White Paper on Wayside Energy Storage for Regenerative Braking Energy Recuperation in the Electric Rail System

Ahmed Mohamed1, Andrew Reid2,
and Thomas Lamb3.

1. CUNY City College, New York
2. Con Edison, New York
3. New York City Transit, New York

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Executive Summary

This white paper summarizes the main findings and recommendations of a collaborative study that was conducted by the City University of New York (CUNY), Con Edison, and New York City Transit (NYCT). It pertains to the application of wayside energy storage systems (ESS) for recuperation of regenerative braking energy within the NYCT subway system.

THE OPPORTUNITY

NYCT consumes more than 1,600 GWh of electricity per year, with more than half of NYCT rolling stock and all new ones capable of regenerating energy upon braking. The trains produce “regenerative braking energy” or “regenerative energy” during deceleration, which if properly captured and reused, can result in energy savings and peak demand reduction.

THE BARRIERS

Trains are powered by touching contact shoes against a direct-current (DC) “third rail” that runs parallel to the traction rails. When trains with regenerative braking capability decelerate, any resulting regenerative energy is injected back to the third rail. While this may lead us to think that regenerative energy has to result in significant energy saving and peak demand reduction, in practice it does not.

Trains may consume about ~18kWh during acceleration and can potentially reproduce a substantial portion of this acceleration energy (e.g., up to two thirds of that value) during deceleration. Since trains take only about 20 seconds to brake, this high amount of energy injected back to third rail is done in a short time, at very high power. Regenerative energy can contribute to feeding auxiliary loads onboard the decelerating train. Trains may successfully inject regenerative energy to the third rail when, for instance, a decelerating train coincidently exists in the vicinity of an accelerating one, allowing for an effective transfer. However, these low probability events are not frequent enough to collectively result in substantial energy saving and/or peak demand reduction.

If a large enough load (e.g. 10 kWh) is connected to the third rail near enough to the decelerating train while this energy is being injected, that load can utilize the regenerated energy. However, if there is insufficient load then local voltage will rise and protection devices will electrically disconnect decelerating trains, preventing flow of regenerated energy from creating an overvoltage.

THE HIGHEST VALUE SOLUTION

Several solutions exist to maximize recapture of regenerative energy by connecting an ESS device (or devices) near the track-side (wayside ESS) capable of fast energy capture from the third rail, thereby eliminating the need for train synchrony. When a train decelerates, it will charge the proposed ESS fast enough to avoid overvoltage in the 3rd rail. When it or an adjacent train accelerates, it could partially receive its propulsion energy from the ESS, offsetting the energy and power that otherwise would typically be drawn from the rectifier substation. Other uses of the stored regenerative braking energy might be considered if ConEd can utilize the power for network or system needs.

THE RESEARCH QUESTION

The fundamental questions addressed include:

1. To what extent do energy savings and peak demand reduction stem from existing regenerative energy configuration? What are the cost savings?

2. How much regenerative energy can NYCT trains produce during deceleration (e.g. during heavy peak periods with higher chances that accelerating and decelerating trains meet at passenger stations)?
3. How much energy savings and peak demand reduction can be achieved if wayside ESS is utilized?
4. What are the general design considerations for wayside ESS technologies including system size and optimal placement?

THE METHODOLOGY

1. Field Measurement: two experiments were conducted to answer the first two questions: 1.) to evaluate the extent to which regenerative energy results in energy savings and peak demand reduction, an On/Off experiment was conducted by disabling braking capability from all trains running on the 7-Line for four weeks. Substation energy/power consumption data were acquired and compared with the data collected when regenerative energy is enabled 2.) to quantify the amount of regenerative energy that trains can produce, installed metering provided measurements on trains running on the 7-Line, and 11 datasets on train speed, third rail voltage, and train current and power were collected and analyzed.
2. High-Fidelity Modeling: a high-fidelity physics-based transient model was developed for the NYCT system with integrated ESS to quantify the amount of energy saving and demand reduction that may result from adding ESS. The model of the train (without ESS) was verified and validated against real measurements and then used to model the impact of incorporating ESS. It was also used to determine the functional requirements of ESS.

KEY FINDINGS

Some of the major findings of this study include:

- A single NYCT train running on the 7-Line draws about 15-20 kWh during acceleration. The average train peak demand is about 4 MW.
- If regenerative braking energy is recuperated, both peak demand and energy of the rectifier substations are reduced by the same proportion.
- Under ideal conditions, occurring during short time intervals in the day, NYCT trains can on average reproduce ~50% of acceleration energy during deceleration. “Ideal conditions” refer to the existence of a coincident load near the decelerating train (i.e. a high auxiliary load or an accelerating train), which can receive the back-injected regenerative energy before overvoltage takes place. Chances increase during peak periods.
- Because “ideal conditions” are infrequent, existing regenerative braking configurations result in only ~8% reduction in the energy consumption and peak demand of the substations supplying the NYCT 7-Line over a 24-hour timeframe, since it is not actively managed.
- Demand/energy savings can be increased to ~35% with proper design and deployment of wayside ESS, since ideal conditions would be guaranteed for longer durations of the day.
- Potential energy and demand reduction is considerable. The rectifier substations supplying the 7-Line alone peak twice (AM and PM peaks) at around 25-MW in weekdays.
- Since regenerative energy needs to be captured within only ~20 seconds, a high-power fast-response storage technology is required. Simulations indicate flywheels and super-capacitors (SC) are viable candidates considering capital costs for this application (excluding installation and maintenance costs).
- Batteries may be deemed feasible, especially if a hybrid battery/SC or battery/flywheel is considered,

provided that other benefits are stacked over the regenerative energy capture purpose, e.g., 1) the resilience benefit of having the batteries pull trains to the nearest passenger station in case of a blackout; or 2) using the battery system to provide possible distribution benefits, and/or system benefits via NYISO market participation.

- Wayside ESS would benefit the NYCT system, substantially reducing peak power demand. The benefit of regenerative energy may however be devalued at other times of the day, even though energy savings could still be achieved. On the other hand, regenerative energy may be useful to Con Edison as an energy efficiency measure.

CONCLUSION AND NEXT STEPS

The study evaluated one potential solution for the capture of regenerative energy, wayside energy storage. The study concluded that capturing regenerative braking energy results in energy saving and peak demand reduction, benefiting both NYCT and Con Edison. The next steps for this effort include:

- The research team will continue to evaluate alternative solutions (e.g. reversible substation option) using modeling and simulation as part of a NYSERDA funded project.
- Potential technology demonstration.

Introduction

The New York Metropolitan Transportation Authority (MTA) consumes approximately 2150 GWh per year for traction power, while the MTA NYCT alone consumes about 80 % of the total annual MTA energy consumption (Dayton T. Brown, 2013). Even though electric transportation systems already provide relatively low energy consumption per passenger, there is potential for significant energy efficiency enhancement, as well as peak power and carbon footprint reductions throughout the NYCT system via regenerative braking.

