TCRP

Web-Only Document 51:

Guiding the Selection and Application of Wayside Energy Storage Technologies for Rail Transit and Electric Utilities

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TCRP J-6/Task 75 (WOD 51):

Guiding the Selection and Application of Wayside Energy Storage Technologies for Rail Transit and Electric Utilities

FOREWORD

By Lawrence D. Goldstein
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TCRP Web-Only Document 51 (WOD 51) is a comprehensive guide for identifying and implementing effective wayside energy storage systems for rail transit. Energy storage applications addressed include braking energy recapture, power quality voltage sag regulation, peak power reduction, and the development of energy storage substations. The guide identifies opportunities and constraints along with analytical methods for determining potential benefits for cost-effective energy storage applications. It takes the reader through required evaluation steps: needs assessment, simulation modeling, measuring potential economic benefits, and selection of alternative applications. The study concludes that wayside energy storage devices can be designed to help resolve propulsion power demands while addressing issues of voltage sag and energy inefficiency in the context of increasing utility costs.

Rail transit has been in the midst of an extended period of increasing ridership as a byproduct of changing economic conditions along with a rise in price of gasoline. This increase in demand is taxing the ability of transit systems to meet capacity requirements in the context of limited system-wide revenues. To compound the problem, the price of electricity that powers rail transit systems is rising because of a rapid growth in demand for electrical power nationally coupled with limited capacity of an already strained electrical grid. In addition, existing rail power substations may not be adequately equipped to accommodate operation of heavier trains with more passengers, to operate higher performance trains, or to operate more frequent trains on shorter headways.

This research was predicated on the belief that there is a way out of this dilemma for rail transit—using trackside energy storage systems. Successful applications of test systems have previously demonstrated that energy storage can be used to recycle regenerated energy from braking, to reduce voltage sag between existing substations, and to reduce peak power demands that help to decrease system-wide electric utility costs. In particular, trackside energy storage units in the form of advanced batteries, electrochemical capacitors, and flywheels have evolved in recent years; and several countries have developed pilot energy storage programs.

Other than in a few scattered trials, however, energy storage is new to U.S. transit agencies. There appear to be a variety of reasons for this lack of experience. The average transit agency is often overwhelmed by the need to assimilate knowledge on new storage technology quickly and to learn how to perform necessary engineering analyses for efficient design and operation of available energy storage technologies while experiencing an ever-increasing demand for limited financial resources. Transit agencies have also experienced a need to understand the current state of energy storage technology, the role of utilities as potential partners, and the expected direction of new research and its affect on transit operations. Of particular interest is the fact that, although saving energy is often a prime motivating factor for energy storage, careful analysis is required to determine the payback period. Using the guidance provided, readers will also find this study helpful when considering potential benefits linked to solving associated problems: peak power reduction to offset utility charges, power quality improvement through elimination of power voltage sag, and use of energy storage as a replacement for more costly energy substations.

This study leverages work previously prepared by APTA and supported by TCRP that helped to create the Energy Storage Research Consortium. APTA and the Electric Power Research Institute jointly established the consortium, bringing together a diverse member base: Sandia National Laboratories; several transit agencies including the Washington Area Metropolitan Transportation Authority, Los Angeles County Metropolitan Transportation Authority, New York City Transit, the Long Island Railroad, and Bay Area Rapid Transit; state research organizations including California Energy Commission, Sacramento Municipal Utility District (SMUD), New York State Energy Research and Development Authority, and the New York Power Authority; and consultants from Systra-USA, Inc. The consortium initiated the energy storage analysis program by performing a needs assessment for rail transit agencies. This needs assessment recommended preparation of a technology awareness study to help agencies examine potential use of energy-saving technologies such as wayside energy storage devices.

In response, WOD 51 identifies and describes the engineering analyses required for selecting and sizing applicable energy storage technologies. The various study components include an evaluation of the problems that wayside energy storage could solve plus a review and analysis of the detailed computer simulation methods needed to assess performance and calculate potential rate of return. The study also examines how agencies might benefit from collaboration with electric utilities.

The primary audience for this study includes transit agencies, energy storage vendors, and utilities—all of whom need to join forces to implement a successful wayside energy storage system. In particular, through use of this guide, transit agencies can begin to look at what is involved in implementing energy storage programs. The study will provide particular value as it helps agencies to identify what steps are necessary to determine the appropriate energy storage application, the physical location of the devices, and the potential for cost recovery. Such procedures would serve as input to full system design or procurement.

Guiding the Selection & Application of Wayside Energy Storage Technologies for Rail Transit and Electric Utilities

Transportation Research Board
Transit Cooperative Research Program
Project J-6/Task 75

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1 Introduction

The topic of energy use continues to expand in importance as conventional energy sources diminish and as concerns over environmental affects related to energy use escalate as do concerns for the cost of energy. Public transportation agencies, and in particular electric rail transit systems, the subject of this report, are examining a diversity of approaches to improve operating efficiency, reduce energy use, and improve operational effectiveness. The driving forces affecting energy use are rooted in the fact that many U.S. rail transit systems are seeing rapidly increasing ridership placing heavy demands on propulsion systems and the consequential rise in energy use. Figure 1–1 shows the overall energy used by transit between the years 1950 and 2006. The sharp decline in transit energy use after 1955 is a result of a national shift away from transit to the automobile resulting in the removal of streetcar infrastructure. With increased ridership and continued expansion of transit systems beginning in the late 1970s, energy use is expected to continue its rapid growth.

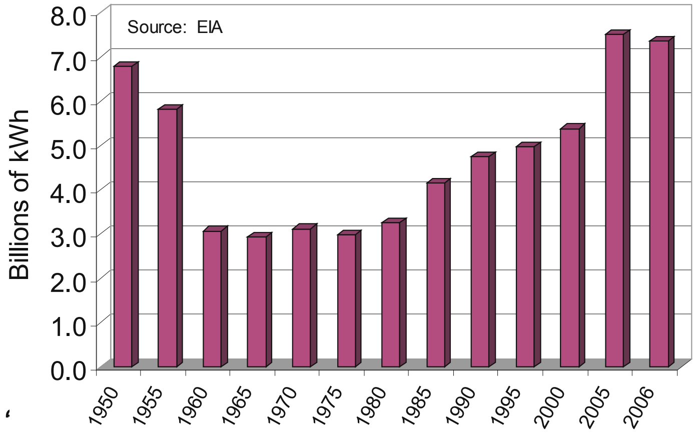


Figure 1-1: Electricity consumed in public transit in the U.S.

To meet energy and operational demands, agencies are examining energy storage technology as solutions to four principal problem areas; 1) braking energy recapture improvement, 2) peak power demand reduction, 3) voltage stabilization and 4) utilization of energy storage systems as replacements for traditional power substations. Traditional wisdom supported by some measurement data provides an argument for the need to better capture railcar braking energy, in which energy storage systems act to raise electrical power supply line receptivity and consequently the ability to utilize rather than waste excess energy from braking. Improving braking energy recapture and reducing peak power demand spikes saves energy and reduces energy cost based in proportion on local utility rate plans. Finally, energy storage is being considered as a lower cost alternative to traditional propulsion power electrical substations. Energy storage substations when electrically charged perform like traditional substations, providing distributed power along the track alignment, while also reducing peak power demand, serving as a recovery source for excess braking regeneration energy, and improving the power quality and voltage supply. With these potential benefits from four applications of energy storage technology, transit agencies are looking for guideposts to assess the effectiveness of each application, the performance characteristics of competing energy storage designs, and estimations on energy cost savings.

2 Study Objectives

To address the need of transit agencies to reduce energy use and their need to better understand how energy storage may help, the American Public Transportation Association (APTA) in association with the Electric Power Research Institute (EPRI) developed a group called the Energy Storage Research Consortium, dedicated to accelerating the understanding, coordination and application of energy storage technologies within transit and utilities. From this initiation and publication of an APTA white paper examining the potential of energy storage in transit, a Transit Cooperative Research Project (TCRP) Quick Study was granted with the intent of providing a more concrete examination of energy storage potential utilizing transit agency data and detailed computer simulations. Analyses are performed on varying transit system configurations according to size and frequency of operation, variations in energy storage technologies, and system configuration options. From these analyses, energy storage application guidelines are provided together with results from actual computer simulations showing potential energy savings and energy cost reductions.

3 Potential Benefits of Energy Storage

Energy storage technology can be used to address four main principal problem areas, but which application has the better return on investment and how well do these systems perform? To answer this question, the first inclination is to use energy storage to recapture regenerated braking energy. In fact, there has been significant research on this topic for energy storage devices installed directly on vehicles. Advanced train control systems like “Communication Based Train Control (CBTC)” have the ability to control train operations more closely than conventional systems. CBTC offers greater ability to optimize train operations, and such systems may enhance the usefulness of energy storage devices. On the other hand there has been less research on using energy storage for transit power quality, peak shaving or substation replacement.

To analyze the effectiveness of energy storage for capturing a larger share of the regenerative braking energy, many variables must be considered. A detailed analysis is complicated requiring computer simulation of a transit system propulsion power circuit and an iterative solution technique to find an optimum system design. However to gain an order of magnitude estimate we can begin with a few assumptions.

First, most rail transit cars built today are capable of using propulsion motors as generators during braking deceleration, which means normally wasted braking energy could be recycled within the system to propel the train-set. Recapturing this energy is done to some degree by transit systems designed today, but there are limitations. The amount of energy recycled during braking is dependent on electrical receptivity. The power generated by a vehicle in braking is automatically distributed to the electrical line of the transit power system in proportion to the electrical receptivity of that line. Receptivity is a measure of the ability of the electrical line to accept the added power and this added power is seen as a voltage rise to the system. As power is added it raises the line voltage, and it is the limit of this voltage that controls the amount of power that can be introduced. Voltage limits are set to protect equipment. Accelerating trains within close proximity of the supplied voltage can draw the added power injected by regenerative braking, but if trains needing power are not present in the same vicinity and if the system voltage limit is exceeded, this added power cannot be used and must be diverted to electrical resistors on the railcar, dissipating the energy as wasted heat. Usually, the allowable distance in which to claim excess braking energy is the track segment measured between propulsion power substations along the alignment that are often placed a mile apart or longer.

From propulsion power data collected by transit agencies operating light and heavy rail systems without energy storage, the percentage of braking energy reused by neighboring trains varies, depending on many factors such as age of the system and conditions including train operating density commonly referred to as train headway. Energy storage provides the added capacity to accept additional power distributed to the line system should receptivity limits be exceeded or in the event other trains are unable to utilize excess braking regenerated energy at the time needed. Theoretically, an energy storage system if sized sufficiently can store surplus energy for use at a later time when needed by a local train and improve recapture efficiency to 100 percent within the region between substations affected by an energy storage system. But in reality, when examined from a systems perspective, the amount of improvement is less. Simulation case studies described in following sections show a modest improvement when measured over the entire system. But beyond the regenerative braking application, energy storage has been found of equal or greater importance for addressing other problems in the electrical infrastructure, namely low voltage conditions along the power distribution system, peak power demand costs, and high costs of conventional substation designs.

Low voltage of the electrical power system is becoming more of a problem for transit systems, especially those of earlier design. As ridership increases around the country, transit agencies are seeing higher demands placed on their system resulting from the operation of more frequent and longer trains to meet the demand. This added burden is taxing the electrical propulsion power system beyond its intended design. The result is a loss in propulsion power quality and the necessary voltage to power the trains at desired operating envelops. It is the opposite problem of too much voltage in the system of regenerative braking. As voltage drops, supply electric current increases inversely to provide the same level of power. But there are limits placed on electric current because of the need to protect electrical equipment from overheating, and this limit when combined with low voltage results in a reduction of delivered power, thus negatively affecting railcar performance. Transit agencies are looking closely at energy storage to help prop up this low or sagging voltage. From simulation studies discussed later, it appears that voltage sag protection is a significant problem that energy storage systems might fix.

Discussions in following sections analyze these problem areas in addition to the use of energy storage devices to replace conventional electrical power substations and reduce peak power demand.

4 Transit Agency Needs Assessment

To focus the investigation on the potential benefits of storage and select appropriate transit system designs for computer simulation, the study team interviewed various U.S. transit agencies to ascertain their needs. The team composed a survey outline that posed questions regarding energy costs, operational problems, transit system age, ridership change, expansion plans, and availability of propulsion power data. Candidate transit agencies were identified and site visits conducted from which selections of transit agencies were made for further simulation studies The study team selected Los Angeles County Metropolitan Transit Authority, Sacramento Regional Transit Authority, New York City Transit, Washington Metropolitan Area Transportation Authority, and Long Island Railroad. Other agencies considered included the Regional Transportation District of Denver, Houston Metro, and Miami-Dade.

From detailed on-site meetings with selected agencies, the project team discovered that all were experiencing problems with voltage sag. And generally, all transit systems interviewed were considering the use of energy storage to address a range of problems. Table 4–1 highlights the spectrum of needs across the selected rail agencies. It is noteworthy to point out that New York City Transit in cooperation with NYSERDA (New York State Energy Research and Development Authority), is testing a long-term battery for overnight storage of electrical energy in an effort to reduce high utility charges associated with daytime refueling of Compressed Natural Gas (CNG) buses. The stored energy, which would be captured at night when electrical rates are lower, would be used to operate CNG fuel compressors that fuel busses at peak power demand times in morning hours.

Choosing the best energy storage device (ESD) for applications like those listed in Table 4–1, will require detailed knowledge of energy storage device characteristics. Energy storage technology has been under development since the dawn of time beginning with storing potential energy in a raised weight to today’s complex electro-chemical reactions and advanced mechanical flywheels. Selecting the optimal energy storage technology for a specific need is dependent on a number of distinguishing characteristics of energy storage systems. Consideration must be given to the amount of energy that must be stored and for how long, the rate at which the energy storage device can be charged and discharged, cycle life and long-term durability. The types of systems that can meet a particular demand could be highly varied ranging from mechanical flywheel devices, to electro-chemical batteries and electro-chemical capacitors. Obtaining further information on power charge and discharge cycle characteristics which affect ESD life is needed for a thorough analysis, but a simple breakdown by application can be helpful as a guide to selecting the best technology. One method used to provide such delineation is a plot of power density vs. energy density, often referred to a Ragone Plot.

Power and energy can be viewed as characteristics that depict the rate of energy delivery and the amount of energy stored, respectively. Some devices store large amounts of energy efficiently but may be unable to charge or discharge this energy over a short time span. The ability of an ESD to discharge and charge quickly may be desirable if there is a need to correct power quality problems often associated with electrical line voltage drop. Voltage sags can occur on a time scale of only seconds, especially for electrical utilities. In such a case, electrical energy from an ESD would need to be quickly injected into the electrical supply line or a transit system third-rail to correctively elevate the sagging voltage. The distinction between energy density and power density can also be seen through an electric car analogy. Energy density and power density can be associated with the range of an electric car and its acceleration, respectively. By simply viewing an ESD Ragone plot together with general knowledge about the characteristic propulsion load demand of a rail system alignment, a preliminary selection of an appropriate storage technology can be estimated. A typical Ragone plot rendition is represented in Figure 4–1. More detailed plots of current ESD technology are obtained through the Electric Power Research Institute or from government sources such as the U.S. Department of Energy and its various research laboratories such as Sandia National Laboratories, Argonne National Laboratories, or Idaho National Laboratories among others.

Another example of the tradeoff made between the relative benefits of specific energy versus specific power is the difference in headway scheduling between heavy rail (subway) and light rail systems. A heavy rail transit system may operate many trains at short headways of two-minutes versus a light rail system with headways of 5, 15 or even 20 minutes. Each rail system may require a different energy storage characteristic to meet the intended demand. Charge and discharge cycling rates within a corridor of interest or as measured between electrical substations along the alignment are also dependent on the number of vehicle station stops or in the case of light rail systems, also the number of urban traffic stops. Each stop introduces the opportunity for an ESD discharge or charge cycle potentially affecting the need for rapid response. Selecting an ESD from knowledge of energy storage characteristics and system load demand also requires selection of ESD capacity (kWh). Energy storage capacity affects the time of discharge as a function of power level. An example of this relationship is seen in Figure 4–2, showing two curves of different ESD energy capacity (kWh) and their respective power delivery response times. From this discharge characteristic information, candidate energy storage technologies and sizing specifications begin to emerge.

Table 4-1 Energy storage application by mode and transit property

Agency	**Rail Mode**	**Location**	**Energy Storage Application**				**Comments**
			Braking Energy Recapture	Power Quality – Voltage Sag	Peak Power Reduction	Energy Storage Substation	
Los Angeles County Metropolitan Transportation Authority	Light Rail	Los Angeles, California	Yes	Yes	Yes	Yes	LACMTA expansion is considering utilizing energy storage to reduce number of power substations. LACMTA also won a large TIGGER grant to evaluate energy saving technologies including energy storage.
Sacramento Regional Transit	Light Rail	Sacramento, California		Yes			Currently demonstrating a battery energy storage system installed on a weak power section of alignment.
Washington Metropolitan Area Transportation Authority	Heavy Rail	Washington, DC	Yes	Yes	Yes		WMATA has selected candidate sites for a battery energy storage system and has FTA funded support.
New York City Transit Authority	Heavy Rail	New York City, New York	Yes	Yes			Currently demonstrating a battery substation
Long Island Rail Road (LIRR)	Heavy Rail	Long Island, New York		Yes			Under contract to install mechanical flywheels.
Metro-North Railroad	Commuter Rail	Northeast Corridor		Yes			Studies previously conducted and data available for energy storage modeling

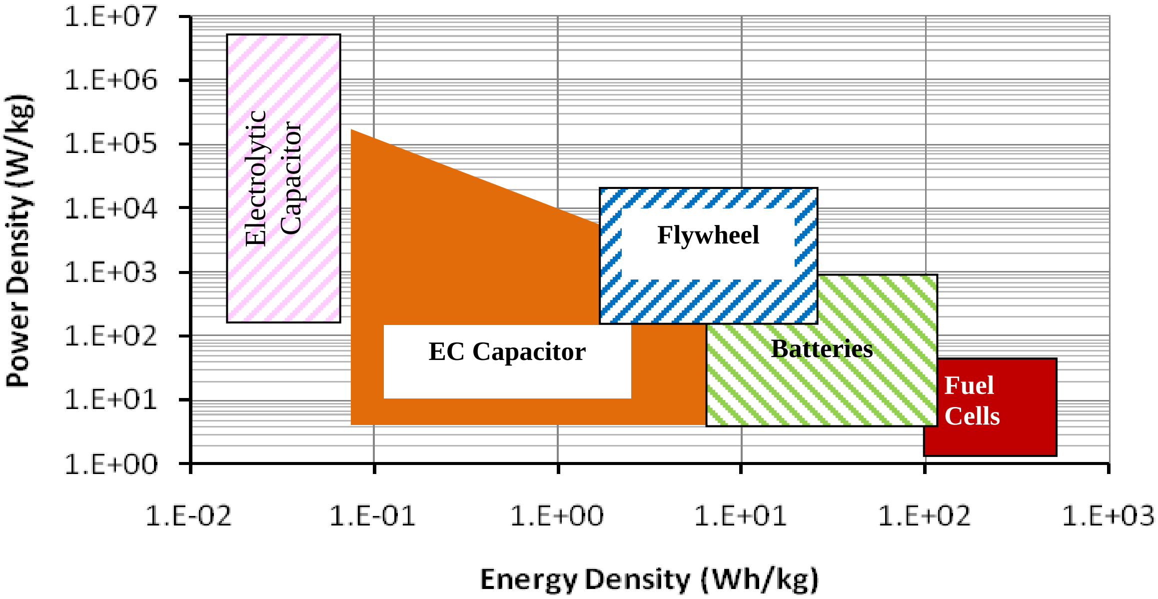


Figure 4-1: Ragone Chart for energy storage device

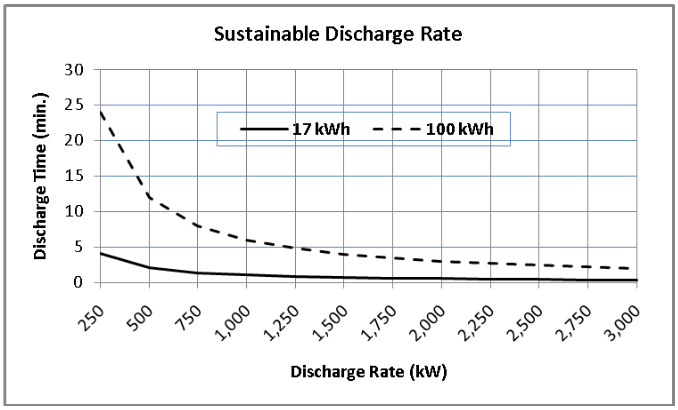


Figure 4-2: Sustainable discharge rate for energy capacity

4.1 Vendor data summary

Detailed information on specific energy storage device operational data for use in subsequent computer modeling was obtained from energy storage vendors participating in the APTA/EPRI Energy Storage Research Consortium. Figures 4–3 through 4–5 summarize the variation in performance measures as a function of energy and power availability, discharge and charge times, and number of charging cycles capable over the life of the device. From this data and other generalizations regarding charge and discharge rate, device efficiency, and charging current limitations among others, simulations were performed of energy storage device performance as part of this transit propulsion system modeling study. Each data point in the figures represents a vendor supplied characteristic from which verification could be made against modeling assumptions.

