

Return on Investment from Rail Transit Use of Wayside Energy Storage Systems

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ABSTRACT

New trains with AC propulsion promise higher performance, reduced starting energy use, regenerated braking energy savings, lower maintenance, and a broadened range of operating conditions. However, some Transit Operators have found that these new trains have not fully achieved the expected regenerated energy savings. Transit Operators have also experienced traction power problems such as severe voltage sag or train low voltage shutdown due to the increased power demand of these higher performance AC trains. An effective Energy Storage System (ESS) can resolve these problems at a favorable capital cost. Candidate ESS technologies include flywheels, supercapacitors, and batteries. This paper analyzes the ESS economic benefits in two dimensions: energy and power savings, and capital costs to correct voltage sag. These costs are used to calculate a return on investment (ROI) for a range of ESS cost inputs, at two typical US transit systems: an urban subway system with 10-car trains and a suburban light rail line that runs trains of two to four railcars. ROIs range between 15% and 35% depending on the ratings, conditions, and usage of the rail system and ESS. The paper then presents results of a rail network simulation quantifying ESS performance in supporting traction power voltage on a dense East Coast electric commuter railroad.

INTRODUCTION

In the US and around the world, new electrically propelled subway rail trains and light rail vehicles (LRVs) use AC propulsion with induction traction motors and variable voltage, variable frequency drives. Benefits of these AC trains over older trains include higher performance, reduced starting energy use, regenerated braking energy, lower maintenance, and a broadened range of operating conditions. However, Transit Operators have found that without an Energy Storage

System (ESS) available to capture the regenerated power, AC trains and earlier DC chopper trains have not fully delivered their potential economic benefits.

Transit Operators have growing interest in finding an ESS solution to capture the full energy savings benefit of regenerative braking, to reduce the peak power usage which incurs high peak power demand charges, and to mitigate voltage sag and dropout problems. Transit Operators have limited capital budgets for traction power improvements to resolve these problems. An effective ESS can resolve these problems at a favorable capital cost.

ESS technologies include flywheels, supercapacitors, and batteries. Transit Operators have installed ESSs on the wayside and on railcars or electric locomotives. Figure 1 shows a wayside ESS. This paper summarizes typical requirements for a transit wayside ESS, and notes the strengths and weaknesses of the candidate technologies against the requirements.

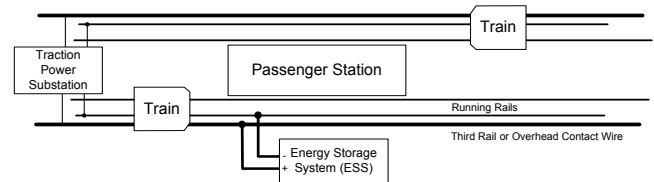


Figure 1 Transit Wayside Energy Storage System

To calculate energy and power savings, the authors developed a Traction Power Cost Analysis (TPCA) tool which determines the optimal capacity ratings for an ESS for selected rail transit system applications. The authors use the TPCA to quantify ESS energy savings and peak power reduction cost savings, and to calculate return on investment (ROI) for a range of capital and operating costs, on two typical US transit systems: an urban subway system with 10-car trains and a suburban light rail line that runs trains of two to four LRVs.

To assess voltage support costs and benefits, the authors estimate the cost to install a new substation to resolve a low voltage condition, for both urban and suburban locations. The paper compares these capital costs to the estimated costs of an ESS installation which provides the equivalent level of voltage support. The paper then evaluates the capability of a single ESS installation to provide voltage support at a busy junction in a dense urban / suburban electric commuter railroad.

ESS COST SAVING OBJECTIVES

Transit operators need three types of economic benefits from an ESS:

Reduce Total Energy Consumption

The ESS must capture and enable reuse of energy regenerated by trains during braking. This savings directly reduces the Transit Operator's electric energy costs. Further, it reduces platform heating in subways, an important summertime consideration. This energy savings also delivers a quantified reduction in carbon dioxide emissions, which is important in Kyoto Treaty countries.