Regenerative braking is based on the ability of an electric motor to act as a generator during deceleration, whereby the kinetic energy stored in the rotor as mechanical inertia becomes a prime mover, sending electric power back to the power supply when the train decelerates. Today this approach requires electric train cars to interface with the third rail through a bi-directional traction inverter. Fortunately, most of the existing and all future NYCT trains have this capability.

Even if the energy provided by regenerative braking is not completely utilized, it is favorable over traditional frictional braking, as it does not generate wear and tear, dust, smell, heat or sound (Vuchic, 2007). However, there is potential for substantial economic payoffs if the regenerated energy is better harvested and reused for the following reasons: 1.) The regenerated energy is significant 2.) High number of passenger stations and frequent train stops are characteristics of the NYCT system, and urban transportation generally.

Currently, the regenerated energy produced by NYCT trains contributes to primarily supplying the train’s auxiliary loads and equipment, e.g. the onboard air-conditioning system, which does not result in considerable energy savings (LTK, 2007) The rest of the regenerated energy is sent back to the third rail. Unless train time-synchronization is achieved through a coincident train accelerating or driving uphill within the same section of the decelerating (i.e. braking or driving downhill) train, the energy has to be converted to heat at the station through the use of resistors. This occurs because the regenerative energy reinjected to the third rail causes power supply in excess of load demanded, leading to a transient over-voltage. As the third rail voltage exceeds the maximum allowable voltage (720 volts DC) to supply the train, protection devices are tripped.

Energy storage systems (ESS) can store regenerated energy and release it when needed, eliminating the time-synchronization requirement. Several existing storage technologies may be considered for wayside storage: batteries, ultracapacitors, and flywheels. What type of storage technology or wayside storage makes more sense in the NYCT system? In order to arrive at a more definitive answer, the regenerated energy that can be captured using the respective storage technologies must be accurately simulated. Moreover, the impacts of these various technologies on the third rail voltage need to be analyzed.

Trains typically take between ~15-20 seconds to brake from their nominal speed to a complete stop. During this time, the regenerative energy is sent back to the third rail; the amount of available stored energy depends on the dynamic characteristics of the storage technology. Precisely performing the aforementioned assessment of the various storage technologies requires electromagnetic transient analysis instead of static steady-state models for enhanced accuracy.

Current State of the NYCT System

TRAIN REAL MEASUREMENTS — HOW MUCH REGENERATIVE ENERGY CAN TRAINS IDEALLY PRODUCE?

Real-time measurements were collected for trains running to and from a passenger station located on the 7-Line (103rd St. Station) for both the Eastbound (EB) and Westbound (WB) directions. Measurements were collected during times when the probability that trains meet a passenger station is high; therefore, we will assume this case to represent the best case scenario. The objective of collecting these data was twofold: 1.) to quantify the amount of regenerative energy that trains can continuously produce if conditions are made appropriate for them (e.g. wayside ESS is deployed) and 2.) to verify and validate the developed models by comparing the simulation model output against real measurements. The measurements include speed, voltage, current, power profile and integration of power collected at a rate of 5000 samples per second. Table I summarizes the energy during acceleration and deceleration of different train cycles.

TABLE I. ENERGY DURING ACCELERATION AND DECELERATION

Name of Data Set	Acceleration			Deceleration		
	Energy (kWh)	Duration (s)	Peak Power (MW)	Energy (kWh)	Duration (s)	Peak Power (MW)
DCC_0411 103rd EB	15	30	3.8	10	30	-2.5
DCC_0412 103rd WB	21	38	4	7	25	-2
DCC_0415 103rd EB	16	27	3.8	10	30	-2
DCC_0420 103rd EB	11	38	3.9	8	22	-2.1
DCC_0425 103rd EB	19	33	4.1	8	25	-2.5
DCC_0431 103rd EB	14	30	3.5	10	30	-2.8
DCC_0437 103rd EB	20	34	4	10	22	-2.5
DCC_0421 103rd WB	20	35	4	8	30	-2.9
DCC_0427 103rd WB	21	40	4	9	22	-3
DCC_0433 103rd WB	21	40	4	8	25	-2
DCC_0439 103rd WB	20	35	4.1	10	30	-2.5

The table shows that the regenerative energy produced during deceleration can reach up to more than two thirds of the acceleration energy during ideal conditions, averaging approximately 50%. As a sample, Figs. 1, 2, 3, 4 and 5 show the 3rd rail voltage, total current, power, speed and energy measurement sets corresponding to the first row of Table I respectively. The change in total energy during acceleration (0 s to 32.77 s) is approximately 15 kWh and the change in total energy during deceleration (32.77 s to 68 s) is approximately 10 kWh. Note that in an 'ideal' scenario, the voltage (Fig. 1) does not exceed its upper limit (typically set between 680-780 V) during deceleration, enabling the negative current/power (Figs. 2 and 3) to flow to the third rail without interruption. Had the conditions not been suitable (the case during most of the day), then negative power would cause the voltage to rise until it quickly reaches an upper limit. This would trigger protection to disconnect the train from the third rail and stop the flow of regenerative energy.

