,084	$57,692
82nd St.	2.0	2.0	408,827	$57,236
Junction Blvd.	1.48	2.04	355,889	$49,824
		Total	3,166,877	$443,363

We can calculate the maximum capital and operating cost of individual ESS solutions to provide a 10-year break even timeframe. Table 3 gives the maximum allowable per unit cost of ESS required to break even at 10 years.

Table 2. Maximum ESS Cost for 10-Year Return-on-Investment

Station	Total kWh/year	Maximum ESS cost for 10-year ROI
34th St.	570,256	$798,359
90th St.	533,412	$746,776
Grand Central	463,073	$648,302
33rd St.	423,336	$592,671
69th St.	412,084	$576,917
82nd St.	408,827	$572,358
Junction Blvd	355,889	$498,244

If capital expenditure and operating costs are amortized across all ESS installations, as shown in Table 3, the maximum allowable ESS cost for a 10-year return-on-investment (ROI) drops to $403,000 meaning if the installation and operating costs for each ESS are less than $403,000 the ROI for the entire line would be 10 years. This is calculated as the composite cost of ROI where the energy savings across all installed stations are used to offset ESS cost. However, the ROI on individual installations diminishes as you move toward the bottom of the table and the ROI starts to exceed the expected service life of the ESS. These factors would need to be taken into account in any ESS evaluation.

Table 3. Maximum ESS Cost for 10-Year Composite ROI

Station	Total Saved kWh/year	10-year Composite Break-even Max Cost per ESS	Total Cap Ex and Operating Costs	Individual ESS ROI
34th St.	570,256	$798,359	$798,359	10.0
90th St.	533,412	$772,568	$1,545,135	10.3
Grand Central	463,073	$731,146	$2,193,437	11.3
33rd St.	423,336	$696,527	$2,786,108	11.8
69th St.	412,084	$672,605	$3,363,025	11.7
82nd St.	408,827	$655,897	$3,935,383	11.5
Junction Blvd.	355,889	$633,375	$4,433,627	12.7
103rd St.	333,161	$612,507	$4,900,053	13.1
Mets Willets Pt.	321,249	$594,422	$5,349,802	13.2
61st St.	314,693	$579,037	$5,790,371	13.1
Queensboro Plaza	308,389	$565,647	$6,222,116	13.1
46th St.	281,759	$551,382	$6,616,580	14.0
111th St.	253,114	$536,226	$6,970,939	15.1
Courthouse Sq.	253,003	$523,225	$7,325,144	14.8
52nd St.	202,645	$507,256	$7,608,846	17.9
Hunters Point	178,749	$491,193	$7,859,095	19.6
40th St.	175,199	$476,728	$8,104,373	19.4
Vernon Blvd.	148,631	$461,803	$8,312,456	22.2
Times Sq.	132,497	$447,261	$8,497,952	24.1
74th St.	122,440	$433,468	$8,669,367	25.3
Flushing Main St.	79,963	$418,158	$8,781,316	37.4
5th Ave.	62,795	$403,147	$8,869,230	45.9

6.2 Voltage Regulation

In voltage regulation applications, energy storage is used to reduce the level of fluctuation in the traction power system voltage. Trains are normally designed to operate within a given range of voltage. If voltage fluctuates outside this range, train operation can be adversely affected. Energy storage can be used to help keep voltage fluctuations within the operating limits of the train.

Undervoltage conditions are caused by momentary overloading of the power system, usually from too many trains operating in close proximity, or simultaneous acceleration of several trains in a single area. Energy storage can be used to supplement the traction power substations to help mitigate excessive these undervoltage conditions, or voltage sag.

Overvoltage conditions are caused by regenerative braking of trains in locations where there is insufficient electrical load available to absorb the energy produced by the trains. Energy storage can help ensure there is sufficient electrical load available to mitigate such overvoltage conditions. This operation is similar to the energy-recovery application:

- Use of ESS for voltage regulation could enhance regenerative braking performance since regeneration is dependent on 3rd-rail voltage-level reflecting receptivity.
- System already shows healthy regeneration performance with respect to total available energy, so benefit cost analysis may indicate use of ESS for voltage regulation is not cost-effective.
- Cost/benefit, see Energy Recovery above.

6.3 Emergency Backup

In emergency backup applications, energy storage is used to provide energy to the traction power system in the event of partial or complete disruption of the traction power supply.

A typical scenario involves using energy storage, during a partial or complete traction power outage to enable trains to travel to the next station where passengers can safely disembark.

Requirements for energy storage such as required power, energy capacity, and duration of operation, depend on the specific emergency operating procedures intended by the transit authority. Cost/benefit is not analyzed here.

6.4 Peak Shaving

In peak shaving applications, energy storage is used to store and release energy with the intent to reduce short-term fluctuations in transit system power demand.

The objective of peak shaving is to reduce peak power demands to minimize size of power delivery equipment and/or realize financial benefit through reduction of utility power demand charges:

- Short-term peak shaving designed to reduce train acceleration peak power usage could save energy and peak demand costs.
- Could improve regenerative braking receptivity at some stations.
- ESS requires approximately 3 MW charge peak instantaneous power and 5 MW discharge peak instantaneous power capacity if distributed at many locations, more if limited distribution.

