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Energy Storage and Alternatives to Improve Train Voltage on a Mass Transit System

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ENERGY STORAGE AND ALTERNATIVES TO IMPROVE TRAIN VOLTAGE ON A MASS TRANSIT SYSTEM

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ABSTRACT

The wide separation of substations in the Bay Area Rapid Transit system's transbay tunnel contributes to voltage sag when power demand is high. In the future, expansions to the system will exacerbate this problem by increasing traffic density. Typically, this situation is remedied through the installation of additional substations to increase the system's power capacity. We have evaluated the efficacy of several alternatives to this approach – specifically, installation of an 8 megajoule energy storage system, modification of the existing substations, or reduction of the resistance of the running rails or the third rail. To support this analysis, we have developed a simple model of the traction power system in the tunnel. We have concluded that the storage system does not have sufficient capacity to deal with the expected voltage sags; in this application, the alternatives present more effective solutions. We have also investigated the potential impact of these system upgrades on expected future capital outlays by BART for traction power infrastructure additions. We have found that rail or substation upgrades may reduce the need for additional substations. These upgrades may also be effective on other parts of the BART system and on other traction power systems.

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Introduction and Summary of Conclusions

The Bay Area Rapid Transit (BART) system sporadically experiences voltage sags in the East Bay – San Francisco transbay tunnel.[1] Voltage sags may result from insufficient power supply, as during a substation outage, or from large power demand, as during train accelerations. BART delivers power to its trains through DC powered third rails, which are nominally above 1000 V. When a power outage occurs or the power demand from trains is high, the rail voltage drops, and if it drops below 750 V, the motors on any affected trains shut off to avoid damage until the voltage recovers.[2] This type of event is of concern to BART as it is hard on the train motors and contributes to maintenance costs, and in addition causes passenger discomfort as the motors switch on and off. Thus, the traction power system is designed to maintain the voltage well above this level at all times. This design constraint has led BART planners to anticipate the need for $75 million of additions throughout the power system in order to handle traffic levels up to the year 2002.

The voltage sag problem in the BART transbay tunnel will become worse in the future unless upgrades or additions to the traction power system are implemented, because of expected increases in traffic density. Trains will be more closely spaced in the tunnel after completion of the extensions to the system that are presently planned or under construction. The standard method to improve train voltage involves installation of additional substations to increase the system's power capacity. In an analysis of the BART traction power system, Parsons DeLeuw (PDL) recommended the installation of additional power capacity based on the requirement that the voltage be maintained above 750 V at the maximum expected future loads and traffic densities, even during substation outages.[3] It may be possible to alleviate the need for some of these additions through other, perhaps cheaper, traction power system upgrades. In this study, we have considered three possible alternatives in the context of the transbay tunnel: installation of an energy storage device, reduction of rail resistance, and substation modification to prevent voltage sag.

To evaluate the efficacy of these alternatives, we have developed a simple electrical model of the BART tunnel,[4] and have employed this model to analyze voltage sag data gathered by Pacific Gas and Electric (PG&E).[1] For four months in 1993, PG&E measured the voltage at a breaker near the middle of the tunnel, and found that the voltage dropped below 850 V on 25 occasions. We have simulated the deepest of these measured sags, using BART records of train motion[5] to identify the locations and behaviors of the trains during these events. We have evaluated the impact of energy storage, modified substations and reduced rail resistance on the measured voltage sag problem in the transbay tunnel. In addition, we have examined these alternatives in the context of potential future sag problems similar to those considered in the PDL study.

The measured severe voltage sags in the tunnel were caused by large power and energy demands from accelerating trains, about 7 megawatts (MW) and 100 megajoules (1 MJ = 1 MW·sec), coupled with large rail losses. When a train in the middle of the tunnel demands power, the voltage at the train drops due to voltage sag at the substations and voltage drop along the rails. Rail losses can be considerable, since a train may be as far as 1.8 miles from a substation while in the tunnel.[6] In the most severe measured voltage sag event, in which the voltage dropped close to 750 V, simulations indicate that approximately 90% of the voltage drop occurred in the rails.

Under normal operating conditions the voltage sag in the tunnel is not deep enough to cause train motors to shut down. Our calculations indicate that this will remain the case even with the short headways expected in the future with the introduction of an advanced automatic train control (AATC[7]) system. With the planned 97 second headways, the calculated train voltages always remain over 750 V. Severe sags do result, however, from off-nominal train behaviors that involve accelerations in the tunnel. Nominally, trains are speed-maintaining in the tunnel and undergo significant accelerations only at the ends where the passenger stations are located. However, events such as traffic backups, interfering trains, or resets of the Sequential Occupancy Release System (SORS)[8] can cause trains to accelerate in the tunnel, thus demanding significantly more power than usual.