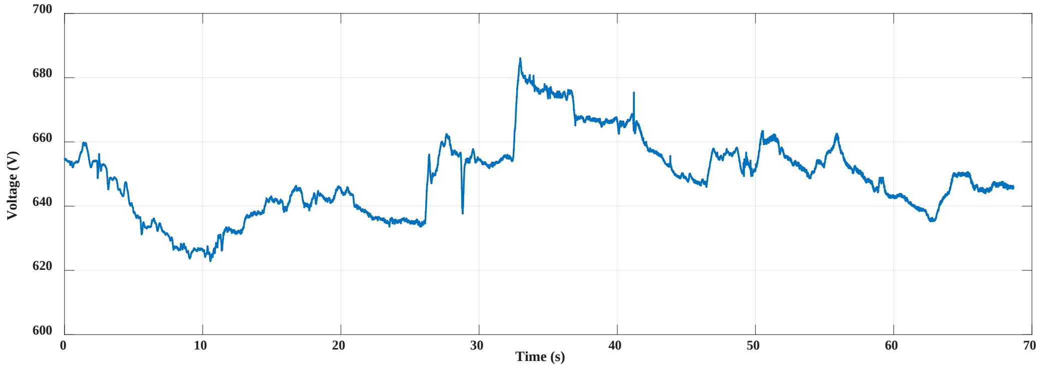

Fig. 1. Voltage Profile

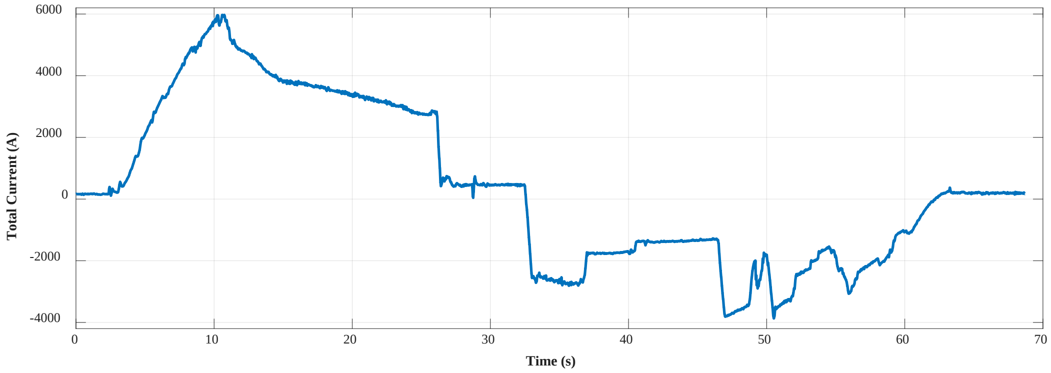

Fig. 2. Total Current Profile of Eastbound Train

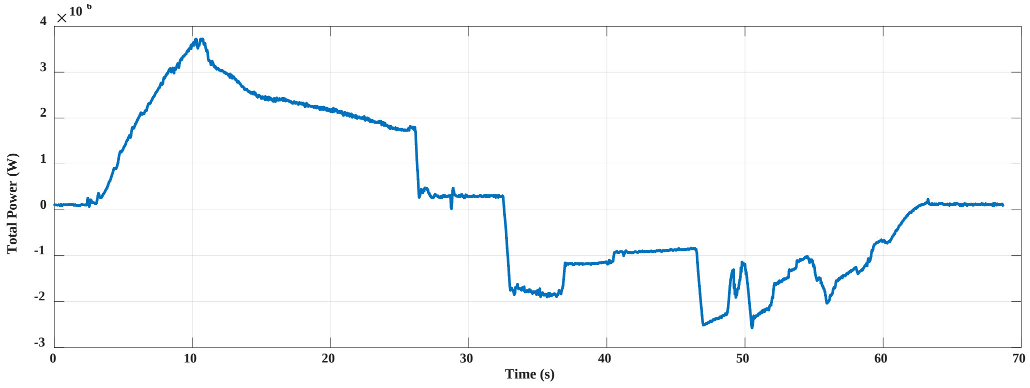

Fig. 3. Total Power Profile

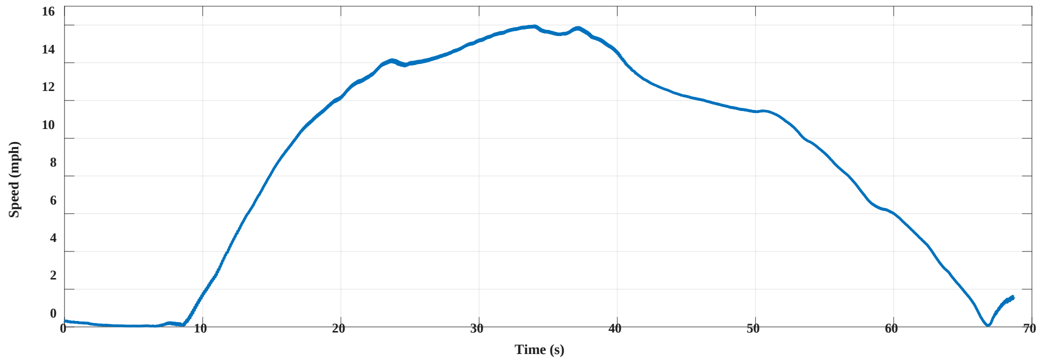

Fig. 4. Speed Profile

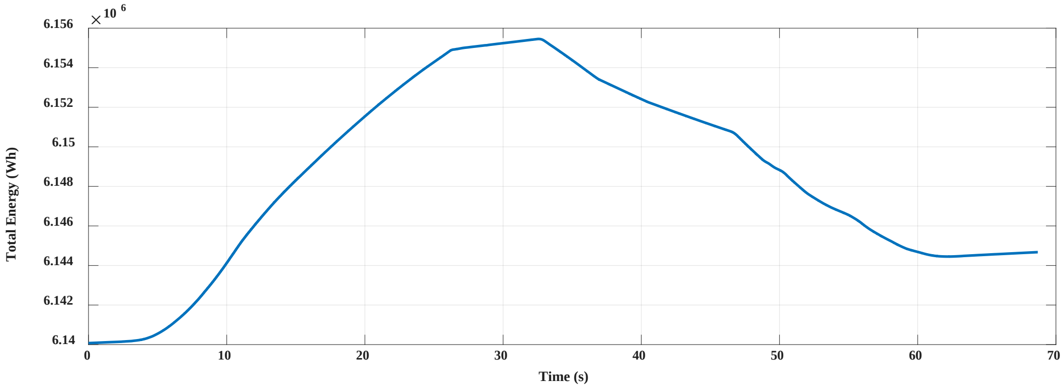

Fig. 5. Total Energy Profile

ON/OFF STUDY — HOW MUCH SAVINGS DOES REGENERATIVE ENERGY CURRENTLY RESULT IN?

In order to quantify the current effect of regenerative energy on NYCT energy consumption and peak power demand, Con Edison in collaboration with NYCT turned off the regenerative braking capability from all the trains running on the 7-Line, and compared the energy consumption between the “On” and “Off” cases. Study results showed a total of about 8% energy saving (in weekdays) on the entire 7-Line (Figs. 6, 7). This adds up to about 32.4 MWh.

Moreover, Fig. 7 shows regenerative braking results in about ~8% demand reduction during the evening peak (27.3 MW reduced to 25.0 MW), reducing the peak by 2.4 MW and 3.3 MW during the morning and evening peaks respectively. Typically, the terminal substations (end of the line on both sides) are found to witness less energy saving than central ones (Fig 8) possibly due to lower train frequencies at those stations.

More reduction was noticed at the end of the line on the Queens side (Corona & Lawrence rectifying substations) with 7.3 MWh savings, when compared to that of the Manhattan side (7 Ave. and Park Ave. rectifying substations) with 5.7 MWh savings, possibly due to voltages rising beyond the cutoff in Manhattan.

The key takeaways of this study are: 1.) since demand increases when regenerative braking capability is disabled, regenerative energy contributes to some energy savings and demand reduction. However, these savings only equate to about 8% on a weekday (and lower during weekends when train frequencies reduce), and 2.) substation location plays an important role in determining maximum cost savings.