- Reduction of peak demand using short-term peak shaving may not be feasible or economical without a control system more complex than those based solely on 3rd-rail voltage. Grid voltage for 3rd rail does not reliably reflect peak-power consumption and is not an accurate control mechanism. See ESS Control on page 27.
- It would use regenerative braking energy already realized, resulting in little energy savings. This would be offset by demand-reduction.
- Intent to shave short term (i.e., single train) peaks requires 5 MW over 10 seconds discharge (14 kWh) and active control mechanism, increasing ESS cost.
- Could potentially reduce generation capacity costs, spinning reserve requirements, and transmission line congestion at peak periods.
- See Load Shifting analysis for estimated demand savings.

6.5 Load Shifting

Load shifting is similar to peak shaving applications but with the intent to shift bulk amounts of electrical energy from one time period to another.

The objective of load shifting is to realize financial benefit through reduction of utility energy and/or power demand charges by storing energy in periods of inexpensive electricity and then to release energy back into the transit system during periods of relatively expensive electricity.

Load shifting will generally entail use of energy already returned via regenerative braking in addition to resistor energy resulting in minimal energy savings.

ESS design requirements are based on the amount of demand reduction desired. Peak demand on the 7 Line is approximately 26 MW for 2 hours, twice per day. A 25% reduction in demand would require a total of 26 MWh of storage recharged overnight. Control would be based on power draw at each individual substation.

Figure 11. Power Demand at the Roosevelt Avenue and 78th Street Substation During a Weekday

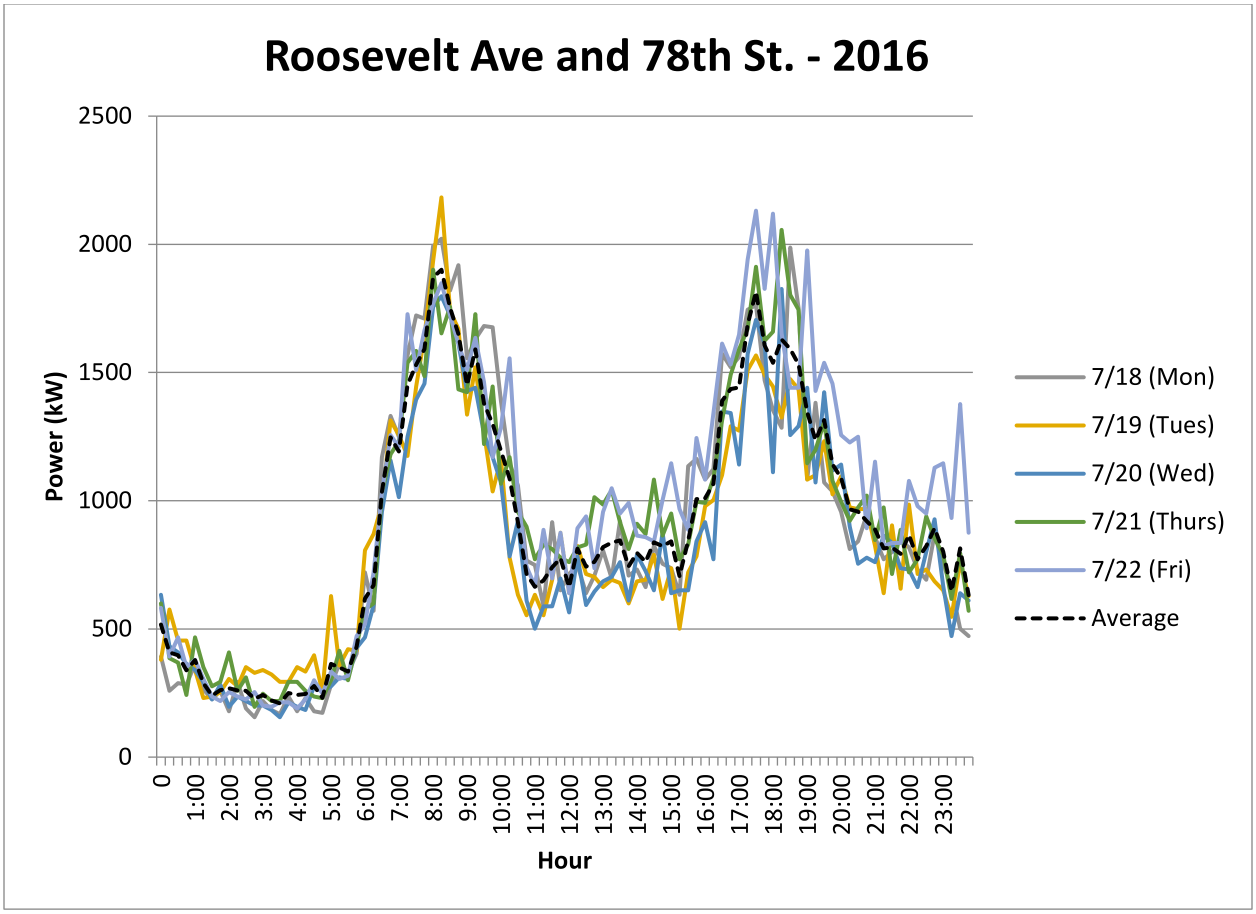


Figure 11 shows demand at the Roosevelt Avenue and 78th St. substation, one of 13 substations serving the 7 Line. Weekday peak demand occurs from about 7:00 a.m. to 9:00 a.m. and again from about 5:00 p.m. to 7:00 p.m.