Based on simulations of BART train operations in the transbay tunnel under present conditions, analysis of the voltage sags measured by PG&E[1], and discussions with BART staff[9] and other traction power experts[10, 11], we have drawn the following conclusions:

- Anomalous acceleration of multiple trains far from substations leads to unacceptably low train voltages (<800 V) in the transbay tunnel. This occurred at an average rate of approximately once per month over the period measured by PG&E.

- SORS resets that occur while multiple trains occupy the tunnel cause the majority of such events.

- Under present operating conditions, these events rarely result in voltage drops severe enough to cause propulsion cut-outs.

- Over 10 MJ of storage capacity is likely to be required to alleviate events that do cause propulsion cut-outs.

- Over 100 MJ of storage capacity would be required if three trains simultaneously attempted to accelerate in the middle of the tunnel (such as after a delay or a SORS reset).

- The following alternatives to energy storage have the potential to substantially increase the voltage at trains during acceleration-induced sags.

    1. Reduce the power demand by modifying the train control system to prevent simultaneous train accelerations far from substations.

    2. Improve the power supply with:

        a. rail upgrades,

            i. increasing the return path conductivity by connecting an additional conductor in parallel with the running rails, or

            ii. increasing the third rail conductivity; or

        b. substation upgrades,

            i. retrofitting the existing rectifier/transformers with thyristor-controlled rectifiers to maintain the substation output voltage independent of power demand, or

            ii. changing substation transformer taps to increase the nominal system voltage.

- These alternatives may be more cost-effective than either energy storage or the traditional solution of installing additional rectifier/transformers; however, this study gives only first order approximations of the costs associated with each alternative, and additional study is necessary.

- The impacts of these alternatives other than those on train voltage have not been considered; potential drawbacks and even show-stoppers exist which should be considered in a more in-depth feasibility study.

In the future, BART is expecting to operate trains in the tunnel with 97 second headways.[12] This mode of operation will exacerbate the present voltage sag problem. Based on simulations of future train operations, we have reached the following conclusions:

- BART's present traction power system in the transbay tunnel is adequate to maintain the voltage during nominal 97 second headway operations.
- Without system upgrades, a SORS reset during 97 second headway operations would invariably cause a voltage sag severe enough to lead to propulsion cut-outs.
- Closer headway operations will significantly increase the storage size required to alleviate such voltage sags, probably to a level of at least 50 to 100 MJ of storage capacity. Reasonable scenarios, such as start-ups of multiple trains after a delay, may require even more storage capacity.
- Substation and rail upgrades may avert most of these propulsion cut-out events. Moreover, they may substantially improve the voltage during an outage with nominal 97 second headway operations. Thus, such upgrades may reduce the need for additional rectifier/transformers.

Based on these conclusions, we believe that BART should evaluate the feasibility and cost of alternatives before proceeding with installation of an energy storage device or the 15 additional rectifier/transformers identified by Parsons DeLeuw[3] to support future traffic levels.

The modeling and analysis contained in this study target the BART transbay tunnel, but are applicable to other parts of the BART system and other traction power systems where substations are widely separated. Increased running or third rail conductivity is expected to improve the voltage at any location on a system with several miles between substations. Thyristor-controlled substations are similarly effective, and additionally present power and energy management capabilities which may add to their value on BART and on other systems. If at least one of these alternatives is feasible and more cost-effective than additional rectifier/ transformers, further study results would benefit both BART and other similar US transit systems.

The following five sections will elucidate the reasoning which led to these conclusions. The first section describes in detail the cause of the low voltage at BART, including a discussion of the deepest voltage sags measured by PG&E[1]. The second section describes some potential solutions to the voltage sag problem, including energy storage, substation modifications, and rail upgrades. Partial estimates of the costs of these options are presented. The third section introduces the traction power model which we developed to analyze the utility of storage on the BART system, with the details relegated to the appendices. Finally, the fourth and fifth sections investigate the voltage sag problem and its potential solutions in detail, for system operations in the present and in the future.