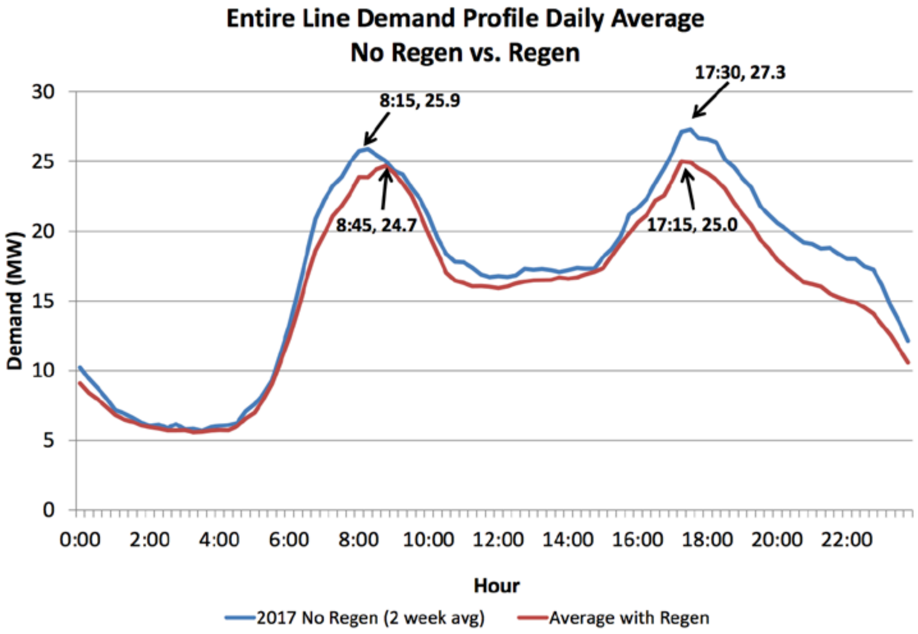

Fig. 6. Power demand with and without regenerative energy

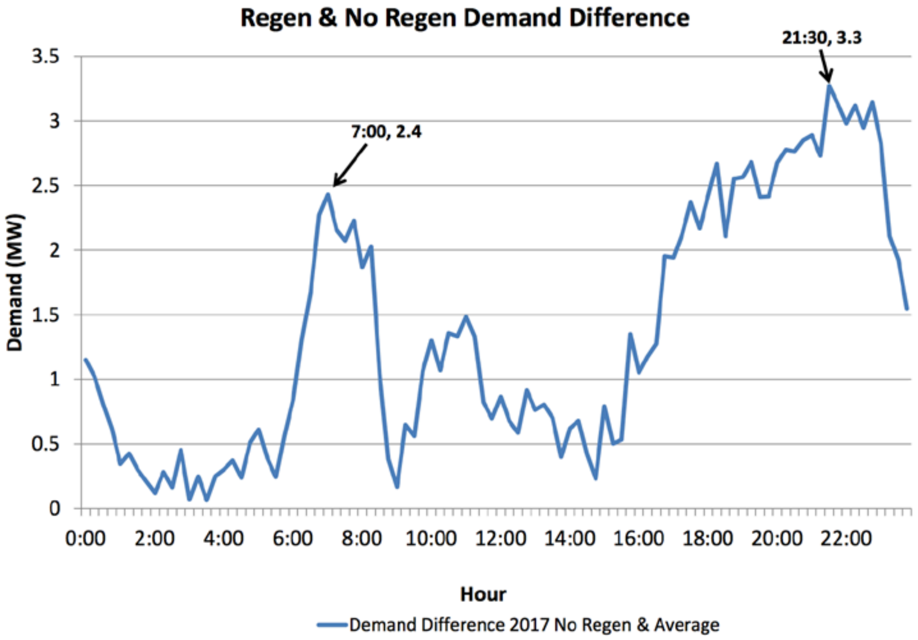

Fig. 7. Power demand difference with and without regenerative energy

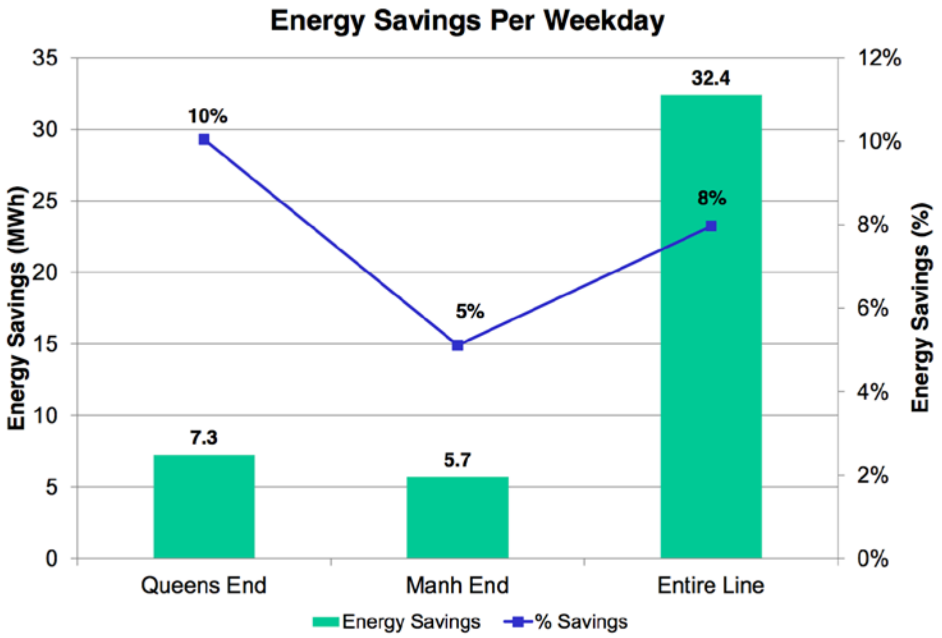

Fig. 8. Energy saving

Analysis of ESS Sizing, Charging Rates, and General Design Considerations

EXAMPLE: CORONA YARD NON-WIRES SOLUTION

We focused our research in this project on the 7-Line (Flushing) which consists of 13 substations (8 in Queens and 5 in Manhattan). Without loss of generality, we focused our modeling on the substations and passenger stations within the area depicted in Fig. 9 (“Corona Yard” region). Corona Yard was the primary focus area since two of the four primary feeders supplying this area are relatively congested and may become a part of Con Edison’s Non-Wires Solutions program. As such, the extent to which regenerative energy could contribute to energy savings and to relieving congestion (peak demand reduction) in this area was quantified taking into consideration wayside ESS deployment.

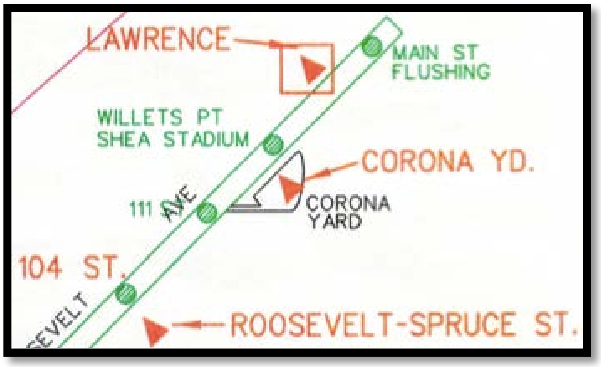

Fig. 9. Corona Yard: the area of interest in this study

Three substations, Lawrence, Corona Yard and Roosevelt-Spruce, and four passenger stations, Main ST Flushing, Willets PT, 111th AVE and 103rd ST, have been included in the modeling and analysis. Assumptions regarding the number of trains and the number of round trips on the 7-line are presented in Table II.