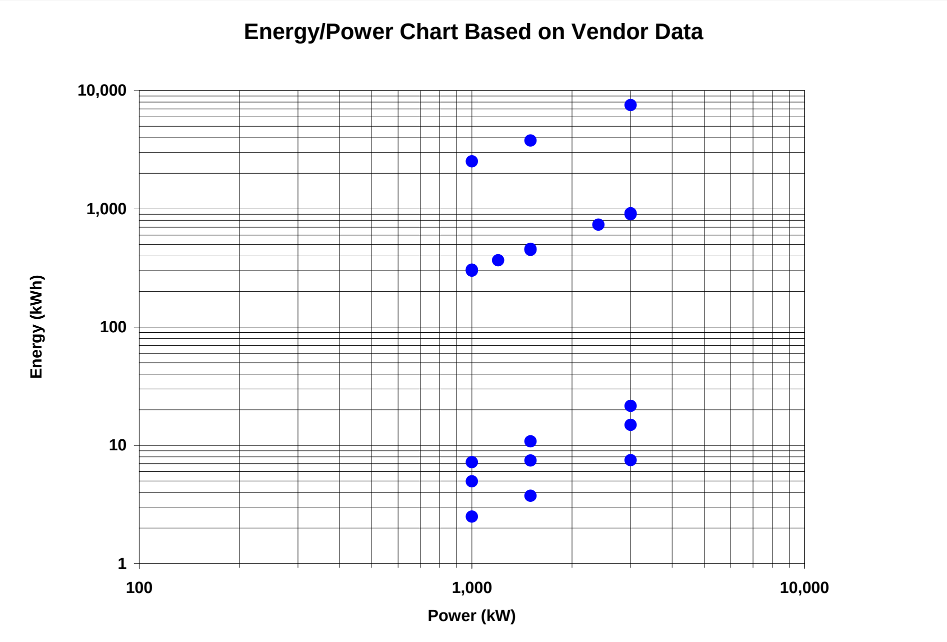


Figure 4-3: Energy/power for energy storage device

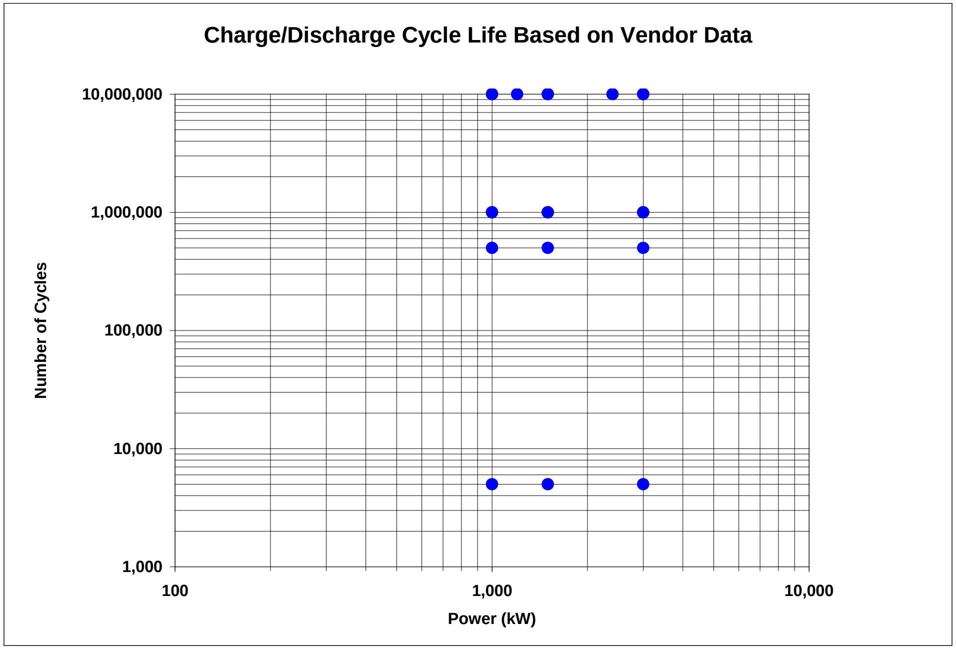


Figure 4-4: Cycles/power for energy storage device

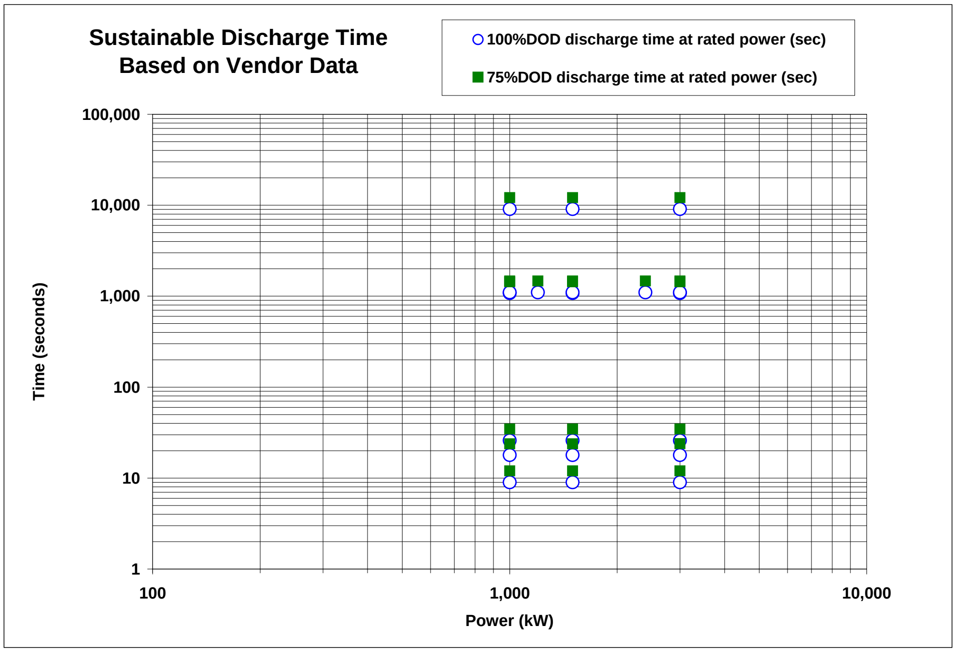


Figure 4-5: Sustainable discharge time for energy storage device

5 Simulation and Modeling Approach

From the information provided earlier and additional details on vehicle and system characteristics summarized in this section, a computer system model can be built and simulations performed. The software selected for simulation is SYSTRA's RAILSIM Load Flow Analyzer. As part of this simulation software, SYSTRA originally developed an energy storage device model as part of the RAILSIM package to assess the suitability of flywheel applications for rail and transit agencies in support of a rail traction power system study[4]. After consultations with the ESD vendors, the consortium determined that the ESD model in RAILSIM is suitable for general modeling applications including other types of storage media, such as batteries, electrochemical capacitors and hybrid batteries, where power control devices are used.

The input data for the load flow model requires parametric data defining characteristics of the rail electrified track system, train operation schedule, vehicle propulsion design including the performance of regenerative braking, electrified line network and the energy storage device. These are summarized in the following sections. Details on the organization, reporting and post-processing of simulation results, and software validation are contained in Appendix C.

The simulation models and the assumptions used for selecting and sizing energy storage devices are based fundamentally on the further assumption that using energy storage devices principally for energy saving may not provide the expected return on investment given current costs of electrical energy and energy storage devices. From interviews and discussions with transit agencies in the United States and from simplified calculations of energy saving potential, payback periods were exceedingly long. Simulation results validate this assumption. However, it was apparent that energy storage devices could serve to address other needs of transit such as voltage protection or substation replacement as the primary function, but not necessarily the only function. As a starting point for simulations, component and ESD sizing were based on the primary motivation for eliminating voltage sag problems, and from the resulting ESD design given this function, determine the additional benefit of energy saving. This added benefit shown by simulation is discussed in Section 6.

5.1 Track alignment data

Track alignment refers to the mechanical design of the rail track system. It includes track elevation gradients, curve and tangent lengths, varying speed limits and station stops. This track data is spatially mapped as data into the simulation model for each rail mode considered.

5.2 Train operations data

Train operation refers to the scheduling of trains and number of trains operating per hour in a designated section of the track alignment. For light rail and heavy (subway) rail systems, train operations are usually based on headways or simply the time between trains passing a segment of track alignment. Light rail and subways are normally scheduled using identical train consists (number of cars) dispatched at regular time intervals according to the time of the day. For commuter rail and mainline train operations, general operating timetables are applied directly as part of the simulation. Because of the nature of the commuter and mainline railroad operations, most trains are unique in length, operational frequency and station stop patterns, and as a result each train must be modeled individually as part the simulation input data.

5.3 Vehicle characteristics data

Rolling stock parameters and characteristics determine the interaction between the trains' movement and their interaction with the traction power supply system. Characteristic curves include propulsion tractive effort, braking resistance (friction, dynamic, regenerative, or appropriate combinations) and motor/generator propulsion system efficiency.

Power available for train operation is controlled by the voltage level at the train connection with the traction power supply line or third rail. If the voltage seen by the train is less than a specified minimum, power will not flow to the train because of circuitry control algorithms that protect circuit devices from low voltage conditions. . Similarly, power provided by the train to the power supply line when regenerating from braking is also controlled by the voltage level at the power supply line, but in this case there is a maximum voltage limiting regenerated power rather than a minimum. Voltages controlling train propulsion operation and regenerative braking capability are clearly depicted in Figure 5–1.

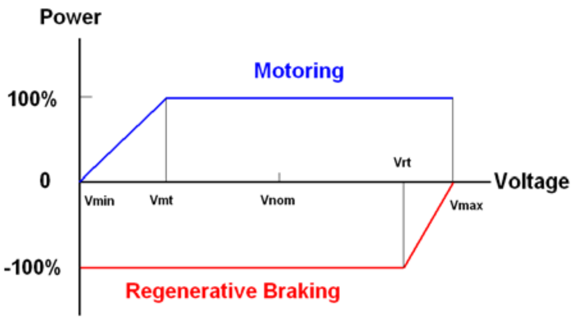


Figure 5-1: Power control diagram for vehicles

In the motoring mode,

- If the train voltage is above Vmt (referred to as motoring taper voltage), the train's power demand can be fully met by the traction power system.
- If the train's voltage is at or below Vmin (minimum system voltage), no traction power is available. The under-voltage protection relay normally stops current supply to the motors at Vmin.Between Vmin and Vmt, the train traction power demand is partially met

In the regenerative braking mode,

- If the train voltage is below Vrt (referred to as regenerative taper voltage), the train's regenerative power can be fully accepted by the traction power system (100% receptivity).
- If the train's voltage is at or above Vmax (maximum system voltage), no regenerative power is accepted by the traction power system (0% receptivity). The over-voltage protection relay will ensure that this voltage limit is not exceeded.
- Between Vrt and Vmax, the train regenerative power is partially accepted by the traction power system (partially receptivity).

5.4 Electrical network data

For the electrical network data input, the start point is the electrical single line circuit diagram. Individual components of the network include: substations (rectifiers or inverters), circuit breaker houses, energy storage devices (ESD), third rail (or OCS) conductors, running rails; feeder connections (both positive and negative), negative reactors (where installed), cross-track bonding connections, etc. Parameters for these components are the constituents of the load flow model.

The electrical network simulation and the train movement simulation are carried out in discrete time steps. The time step is a user defined input parameter (with a resolution of 0.1 second). For a given instant of time, the locations and power demands (or back-feeding powers) of trains are known from the train movement simulation module.

The electrical network is formed by nodes and branches. Fixed plants (substations, feeder connection points, etc.) form fixed nodes, whose locations do not change over time. Trains are moveable nodes, whose locations change with time. From the locations for all the nodes in the circuit, resistances between nodes and ground and resistances for branches between nodes are calculated for the given time instant. A set of linear equations are then formed and solved. The solution process is an iterative process for the following reasons:

- The number of linear equations is equal to the number of electrical nodes in the network. This number changes with system and with time for a given system. As a general solution algorithm, it is not feasible to have a closed-form solution for the equations
- There are non-linear elements in the electrical network. For example, the diodes can only allow the current to flow in one direction.
- The amount of a train's power demand or feedback is dependent on the voltage level, as illustrated by the power control diagram in the last section.
- Where an energy storage device is used, the state of the ESD (charging, discharging, or idle) is dependent on the voltage level, as illustrated by the ESD power control diagram in the next section.

Firstly, a set of voltage values are assumed. Secondly, based on this set of values, all elements in the equations are defined. Thirdly, the equations are then solved and a new set of values are obtained for the voltages. Fourthly, the new set of voltages is compared against the last set of voltages. If the maximum difference exceeds a predefined voltage tolerance by the user, a new solution process starts

The process is repeated until the user-defined convergence criterion is satisfied. Then the simulation advances to the next time step.

5.5 Energy storage device (ESD) model

ESD is treated as a special type of substation with a finite amount of energy that can be stored or available. Control of charging and discharging cycles in the energy storage device is based on the ESD terminal voltage levels, as shown in the following figure.

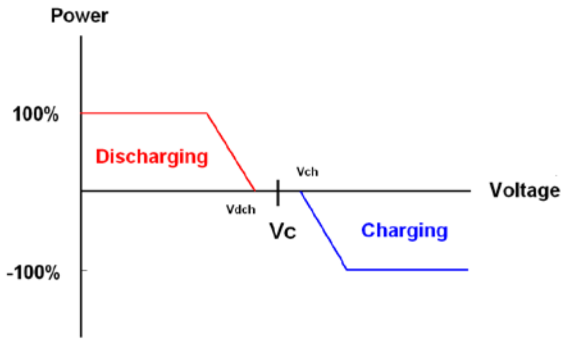


Figure 5-2: Power Control Diagram for Energy Storage Device

The main parameters that define the energy storage device model are:

- Energy storage capacity (kWh)
- Power rating (kW)
- Power conversion efficiency
- Maximum current (charging or discharging) (amps)
- Control voltage (Vc)
- Charging start voltage (Vch)
- Discharging start voltage (Vdch)

The interaction between an energy storage device and the traction power system is controlled by the terminal voltage of the ESD.

- When the ESD terminal voltage is at or below Vdch, the ESD is in discharging mode.
- When the ESD terminal voltage is at or above Vch, the ESD is in charging mode.

5.6 Simulation results

Three systems are selected to reflect the broad range of rail/transit systems: light rail, metro rail and commuter rail. The parameters in the following table illustrate the differences and similarities between the systems modeled. Furthermore, the variation introduced by considering the different rail modes was intentionally established to best examine how such diversity might affect the potential benefit of energy storage.

Table 5-1 System Characteristics Summary

System Parameters	Light Rail	Heavy Rail	Commuter Rail
Miles of Track	7	5 (part of a large system)	5 (part of a large system)
Number of Stations	12	4	NA
Nominal DC Voltage (V)	750	700	685
Number of Traction Power Substations	7 each equipped with 1.5 MW rectifier unit	4	3
Number of Circuit Breaker Houses	1	2	1
Number of Cars per Train	2	8	Cars run without regenerative braking
Headway – Peak Time Morning (min.)	5	2	General Timetable
Headway – Peak Time Mid-day (min)	5	5	General Timetable
Headway – Off Peak (min)	15	15	General Timetable

5.7 Light rail

5.7.1 System parameters

The main operating parameters of the light rail transit (LRT) system being simulated shown in Table 5–1 and repeated here are as follows:

- 7 Miles of track (double track system)
- 12 Stations
- 750V nominal voltage DC traction power system,
- 7 Traction power substations (TPSS); each equipped with 1.5MW rectifier unit
- 1 Circuit breaker house (CBH)
- 2 car trains in operation with regenerative braking
- 5 Minute headway in peak hours
- 15 Minute headway in off peak hours and weekends

5.7.2 Train voltage support requirement

Train voltage is a critical performance parameter for the traction power system. For this particular system, when a train’s voltage falls below 575V corresponding to a voltage sag condition, the train’s power demand cannot be fully met by the traction power system, which will have an adverse impact on the performance of the train. At or below 500V, the train’s traction power motor will be shut down in order to avoid damage to the equipment.

Under normal conditions (when all substations are in service), the simulated train voltages are all above 575V, which are adequate for trains to achieve their on-time performance. We intend to model a case in which one substation is out of service or consideration of replacing a substation with an energy storage device. In this case consider failure or removal of substation at position A4 or A5 TPSS. (Light rail systems usually have single unit rectifier substations. Consideration for rectifier outage is normally required in design specifications). In such an instance, the minimum train voltage can fall to 504V and 559V respectively, both below the required minimum for this system. These sags are shown in Figures 5–3 and 5–4, where it is noted that the data points represent solutions at time steps in the simulation and that a single point could represent more than one simulation appearance.

In order to avoid the excessively low voltage conditions with the removal of rectifier in A4 or A5 TPSS, addition of an ESD can be considered. Addition of an ESD at a sufficient size rating will help support the voltage sag plus provide a potential energy saving benefit by improving capture of regenerative braking. Section 6 discusses the potential energy saving benefit given ESD sizing sufficient for low voltage protection. This simulation and analysis process, by which we begin with a look at voltage support first and energy saving second is carried throughout the various mode analyses.

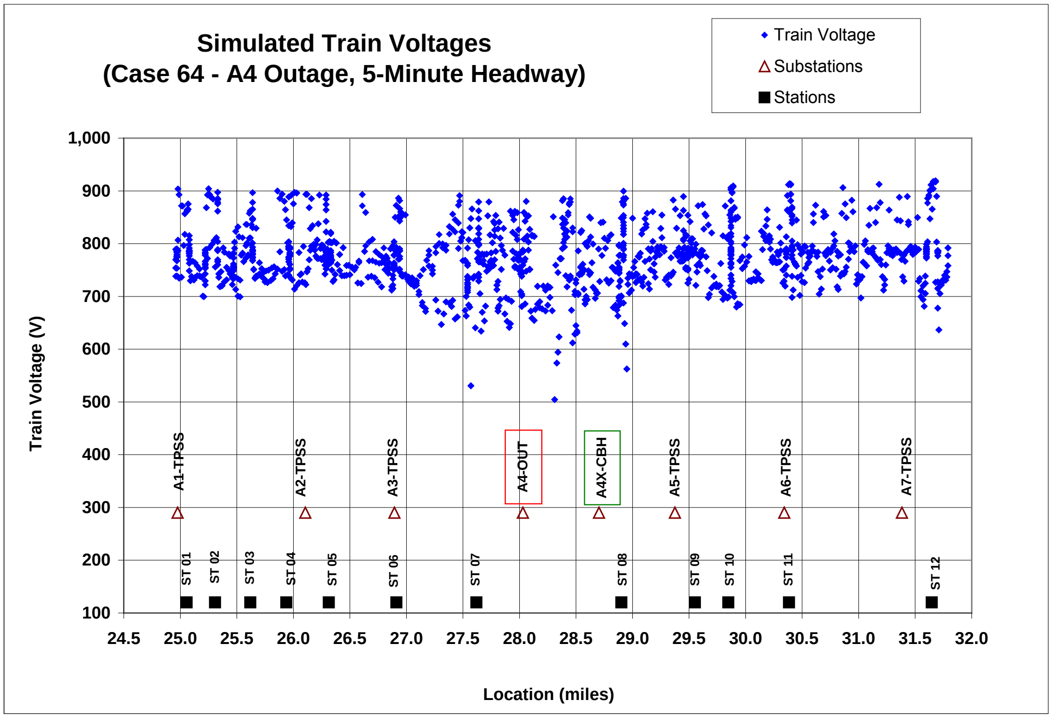


Figure 5-3: Train voltages under A4-TPSS outage condition

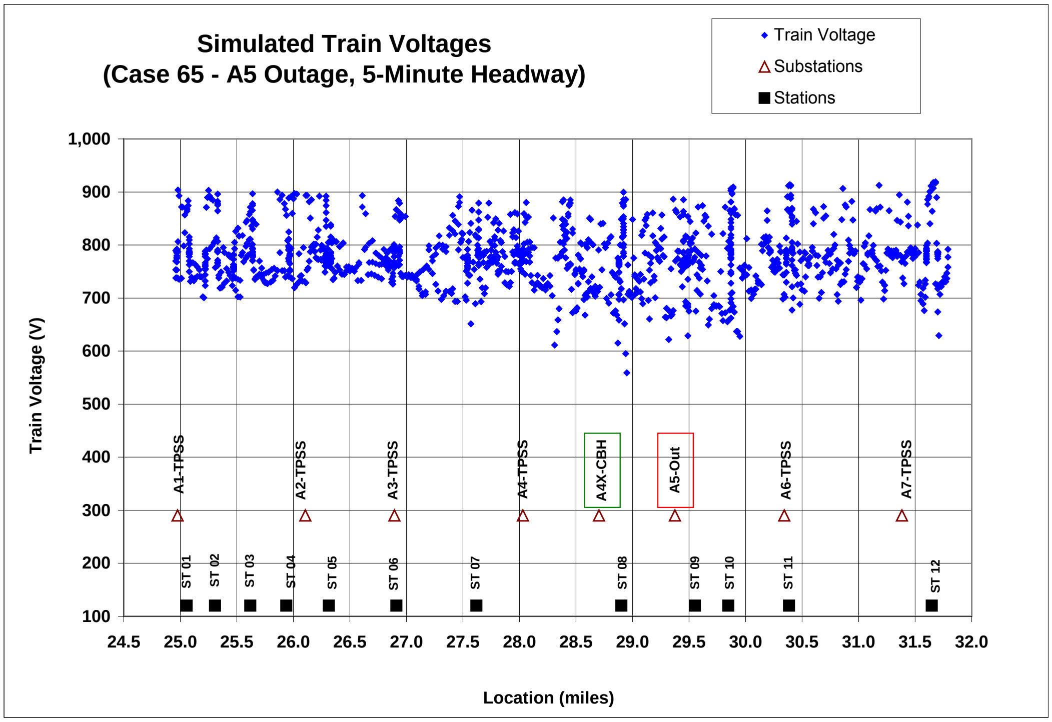


Figure 5-4: Train voltages under A5-TPSS outage condition

5.7.3 ESD option

Returning to the example above, if an appropriately sized ESD is installed in location A4X, the resulting train voltage improvements can be shown in Figures 5–5 and 5–6, given that rectifiers at positions A4 or A5 TPSS are removed.