1. The Problem: Voltage Sag

With the exception of traction power system failures, voltage sags arise from two principal sources, both of which relate to large power demand from trains: voltage drop at the substations, and power loss along the rails between the substations and the trains. Nominally the voltage at BART substations is 1055 V when there is no power load, and drops approximately linearly by 5.3% for every 100% of the rated load.[13] This is referred to as 5.3% regulation. In the transbay tunnel, each substation is rated at 5 MW,[14] so the substation voltage is approximately 1000 V at 5 MW load and 940 V at 10 MW load. Thus, the larger the power demand on the substations from the trains, the more the voltage drops. The voltage at a train may be further depressed by losses in the rails. The DC electrical current from the substations must travel through the contact (or third, or powered) rail to the train, and then must return to the substations via the running rails. In the process, power is lost to heat due to the resistance of the rails, and the voltage drops in proportion to the rail length. Over long distances (on the order of a mile), the associated voltage drop may be significant. In general, whenever there is significant power demand from the trains, voltage sag occurs as a result of power drop both at the substations and in the rails.

Voltage sag is a nonlinear process on the BART system because of the nature of the train motors. When a train is given a command to travel with a certain velocity and acceleration, its motors will demand the power necessary to comply, if possible. However, the power received by a train is the product of the voltage at the train times the current from the substation, and the current in the rails causes the voltage at the train to drop. In order to obtain the required power, the train must then demand more current at the suppressed voltage, and the increased current causes the voltage to drop further. This "feedback" mechanism causes a nonlinearity in the relationship between train power and train voltage. Once enough power is being drawn to cause a significant voltage sag, small increases in power demand can lead to large drops in voltage. In the transbay tunnel, where there is a distance of over three miles between substations, large power demands in the middle of that distance can cause the voltage to drop precipitously.

1.1. Voltage Sag in the Transbay Tunnel

Although voltage sag at BART is not limited to the transbay tunnel, it is a good location for studying the occurrences, causes, and possible remedies of voltage sag. Figure 1.1 shows a diagram of the BART tunnel between Embarcadero station in San Francisco and West Oakland station in the East Bay.[6] The depth of the tunnel is exaggerated in order to point out the hill in the middle; as will be discussed later, trains passing over this hill contribute to voltage sags. With present operations, these sags are small. However, in future operations with more closely spaced trains, the presence of this hill may become an important contributor.

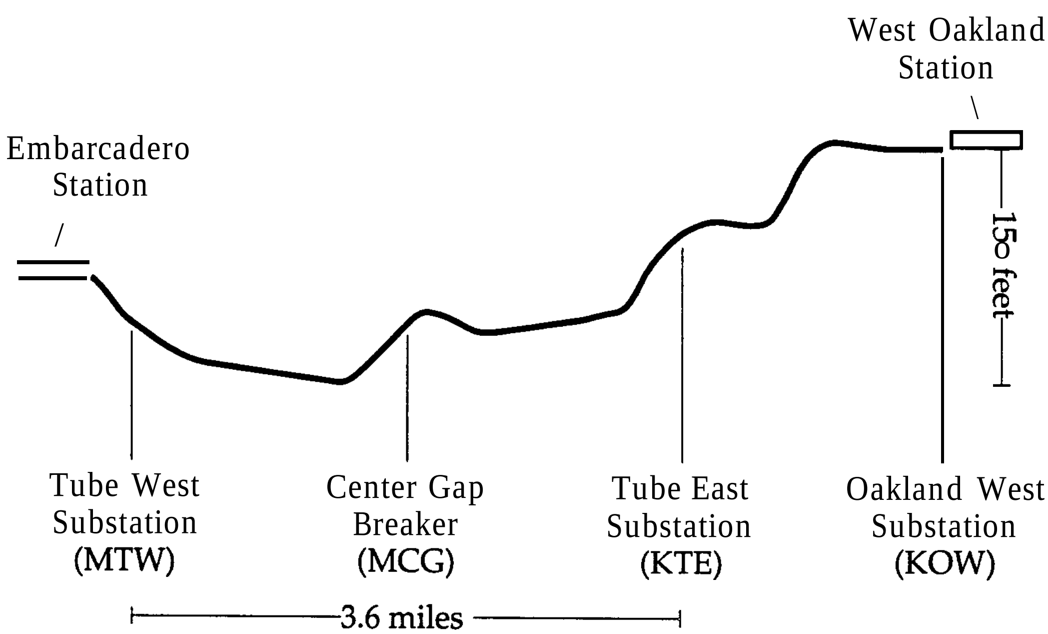

Figure 1.1. Side-view of the BART transbay tunnel, with the vertical scale expanded by a factor of 50. Locations of the substations and of the Center Gap Breaker are indicated.