A 25% reduction in demand power requires a distributed ESS with capacity of 500 kW over approximately 5 hours (2500 kWh) at each of 13 substations. This demand response would be a dispatchable distributed energy resource (DER) where the resource can be called upon to respond to peak demand.

Figure 12. Average Demand versus Load Shift at the Roosevelt Avenue and 78th Street Substation

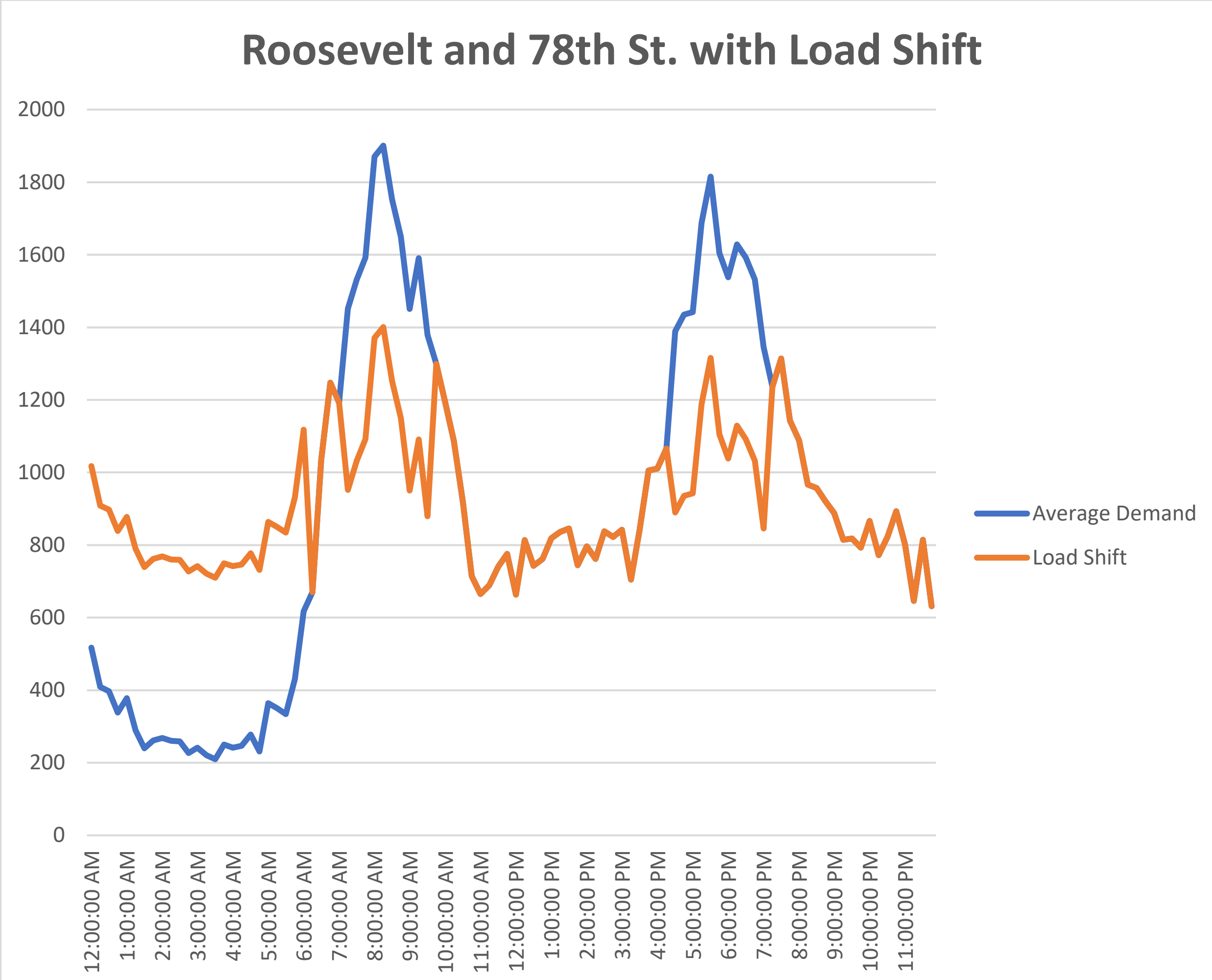


Figure 12 shows the average demand at the Roosevelt and 78th St. substation as well as the demand with load shifting ESS implemented. The ESS would charge overnight, in this case from midnight to about 6:00 a.m. The energy would be discharged into the system during peak demand periods, in this case from 7:00 a.m. to 9:00 a.m. and from 4:00 p.m. to 7:00 p.m., resulting in more than 25% demand savings.

A 25% reduction in peak demand power across the 7 Line would save 78000 kW of demand power and approximately $2,159,820 in demand charges annually.

Twenty-five percent (25%) demand reduction would result in $166,140 annual savings per substation. The maximum ESS cost to realize a 10-year ROI would be approximately $1,661,400 per substation (based on current demand power rate).