Reduce Peak Power Demand Charges

The ESS must reduce peak power demand charges. Electric utilities in North America and Europe charge industrial customers for peak power demand, in addition to charges for total energy used.

Peak power demand is determined by the time period(s) with the highest energy usage. Each electric utility sets a time period for measuring power usage; typically it is one or two intervals of five, fifteen, or thirty minutes duration. Peak power demand charges are set by the period with the highest energy usage in a billing cycle, which is typically one month. Power demand charges during peak hours of the peak season can be as much as five times higher than charges during base periods. Some Transit Operators report that their peak power demand costs are higher than their total energy use costs. The peak power demand is calculated by dividing the energy used in the peak period by the duration. The units are kWh / h, or just kW.

Reducing the energy used during these peak demand periods can deliver significant energy cost savings. An ESS that captures train braking energy and enables its reuse will reduce the peak power demand charge.

Provide Voltage Support

Some Transit Operators need an ESS to provide traction power voltage support to mitigate traction power voltage sag problems. Voltage sag results from physical limitations of the traction power supply including substation location, rating, and loads. It can also occur as new trains or extended operations overburden existing traction power supplies; for example, higher density service, a line extension, or a new fleet of higher performance AC trains. An ESS located at a track section with low supply voltage can provide current to trains when it is needed, decreasing the voltage drop so that operations are not limited or disrupted.

ESS PERFORMANCE REQUIREMENTS

To fulfill these objectives, a transit wayside ESS must capture and enable reuse of train braking energy which would otherwise be lost; it must reduce the trains' peak power demand on the traction power supply; and it must supply power when needed to correct a voltage sag condition.

For major urban rail lines, the ESS must operate at a high duty cycle during long rush hours with close headways. In practice, this means the ESS must operate at a duty cycle above 40%. In other words, it must discharge 15 s, idle for 20 s, charge for 15 s, idle for 20 s, and repeat the cycle continuously through extended rush hour periods.

The ESS must handle the peak braking and acceleration power and energy of the Transit Operator's trains. The required power and energy varies dramatically between a suburban one or two-car LRV line and an urban ten-car subway. The control algorithm must capture the regenerated energy, accommodating the changing pattern of train arrivals and departures. Additionally, the control algorithm must accommodate the charge / discharge pattern needed to provide voltage support for accelerating trains in an overburdened traction power system.

To provide an acceptable return on investment, the ESS must be completely automatic, require little maintenance, be self-protecting during emergency or failure conditions, and be highly efficient with very low waste energy during charging, discharging, and idling.

As with all transit equipment, the ESS must be safe for staff and the public under all normal and abnormal

conditions, as well as for maintenance staff working on the traction power or third rail equipment. The ESS must be stable under all conditions and electromagnetically compatible with the Transit Operator’s signal system and other equipment.

The ESS must permit low-cost installation and therefore must fit in an existing space, a small enclosure, or a small building, with minimal heating and cooling requirements. The ESS must also be easily connected to the traction power system.

ESS TECHNOLOGIES

Transit Operators have evaluated and tested flywheels, supercapacitors, and batteries for transit ESS application. Table 1 summarizes the advantages and obstacles for each. Reference [1] describes the characteristics of each in greater detail. Flywheel demonstration projects in the transit industry at New York City Transit, London Underground, Paris, Lyon, and others. Both wayside and railcar demonstration projects are under way [2] [3]. The highest rated unit demonstrated to date is a 1 MW, 7kWh FESS, and larger units are now under development. Supercapacitor projects are under way in Portland OR (US), Koln and Dresden (Germany), and Madrid (Spain). [6] [7] [8]

ESS Feature	Flywheel	Supercap	Battery
Energy density	○	○	●
Cost / kWh	○	○	●
Power density	●	●	○
Cost / kW	●	●	○
Maintenance	●	○	○
Configurable rating	●	●	●
Operating life	●	○	○
Proven technology	○	○	●
Hazardous materials	●	○	○
Now in service	○	●	○
Key: ● Better ○ Average ○ Worse			