From simulation results, the above figures indicate that the new ESD installation in A4X location will be adequate for train voltage support with either A4 or A5 TPSS rectifier removed. The minimum train voltages for a system with energy storage are summarized in Table 5–2.

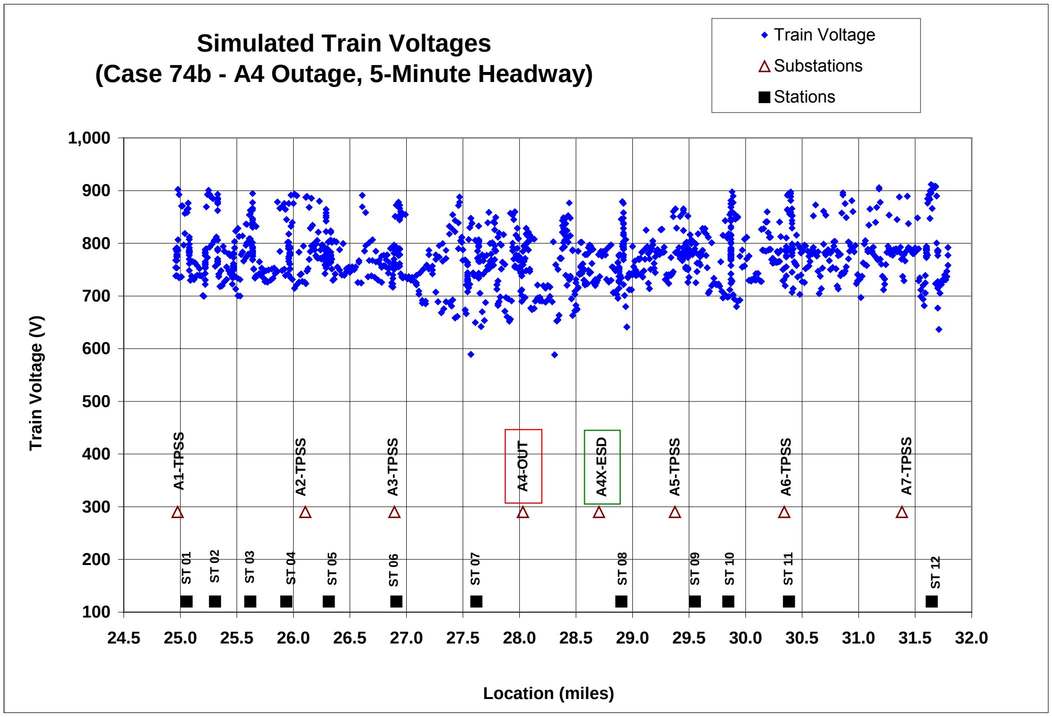


Figure 5-5: Train voltages under A4-TPSS outage condition with storage

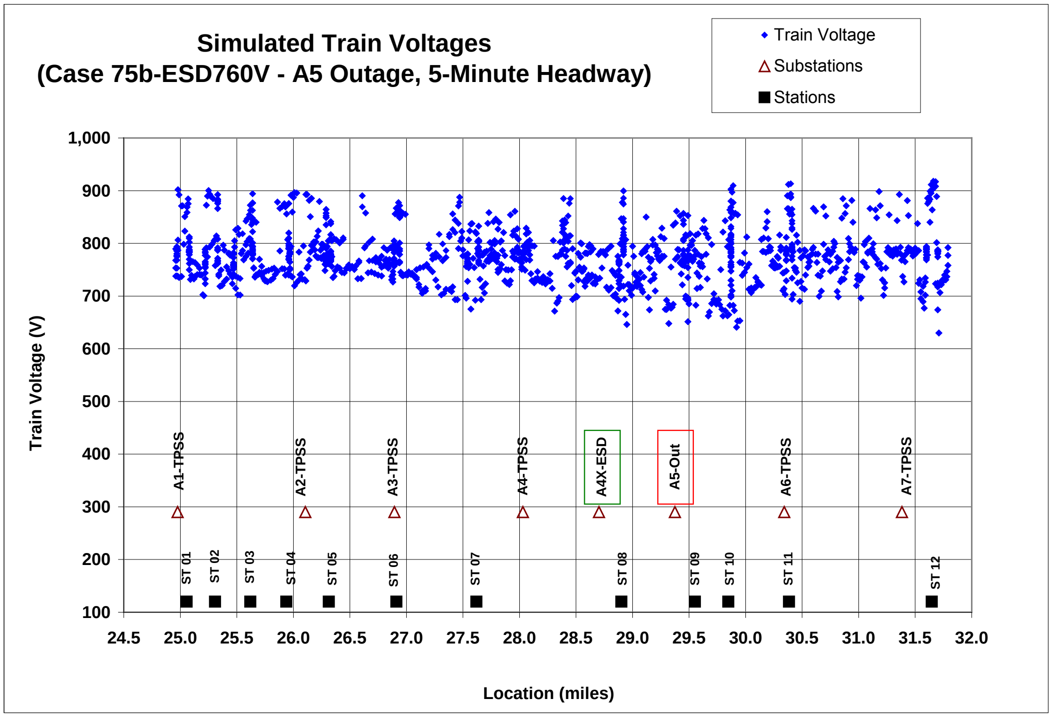


Figure 5-6: Train voltages under A5-TPSS outage condition with storage

Table 5-2 Minimum train voltage and ESD energy summary

Case #	Scenario	A4X Type	Minimum Train Voltage (V)	Voltage Improvement (V)	ESD Energy (kWh)
64	A4 outage	CBH	504	n/a	n/a
74b	A4 outage	ESD (Vc=760V)	588	84	3.1
84	A4 outage	TPSS	605	101	n/a
65	A5 outage	CBH	559	n/a	n/a
75b	A5 outage	ESD (Vc=760V)	630	71	3.7
85	A5 outage	TPSS	632	73	n/a

Note - ESD power rating at 1500 kW

5.7.4 ESD parameters

Table 5–3 shows the minimum energy and power rating requirements for the optimized ESD under voltage support mode as presented above. In this table, variations in voltage set point for the ESD shown as cases 74a and 75a are also included.

Table 5-3 Energy and power rating summary in voltage support mode

Case #	Scenario	ESD Mode	ESD Energy (kWh)	ESD Power (kW)
74a	A4 outage, A4X-ESD Vc=720V	Voltage support	1.90	1,500
74b	A4 outage, A4X-ESD Vc=760V	Voltage support	3.10	1,500
75a	A5 outage, A4X-ESD Vc=720V	Voltage support	1.30	1,500
75b	A5 outage, A4X-ESD Vc=760V	Voltage support	3.70	1,500

5.8 Metro rail

5.8.1 System parameters

A similar simulation analysis, again looking at the conditions of low voltage, primarily and regenerative braking energy, is performed for part of a heavy rail (subway) system using the simulation parameters shown in Table 5-1 and repeated here.

- 5 Miles Metro System; 4 Stations
- 700V DC traction power system
- 4 Traction substations
- 2 Circuit breaker houses (CBH)
- 8 Car trains with regenerative braking
- 2 Minute in peak hours (AM & PM)
- 5 Minute headway in midday hours
- 15 minute headway in off peak and weekend operations

Simulation results indicate for the system considered that there will be low voltage occurrences at the east end of the track, as shown in Figure 5–7. Computer simulations show that if a minimum 3MW sized ESD is installed at location G05B, the low voltage occurrences at the east end of the track will be eliminated, as shown in Figure 5–8. Following sections discuss the potential energy saving benefit given this size of ESD.

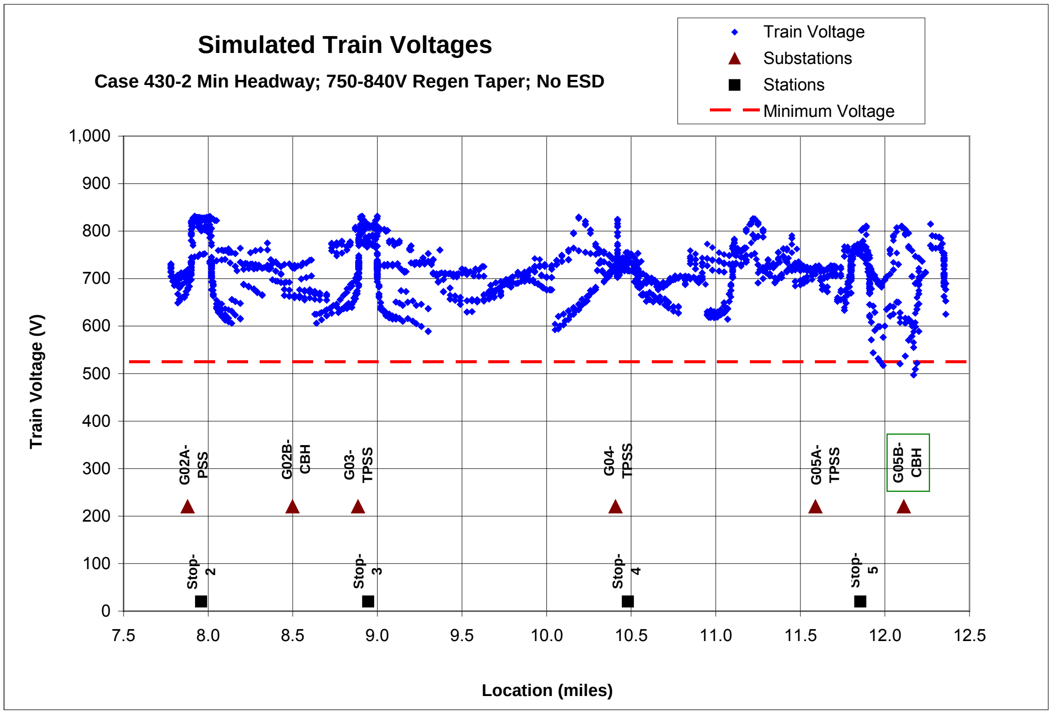


Figure 5-7: Train voltages with CBH at G05B (metro rail)

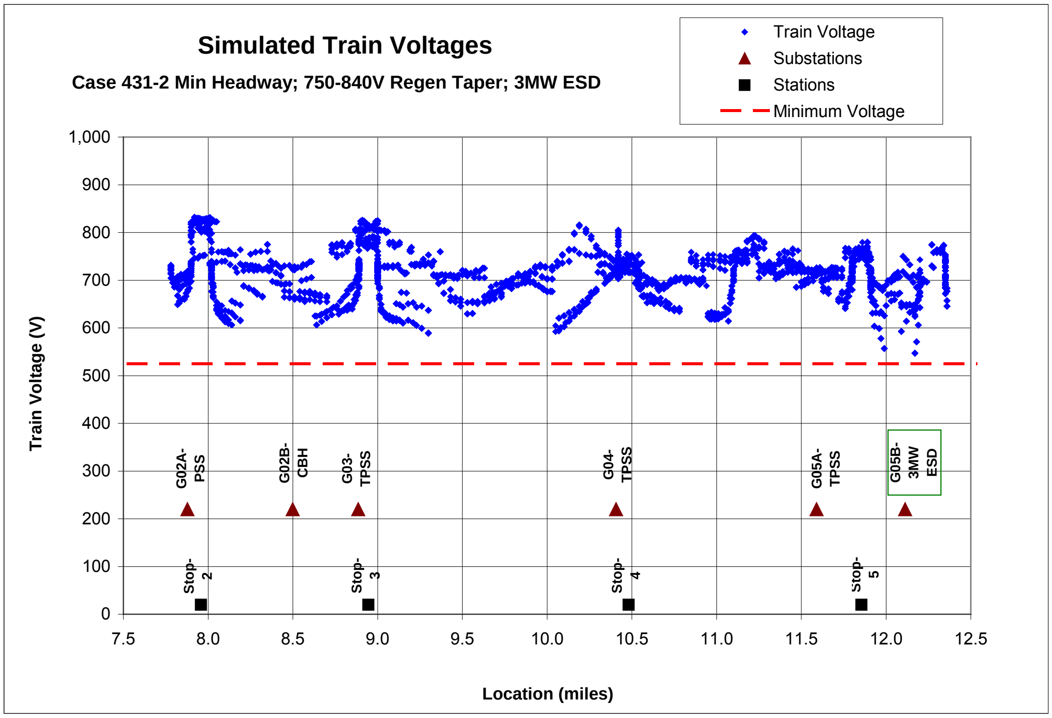


Figure 5-8: Train voltages with CBH at G05B (metro rail) with storage

5.9 Commuter rail

5.9.1 System parameters

A similar simulation analysis, again looking at the conditions of low voltage, is performed for part of a commuter rail system using the simulation parameters shown in Table 5-1and repeated here.

- 5 Miles of track in a large commuter rail network;
- 685V DC traction power system
- 3 Traction substations
- 1 Circuit breaker houses (CBH)
- Trains without regenerative braking
- Operation schedule according to timetable

Train voltage plots under different options at location MP-35 are shown in Figures 5–9 through 5–11.

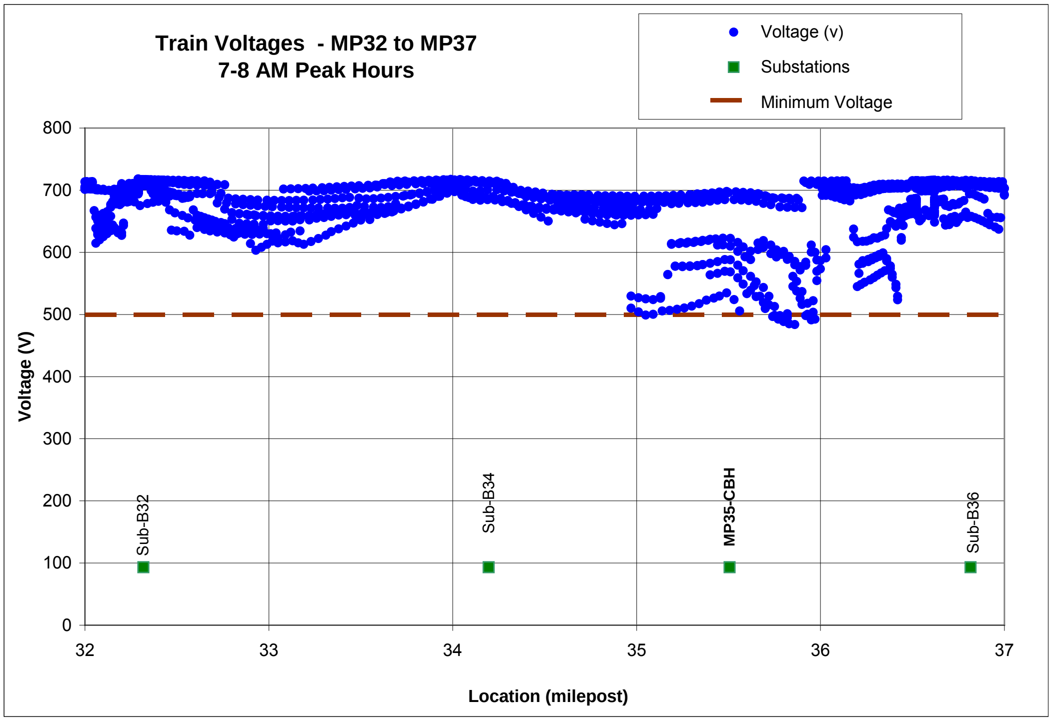


Figure 5-9: Train voltages under CBH option

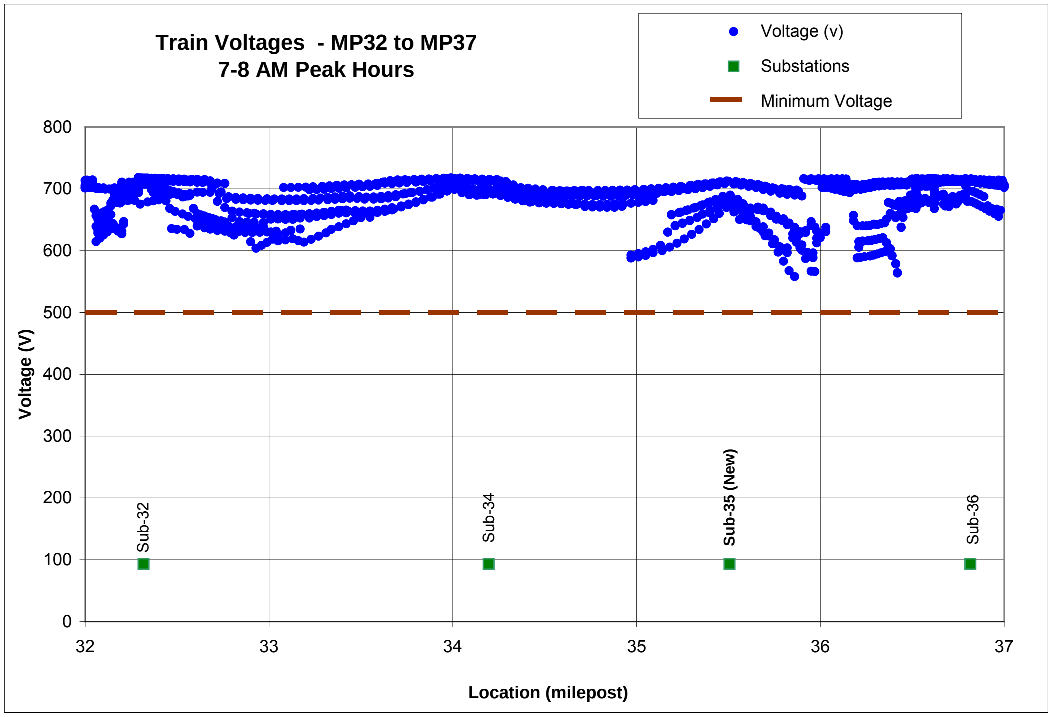


Figure 5-10: Train voltages under substation option

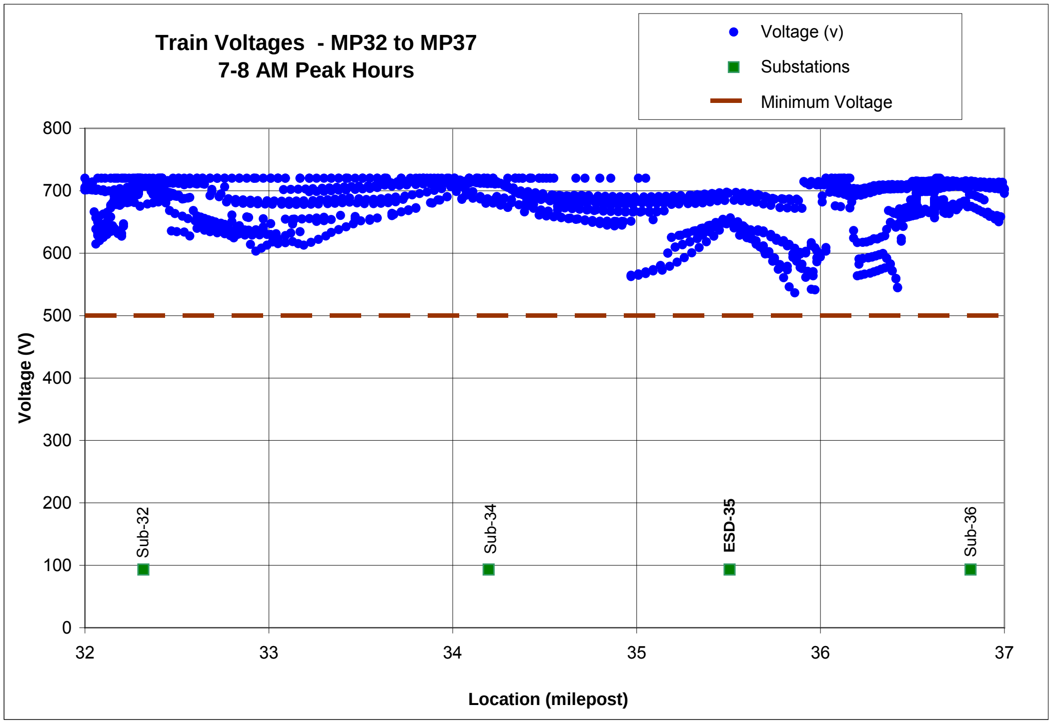


Figure 5-11: Train voltages under ESD option (commuter rail, 4MW ESD)

6 Economic Measures of Benefit

In addition to providing voltage support as demonstrated in the simulation results, an ESD installation can also help capture more regenerative braking energy that may be otherwise wasted. A direct benefit of recovering braking energy is the energy cost saving. This section demonstrates the energy cost savings achievable for the light rail and the metro rail systems.