Resultant Bulk System Benefits include:

- Avoided Generation Capacity Costs (AGCC).
- Avoided Location Based Marginal Price (LBMP), including costs of energy, congestion, losses, CO_2, SO_2, and NO_x greenhouse gas emissions.
- Avoided Transmission Capacity Infrastructure and Related Operations and Maintenance (O&M).
- Avoided Transmission Losses.
- Avoided Ancillary Services (spinning reserve, frequency regulation).

6.6 Frequency Regulation

In frequency regulation applications, energy storage is used to inject or withdraw energy from the traction power system in response to a utility transmission system's frequency deviations or power imbalance.

When generation dispatch does not equal actual load and losses on a moment-by-moment basis, the imbalance will result in the transmission grid's frequency deviating from the standard. Minor frequency deviations affect energy consuming devices; major deviations cause generation and transmission equipment to separate from the grid. Frequency regulation can prevent these adverse consequences by rapidly correcting deviations in the transmission system's frequency to bring it within the acceptable range.

The objective of frequency regulation is to realize financial benefit by offering regulation services to the utility transmission system market.

- ESS could be used to participate in the regulation market if load shifting is utilized.
- New York State Independent System Operator (NYISO) regulation market generally reflects the demand profile and market prices that are less than demand pricing.
- Demand power costs are charged based on peak demand while regulation market is per MWh supplied. Potential savings well below load shift savings.
- At a maximum price of about $20/MWh, load shift power savings would be worth about $1,560,000.

7 ESS Control

ESS charge/discharge cycles can be controlled using passive or active methods. ESS control is especially critical to the successful implementation of energy recovery and peak shaving applications. The typical control parameter for both methods at the wayside is 3rd-rail voltage. In concept, rising voltage indicates regenerative braking and would cause the ESS to charge while decreasing voltage would indicate that trains are accelerating and cause the ESS to discharge and put power back into the 3rd rail. However, 3rd-rail voltage variation in grid operation is more complex and doesn't necessarily lend itself to simple ESS control.

Figure 13. Train Power and 3rd-Rail Voltage Profiles Over Time Using 640 VDC During Early Phase of a Trip

Figure 13 shows the 3rd-rail voltage in conjunction with the train power profile. Selection of a baseline ESS control voltage set point at 640 volts direct current (VDC) based on correlation to hotel loads (time 3480 seconds) would be expected. This figure shows reasonably good correlation of voltage increases to regenerative braking, which may help to recover the energy going to the resistors, assuming that the resistor energy is due to insufficient receptivity, as likely indicated by 3rd-rail voltage of 712 VDC at time 3537s. Paradoxically when a substantial amount of energy is going to the resistors the 3rd-rail voltage decreases (time 3540 s), which could result in the ESS not going in to charge mode at the time that it could recover the most wasted energy.

Since the voltage variation band is narrow, using voltage rise to trigger ESS charging would cause ESS to charge using regenerative braking energy already returning to the 3rd-rail grid resulting in no net energy savings (time 3445 seconds).

Figure 14. Train Power and 3rd-Rail Voltage Profiles Over Time Using 640 VDC During Later Phase of a Trip

Later in the same trip, as shown in Figure 14, the baseline ESS setting of 640 V would result in ESS charging where successful regenerative braking is already occurring and little to no resistor energy is being produced (time 4980 s). This, along with the moderate 3rd-rail voltage variation when the train is accelerating (4950 s), which would result no ESS discharge and in no energy savings.

The 3rd-rail grid is more dynamic than previous train-to-train testing has indicated. Potential ESS control mechanisms require more study. For instance, it may be possible to choose site specific trigger voltages or use a more complex control mechanism based on 3rd-rail power draw at the substation, which would improve ESS performance and result in energy savings.

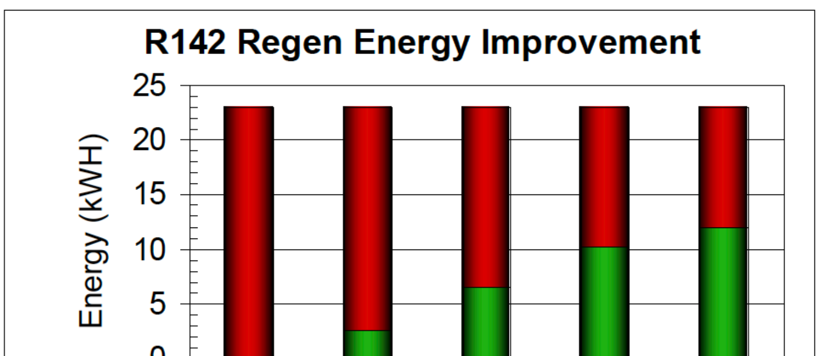
8 Previous Findings

There has been a significant amount of previous work regarding regenerative braking performance. Some of the findings from those efforts have found their way into the current thinking regarding regenerative braking, including ESS system design efforts and the MTA Sustainability efforts.

LTK Engineering Services (LTK)/NYPA published a 2007 simulation-based study which concluded that, on lines with relatively short train headways and the resulting high traffic volumes, regenerative braking alone would save approximately 30% in energy costs during peak hours while the addition of ESS would result in possible additional savings of about 0.4%.