Table 1 ESS Technology Comparison

TRACTION POWER COSTS

Payments to electric utilities for electric energy and peak power demand are a significant operating expense for Transit Operators. Energy and peak power costs fluctuate and trend over time in response to complex market, regulatory, commercial, and political forces. Table 2 is a snapshot of U.S. utility rates during summer

2004. These rates are used to calculate cost savings in the case studies below.

	East Coast	West Coast
Energy Cost	\$0.07 / kWh	Variable by time of day and season: ~\$0.08 / kWh base ~\$0.13 / kWh during summer peaks
Peak Power Demand Cost	~\$7.0 / kW monthly charge, set by the maximum half hour of peak demand in the month	Variable by time of day and season: [N1] ~\$0.34 / kW monthly charge for the max half hour Plus ~\$0.70 / kW monthly charge during Partial Peak hour Plus ~\$7.5 / kW monthly charge during summer Peak hour.
Note [N1] Definitions of Peak and Partial Peak hours depend on the season. In a typical summer work day, Peak hours are 12 noon to 6 pm, and Partial Peak hours are 8:30 am to 9:30 pm.		

Table 2 Example Energy and Power Costs

ENERGY SAVING CASE STUDY APPROACH

The authors developed and used a Traction Power Cost Analysis (TPCA) tool to evaluate ESS savings. The TPCA models the power flow between the traction power supply, the train, and the ESS. Inputs include the train acceleration and braking current and voltage profiles versus time, as well as operating characteristics for the rail line including schedule, train length, and headway.

In the TPCA, the ESS power rating is an adjustable parameter which is used to select and optimize the ESS configuration. The TPCA assumes the ESS fully meets the requirements listed above, up to its rating limit. To simplify calculations, the TPCA uses train regenerated energy as an input, and constrains the energy returned by the ESS to balance the input quantity. The TPCA calculates the energy used by the train and saved by the ESS, per car per stop/start cycle. The TPCA extends the calculation to cover the rush hour, day, and year. It also calculates the average power used in the peak power demand interval. Finally, it calculates the resulting costs and savings.

The authors used the TPCA to calculate energy and power savings for two US rail lines:

- An East Coast urban subway line with ten car trains and a two minute rush hour headway. The electric utility typically uses the two fifteen minute intervals with highest power use to calculate peak power demand.
- A West Coast suburban light rail line with two to four car trains and a fifteen minute rush hour headway. The electric utility typically uses a five minute interval to calculate peak power demand.

The TPCA assumed a continuous standby loss of 2.0 kW.

ENERGY AND POWER SAVING CASE STUDY RESULTS

All traction power savings result from the capture and reuse of train regenerated energy. The peak power demand is too long for the reduction of instantaneous power to translate directly into a reduced peak power demand charge.

Therefore, two sets of real-world parameters govern ESS effectiveness in energy and peak power demand savings:

1. The power and energy characteristics of train regenerative braking.
2. The ESS power and energy ratings compared to the train's characteristics.

Data on train regenerative braking indicates there is significant variation in train regeneration effectiveness not related to line receptivity. Maximizing traction power cost savings requires effective train regeneration under a broad range of conditions.

The ESS power rating and energy capacity must be large enough to capture a significant portion of the regenerated train energy. For ESS to capture energy when two trains arrive at the same time, the ESS ratings must be up to twice as big.

For a two-track line, there is no benefit to an ideal ESS rating larger than that needed to capture regenerated energy from two trains. However, a larger energy capacity enables ESS to work in less than ideal conditions, and to provide both traction power savings and voltage support.