6.1 Electricity cost saving analysis – light rail

It has been shown that an ESD can effectively mitigate problems associated with low train voltages for this system. With the installation of the ESD in location A4X, the system's receptivity (the ratio of utilized regenerative energy over the total available regenerative energy) will also be improved, resulting in a greater potential to recover regenerative braking energy. As a result, the energy saving ratio due to regenerative braking (the ratio of energy consumption with regenerative braking over the energy consumption without regenerative braking) can be improved.

When all substations are in service and we do not experience a voltage sag problem, we can take a different look at the effect of energy storage, principally to save energy. The control voltages of the ESD may be adjusted to best optimize energy saving rather than providing voltage support, thus maximizing the capture of regenerative energy. So, when voltage support is not needed, an adjustment in the voltage settings of the ESD can be made for optimal energy saving. Table 6–1 compares system-wide energy saving potential resulting from variations in ESD control voltages. This table also demonstrates the corresponding energy and power rating requirements for the ESD. An electricity cost saving analysis utilizing this strategy is undertaken in the next section.

Table 6-1 System-wide Energy Summary (light rail)

Case #	A4X Type	Receptivity (%)	Energy Savings (%)	ESD Energy (kWh)
60	CBH	83.6	29.9	n/a
70a	ESD (Vc=720V)	84.1	30.1	0.20
70b	ESD (Vc=760V)	84.5	30.2	1.30
70c	ESD (Vc=793V)	88.0	31.5	2.30
80	TPSS	83.3	29.8	n/a

Note - All TPSS in normal operation

This table also illustrates that an ESD installation at the A4X location can help improve the system-wide energy saving ratio, expressed in per cent. Without the ESD, the energy saving ratio is 29.9%. With the ESD, the ratio improves to 30.1% or 31.5%, depending on ESD voltage setting. If the same location is installed with a rectifier substation, the ratio is decreased to 29.8%. Remember that this is a system-wide energy comparison that indicates the effect of a single ESD installation on the entire system, and that the projected change in energy saving ratio percentage must be viewed in this context.

To examine the potential energy and cost saving benefits of energy storage, a simple electricity cost analysis can be performed using the options noted above. We start with a comparison of the 15-minute power averages across all substations in the system under normal operation with and without an ESD, as shown in Table 6–2.

The 15-minute averages are used because of the correlation with utility peak power charging average time periods, which are in most cases 15-minutes.

Table 6-2 15-Minute Average Power Values by Substation

15-Minute Average Power (kW)				
Substation	5-Minute Headway		15-Minute Headway	
	With A4X-TPSS	With A4X-ESD	With A4X-TPSS	With A4X-ESD
A1	403	406	162	165
A2	449	458	178	185
A3	388	408	152	156
A4	382	410	153	159
A4X	208	0	81	0
A5	366	395	137	144
A6	412	425	153	162
A7	361	368	134	138
Sum	**2,969**	**2,870**	**1,150**	**1,110**

From the above table it can be seen that the 15-minute average power in each substation for 5-minute headways represents the peak power demand, while 15-minute headways are less when measured over the same 15-minute period. This table also shows the utility supplied power to each substation along the alignment. Higher power requirements are shown near the ESD because there is no supply at that point and neighboring substations would need to provide the additional power to charge the ESD, although only marginally. Both the 5-minute and 15-minute headway conditions are used to compute the overall energy saving in a 24 hour period. More specifically, returning to Table 6–2, the following 24-hour train operation schedules are assumed:

- 5 minutes in peak hours (6-10AM and 4-8PM)
- 15 minutes in off-peak hours and weekends
- No train service between 1AM and 4AM on any day

Using actual published electricity tariffs from a USA utility company[3], the annual cost for each substation is calculated based on individual traction substation billing arrangements. These are shown in Table 6–3.

This table indicates that the ESD installation will have an annual electricity cost saving benefit of $45,169 based on the current tariffs compared against a full rectifier installation in the A4X location.

Assuming that the energy cost increases at 5% per year, the annual cost savings over 10 years' time are shown in Table 6–4.

Table 6-3 Summary of Annual Electricity Cost Saving due to ESD (all figures in US $)

Annual Electricity Cost Summary			
Substation	**With A4X-TPSS**	**With A4X-WESS**	**Savings with WESS**
A1	$182,342	$184,763	-$2,422
A2	$202,057	$207,687	-$5,630
A3	$173,973	$181,808	-$7,835
A4	$172,945	$183,581	-$10,637
A4X	$93,875	$0	$93,875
A5	$161,894	$172,907	-$11,012
A6	$181,397	$189,110	-$7,713
A7	$159,353	$162,810	-$3,456
Sum	**$1,327,835**	**$1,282,666**	**$45,169**

Table 6-4 Summary of Cost Savings in 10 Years

Total Energy Cost Saving Over 10 Years (Assuming 5% Annual Increase)	
Year	**Yearly Cost Savings (US$)**
1	45,169
2	47,428
3	49,799
4	52,289
5	54,904
6	57,649
7	60,531
8	63,558
9	66,736
10	70,072
Total	**568,135**

6.2 Energy cost savings – metro rail

Similarly as in the light rail system calculations, the estimated annual cost for the metro rail track section and cost savings [3] under different options are shown in Table 6–5.

Table 6-5 Summary of Annual Electricity Cost Savings (All figures in US $)

Substation	**3MW Sub**	**3MW ESD**	**4MW ESD**
Total annual cost	$4,831,516	$4,776,365	$4,760,599
Savings over 3MW Rectifier Sub Option	$0	$55,152	$70,917

Assuming that the energy cost increases at 5% per year, the annual cost savings over 10 years' time are shown in Table 6–6. These annual saving data are derived from daily savings in which weekdays are constructed from combining time periods for off-peak and peak hours associated with different percentages of energy savings due primarily to train headway differences.

It should be pointed out that the above calculations are based on ESD installations at locations where voltage supports are required. If the motivation of an ESD installation is primarily on energy saving, the consideration for the location of the installation for optimum energy saving may be different. In addition, considerations for the candidate systems for such installations are different in order to maximize the amount of energy recovery.

Table 6-6 Summary of Cost Savings in 10 Years

Total Energy Cost Saving Over 10 Years (Assuming 5% Annual Increase)		
Year	**3MW ESD**	**4MW ESD**
1	55,152	70,917
2	57,909	74,463
3	60,805	78,186
4	63,845	82,096
5	67,037	86,200
6	70,389	90,510
7	73,909	95,036
8	77,604	99,788
9	81,484	104,777
10	85,559	110,016
Total	**693,694**	**891,990**

7 Guiding the Selection of Energy Storage Application

7.1 Selection of ESD power rating and energy capacity

The ESD power rating and energy capacity are dependent on a number of parameters, such as:

- Traction power system parameters, including voltage level, substation spacing, third rail (or OCS) resistance, running rail resistance
- Location of the proposed installation,
- Desired voltage improvement (in voltage support mode)
- System-specific requirement on contingency performance
- Train characteristics, consists and power rating
- Train schedules

The selection process is an iterative process. First, initial assumptions are made on power rating, energy capacity and control voltage levels. Second, simulation results are analyzed to check if these assumptions are appropriate. If not, adjustments are made and further simulation results are analyzed. This process is repeated until a satisfactory set of results is found.

7.1.1 Power rating

Power rating requirements from the three simulated transit systems are shown in Figure 7–1.

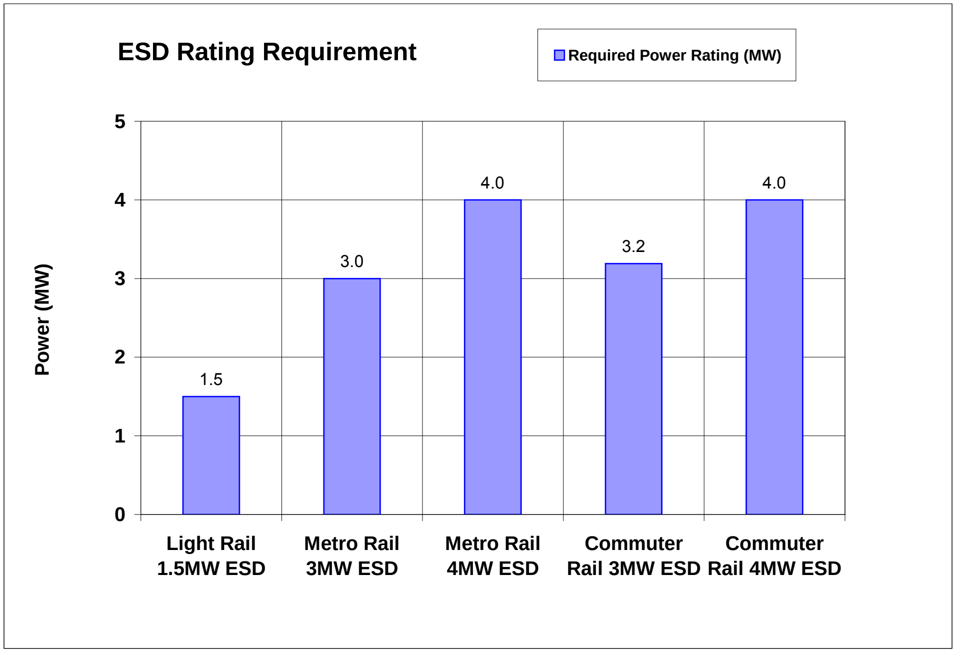


Figure 7-1: ESD power rating versus system type and power rating

7.1.2 Energy capacity

Energy capacity requirements from the three simulated transit systems are shown in Figure 7–2.

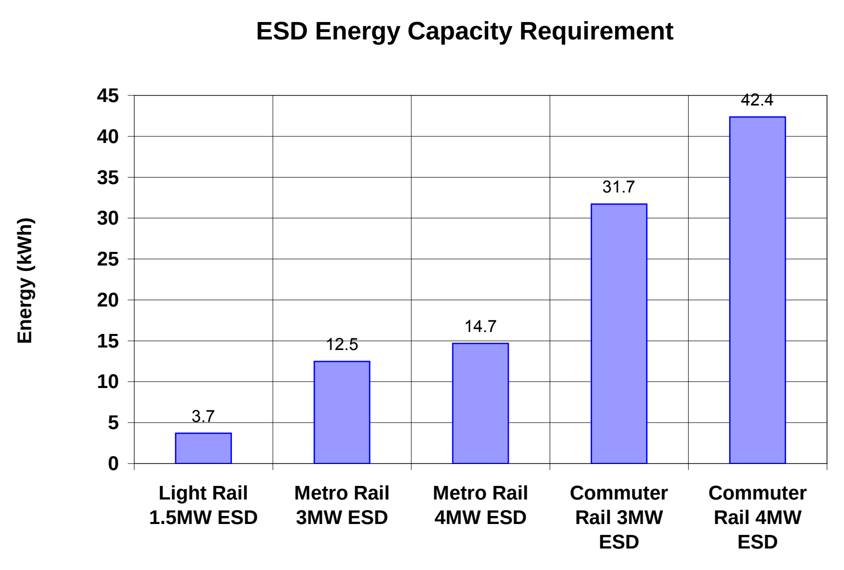


Figure 7-2: ESD energy capacity versus system type and power rating

7.2 Load cycles

Load cycles from the three simulated transit systems; light rail, heavy rail and commuter rail are shown in Figures 7–3 through 7–8.

7.2.1 Light rail

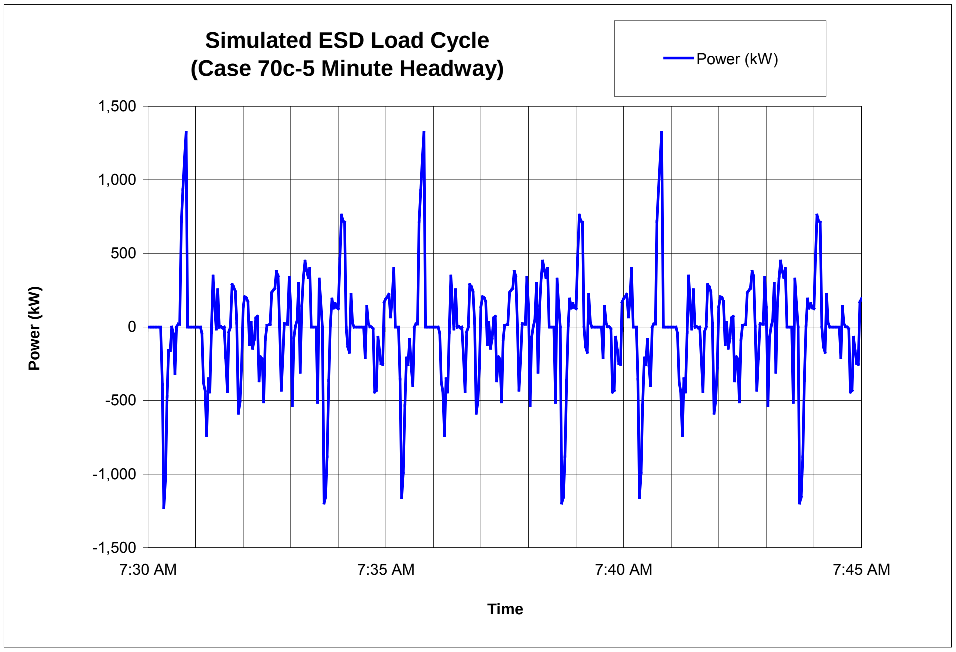


Figure 7-3: Peak hour ESD load cycle (light rail, 5-minute headway)

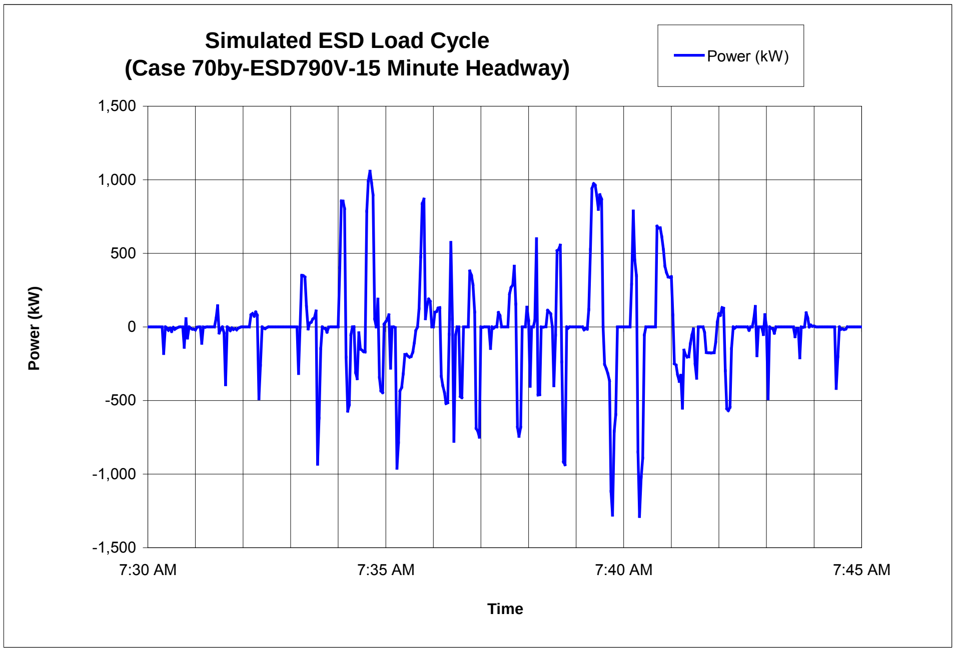


Figure 7-4: Off hour ESD load cycle (light rail, 15-minute headway)

7.2.2 Metro rail (heavy rail)

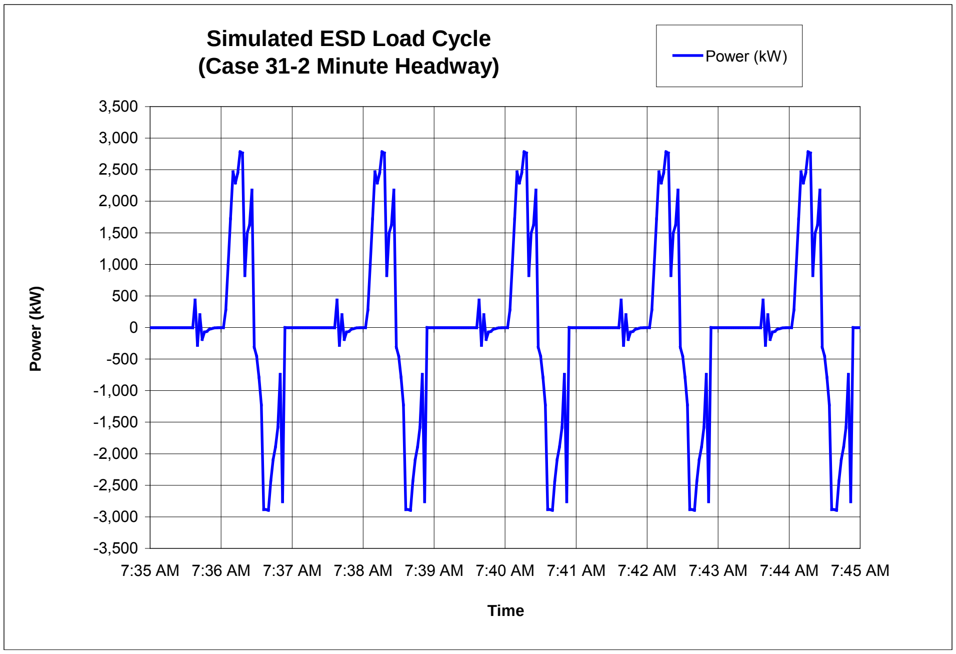


Figure 7-5: Peak hour ESD load cycle (metro rail, 2-minute headway)