NYCT/NYPA/Turner Engineering Corporation (TENCO) Regeneration Energy Improvement Project (REIP) study performed in 2007 concluded that the maximum regenerative energy possible would be 12 kWh per stop (Figure 15). This was based on one braking train to one accelerating load train testing on an electrically isolated track rather than a 3rd-rail grid. This study concluded that regeneration performance was limited by the available load presented by a single accelerating train. It is important to note that the goal of that project was to quantify train-to-train regeneration energy savings and to identify means to increase the savings. It was not intended to be a measure of regenerative braking performance in the subway system. While regenerative braking into one load train may be limited to 12 kWH the limit in a 3rd-rail grid configuration where the load dynamics are much more complex is significantly higher, as shown in Figure 8.

Figure 15. Maximum Regenerative Energy Improvement on R142 Train



	Accel to 40 mph	Typical Regen - Unmodified	Full Brk Regen - Modified	Med Brk Regen - Modified	Max Possible Regen
Savings (kWH)	0%	11%	28%	44%	52%
Consumed	23	20.5	16.5	12.8	11
Saved (kWH)	0	2.5	6.5	10.2	12

City University of New York (CUNY)/ConEd/NYCT performed a study pertaining to the application of wayside energy storage systems (ESS) for the recuperation of regenerative braking energy within the NYCT subway system. This work concluded that existing regenerative braking configurations result in only ~8% reduction of energy consumption and peak demand across the entire 7 Line. This conclusion was based on the substation metered power readings. Since some of the substations that feed the 7 Line also supply power to other lines and only the 7 Line trains had regenerative braking turned off during the test period, it is expected that the measured energy savings were low.

The analyses of ESS implementations are typically based on single train power dynamics, which result in higher charge/discharge rate requirements than those seen at the 3rd-rail interface. This leads to a conclusion that only high-power, fast-response storage technologies are feasible.

9 Summary

Table 4. Mean Round Trip, Weekly and Annual Energy (kWh)

7 Line Energy	Energy Used	Braking Energy	Regenerative	Resistor
Per Train Round Trip	945	260	189	46
Per Week	1,840,860	506,480	368,172	90,000
Per Year	106,160,361	26,336,960	22,441,563	6,335,164

-Seventy-seven percent (77%) of available braking energy (16% of total traction energy) is being returned through regenerative braking.

-Twenty-three percent (23%) of available braking energy (5% of total traction energy) is dissipated through onboard resistors.

-Per year currently saved through regenerative braking: $3,141,819 (22,441,563 kWh) on 7 Line.

-Potential available energy (resistor) annually: 6,335,164 kWh ($ 886,923).

Table 5. ESS Applications and Potential Savings

Application	Potential Energy Savings	Potential Demand Savings	Potential Cost Savings
Energy Recovery	6335164	Included	$886,923
Voltage Regulation	6335164	Included	$886,923
Emergency Backup	Not Assessed		
Peak Shaving		78000	$2,159,820
Load Shifting		78000	$2,159,820
Frequency Regulation		78000	$1,560,000

-Unused (resistor) energy may be available to wayside ESS, need to further evaluate benefit cost.

-Individual stations could be potential candidates for energy recovery ESS based on resistor energy.

-Potential energy savings are limited by total available braking energy.

-Load Shifting application has best cost/benefit with fewer technical hurdles.

-ESS energy requirement is dependent on distributed design. Total requirement dependent on application.

Area for further study:

- Current utilization of regenerative energy in the 3rd-rail grid is not quantified or well understood. Further study in this area would help guide the appropriate application of ESS.
- Application of this data to other NYCT lines should be done with caution. Trains operating on other lines might not perform the same as the R188 on the 7 Line. The 7 Line uses 11-car consists (railroad vehicles forming a complete train), while other lines typically use 10-car consists. The 10-car trains will weigh about 100,000 pounds. less than the train measured in this project. The resultant kinetic and available electrical energy associated with braking events should also be proportionately lower on the 10-car trains. Additionally, there are variations in the implementation limits and logic for regenerative braking across the various car types, inverters, and propulsion controllers.

Key concepts from this study:

- An understanding of the current performance with regards to regenerative braking and energy budget is key to the evaluation of potential ESS applications.
- A rigorous approach to energy budget calculation and cost/benefit analysis with respect to specific ESS installations is very important in order to adequately plan, design, and evaluate proposals and to ensure energy and money savings.

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Appendix A

A.1 Data Reduction/Analysis

Data acquisition direct measurements (100 s/s):

- 3rd-rail current in/out of each car (A)
- Resistor current for each inverter (A)
- 3rd-rail voltage (V)
- Train velocity (GPS) (m/s)
- Track RFID tag (6-bit ASCII)
- Date/Time

Data reduction computed values:

- Total 3rd-rail instantaneous power (sum of car 3rd-rail current x 3rd-rail voltage) in watts:
    - $\boldsymbol{Total\ Power_{3rd} = \sum_{car=1}^{11}(Vlink_{car} \times Ilink_{car})}$
- Total resistor power (I^2R, sum of resistor current squared x resistor bank resistance of 0.84 Ω) in watts:
    - $\boldsymbol{Total\ Power_{Resistors} = \sum_{bank=1}^{15}(Ibank_{bank}{}^{2} \times 0.84)}$
- 3rd-rail energy (integration of Total 3rd-rail Power over time in W-s converted to kWh):
    - $\boldsymbol{Energy_{3rd} = \int_{t0}^{t} Total\ Power_{3rd}\,(t) \times 27.8}$ E-6
- Resistor energy (integration of Total Resistor Power over time in W-s converted to kWh):
    - $\boldsymbol{Energy_{Resistor} = \int_{t0}^{t} Total\ Power_{Resistor}\,(t) \times 27.8}$ E-6
- Train kinetic energy ($1/2mv^2$, train mass estimated at 1e6 pounds):
    - $\boldsymbol{KE = 1/2(1E6 \times V^2)}$
- Track RFID tag value (convert 6-bit ASCII to numeric value).
- Track (C1, C2, M).
- Energy Used (energy used by train from 3rd rail), calculated when 3rd-rail current is positive.
- Regenerative Energy (energy returned from train to 3rd rail), calculated when 3rd-rail current is negative.
- Total Braking Energy (Regenerative Energy + Resistor Energy).
- Day of the week.
- Time of day.

A.2 Instrumentation

The DCC was outfitted with a data acquisition system comprised of 11 Dewesoft Krypton modules configured to measure the output of current and voltage transducers on each car.

- Installed data acquisition system comprises the following hardware:
  - Dewesoft Krypton 3xSTG modules, Qty 11
  - Dewesoft DS-IMU module, Qty 1
  - Transcore AI1422E Reader, Qty 1
  - Transcore AA3233 Rail Antenna with Subway Modification, Qty 1
  - LEM LV 1000/SP9 Voltage Transducer, Qty 7
  - LEM HTC 2000/SP4 Current Transducer, Qty 26
  - Panasonic Toughbook CF-31, Qty 1
  - DewesoftX Software

Table A-1. Channel List

DAC Channel	Signal Name	Signal Description	Units/Volt	Range	Sample Rate
1	ILink Car 1	DC Link current	220 amps	±10V	100 s/s
2	IBank1 Car 1	DC Resistor Bank current	220 amps	±10V	100 s/s
3	IBank2 Car 1	DC Resistor Bank current	220 amps	±10V	100 s/s
4	VLink Car 2	DC Link voltage	150 volts	±10V	100 s/s
5	ILink Car 2	DC Link current	220 amps	±10V	100 s/s
6	IBank1 Car 2	DC Resistor Bank current	220 amps	±10V	100 s/s
7	VLink Car 3	DC Link voltage	150 volts	±10V	100 s/s
8	ILink Car 3	DC Link current	220 amps	±10V	100 s/s
9	IBank1 Car 3	DC Resistor Bank current	220 amps	±10V	100 s/s
10	VLink Car 4	DC Link voltage	150 volts	±10V	100 s/s
11	ILink Car 4	DC Link current	220 amps	±10V	100 s/s
12	IBank1 Car 4	DC Resistor Bank current	220 amps	±10V	100 s/s
16	ILink Car 5	DC Link current	220 amps	±10V	100 s/s
14	IBank1 Car 5	DC Resistor Bank current	220 amps	±10V	100 s/s
15	IBank2 Car 5	DC Resistor Bank current	220 amps	±10V	100 s/s
16	ILink Car 6	DC Link current	220 amps	±10V	100 s/s
17	IBank1 Car 6	DC Resistor Bank current	220 amps	±10V	100 s/s
18	IBank2 Car 6	DC Resistor Bank current	220 amps	±10V	100 s/s
19	VLink Car 7	DC Link voltage	150 volts	±10V	100 s/s
20	ILink Car 7	DC Link current	220 amps	±10V	100 s/s
21	IBank1 Car 7	DC Resistor Bank current	220 amps	±10V	100 s/s
22	VLink Car 8	DC Link voltage	150 volts	±10V	100 s/s
23	ILink Car 8	DC Link current	220 amps	±10V	100 s/s
24	IBank1 Car 8	DC Resistor Bank current	220 amps	±10V	100 s/s