Figure 2 shows power and energy profiles versus time for the train, ESS, and substation, for an example US

subway. Reference [1] provides similar data for a US light rail line. The train power profile versus time is a composite from field measurement data of normal train acceleration and regenerative braking cycles. The TPCA calculates the power captured and returned by an ESS with the selected power rating. The substation curve shows the traction power supply output, which is the difference between the train usage and the ESS supply. The energy curves are the corresponding time integrals of the power curves. Table 3 summarizes the results for the subway and a light rail line.

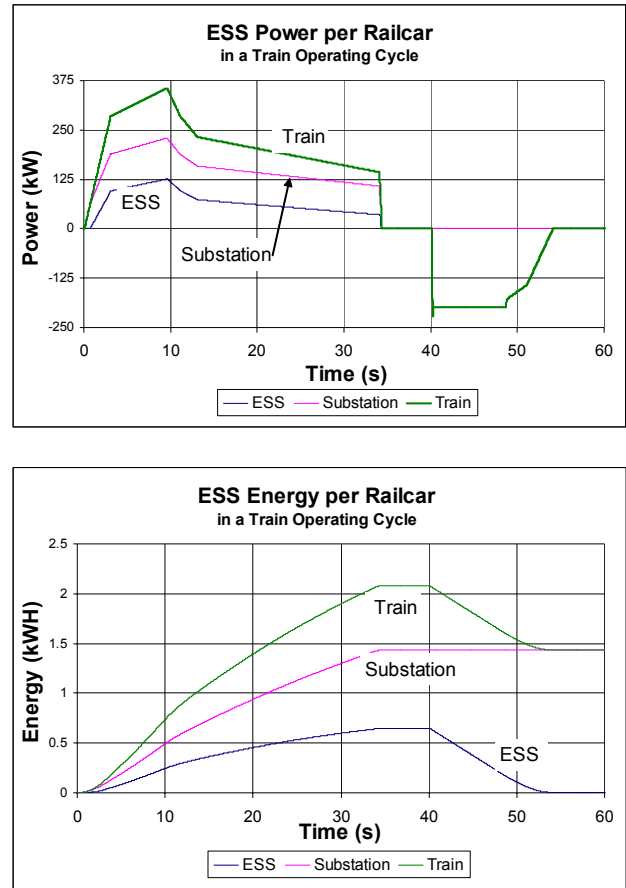


Figure 2 ESS Performance for East Coast Subway

For the modeled subway line with ten-car trains at a seated passenger load, a well-sized ESS of 2.0 MW rating will provide energy savings of up to 5.4 kWh per train start/run/stop cycle, for an energy savings of 31 % compared to a cycle with no regeneration. This equates to a savings of 5.4 MWh per day per ESS or 1.61 GWh per year. Using the Table 2 energy costs, this is a savings of \$113,000 per ESS installation. See Table 3.

The ESS will reduce the peak power demand averaged over a fifteen minute interval for 10-car trains on two tracks, from 1.21 MW to 1.02 MW per train for a per-train savings of 193 kW. This 16% peak power demand

reduction yields a savings of \$32,364 per year. Thus the total potential savings per year per ESS is approximately \$145,000, minus maintenance costs. A \$12,000 annual allocation per ESS installation for maintenance is included in the ROI analysis below.

ESS Parameter	US East Coast Subway	West Coast Light Rail
Train length	4 to 10	2 to 4
Operating hours per day	24	20
Rush hour headway	2 min	15 min
Train load assumption	AW2	AW2
ESS rating	2.0 MW	0.6 MW
Projected energy per cycle w/o ESS	21 kWh [N1]	9.6 kWh [N2]
Energy recovered per cycle	6.4 kWh [N1]	2.2 kWh [N2]
Energy recovered per cycle (%)	31%	23%
Energy recovered per ESS per day	5.4 MWh	0.23 MWh
Energy saving per year	\$113,000	\$7,600
Peak power demand period	15 min	5 min
Peak power demand w/o ESS	1,200 kW	830 kW
Peak power demand reduction	193 kW	100 kW
Peak power demand reduction	16%	12%
Power savings per year	\$32,000	\$5,900
[N1] Train length is 10 cars. [N2] Daily average train length is 2.5 cars		

Table 3 ESS Results Summary

RETURN ON INVESTMENT FROM ENERGY AND POWER SAVINGS

Using the energy and power savings calculated by the TPCA, Figures 3, 4, 5, and 6 show the range of return on investment (ROI) for the modeled urban 10-car subway, for several sets of variable costs.