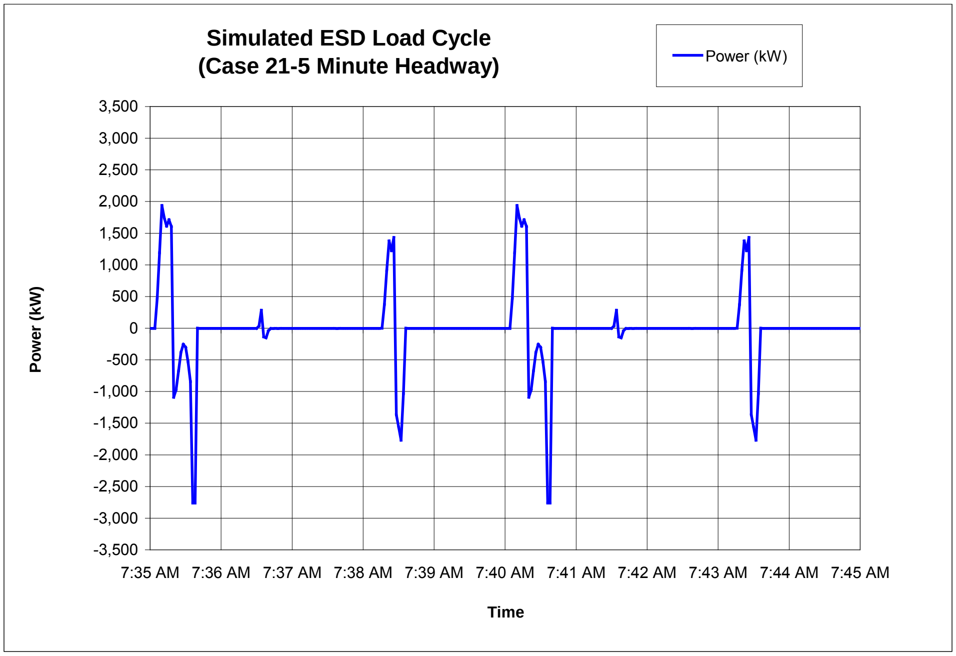


Figure 7-6: Midday ESD load cycle (metro rail, 5 minute headway)

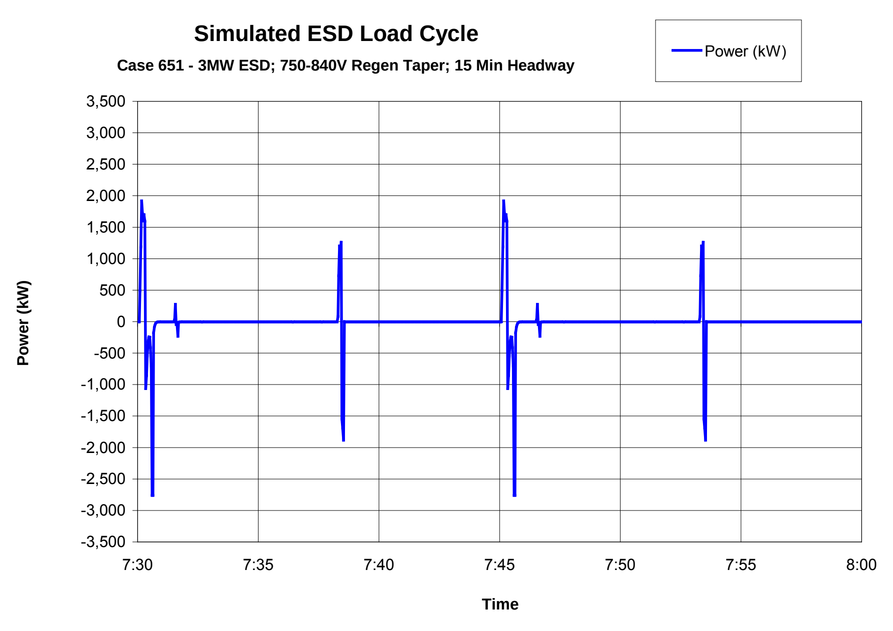


Figure 7-7: Off hour ESD load cycle (metro rail, 15-minute headway)

7.2.3 Commuter rail

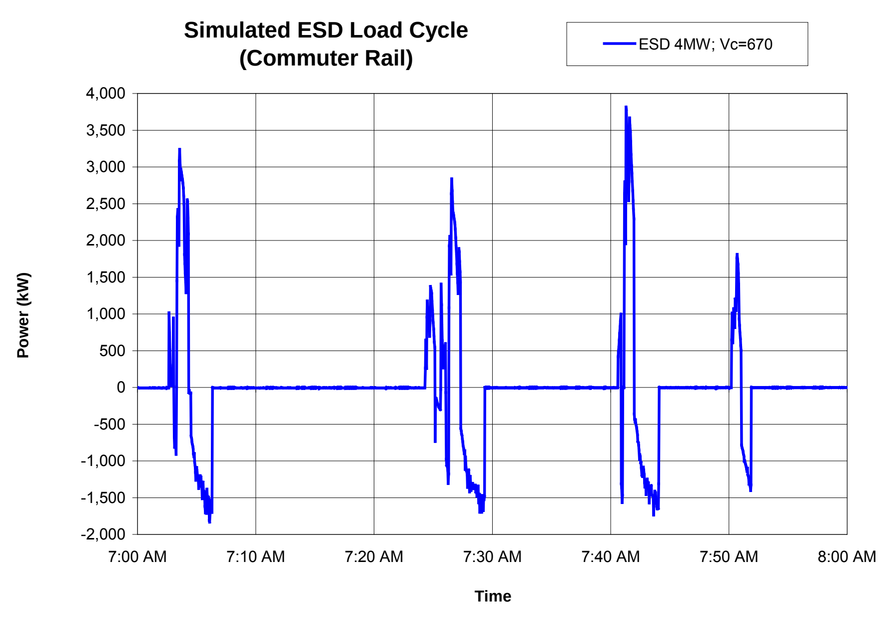


Figure 7-8: Peak hour ESD load cycle (commuter rail)

7.2.4 Summary

Assuming daily operational headways as shown in Figures 7–9 and 7–10 and based on the simulated load cycles as shown in the above section for the three systems, the daily total charge/discharge cycles can be calculated. The total charge and discharge cycles over 1 year and over 10 years are listed in Table 7–1, together with the minimum cycle time period between successive charge/discharge cycles.

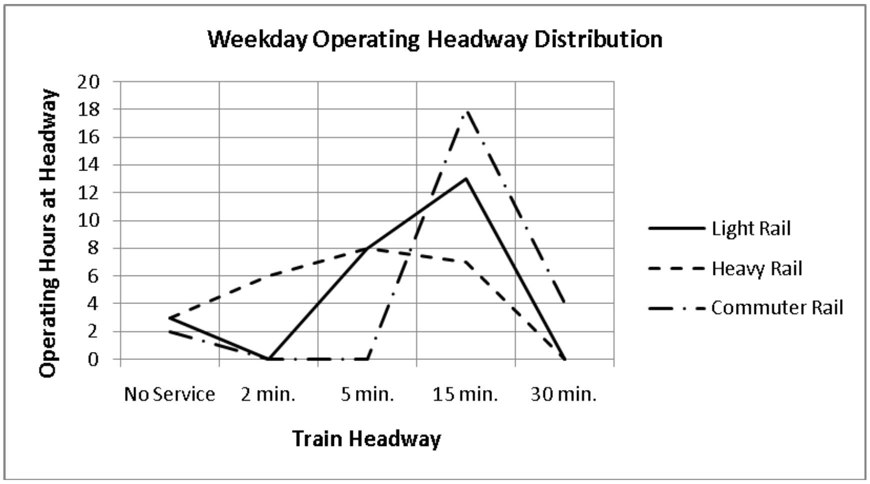


Figure 7-9: Weekday Operating Hours Distribution

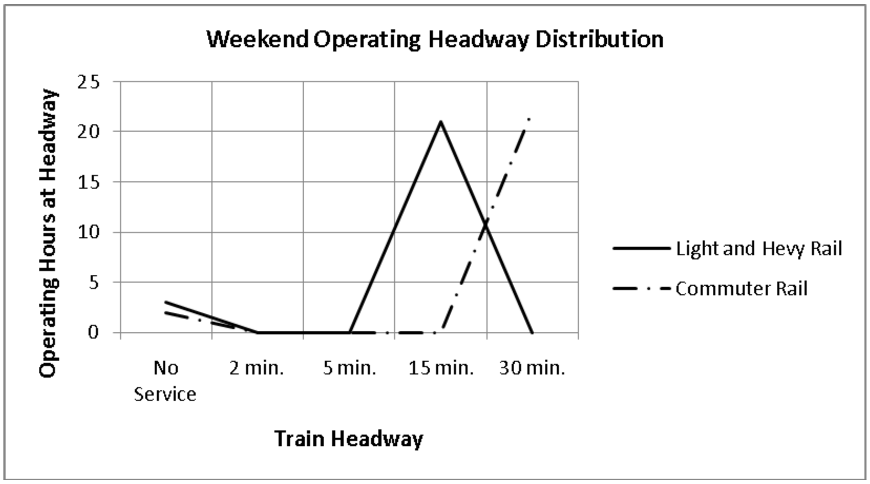


Figure 7-10: Weekend Operating Hours Distribution

This type of information makes it possible to select the types of devices from ESD vendors, as different devices have different life cycle limits and response times. In summary, Table 7–1 simply shows the required life cycles and charge/discharge response times for the ESD under different loading conditions associated with the type of rail mode.

Table 7-1 Summary charge/discharge cycles for the 3 systems

Type	Cycles /year	Cycles /10 years	Minimum cycle time period (minutes)
Light Rail 1.5MW ESD	442,800	4,428,000	0.71
Metro Rail 3MW ESD	161,120	1,611,200	2.00
Commuter Rail 4MW ESD	28,770	287,700	15.00

Note that in the above table, the light rail transit system shows the highest number of charge/discharge cycles and the shortest cycle time period. This is due to the selection of the control settings for the ESD in the system. The power and energy ratings of the ESD were determined by the heavier duties in voltage support mode under adjacent substation outage conditions. However, for the majority of the operation time all substations are in service and the ESD is set to energy recycle mode in order to recycle the maximum amount of regenerative braking energy. As a result, the cycle time period is short and the number of cycles is large.

For the metro rail and the commuter rail systems, the control settings of the ESD installations were set to voltage support mode.

7.3 Sensitivity analysis

A number of parameters are inter-related when trying to optimize the selection of an energy storage device. For example, the voltage improvement requirement that may be needed, the device rating (power and energy), the system receptivity and the amount of energy saving, etc. are all sensitive to the system conditions such as system voltage level, the variation in train schedule, etc.

System receptivity is a significant system characteristic that especially affects the performance of a system with regenerative braking. Many factors affect system receptivity and energy saving figures, such as track alignment and grade, passenger station locations, electrical parameters of the traction power system, vehicle characteristics including weight, train operational characters (acceleration and braking rates, coasting, offsets in headway dispatches on the two tracks, timing deviation from regular headways), among others. From nominal operating conditions and parameter values, variations from nominal are introduced to understand this sensitivity. The following sections illustrate sensitivities to variation in some of the key parameters.

7.3.1 The effect of ESD power rating on voltage improvement

For the metro rail system, if an ESD is installed at position G05B at the east end of the track, the low voltage conditions will be improved. A 3MW installation is required to achieve 525V or better, as shown in Figure 7–11.

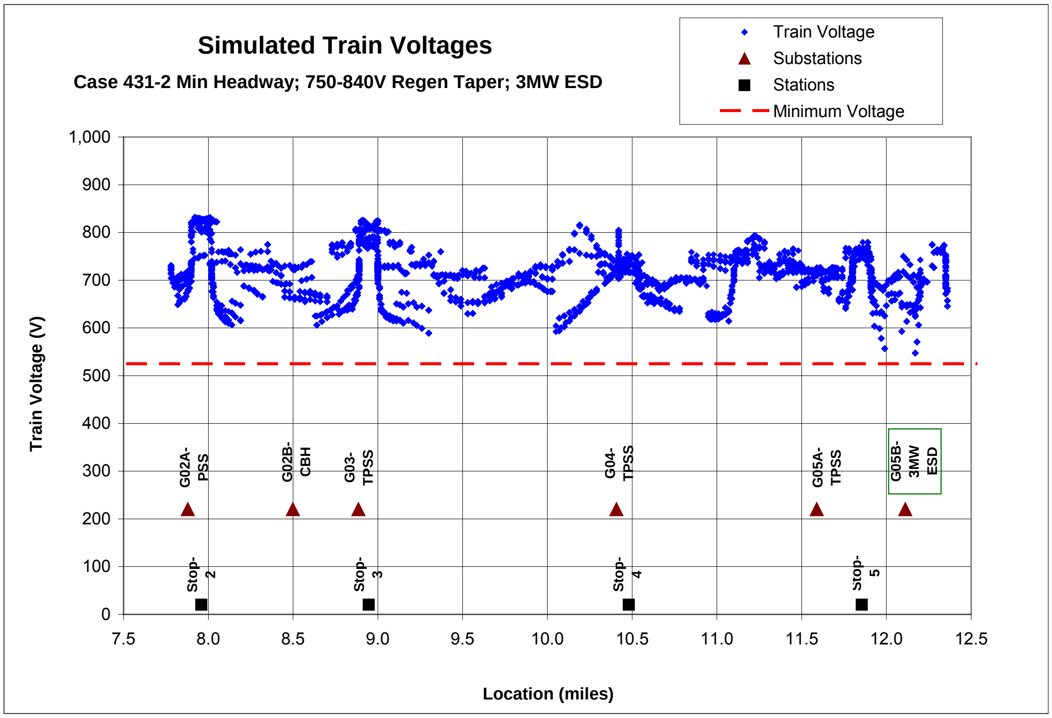


Figure 7-11: Train voltages with 3MW ESD at G05B (metro rail)

The above figure shows that the minimum train voltage near G05 is actually improved to 547V. A larger installation of 4MW will achieve an even better result, with the minimum train voltage improved to 617V near G05B, as shown in Figure 7–12. So it is easily seen that larger power rated devices directly affect minimum voltage level protection.

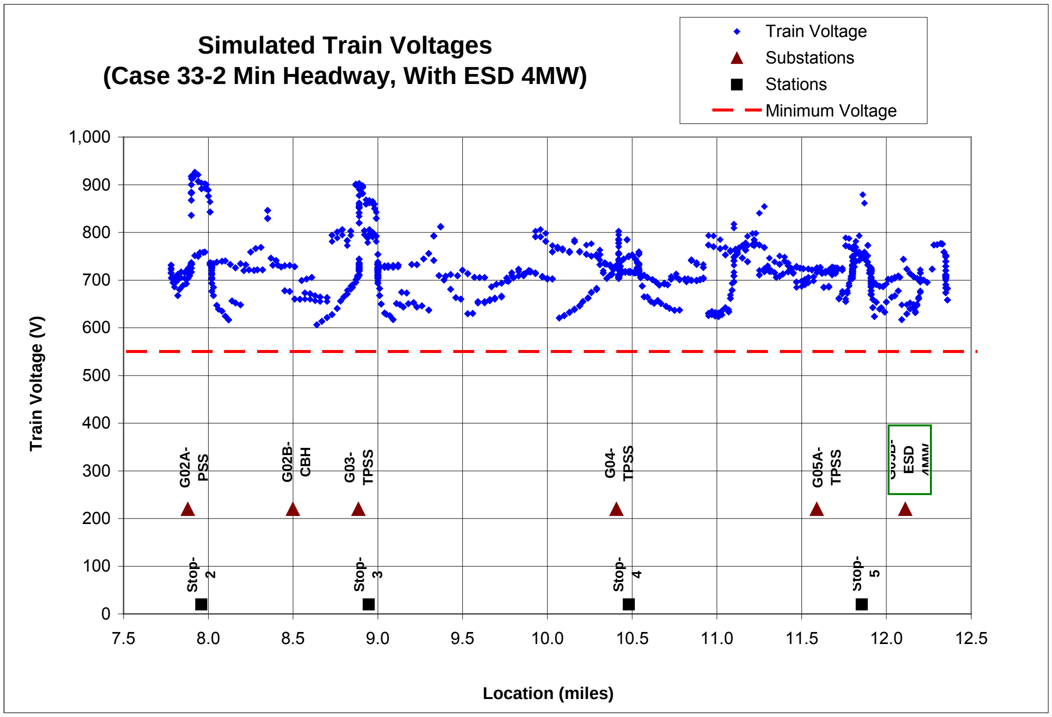


Figure 7-12: Train voltages with 4MW ESD at G05B (metro rail)

7.3.2 The effect of headway offset on voltage improvement and system receptivity

Again, selecting the metro rail system example, operating under a peak hour operation (2-minute headway), simulations for different offsets between east- and westbound train dispatch timing (headway offsets) were performed. Such offsets result in the trains meeting at different locations along the alignment, which in turn affect the train voltage and other conditions in the system. Time-distance plots for three different headway offsets on westbound trains are illustrated in Figure 7–13.

The resulting minimum train voltages and system receptivity (the ability to accept regenerative power) under different installations at different headway offsets are shown in Figures 7–14 and Figure 7-15. Shown in Figure 7-14 is the minimum voltage level set point.

7.3.3 The effect of voltage limit on system receptivity

Receptivity variations versus voltage limits are shown in Figure 7–16. Receptivity in this figure is measured as a percent, where 100 represents full receptivity, i.e. all generated voltage can be absorbed by the electrical system. Higher voltage limits improve system receptivity regardless of headway variations. The figure also shows that for longer headways, the receptivity is lower in general, because fewer trains are present to accept injected voltage.

7.3.4 The effect of headway on system receptivity

Similarly, receptivity variations versus headways are shown in Figure 7–17. As expected, receptivity improves for a larger installed ESD.