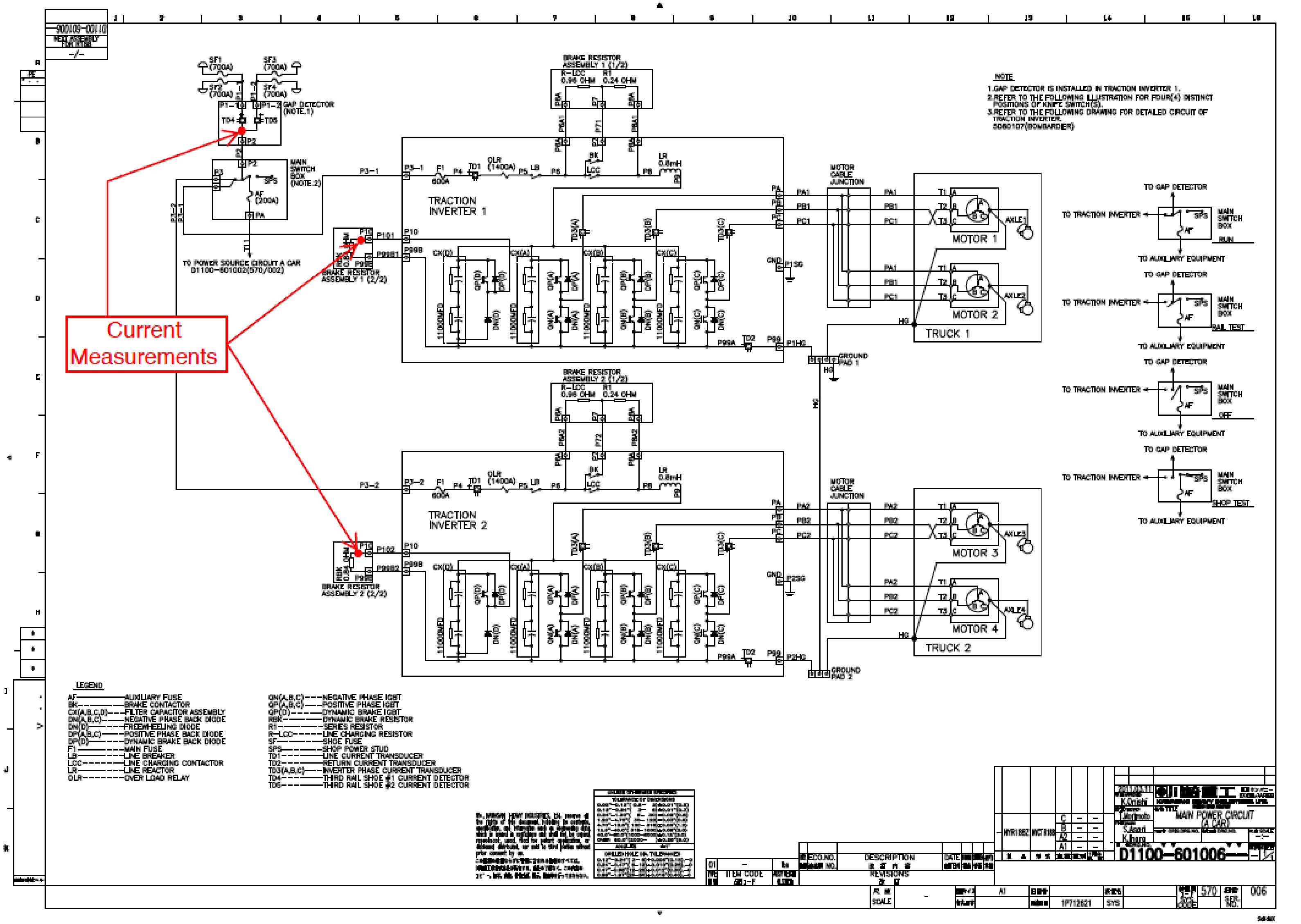
Table A-1 continued

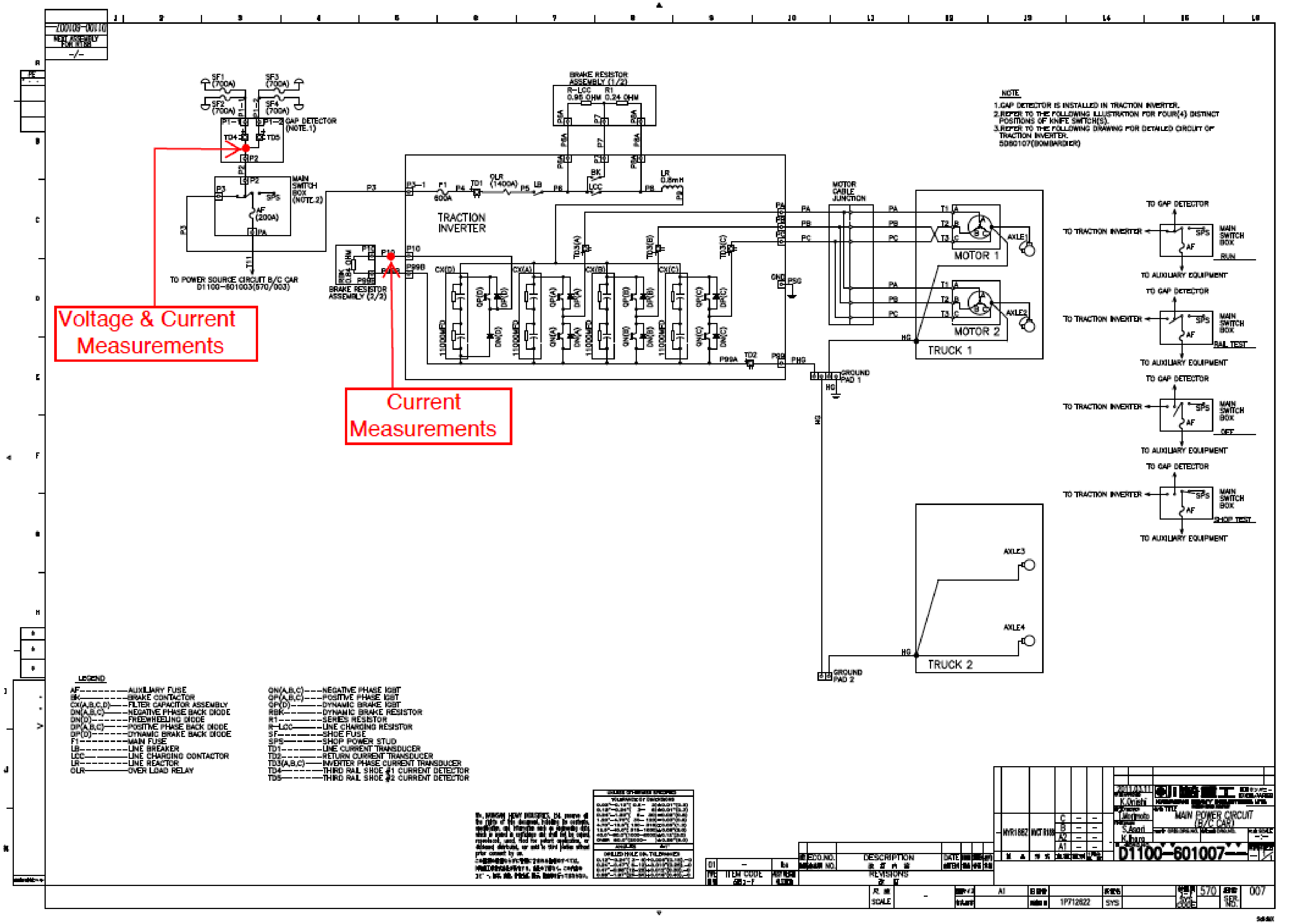
DAC Channel	Signal Name	Signal Description	Units/Volt	Range	Sample Rate
25	VLink Car 9	DC Link voltage	150 volts	±10V	100 s/s
26	ILink Car 9	DC Link current	220 amps	±10V	100 s/s
27	IBank1 Car 9	DC Resistor Bank current	220 amps	±10V	100 s/s
28	VLink Car 10	DC Link voltage	150 volts	±10V	100 s/s
29	ILink Car 10	DC Link current	220 amps	±10V	100 s/s
30	IBank1 Car 10	DC Resistor Bank current	220 amps	±10V	100 s/s
31	ILink Car 11	DC Link current	220 amps	±10V	100 s/s
32	IBank1 Car 11	DC Resistor Bank current	220 amps	±10V	100 s/s
33	IBank2 Car 11	DC Resistor Bank current	220 amps	±10V	100 s/s