Table 4 shows nominal and range assumptions for these ROI calculations.

ESS Cost Item	Nominal	Range
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ESS Cost Item	Nominal	Range
ESS Peak Rating (MW)	2.0	0.5 – 2.5
Energy Cost (\$ / kWh)	\$0.07	\$0.04-\$0.20
Power Cost (\$ / kW)	\$7.00	\$4 - \$20
ESS Cost vs. Peak Rating (\$ / MW)	\$200	\$100 - \$500

Table 4 ESS Nominal Costs and Range

Figure 3 shows the ROI versus ESS peak power rating, for two train types. One train, based on a measured case, has a regeneration period of 9 s, which is short compared to its braking time. The second train has a regeneration period of 14 s, which is a readily achievable duration. ROI for the Short Regen train with other cost factors at nominal levels is about 20%, and for a Normal Regen Train, it is about 35%. This corresponds to cash savings of \$80,000 and \$135,000 per ESS per year. Note that for this train and operating condition, ESS sizes above 2.0 MW do not provide continuously increasing savings, as most of the available energy has been recaptured with a peak rating of 2.0 MW.

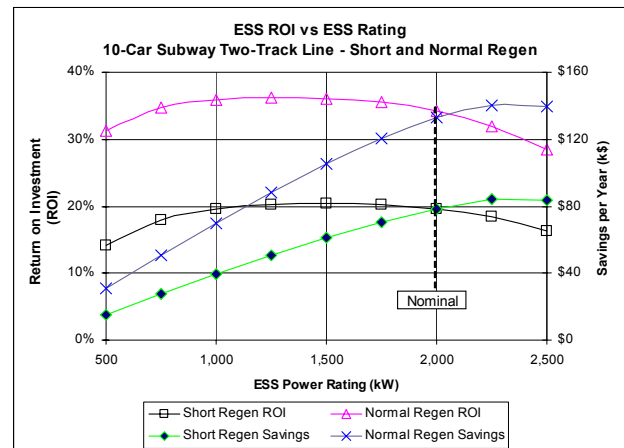


Figure 3 ROI vs. ESS Peak Power Rating

Figure 3 shows that ROI is not sensitive to ESS peak rating over a fairly broad range, for a fixed cost per MW of peak power rating. This means that the bigger the ESS, the greater the savings, over a broad range. The figure also shows that the train capability to regenerate, and the ESS ability to capture the regenerated energy, make a big contribution to payback.

Figure 4 shows the ROI versus ESS capital cost per MW, for the Short Regen and Normal Regen train types. The figure quantifies the expected relation that ROI improves as capital cost is reduced.

Figure 5 shows the ROI versus electric energy cost, for the Short Regen and Normal Regen train types. The figure shows that if the price of electric energy increases, the ROI of an ESS will dramatically improve. For example, an increase in the price per kWh from \$0.07 to \$0.10 results in an ROI increase for the Normal Regen train from 35% to 47%.