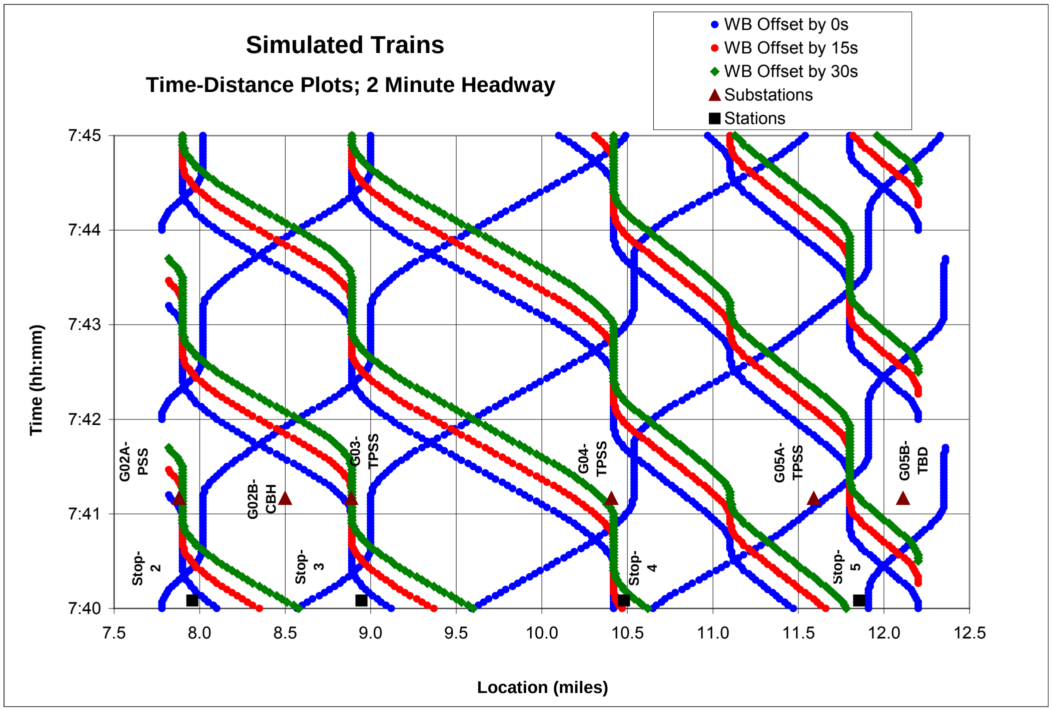


Figure 7-13: Time-distance plot for peak hour trains under different headway offsets for westbound trains (metro rail)

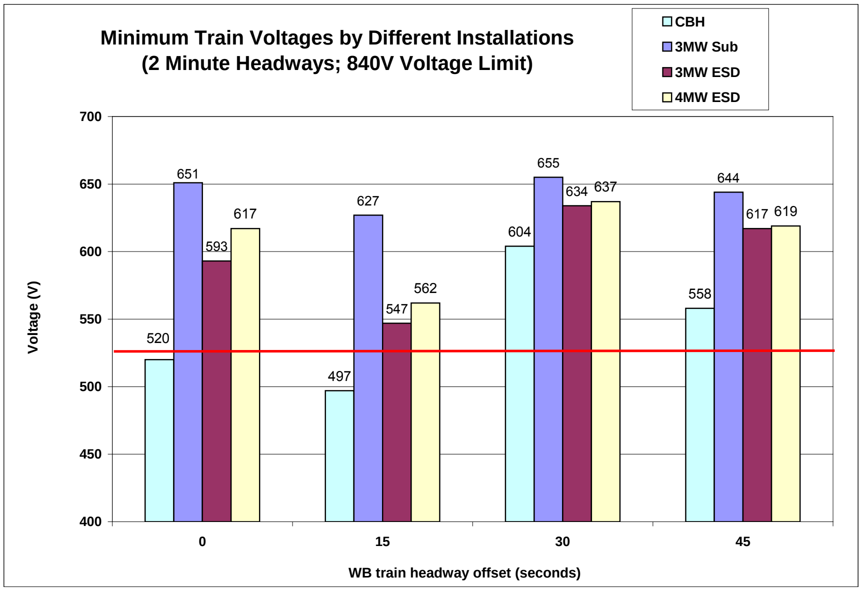


Figure 7-14: Minimum train voltages versus headway offsets (metro rail)

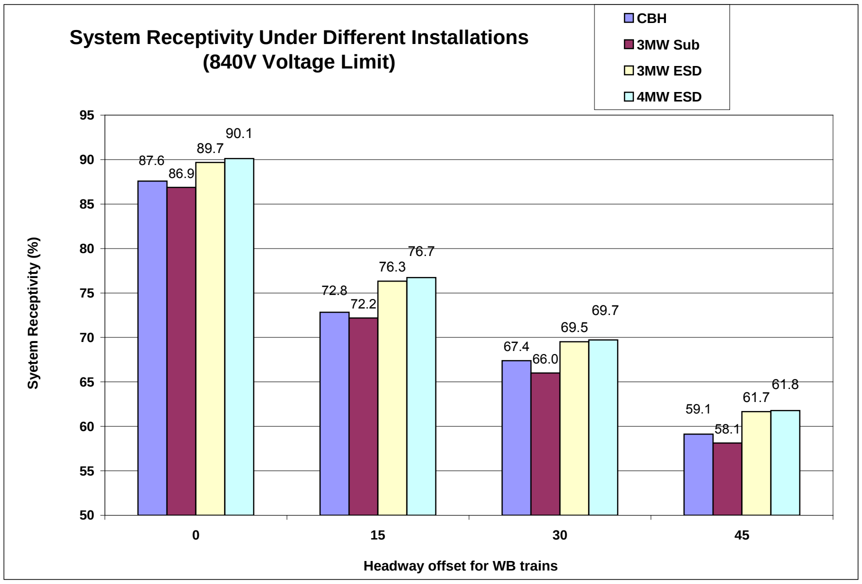


Figure 7-15: System receptivity versus headway offsets (metro rail)

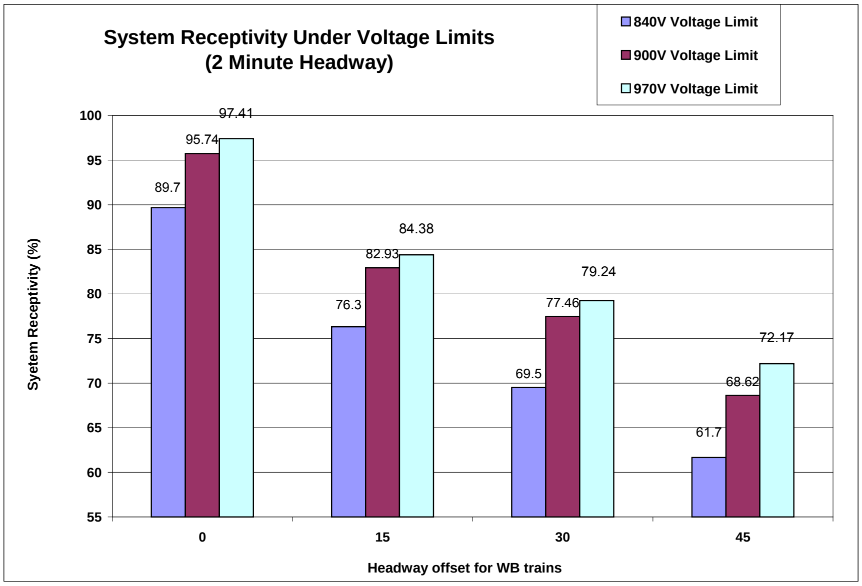


Figure 7-16: System receptivity versus voltage limits (metro rail)

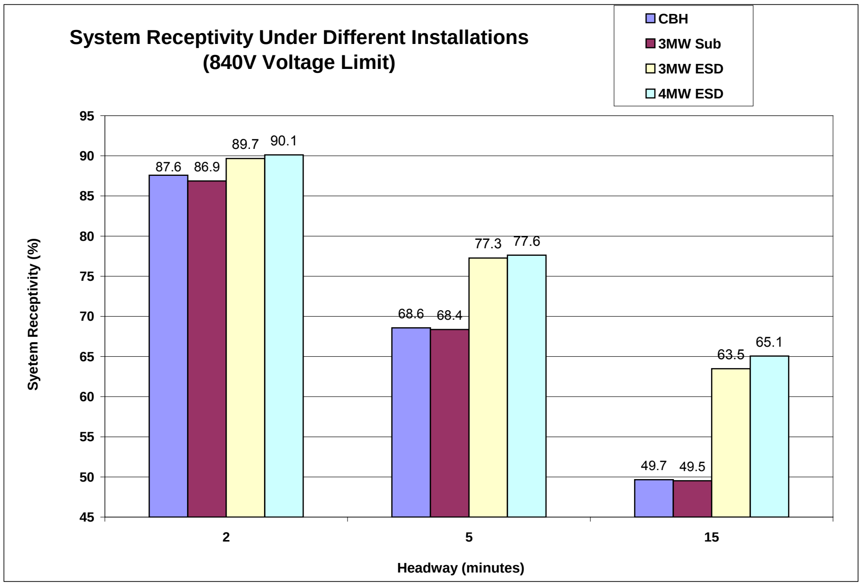


Figure 7-17: System receptivity versus headway (metro rail)

7.3.5 The effect of ESD control voltage on load cycle

Adjusting the control voltage (Vc) of an ESD installation will affect the level of train voltage improvement. For example, a high voltage level setting will improve the low-voltage level margin, but will also demand a higher power rating for the device.

Also, due to electrical circuit resistance losses associated with long distances between the ESD and nearby electrical substations, the charging rate is limited. A higher Vc setting positively affects train voltage level, but consideration must also be given to specification of charging rate. A sufficient charging rate must be achievable so that the ESD is kept at a desired capacity of charge to meet the next discharging demand cycle. This tradeoff not only affects power rating of the ESD but also rate of charge and energy capacity.

Figure 7–18 shows resulting load cycles under different control voltages for the commuter rail system. Notice in this figure the limiting charge rates imposed by the electrical circuits; seen as voltage charge limits between 1.6 and 1.8 MW.

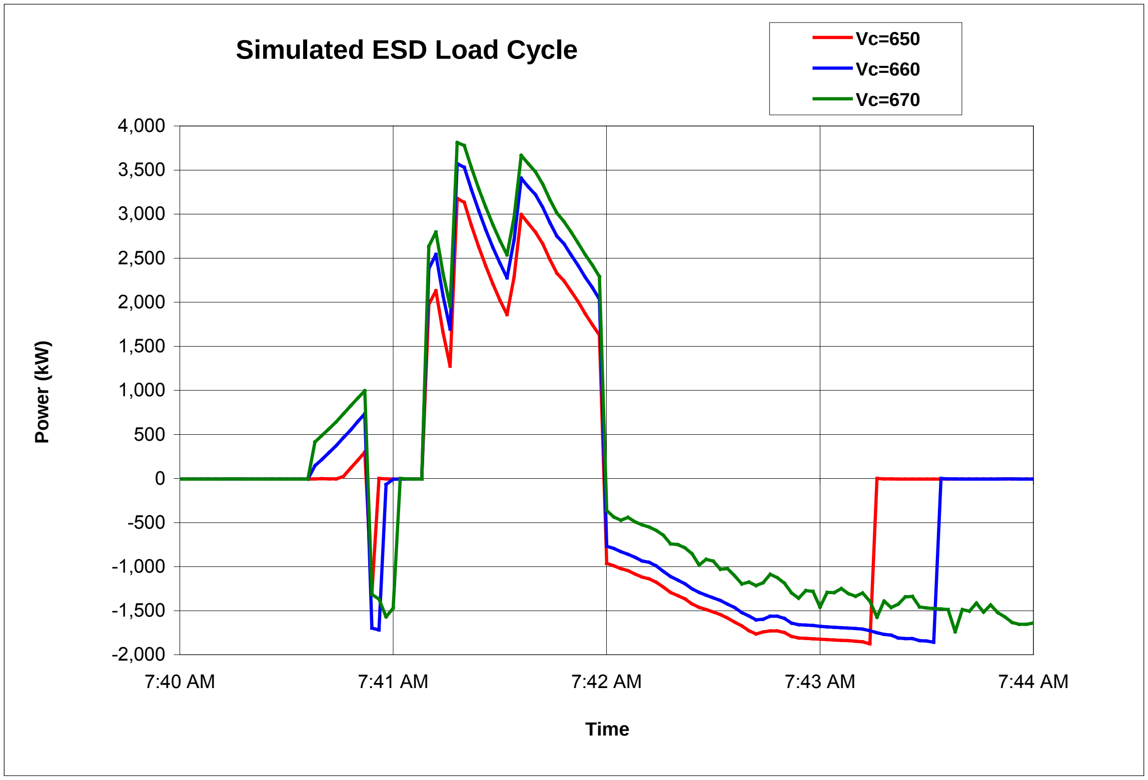


Figure 7-18: ESD load cycle under different control voltages (commuter rail)

Minimum voltage limits are affected by the ESD Vc set point and the associated power and energy specifications for the ESD. As can be seen in Table 7–2, higher Vc values can improve the minimum train voltage level but there are also needed increases in ESD power and energy ratings.

Table 7-2 ESD Rating & Capacity vs. Voltage Improvement (Commuter Rail)

ESD Control Voltage	Vc=650	Vc=660	Vc=670
Max. MW Output	3.2	3.6	3.8
Max. kWh Usage	31.7	37.5	42.4
Minimum Train Voltage	518	529	536

The variations of ESD power ratings and energy capacities versus the desired levels of voltage improvement are shown in Figures 7–19 and 7–20.

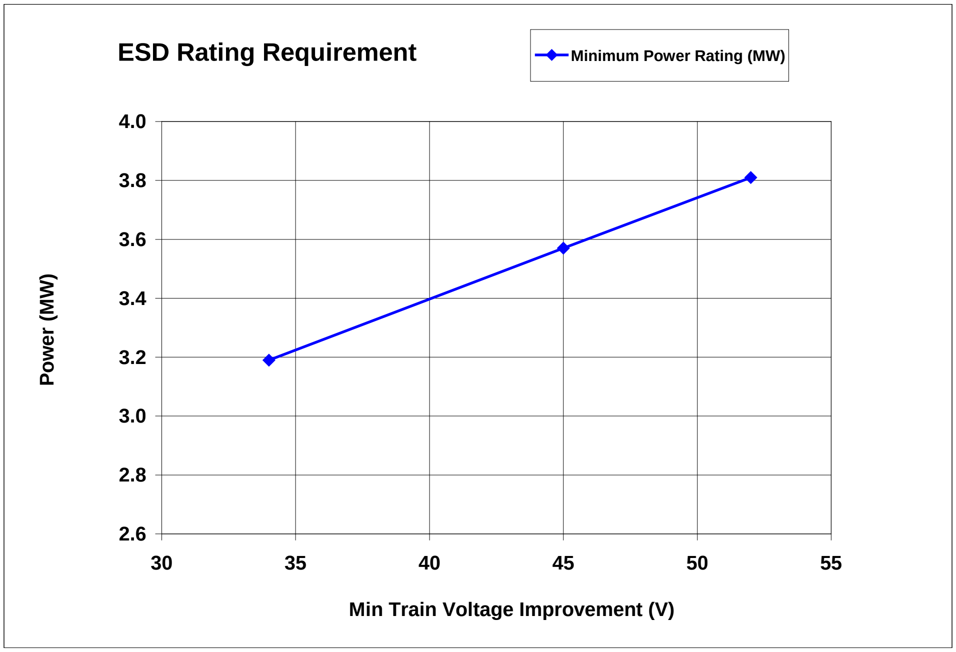


Figure 7-19: ESD power rating vs. voltage improvement (commuter rail)

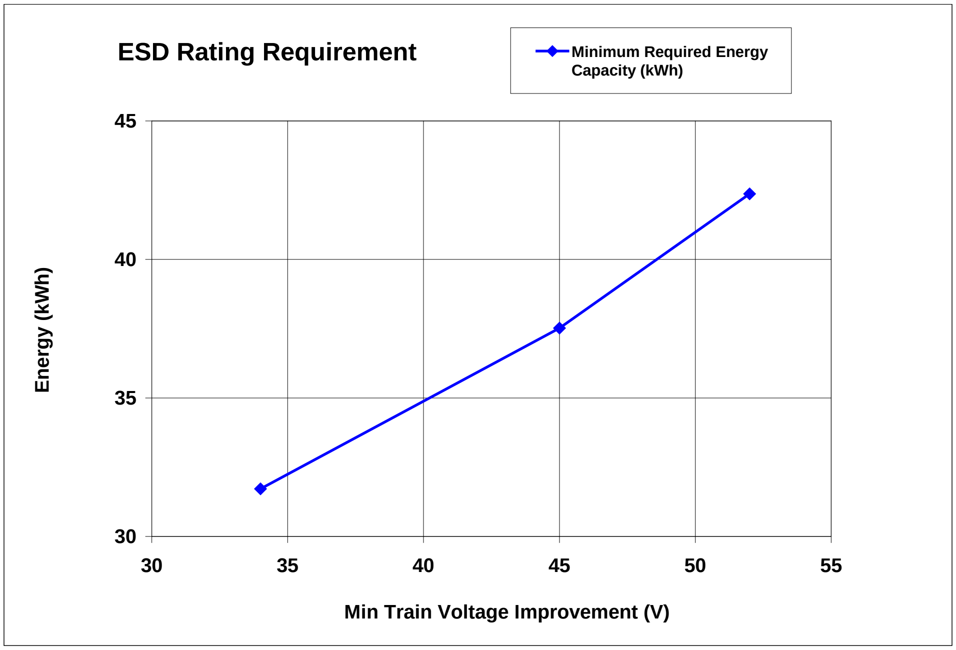


Figure 7-20: ESD energy capacity vs. voltage improvement (commuter rail)

7.3.6 The effect of ESD rating on load cycle

For a given system condition, a larger device has a higher power output, which demands a large energy capacity.

For the metro rail system, simulated load and energy cycles for the ESD at 3MW and 4MW ratings are shown in Figures 7–21 and 7–22. As can be seen in these figures, a larger capacity ESD can provide higher power level discharge, and greater energy availability. Energy availability is represented in Figure 7-22 as the area within the curve. Use of a larger ESD simply means that the magnitude of power and energy discharges are larger, producing a more compliant system by which to meet load cycle demands.

Understanding how parameter selection affects system performance variability will help guide the selection of appropriate energy storage devices and guide selection of key operating parameters. Knowledge of sensitivities also provides insight into how specifications might be written for system design and operation.

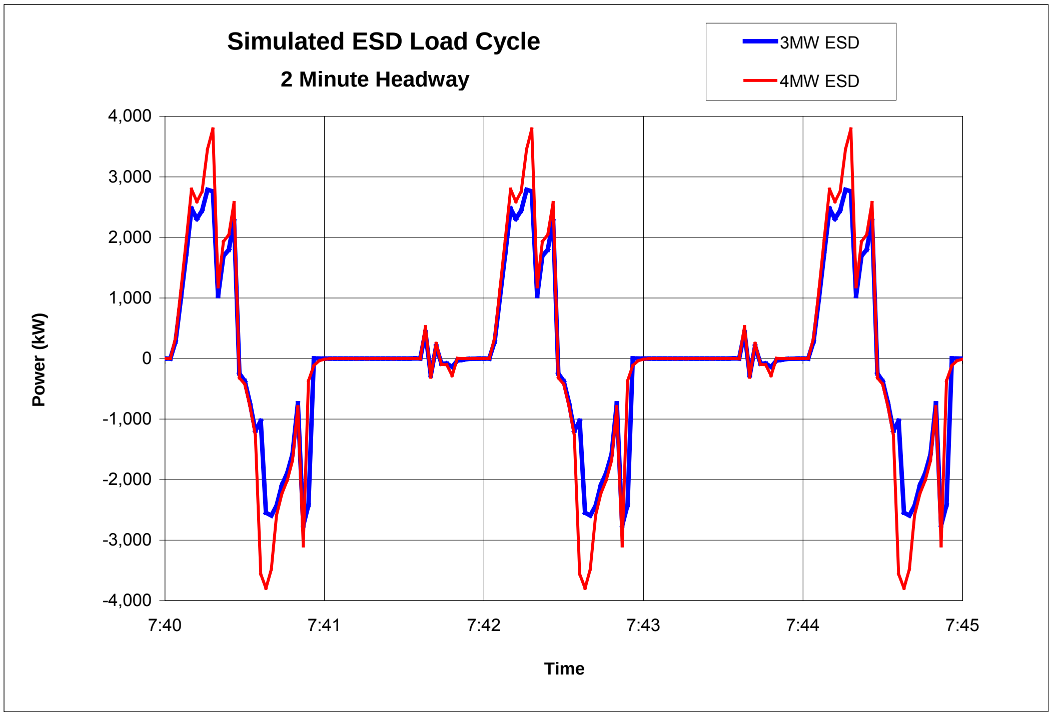


Figure 7-21: Simulated ESD load cycles (metro rail)

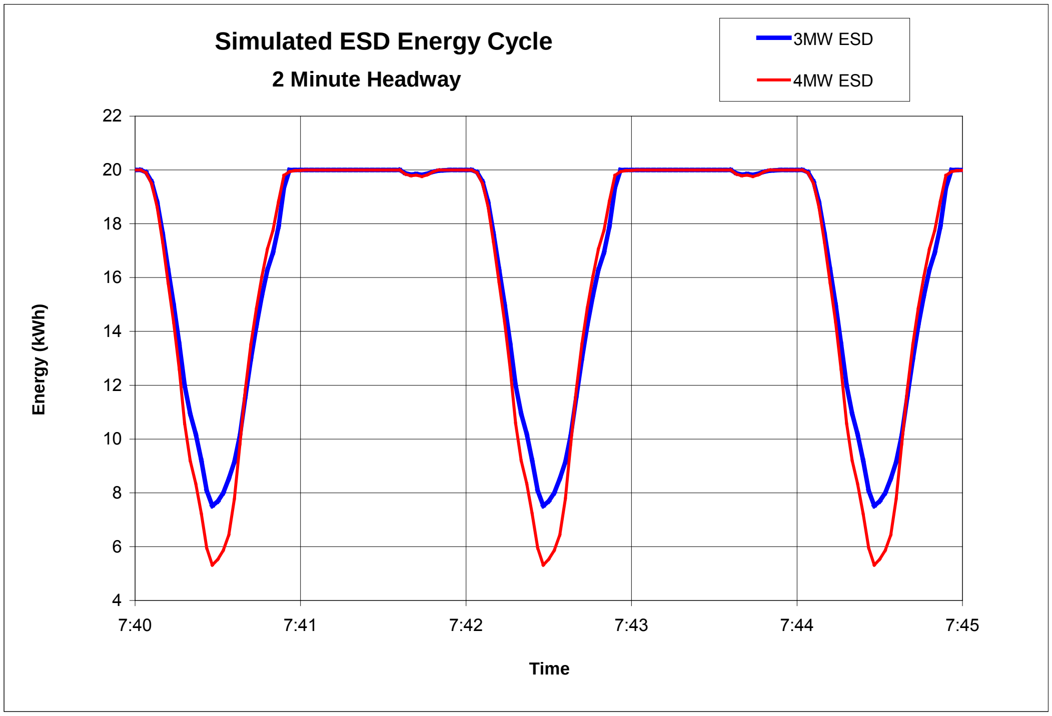


Figure 7-22: Simulated ESD energy cycles (metro rail)

8 Conclusions

This project has taken a detailed look at the potential benefit of wayside energy storage as a solution to several problems transit agencies may face particularly in light of increasing demands on the operation of their systems resulting from increased ridership and infrastructure expansions, and as transit agencies examine ways to reduce energy use. To address these needs an energy storage research consortium was formed at the American Public Transportation Association to gain more detailed knowledge of the potential effectiveness of wayside energy storage concepts. Representatives from transit agencies, energy storage providers, state energy programs, U.S. national laboratories and other associations such as the Electric Power Research Institute began discussions on the science of wayside systems. From this initial dialog, the Transportation Research Board's Transit Cooperative Research Program enlisted its financial and programmatic support to carry the study further and accelerate findings on the potential of wayside energy storage and to produce a guide for the potential application and operation of such systems.