Table A-2. Signal List

I/O Channel	Signal Name	Signal Description
1	GPS/IMU	NMEA 0183 Serial
2	Ethernet	IEEE 802.3
3	RFID	RS 485
4	WWAN	Verizon

A.3 Installation Drawings




Voltage & Current Measurements
Current Measurements
TRACTION INVERTER
BRAKE RESISTOR ASSEMBLY (1/2)
BRAKE RESISTOR ASSEMBLY (2/2)
GAP DETECTOR (NOTE.1)
MAIN SWITCH BOX (NOTE.2)
TO POWER SOURCE CIRCUIT B/C CAR D1100-601003(570/003)
MOTOR CABLE JUNCTION
MOTOR 1
MOTOR 2
TRUCK 1
TRUCK 2
AXLE1
AXLE2
AXLE3
AXLE4
GROUND PAD 1
GROUND PAD 2
TO GAP DETECTOR
TO TRACTION INVERTER
TO AUXILIARY EQUIPMENT
RUN
RAIL TEST
OFF
SHOP TEST
NOTE
1.GAP DETECTOR IS INSTALLED IN TRACTION INVERTER.
2.REFER TO THE FOLLOWING ILLUSTRATION FOR FOUR(4) DISTINCT POSITIONS OF KNIFE SWITCH(S).
3.REFER TO THE FOLLOWING DRAWING FOR DETAILED CIRCUIT OF TRACTION INVERTER. 5060107(BOMBARDIER)
LEGEND
AF—AUXILIARY FUSE
BK—BRAKE CONTACTOR
CX(A,B,C,D)—FILTER CAPACITOR ASSEMBLY
DN(A,B,C)—NEGATIVE PHASE BACK DIODE
DN(D)—FREEWHEELING DIODE
DP(A,B,C)—POSITIVE PHASE BACK DIODE
DP(D)—DYNAMIC BRAKE BACK DIODE
F1—MAIN FUSE
LB—LINE BREAKER
LCC—LINE CHARGING CONTACTOR
LR—LINE REACTOR
OLR—OVER LOAD RELAY
GN(A,B,C)—NEGATIVE PHASE IGBT
GP(A,B,C)—POSITIVE PHASE IGBT
GP(D)—DYNAMIC BRAKE IGBT
RBK—DYNAMIC BRAKE RESISTOR
R1—SERIES RESISTOR
R-LCC—LINE CHARGING RESISTOR
SF—SHOE FUSE
SPS—SHOP POWER STUD
TD1—LINE CURRENT TRANSDUCER
TD2—RETURN CURRENT TRANSDUCER
TD3(A,B,C)—INVERTER PHASE CURRENT TRANSDUCER
TD4—THIRD RAIL SHOE #1 CURRENT DETECTOR
TD5—THIRD RAIL SHOE #2 CURRENT DETECTOR
MAIN POWER CIRCUIT (B/C CAR)
D1100-601007

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