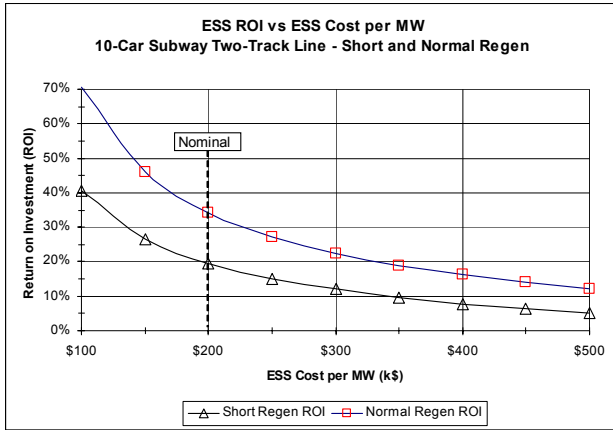


Figure 4 ROI vs. ESS Capital Cost per MW

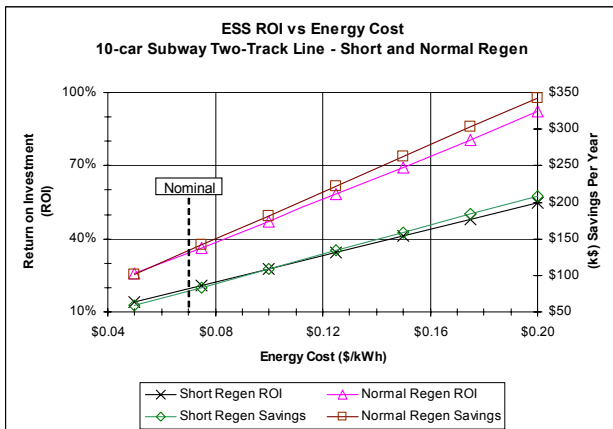


Figure 5 ROI vs. Electric Energy Cost per kWh

Figure 6 shows the ROI versus peak power cost, for the Short Regen and Normal Regen train types. The figure shows that if the peak power price increases, the ROI of an ESS will improve, but not dramatically. For example, an increase in the price per kW from \$7.00 to \$10.00 results in an ROI increase for the Normal Regen train from 35% to 38%.

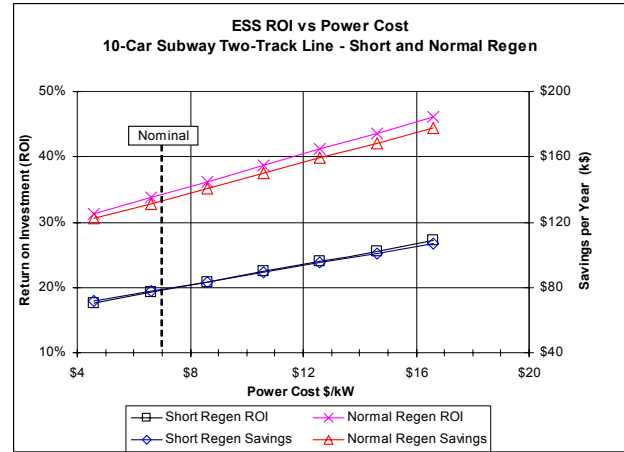


Figure 6 ROI vs. Peak Power Demand Cost

FIXING VOLTAGE SAG: CAPITAL COSTS FOR ESS VS. TRACTION POWER SUBSTATION

Voltage sag results from physical limitations of the traction power supply including substation location, rating, and loads. In some transit systems, the substations are placed farther apart than optimal, due to civil structures or natural barriers such as tunnels, or economic barriers, such as the cost of urban real estate. Voltage sag can worsen when new trains or extended operations overburden existing traction power supplies; for example, higher density service, a line extension, or a new fleet of higher performance AC trains.

A suitably located ESS can supply current near the train when it is needed, decreasing the voltage drop so that operations are not disrupted. To assess voltage support costs and benefits, Figure 7 shows a range of cost estimates to install a new substation to resolve a low voltage condition, for both urban and suburban locations. The Figure also shows the range of capital costs for an ESS installation which provides the equivalent level of voltage support.