Results from computer simulations of candidate systems representing the rail transit modes of light rail, subway and commuter rail demonstrate the potential of energy storage to solve many energy related problems seen by transit agencies. Wayside energy storage devices can be designed to resolve problems of propulsion power voltage sag, energy inefficiency resulting from ineffectual capture of regenerated braking energy, high electric utility costs associated with large propulsion peak demand loads, and the high cost of conventional electrical utility substations installed along the rail line right-of-way. Based on dynamic modeling of system behavior with and without energy storage systems, the study concluded that energy storage is most practical when simultaneously solving more than one of these problems rather than focusing the application primarily on any one problem alone, such as energy savings.

It was determined that using wayside energy storage to mitigate problems associated with propulsion voltage sag is a good starting point in sizing and optimizing the initial system design. Using voltage sag design as a basis, it was then more practical to consider variations in design parameters to optimize other simultaneous benefits including peak power reduction and energy use reduction. However, it is also possible to develop a system that is built around the need to reduce peak power demands or to utilize less costly wayside energy storage substations as replacements for conventional substations. However, determining the effectiveness of such a system requires careful economic analyses to estimate payback periods and allowable capital cost expenditures for system installation. It was also shown from further analyses that system performance is measurably sensitive to energy storage power rating and voltage set point, train headway, degree of multiple train schedule synchronization, and effect of power system voltage limit (electrical line receptivity).

9 Recommendations

Agencies wishing to use wayside energy storage systems to address problems discussed here would benefit from a more detailed simulation modeling exercise to allow optimal energy storage size and performance metrics. However, a full-scale test of proposed energy storage systems would help in confirming modeling assumptions and provide real-world verification of energy storage device performance including the system electrical receptivity, which affects the potential energy saving benefit of wayside energy storage systems. Some agencies are looking at installing wayside energy storage systems, but detailed modeling and careful data collection will also be needed to best understand the performance and long-term durability of these systems.

10 Acknowledgments

The authors greatly appreciate the support of the Electric Power Research Institute (EPRI) for their participation in the APTA Energy Storage Research Consortium, the Sacramento Municipal Power District (SMUD) for their help in the interpretation of utility charge rate plans, and the Transportation Research Board for providing funding and direction for this study. The authors are also indebted to all members of the APTA/EPRI Energy Storage Research Consortium who devoted many hours to discussions and meetings to help outline the scope and application of energy storage research. And finally the authors thank our energy storage industry partners who provided real-world performance data for their devices.

11 References

[1] Symposium: TCRP C-75 Wayside Energy for Transit, APTA/EPRI Energy Storage Research Consortium, American Public Transportation Association, Washington, DC, February 10, 2010.
[2] Energy Storage Vendor Advisory Group, APTA/EPRI Energy Storage Research Consortium, American Public Transportation Association, 2009.
[3] LADPW Electric Rates - Schedule A-1: Small General Service (Effective July 1, 2009) (http://www.ladwp.com)
[4] “Traction Power System Study For Metro-North Railroad,” Railway Age International Conference On Computer Modeling For Rail Operations, February 2004, Florida USA.

Appendix A - Energy Storage Research Consortium

Interest in trackside energy storage for rail applications began as agencies were looking for ways to reduce energy use as fuel prices and electric rates were showing signs of rapid increase. Concurrent with industry awareness of energy storage but unaware of the potential benefit it was clear that information within the industry was fractured and there was a need to better understand energy storage. APTA developed a white paper on the connection between energy storage and transit, highlighting the general categories of technologies and the potential for addressing numerous problems some agencies were seeing.

An energy research consortium was established jointly by the Electric Power Research Institute and the American Public Transportation Association. It was proposed and agreed that the APTA/EPRI consortium might act as an "umbrella" organization to pull this fragmented knowledge together and advance the state of the art with new knowledge as well. This consortium was created consisting of a diverse member base including Sandia National Laboratory that was already researching energy storage; transit agencies including the Washington Area Metropolitan Transportation Authority, Los Angeles County Metropolitan Transportation Authority, New York City Transit, Long Island Railroad and Bay Area Rapid Transit; state research organizations including California Energy Commission, Sacramento Municipal Utility District (SMUD), New York State Energy Research and Development Authority, and the New York Power Authority; and consultants from Systra-USA, Inc. The consortium provided context and support for energy storage research and helped form the basis for this TRB project.

Appendix B - Vendor Advisory Group

In the same way that the APTA Energy Storage Research Consortium unified the transit agencies and government members approach to energy storage, creation of the Vendor Advisory Group has organized the energy storage vendors seeking to do business in this area.

The vendors joining the Vendor Advisory Group are shown in the following table, which also shows their primary product.

Flywheel	Battery	Electro-Chemical Capacitor	Hybrid Battery and EC-Capacitor
	Ultralife		
Pentadyne	Impulse/Envitech	Maxwell	Qynergy
Vycon	Sojitz (Toyo Denki)	EPX	
	Saft Batteries		
	Ioxus		

The purpose of the Vendor Advisory Group was to give neutral technical information on energy storage technologies appropriate for rail to the Study Team for reference while doing the simulations.

Early in the process the study group turned to the industry to provide technical insight into energy storage devices, provide a confirmation of assumptions used in modeling, offer order of magnitude estimates for device costs, and general support to guide the study.

Information from the vendors was solicited using a questionnaire as shown below. The study team was interested in categorizing product variability and operating ranges so that appropriate assumptions could be made within the model simulation studies and that the study group could best envision future technological innovations. The questionnaire addressed units of 1.5 MW and 3 MW storage capacities.

From some of this data, for example, a 1500 KW battery unit required between 8 and 112 battery cells, and power densities ranged from a value of 0.12 kW/ft^3 to 7.5 kW/ft^3. For all the systems considered, the number of lifetime cycles ranged from 5,000 to 10,000,000.

The Vendor data received in response to the questionnaire such as the example shown below was very helpful to the Study Team.

- It gave the team confidence that the charging and discharging control algorithms we have used reflects the actual function of the devices
- It gave the team confidence that the input parameters we have used for the energy storage simulation models are appropriate
- It helped the team decide what types of devices can meet the required power ratings and energy capacities for different systems

- It helped the team decide what types of devices can meet the required life cycles for charging and discharging in different systems

Sample Questionnaire on A 3000 kW Unit (750V DC)			
Category	**Data Type**	**Value (Based on Current Technology)**	**Value (Based on Technology 5 years from Now)**
Electrical	Number of units/cells required		
	Energy Storage Capacity (kWh)		
	Charge efficiency (%)		
	Discharge Efficiency(%)		
	Standing Loss (kW)		
	Charging Current Limit (Amps)		
	Discharging Current Limit (Amps)		
	Power Density (kW/cube_feet)		
	Energy Density (kWh/cube_feet)		
Life cycle	Minimum Cycle Time for Charge/Discharge (minutes)		
	Lifetime Charge/Discharge Cycles (number of cycles)		
	Useful Lifetime (years)		
	Degradation over Time, %		
Environmental	Working Temp Range, deg F		
	Any Special Environmental Requirements (Air conditioning, humidity, vacuum, etc)		
	Does the unit require external power (415V AC)		
	Device dimensions (LxWxH in feet)		
	Footprint (LxW in feet)		
	Any special requirement for disposal of retired/replaced units		
Application	Voltage support		
	Peak Shaving		
	Energy Savings		

To provide the vendor community with some level of knowledge regarding the power and cycling needs their devices may need to support, the study team performed simulations of generic system designs incorporating energy storage devices and developed a generic load demand profile as seen in **Figure B-1**. From this information, vendors were able to gauge the potential match of their device characteristics with the demand profile of an average system.

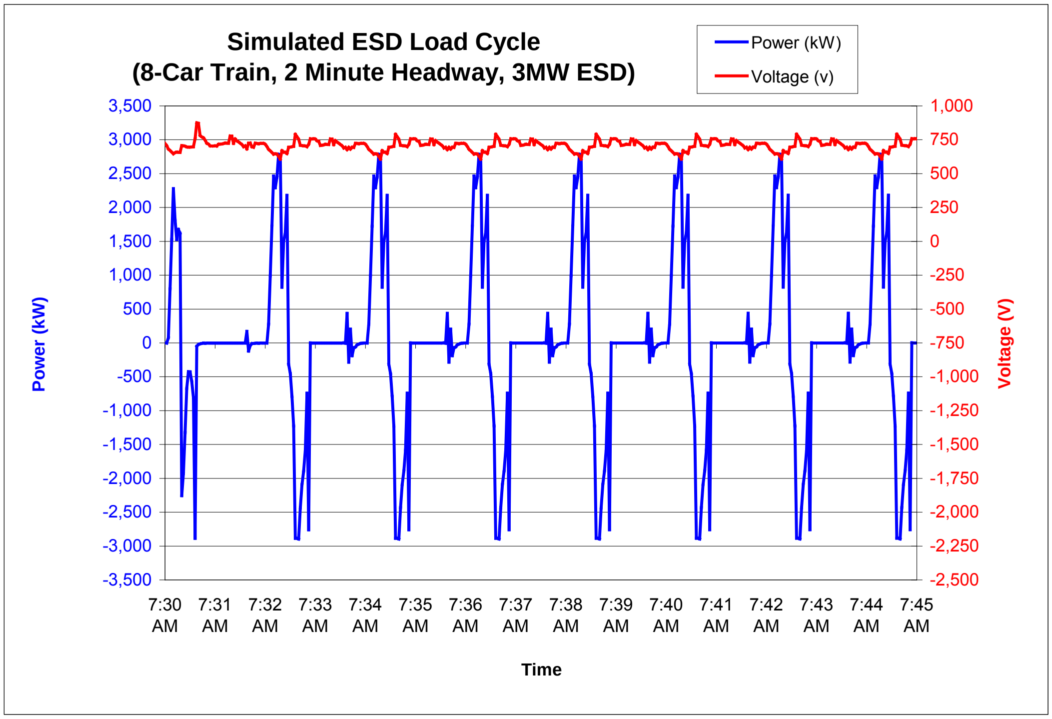


Figure B-1: Simulated Generic ESD Load Cycle

Appendix C – Simulation Software

The RAILSIM Load Flow Analyzer is time-based simulation software that integrates the train movement simulation with electrical network simulation.

C.1 Train movement simulation

The train movement simulation calculates the interaction between trains and the track alignment. The speed limits determine how fast the train can travel. The vehicle characteristics determine how fast the train can accelerate and decelerate. These in turn will determine how much power the train will demand from the traction power system or how much power it can make available for returning to the traction power system (regenerative braking power is treated as negative power demand).

Typical train speed and power demand for the eastbound trains from the metro-rail example are shown in Figure C-1 and Figure C-2. Similarly, train speed and power demand for the westbound trains are shown in Figure C-3: Speed profile for westbound train (metro rail) and Figure C-4.

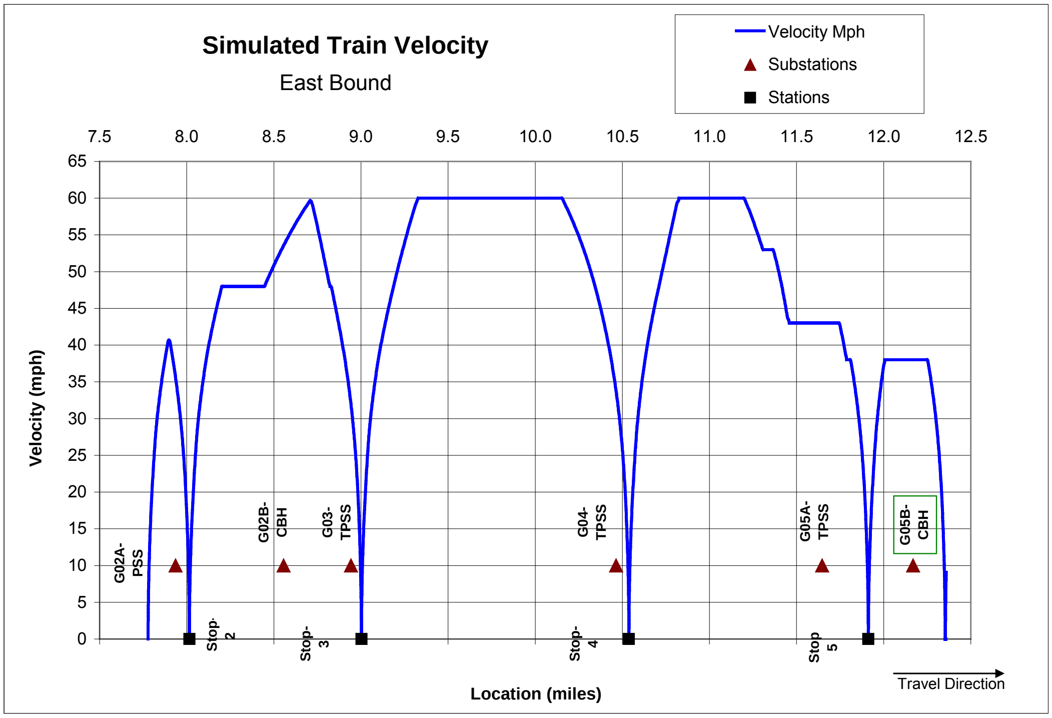


Figure C-1: Speed profile for eastbound train (metro rail)

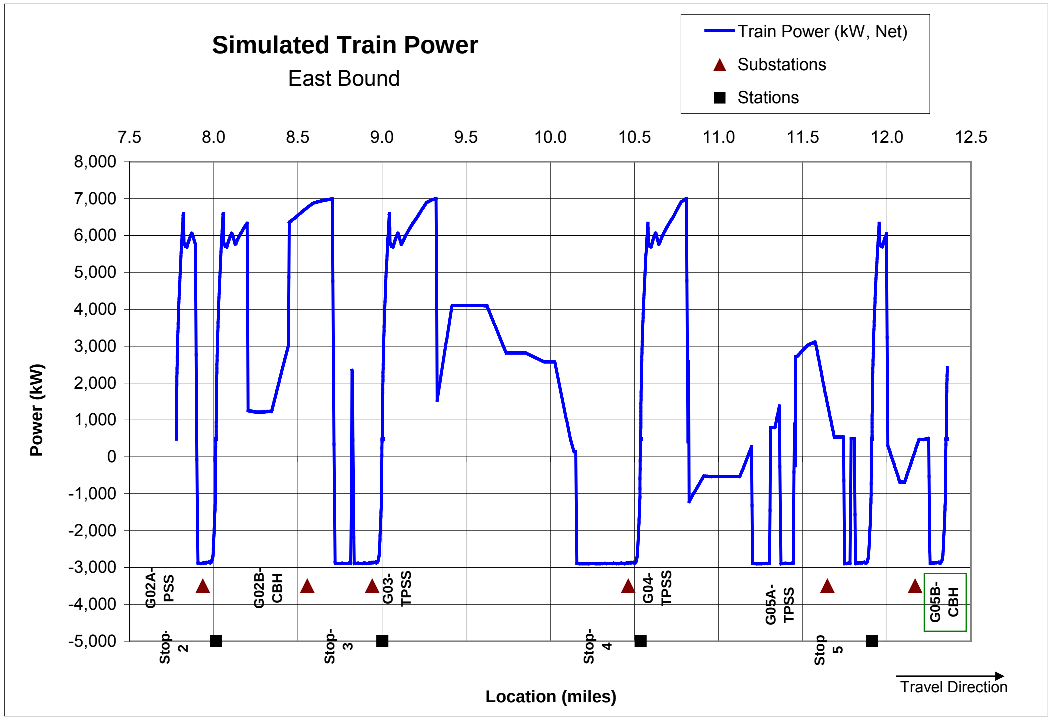


Figure C-2: Power profile for eastbound train (metro rail)

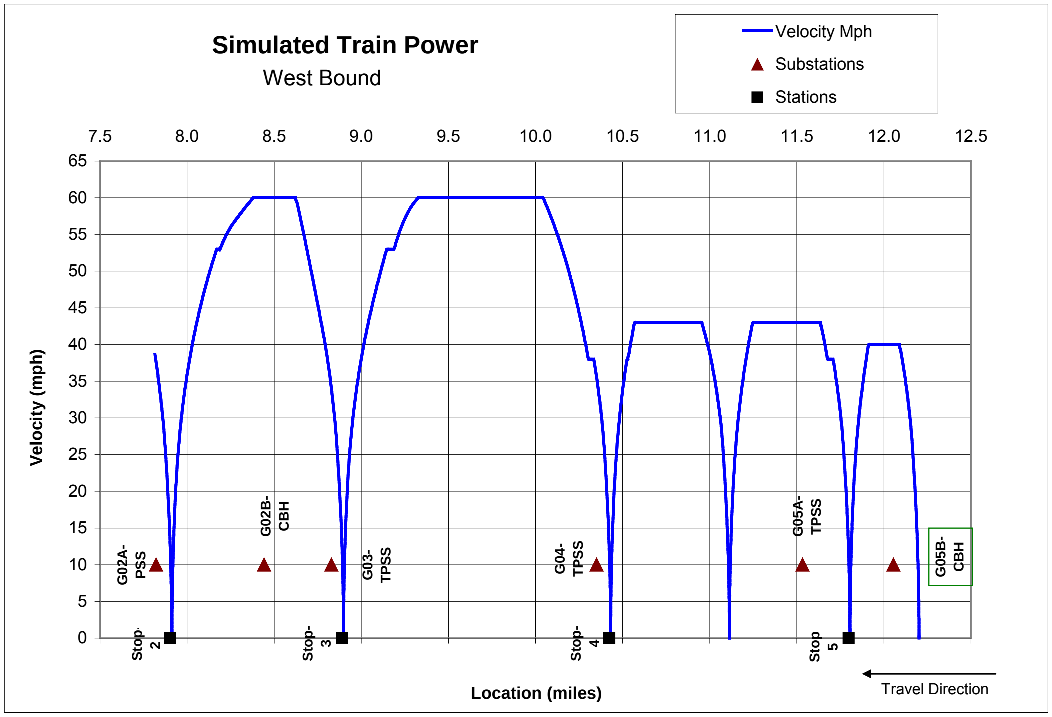


Figure C-3: Speed profile for westbound train (metro rail)

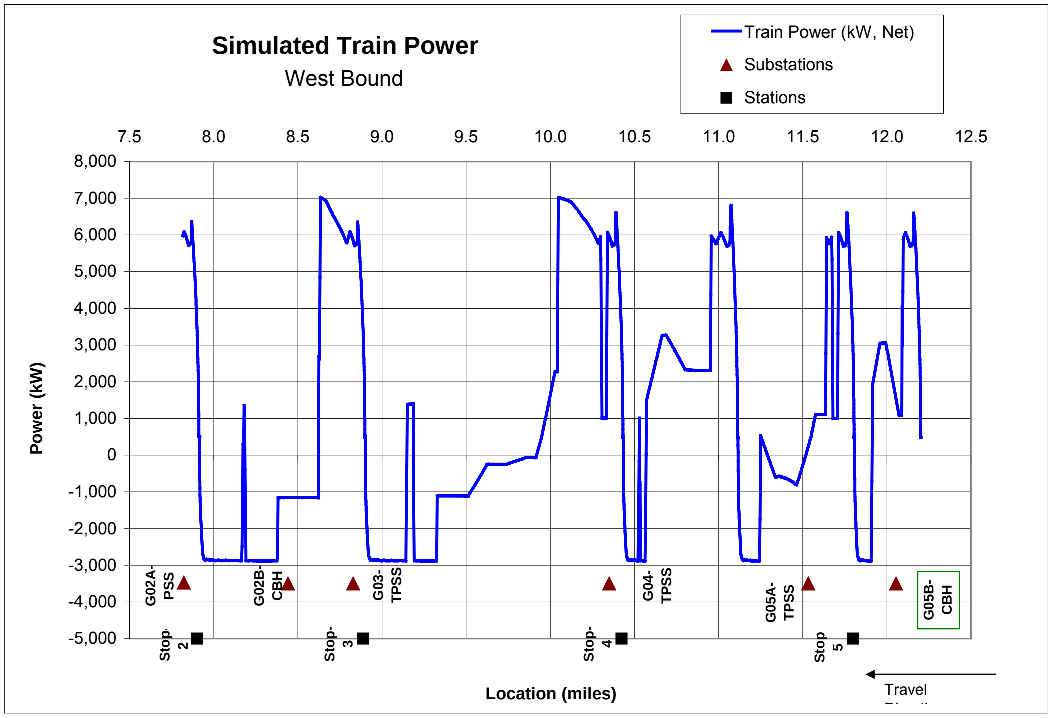


Figure C-4: Power profile for westbound train (metro rail)

C.2 Electrical network simulation

The electrical network simulation determines the voltage and current in the traction power system. Based on the train operation schedules or headways, the simulator calculates the locations of all the trains at any given time instant and their power demands across the system. This data is fed into the electrical network simulator to perform the load flow simulation for the given time instant.