TABLE II. TRAIN TIMETABLES

Number of trains in AM services	36
Number of trains in Midday services	21
Number of trains in PM services	34
Number of trains in Late night services	6
Total typical daily round trips	311
Total typical Saturday round trips	220
Total typical Sunday round trips	173

As an example of the results achieved from the study, a high-level block diagram of the simulation model is shown in Fig. 10, where different types of wayside ESS have been placed at the Mets-Willets Passenger station and the consequent simulated demand reduction at the adjacent Corona Yard substation. Power (kW) and energy (kWh) ratings of the three types of ESS technologies, battery, super capacitor and flywheel, indicative of corresponding demand reductions of 10%, 18%, and 24% have been calculated and results tabulated below (Table III). These results also include a comparative study of the storage device costs for the three ESS technologies based on sample prices found in the literature (Table IV). Fig. 11 shows the 24-hour power profile of Roosevelt Avenue and Corona Yard for demand reduction of 10%, 18%, and 24%.

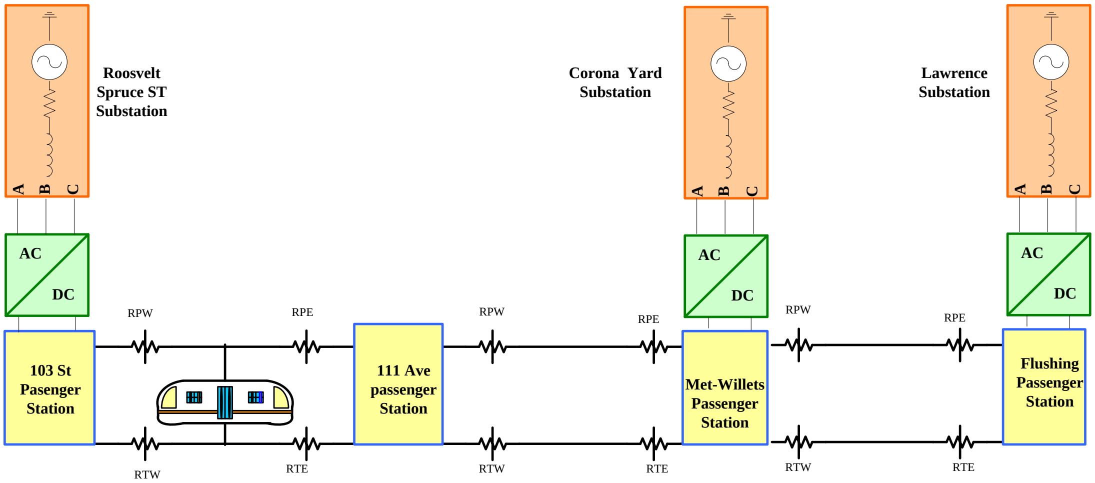

Fig. 10. System overview

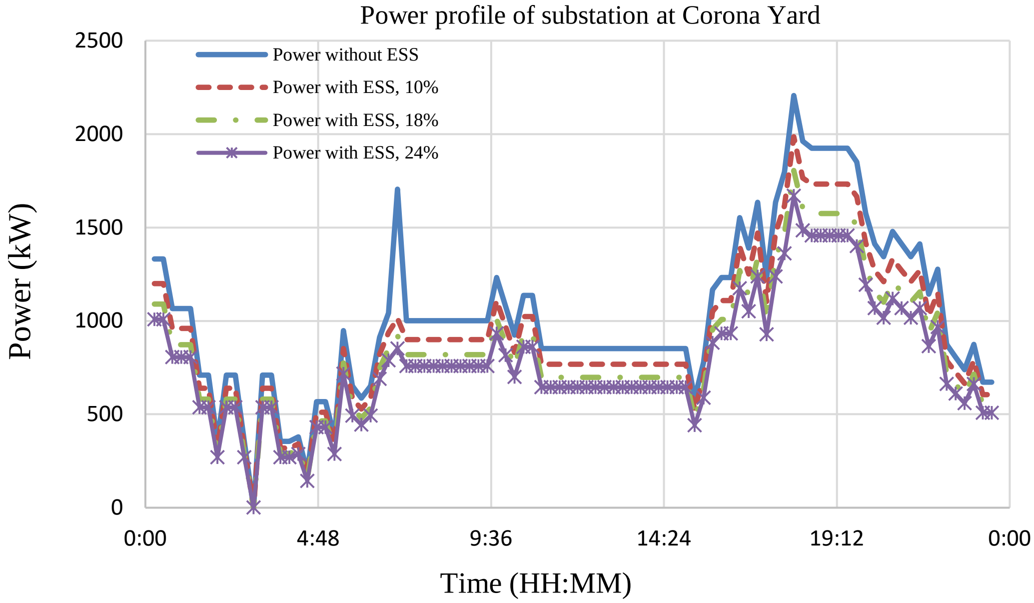

Fig. 11. Substation power for 10%, 18%, and 24% peak demand reduction at Corona Yard

Current discharge profiles for all three types of ESS have been generated in order to achieve the aforementioned percentages of substation peak demand reduction; corresponding power and energy ratings have been tabulated in Table III. These sizes of ESS incur a capital cost[1] for both power and energy; these are presented in Table IV and include only the storage module.

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[1] M. Farhadi and O. Mohammed, "Energy Storage Technologies for High-Power Applications," in IEEE Transactions on Industry Applications, vol. 52, no. 3, pp. 1953-1961, May-June 2016.

TABLE III. CORONA YARD.

	Charging Rate/ Discharging Rate	Sizing for 10% demand reduction		Sizing for 18% demand reduction		Sizing for 24% demand reduction	
		Energy (kWh)	Power (kW)	Energy (kWh)	Power (kW)	Energy (kWh)	Power (kW)
Battery	1C/1C	1111.6	570	1990	995	2072	1036
Supercapacitor (Capacitance)		1.5 (62 F)	570	2.6 (106 F)	995	3.3 (133 F)	1036
Flywheel		3.8	570	6.6	995	7	1036

TABLE IV. CAPITAL COST OF ESS PLACED AT CORONA YARD.

Capital Cost ($) / Type of ESS		Peak Demand Reduction		
		10 %	18%	24%
Battery	1C/1C	1,333,914 – 5,002,180	2,387,872 – 8,954,521	2,486,680 – 9,325,053
Supercapacitor		57,750 – 250,500	100,800 – 437,000	105,250 – 463,900
Flywheel		93,100 – 247,000	162,450 – 431,000	169,400 – 449,400

Table III illustrates the extent to which a battery ESS must be oversized when compared to super capacitors and flywheels. This is due to the relatively slow charging/discharging characteristics of batteries. In order for a battery to charge/discharge at high currents in such a short period of time, it would have to be either oversized or operated at very high C-rates (~30C). Operating a battery (presumed to be Li-Ion) at such high C-rates rapidly degrades its lifetime and capacity retention. It is therefore preferable to oversize a battery even though majority serves as underutilized. On the other hand, a super capacitor or a flywheel is capable of supporting the very high currents required for this application. Table IV shows that super capacitors and flywheels are comparably suitable for this operation whereas a battery is more cost-prohibitive. A battery system may remain feasible if other benefits, e.g., resilience benefits, wholesale market services, or Non-Wires Solution distribution deferral benefits are stacked.