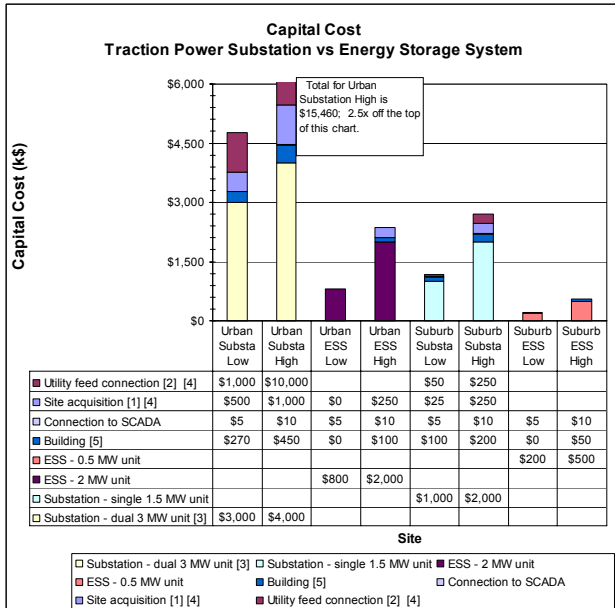


Figure 7

Figure 7 shows that the capital cost of an ESS is much lower than the comparable cost of a new traction power substation. Several key factors are:

- There is no need for a utility feed, which can be very expensive in an urban setting.
- There is typically no need to acquire land, and there may be no need to erect a new building.
- The capital costs for an ESS are lower than those for a new substation.

An ESS is a capital cost-favored solution which can also be deployed more quickly than a substation to resolve a peak power problem.

NETWORK MODELING

The authors analyzed a dense rail network to quantify the extent to which an ESS can provide voltage support. The authors used the Train Operations Model (TOM), a network-level computer modeling and simulation program to quantify traction power voltage under rush hour conditions with and without an ESS in the traction power supply.

The TOM models the effects of a specified set of tracks, stations, and traction power substations with trains operating per a schedule. The TOM models key physical characteristics including train current and performance profiles, traction power substation voltage-current

profiles, and resistance of track and traction power supply. For the ESS study, the software incorporated a model of the ESS, including its charge, discharge, and storage capacity characteristics. The TOM permits the user to observe and report on a broad range of selected parameters, including energy use, power flow, and voltages and currents in the traction power system.

The modeled rail network is typical of a dense East Coast urban / suburban electrified commuter railroad, with trains from six to twelve cars long, running headways down to five minutes. For this study, the modeled trains did not use regeneration, to highlight voltage support effects.

The modeled rail network under study consists of eight tracks intersecting in three interlockings with fifteen traction power substations and seven passenger stations. See Figure 8. This area is the mainline and hub of modeled daily railroad operations, and has low voltage conditions at MP 8.55 on Track 7 and MP 9.88 on Track 9. The modeled time period is a forty minute period from the afternoon rush hour timetable. Figure 9 is a typical TOM output, showing the current supplied by the GO8 traction power substation during a simulated forty minute operating period.

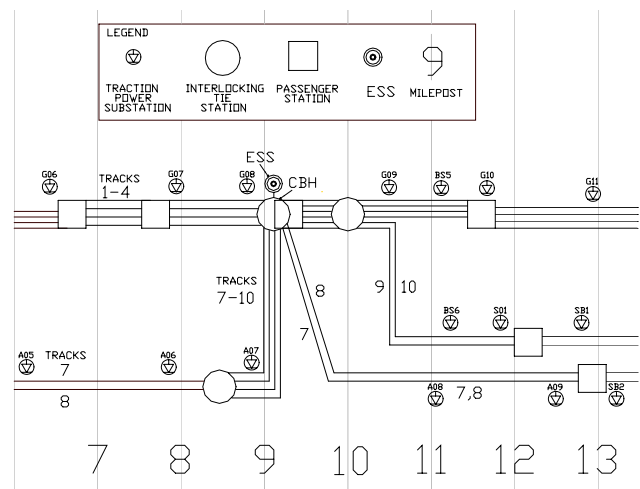


Figure 8 Modeled Commuter Railroad Region

The study placed a single 2.4 MW ESS in a Circuit Breaker House (CBH) at MP 9.1. This CBH connects to line sections powered by traction power substations including G08, G09, A07, and A08.