When the load flow simulation is performed, the train power is modified from the unconstrained curves, depending on the voltage conditions at the given location and time for each train. Figure C-5 and Figure C-6 show power profiles of two selected trains.

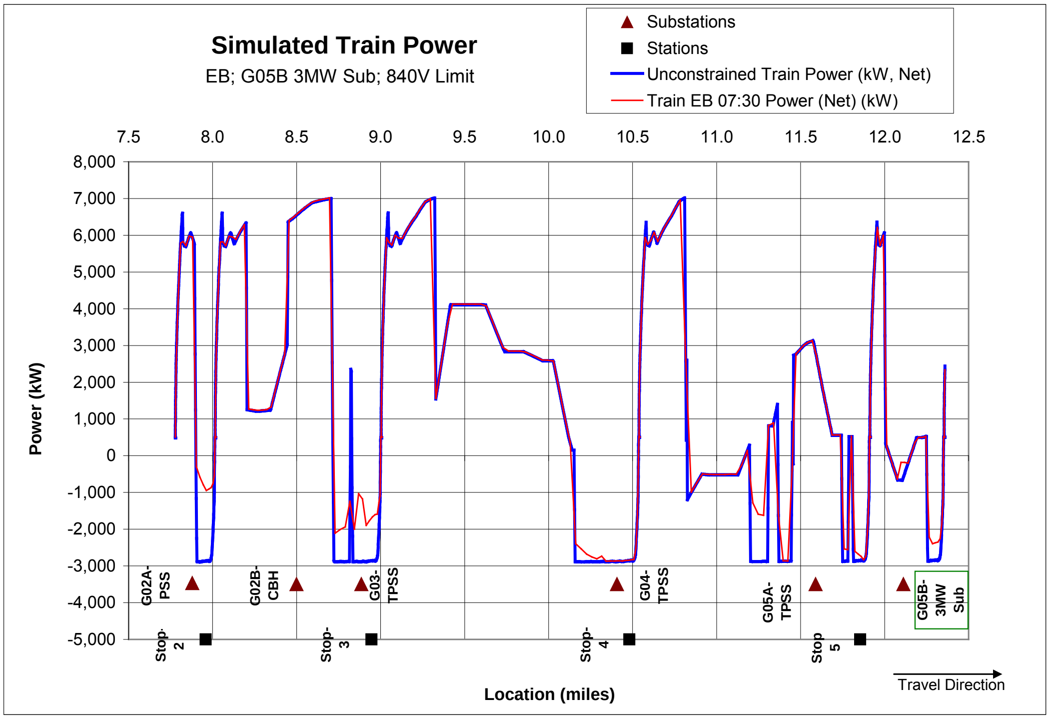


Figure C-5: Power profiles for one eastbound train (metro rail)

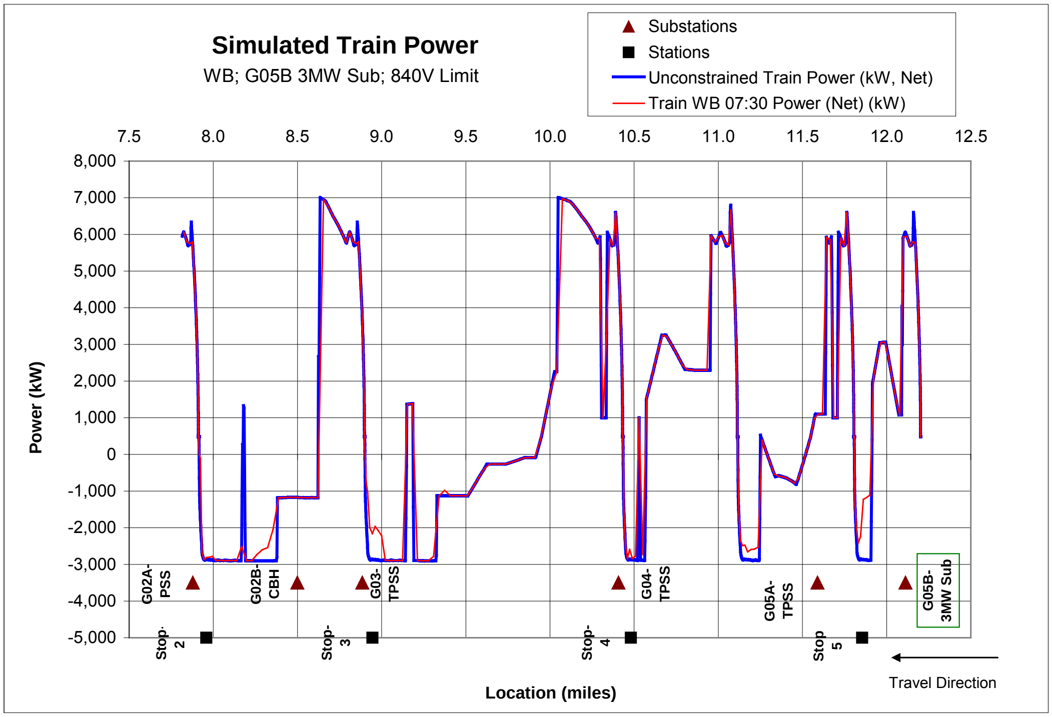
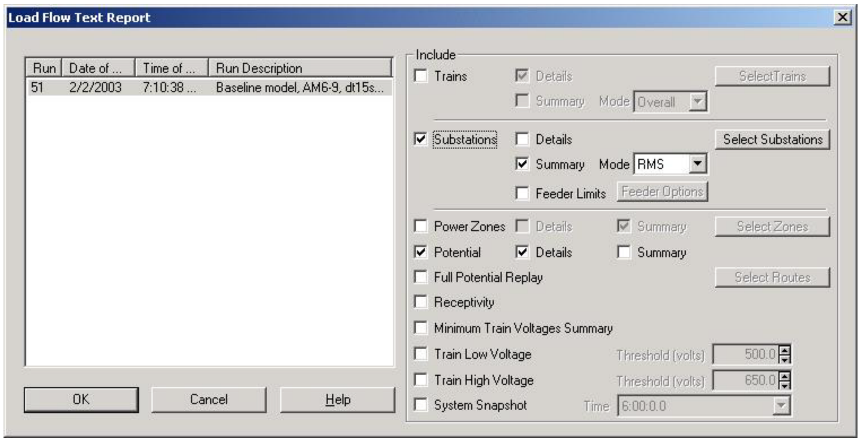


Figure C-6: Power profile for one westbound train (metro rail)

C.3 Organization of Simulation Results

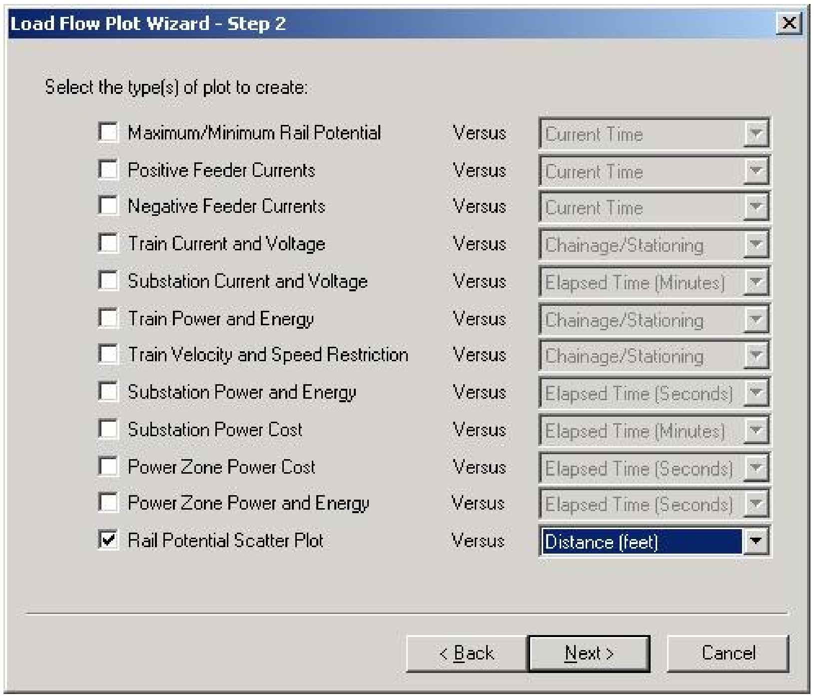
The simulation results are stored in binary data files. A dedicated report generator was developed to present the results in both graphical form and numerical form. Both forms of output can be exported to electronic files. These files can be used for report writing and further analysis. The report and plot wizards of the report generator are shown in the following figures.



Run	Date of ...	Time of ...	Run Description
51	2/2/2003	7:10:38 ...	Baseline model, AM6-9, dt15s...

☐ Trains ☑ Details ☐ Summary Mode Overall
☑ Substations ☐ Details ☑ Summary Mode RMS ☐ Feeder Limits
☐ Power Zones ☐ Details ☑ Summary
☑ Potential ☑ Details ☐ Summary
☐ Full Potential Replay
☐ Receptivity
☐ Minimum Train Voltages Summary
☐ Train Low Voltage Threshold (volts) 500.0
☐ Train High Voltage Threshold (volts) 650.0
☐ System Snapshot Time 6:00:0.0

Report generator text report wizard



Select the type(s) of plot to create:

☐ Maximum/Minimum Rail Potential Versus Current Time
☐ Positive Feeder Currents Versus Current Time
☐ Negative Feeder Currents Versus Current Time
☐ Train Current and Voltage Versus Chainage/Stationing
☐ Substation Current and Voltage Versus Elapsed Time (Minutes)
☐ Train Power and Energy Versus Chainage/Stationing
☐ Train Velocity and Speed Restriction Versus Chainage/Stationing
☐ Substation Power and Energy Versus Elapsed Time (Seconds)
☐ Substation Power Cost Versus Elapsed Time (Minutes)
☐ Power Zone Power Cost Versus Elapsed Time (Seconds)
☐ Power Zone Power and Energy Versus Elapsed Time (Seconds)
☑ Rail Potential Scatter Plot Versus Distance (feet)

Report generator plot wizard

C.4 Post-Processing of Simulation Results

Very often the numerical results are exported by the Report Generator to CSV type files, which are used in Excel to generate tables and plots for analysis and reporting.

The following table shows a processed load table in Excel.

Simulated Substation Average Power (kW)

Headway	G02A-TPSS	G02B-CBH	G03-TPSS	G04-TPSS	G05A-TPSS	G05B-CBH	Total
2min	2,797	0	3,502	3,816	3,405	0	**13,520**
5 min	1,206	0	1,336	1,415	1,657	0	**5,614**
15 min	434	0	526	507	581	0	**2,048**

Figure C-7, Figure C-8 and Figure C-9 show processed graphical plots from these data.

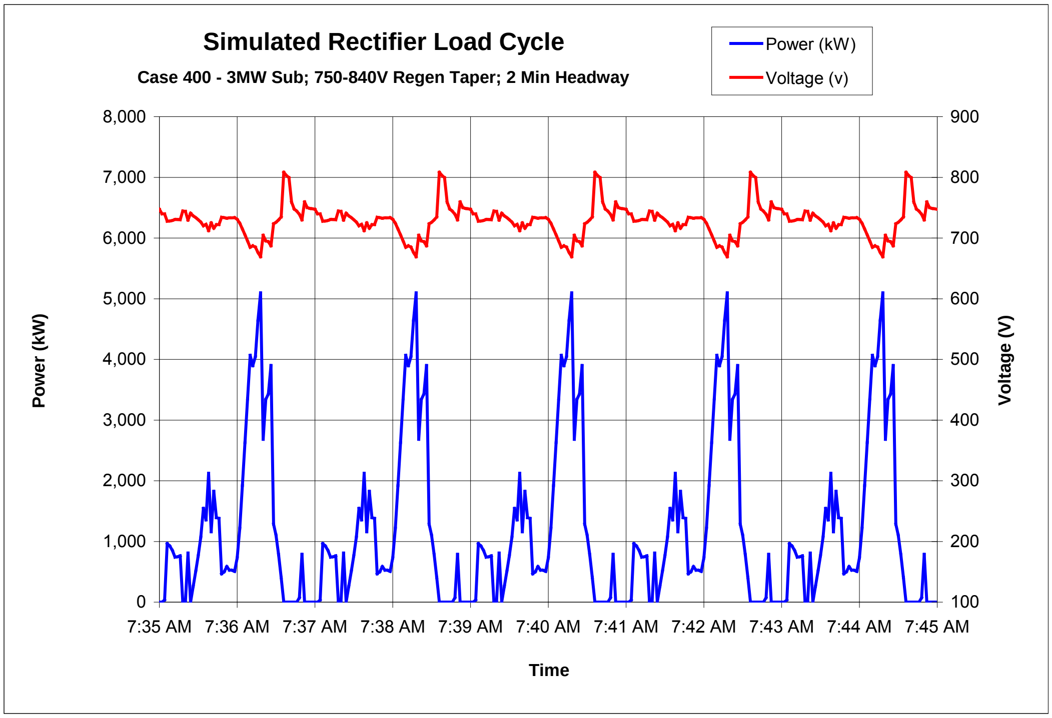


Figure C-7: Rectifier load cycle plot processed in Excel

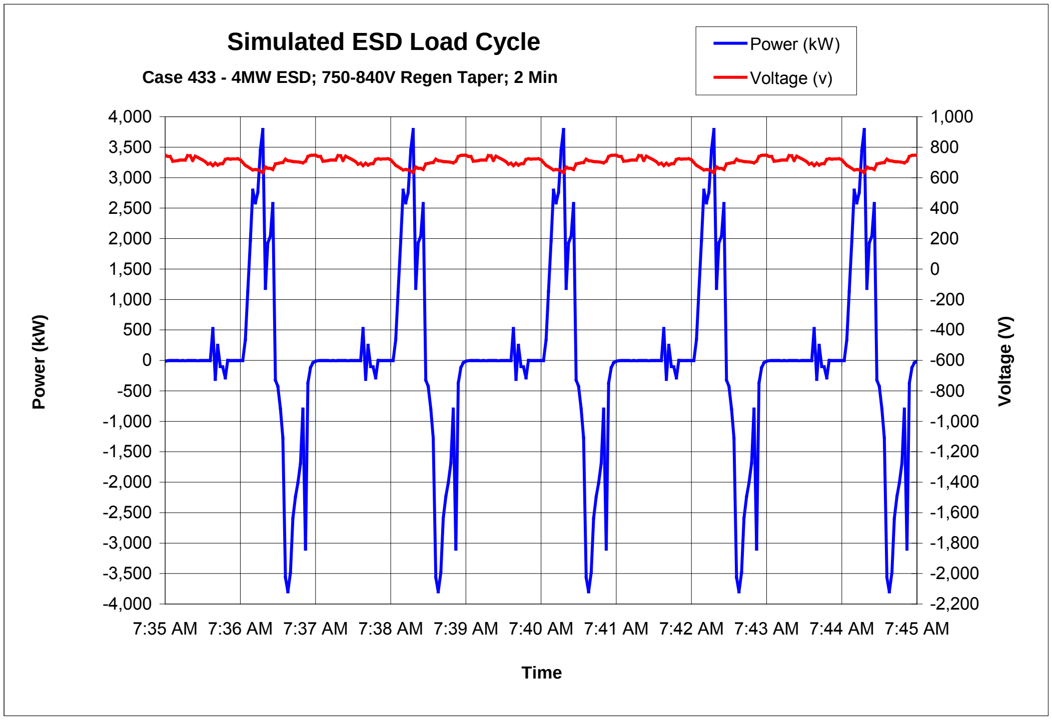


Figure C-8: ESD load cycle plot processed in Excel

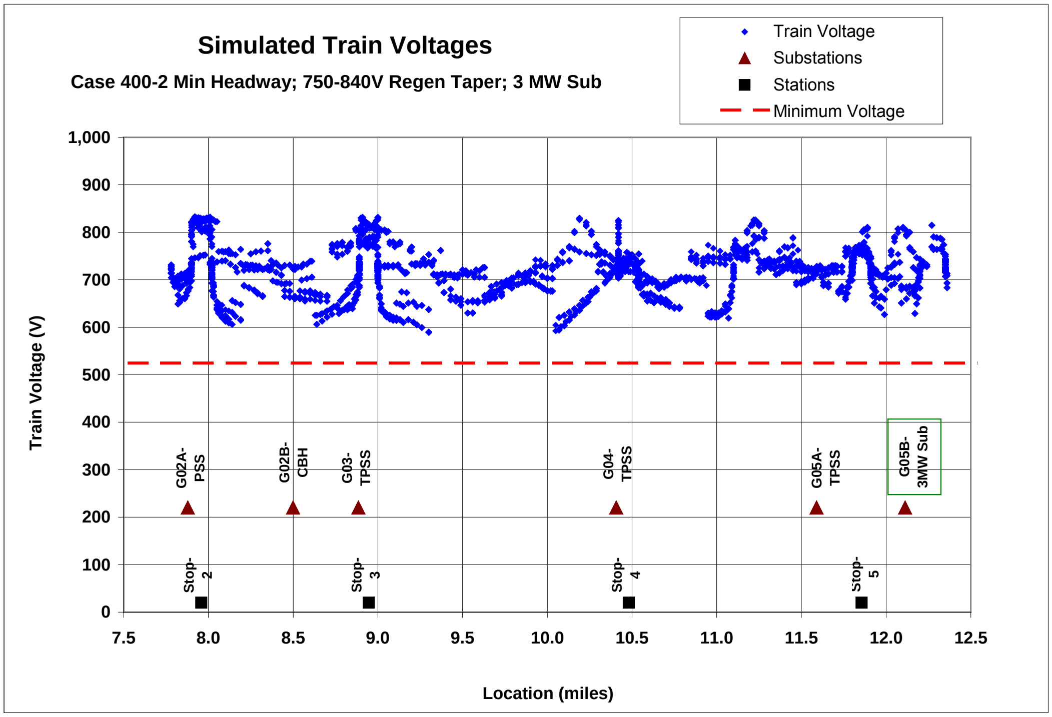


Figure C-9: Train voltage plot processed in Excel

C.5 Software Validation

The software algorithm was validated by comparing simulation results against hand calculation results for a number of scenarios [4].

The software was also validated by comparing simulation results against utility billing records for a past traction power study project. A large volume of data was provided by the utility company in the form of recorded power demand (kW) for each substation. The utility company billed these by time of day, for 24 hours each day. Altogether, 13 months' data was made available from January 2002 to January 2003.

A number of load flow simulation runs were then carried out. The results from the load flow model were compared against the billed data. Two items of data were compared. These are:

- 30 minute interval peak power demand (in kW) for both summer and winter
- Energy consumption (in kWh) for summer months, winter months and a whole year

Both items showed very good agreement between simulated results and the billed data.

The load flow results for peak power demands for both summer months and winter months were within five percent (5%) of the billed data. This is shown in the following table.

Comparison between load flow results
& the billed data (weekday kW power demand)

Time	30 Minute Interval Peak Power Demand Difference %
Summer Months	103.5%
Winter Months	100.9%

The load flow results for energy consumption were within five percent (5%) of the billed data. This is shown in the following table.

Comparison between load flow results
& the billed data (kWh energy consumption)

Time		Energy Consumption Difference %
Weekday	Summer Months	104.7%
	Winter Months	103.9%
	Annual Average	104.5%
Saturday	Summer Months	98.4%
	Winter Months	98.4%
	Annual Average	98.4%
Sunday	Summer Months	95.9%
	Winter Months	96.9%
	Annual Average	96.2%