GENERAL DESIGN CONSIDERATIONS

In order to develop an understanding of the requirements of ESS for regenerative energy recuperation, we hereby analyze all aspects influencing it.

- The amount of regenerative braking energy that a train can produce during deceleration is influenced by:

Design Aspects:

- Regenerative energy varies linearly with the mass of the train. It is also proportional to the maximum velocity of the train just before deceleration is initiated. The impact of the weight of the train tends to be more prominent with the change in the inclination angle of the track.
- The impact of the frontal projected area is minimal. This is because the aerodynamic drag force is minor compared to the other forces impacting the train (e.g. friction). Hence, harnessing regenerative energy in tunneled or open-air stations should not introduce a significant difference.
- Regenerative energy varies linearly with the efficiency of the electric drive (including the motor and the inverter) of the trains. The reason for this is the fact that all the energy transferred from and to a train passes through its electric drive.

Operational Aspects:

- The braking and overvoltage protection (chopper) settings of trains determine how much power/current a decelerating train can inject to the third rail prior to the chopper functioning to dump the regenerative energy.
- For NYCT, the chopper does not operate as long as the voltage is below 680V, after which the chopper operates and the train circuit is disconnected form the third rail.
- Since the maximum velocity is an influential factor, increased regenerative energy can be recuperated if train speed profiles are controlled to enable higher maximum speed right before initiating deceleration. However, the distances between passenger stations have to be considered to maintain safe distance between trains.

- Modeling results show that wayside ESS deployed at a substation contributes to reducing the peak demand at that substation, in addition to the two direct neighboring substations (on both sides). Wayside ESS may be placed at a passenger station to serve the direct neighboring substations. The location of wayside ESS depends on the location of the substation mainly targeted by peak demand reduction. For instance, if peak demand reduction at Corona Yard is sought, placing wayside ESS at Corona Yard or the nearest passenger station (depending on space availability, safety precautions, regulations etc.) is the most effective. Due to their slow response and short lifetime, batteries used for regenerative energy recuperation purposes will need to be largely oversized. This makes batteries cost-prohibitive at today's costs, adding considerable space and weight in comparison for flywheels and super capacitors.
- Large battery systems can also be used at a substation to achieve energy savings and peak demand reduction (similar to a typical commercial building peak reduction scenario), by discharging during morning and evening peaks and slowly charging during off-peak hours.
- Results show that the size of super capacitors required to achieve a certain peak demand reduction target is comparable to that of a flywheel system.
- If batteries are to be used, the chemistry should support fast charging/discharging rates and have very high cycle life.
- If a wayside ESS technology is to be deployed, it is recommend that the chopper/train braking settings are adjusted to enable more regenerative braking energy injection.
- For control of wayside ESS, we recommend using a nested loop consisting of an outer voltage loop regulating the third rail voltage, and an inner current/power loop controlling the ESS current/power.
- We recommend active connection of the wayside ESS (connection through a bi-directional dc-dc converter), versus passive (direct connection of ESS to the third rail). Converters increase the capital cost of deployment, however active connection substantially outperforms passive connection in the

regenerative energy application due to voltage range control.

- The nominal voltage levels on the two sides of the bi-directional DC-DC converter are recommended to be ~500 V on the low-voltage side, with nominal third rail voltage on the high-voltage side. This relatively high voltage on the low-voltage terminal is recommended so that it is close to the voltage of high-voltage terminal. This decreases the input current, reduces the complexity of the converter (and potentially the size and weight), and allows for a larger voltage window (and energy storage) in the case of super capacitors.

Framework for Benefits Costs Analysis

Benefits to NYCT: The major benefit to NYCT is reducing the majority of their demand and energy costs

Benefits to Con Edison: Con Edison uses the New York Public Service Commission approved benefits costs handbook[2].

The BCA aims to "provide consistent and transparent statewide methodologies that calculate the benefits and costs of potential projects and investments." Some of the benefits and costs associated with wayside ESS deployment are as follows.

- Benefits:
    - Avoided Generation Capacity Costs (AGCC)
    - Avoided Energy (LBMP)
    - Avoided Ancillary Services
    - Avoided T&D Capacity Infrastructure
    - Avoided Carbon Dioxide
- Costs:
    - Program Administration Costs
    - Participant DER Costs

The cost effectiveness of potential projects is evaluated through three tests, namely the Societal Cost Test (SCT), Utility Cost Test (UCT), and the Rate Impact Measure (RIM). The SCT evaluates impact on the society, and is thus the primary cost-effectiveness measure. The UCT and RIM assess the preliminary impact on utility costs and ratepayer bills from the benefits and costs that pass the SCT.

Preliminary BCA Analysis: Con Edison performed preliminary BCA analysis using Corona Yard substation as a case study. The analysis showed that batteries do not have a benefit to cost-ratio higher than 1, but super capacitors and flywheels do.

Model Development and Validation

VEHICLE MODELING

There are two main categories for transient modeling of electric rail vehicles:

1. Cause-effect or forward facing method – power consumed by the vehicle is used as an input to determine the speed of the wheel
2. Effect-cause or backward facing method – the speed profile and vehicle properties are used as inputs

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[2] Available online at: https://www.coned.com/-/media/files/coned/documents/our-energy-future/our-energy-projects/coned-bcah.pdf?la=en

to determine the input power to the train

In this project, due to the availability of speed profiles, we use the effect-cause method. The modeling process is presented in Fig. 12. In this model, the speed of the train is taken as an input, and based on equations (1) to (4) describing the vehicle dynamics, the forces applied to the wheels are calculated.

Where *Ftrac* is the tractive effort, *Frol* is the rolling resistance, *Fae* and *Fgr* are the aerodynamic drag force and the force due, respectively. From the traction force (*Ftrac*) calculated in equation (1), the torque and speed at each axle are calculated using equations (5) and (6), respectively. The calculated torque and speed are applied to the gearbox, and the outputted torque and speed from the gearbox are applied to the motor drive. The motor drive includes the braking chopper, induction motor and controller, and an inverter.