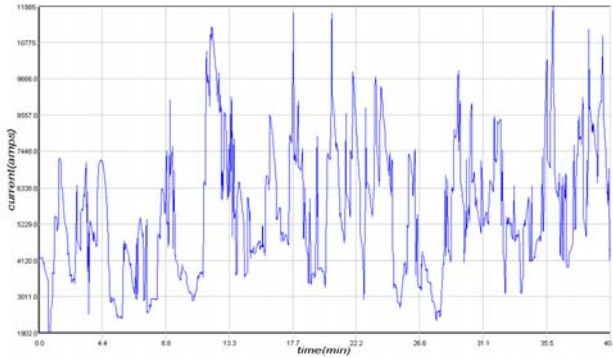


Figure 9 Modeled GO8 Substation Current vs. Time

The authors simulated train operations with several traction power scenarios to assess potential ESS benefits:

- S1] Baseline: Train operations with no ESS.
- S2] 2.4 MW ESS: One 2.4 MW ESS in the CBH.
- S3] Substation Off-line: No ESS, one substation off-line.
- S4] ESS with Substation Off-line: One 2.4 MW ESS in the CBH, one adjacent substation off-line.

The simulation showed that in the baseline network, low voltage problems occur under specific conditions:

- A train accelerating westbound on track 7 west of the CBH, between MP 7.1 and MP 9, causes low voltage at MP 8.55.
- A train accelerating eastbound on track 9 east of the CBH, between MP 9.5 and MP 10, causes low voltage at MP 9.88.

These low voltage conditions become more severe when one of the substations is off-line.

Table 5 provides the simulation scenario results. It shows that the 2.4 MW ESS in the CBH supplemented the traction power supply at MP 9.88. The ESS raised the traction power voltage from 456 V, quite close to the 450 V disruption level where trains shut down, up to 478 V. The ESS could not raise the voltage at MP 8.5. This shows the ESS can provide valuable voltage support for the traction power system when the ESS is placed in the appropriate location.

Condition	V at MP 8.55 (VDC)	V at MP 9.88 (VDC)	ESS Empty (%) [N1]
S1. Baseline – No ESS.	512	507	-
S2. 2.4 MW ESS at CBH.	512	520	25.4%
S2 Impact compared to S1.	0 [N2]	+13	
S3. G08 Offline. No ESS.	471	456	-
S3 Impact compared to S1	-41	-51	
S3. G08 Offline. ESS at CBH.	471	478	28.7%
S4 Impact compared to S3.	0 [N2]	+22	

[N1] This indicates the percentage of time the ESS was fully discharged, and could not provide power to an accelerating train.

[N2] ESS cannot provide support for train at this location because it is discharged when train needs current.

Table 5 Voltage Support Simulation Scenario Results
2.4 MW ESS - Commuter Railroad Peak Hour – No Regen

The simulation study indicates that the best locations for an ESS to provide effective voltage support are:

- Where trains accelerate
- Relatively far from a traction power substation.

The simulation study suggests that systematically placing correctly sized ESS units in low voltage areas can provide substantial support for the traction power voltage sag problems. ESS can provide voltage support both with trains with regenerative braking and those without it. However, combining ESS with regenerating trains provides greater benefits in both energy savings and voltage support.

CONCLUSION AND NEXT STEPS

The analyses show that ESS has the potential to provide a strong return on investment by reducing energy and power costs, and to provide good traction power voltage support at a much lower capital cost than a new substation installation.

To prove the viability of ESS, Transit Operators need measurement data demonstrating the energy and peak power demand savings provided by using an ESS. Transit Operators and ESS suppliers are organizing projects to demonstrate, qualify, place in service, and measure benefits from ESS operations, while quantifying cost, reliability, and maintenance impacts.

Following initial demonstrations and measurements, Transit Operators and ESS suppliers will learn valuable lessons, and will build more capable ESS and railcar systems, capable of delivering important energy, cost, and environmental improvements for the transit system users.

ACKNOWLEDGMENTS

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