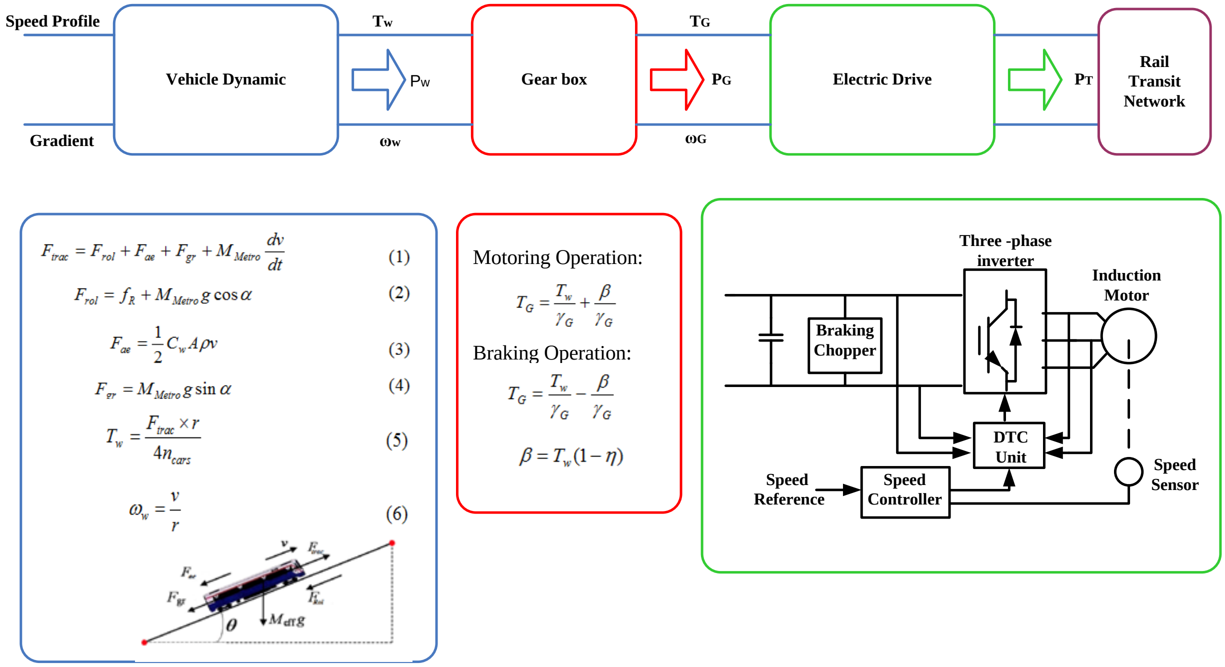

Fig. 12. A block diagram showing the modeling process

MODELING TRAIN MOTION ON THE RAILS

To model an electric train moving on the rail, traction and power rails are modeled by variable resistances located on the west and east sides of the train, as shown in Fig. 13. The value of these variable resistances change based on the train position. Fig. 14 shows the variable resistance model and block diagram of calculating resistance at each time step.

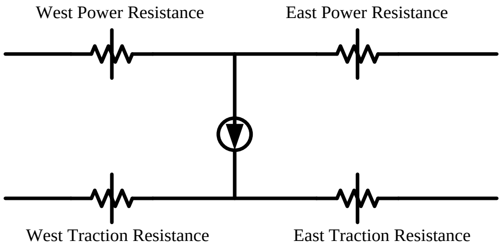

Fig. 13. A schematic diagram of the rail system model

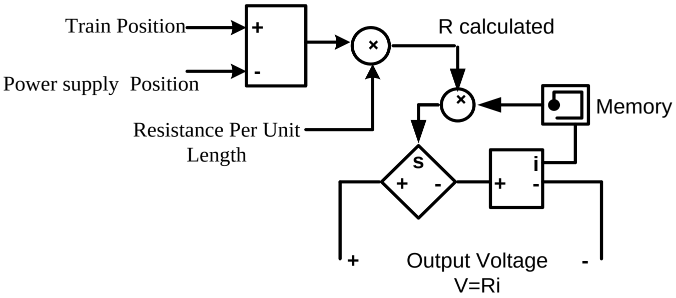

Fig. 14. Simulink block diagram of rail variable resistance

RECTIFIER SUBSTATION MODELING

The electric power supply substation has been modeled by two parallel circuits as shown in Fig. 15. One of the circuits consists of a three-phase Δ/Δ transformer in series with an AC/DC converter. The other circuit consists of a three phase Y/Δ transformer.

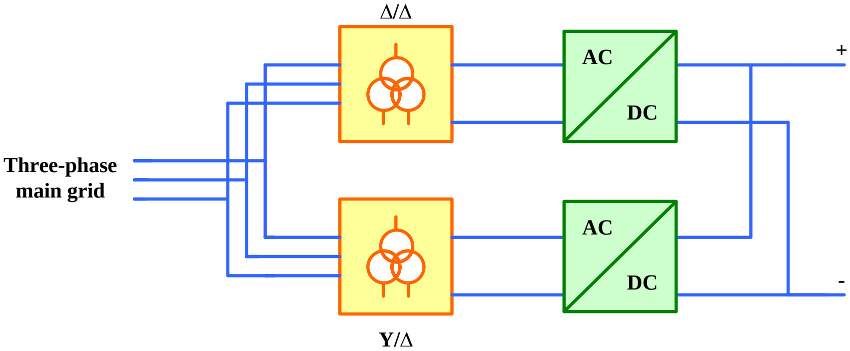

Fig. 15. Block diagram of the substation model

ENERGY STORAGE SYSTEM MODELING

For the energy storage modeling, the various ESS technologies (battery, super capacitor, and flywheel) have been modeled in MATLAB/Simulink. In case of a passive connection, the ESS directly connects to the rail. For the case of active connection, the ESS is modeled as connecting to the rail through a converter as shown in Fig. 16.

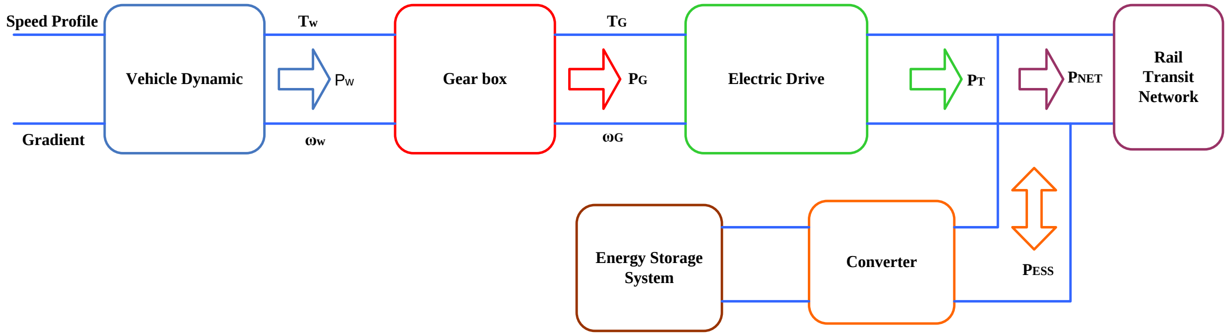

Fig. 16. Block diagram of the model including energy storage

MODELING ASSUMPTIONS

Train Measurements:

The train measurements have been taken at point 2, as shown in Fig. 17.

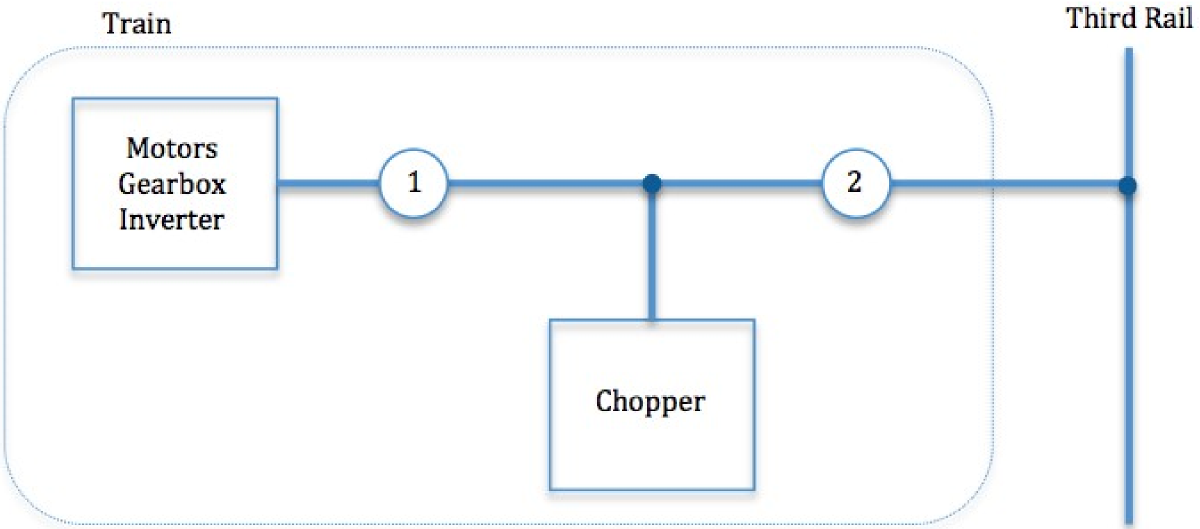

Fig. 17. A schematic diagram showing the location of DCC measurements

Train Braking Parameters:

Trains can inject regenerative braking energy to the third rail until the voltage reaches 720V. The following paragraphs are quoted from NYCT operational documents.

- “During high speed braking, the 0.24 ohm resistor must be inserted in the circuit. The purpose of this resistor is to allow the link voltage to be increased by a maximum 120 V above line voltage, at full power. The IGBT brake choppers limit the increase to 720 V, which is the minimum link voltage required to meet the desired braking performance.”
- “Thus, during high speed braking, at a line voltage of 600 V, the link voltage will be increased to 720 V. At a line voltage of 450 V, the link voltage will be increased to 570V. At a line voltage of 650 V, the link voltage will be clamped to 720 V.”

- "If the line voltage is less than 420 Volts or greater than 720 Volts for more than 10 milliseconds, then the line breaker is opened and braking continues as non- regenerative braking."
- "In regenerative brake (line breaker closed), if the link voltage is greater than 720 VDC, but less than 800 VDC, the line breaker is opened and braking continues as non-regenerative braking."

Model Validation

The developed model has been validated using real data on the 7-Line (Flushing), including: 1) speed, current, voltage, power and energy train measurements; and 2) average 24-hour interval metering data at substations. After successfully validating the developed model, it was used to analyze and compare the various ESS technologies. Figures 18 and 19 show how close our model is to real train current (Figure 18), and 24-h power profile (Figure 19).

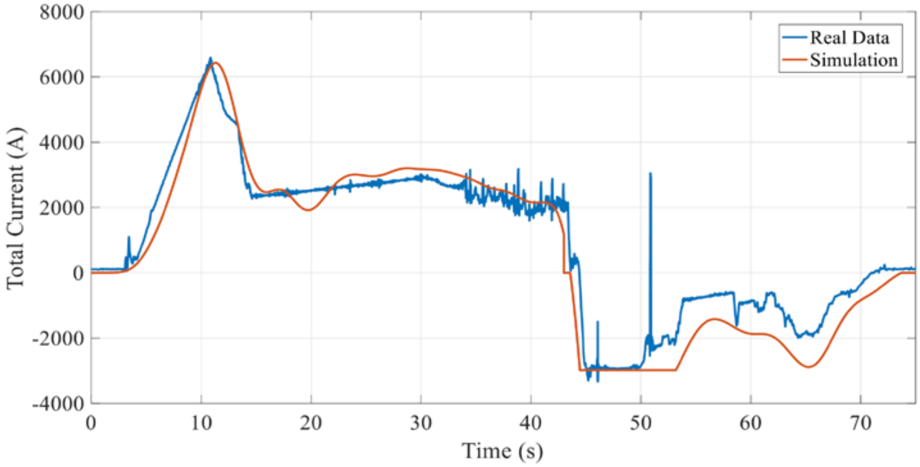

Fig. 18. Model validation with actual train current for an acceleration/deceleration cycle.

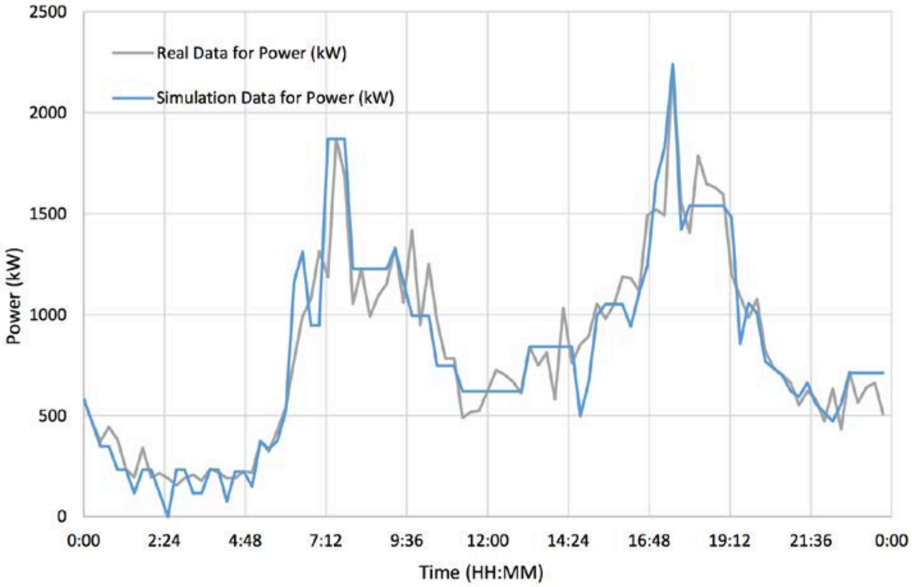

Fig. 19. Model validation with actual 24-h profile.

Acknowledgements

The research team included the following participants.

- From **Con Edison** – funded by the R&D Dept:
  - Damian Sciano
  - Jared Trumpetto
  - Balvinder Deonarine
  - Constantine Spanos
  - Gillian Koch
  - Rebecca Rondina
  - Veran Medray
- From **CUNY City College**
  - Mahdiyeh Khodaparastan
  - Mahmoud Saleh
  - Oindrilla Dutta
  - Yusef Esa
  - Werner Brandauer
- From **NYCT**: Bruce Alexander
- From **Dayton T Brown**: Keith Cummings