As will be shown, the voltage sags on the present system are typically caused by trains in the middle of the tunnel accelerating, which is an off-nominal condition. Normally, trains accelerate as they pull out of the passenger stations at the ends of the tunnel. In the region between the Tube West and Tube East substations, trains normally travel at a constant speed and the power demand is small. However, under certain conditions, anomalous train accelerations may occur in the middle of the tunnel and cause severe voltage sags. For comparison, a train traveling at a constant 68 mph on level track demands less than 2 MW of power, and on a two percent uphill grade such as in the tunnel, 4 MW; whereas an accelerating train may demand over 7 MW. Thus, accelerating trains draw significantly more power than speed-maintaining trains, and can cause voltage sags.

1.2. The Causes of the Measured Sags

In the "BART SMES Application Scoping Study"[1,15] PG&E monitored the voltage at the Center Gap Breaker (MCG) which is located midway between the tube substations, as shown in Figure 1.1, for four months. Of the voltage sags measured by PG&E, we examined BART occupancy records[5] (records of train locations) during the ten events in which the voltage at MCG dropped below 820 V. Nine of these ten sags were identifiable from BART's records as due to trains accelerating near the middle of the tunnel. (We were not able to determine the cause of the tenth sag.) One of the nine was due to trains "interfering," where a train traveled anomalously slowly and a following train repeatedly accelerated, caught up to the slow train, decelerated, and fell behind again. One was due to a train stopping near the middle of the tunnel and subsequently starting up while two other trains were nearby. The remaining seven events were due to resets of the Sequential Occupancy Release System (SORS) that occurred while two or more trains were near the middle of the tunnel.

SORS is a computer-based process that works together with BART's Automatic Train Control (ATC) System to track train movements.[8] Occasionally, this system reports the presence of a stationary train that does not actually exist, and the system must be reset. SORS resets in the tunnel temporarily change the effective speed limit from 68 mph to 25 mph; when the speed limit subsequently returns to normal, all affected trains simultaneously attempt to accelerate, drawing ~7 MW of power each for about 20 seconds. In the worst measured SORS-related voltage sag, two trains – one traveling in each direction – were approximately 1000 feet from MCG. This was the only case where train propulsion appeared to have cut out due to the severity of the voltage sag. The specifications and apparent causes of these ten sags are summarized in Table 1.1.

Table 1.1. The Deepest Measured Sags, Sorted by Depth”

Date	Day	Time	Depth	Duration	Apparent Cause
8/20/93	Fri	6:26:26 AM	761 V	6 s	Interference
10/1/93	Fri	3:18:37 PM	766 V	20 s	(Unknown)
8/9/93	Mon	5:22:56 PM	775 V	23 S	SORS reset
8/31/93	Tues	3:31:39 PM	780 V	21 s	SORS reset
8/2/93	Mon	4:29:14 PM	794 V	26 S	SORS reset
9/17/93	Fri	3:18:37 PM	802 V	14 s	SORS reset
8/17/93	Tues	6:14:39 PM	805 V	18 S	SORS reset
8/18/93	Wed	7:24:50 AM	810 V	14 s	SORS reset
7/21/93	Wed	8:35:02 AM	815 V	6 S	Stopped train
7/7/93	Wed	3:59:07 PM	818 V	7 S	SORS reset

“Depth indicates the lowest measured voltage during the sag; duration indicates the time the voltage remained below 850 V. Numerical data is from PG&E.[1] Note that this table indicates the voltage measured at MCG; the train voltage would be lower, but was not measured. Propulsion cut-outs occur if the train voltage drops below 750V.

The deepest measured voltage sag, which occurred on 8/20, resulted from interfering trains in the center of the tunnel. The train motion (adapted from BART records of train occupancies) is shown graphically in Figure 1.2. A train was traveling well under the 68 mile per hour speed limit, at approximately 50 mph. A second train was following at the speed limit and caught up to the slow lead train. The faster rear train then began a cycle of braking, falling behind, accelerating and catching up to the lead train. This “interference” caused a series of voltage sags, corresponding to accelerations of the rear train. Some indication of this phenomenon is visible at the resolution of the recorded train data, as shown in Figure 1.2; the path of the rear eastbound train (dotted line) deviates somewhat from a constant speed path (solid line). However, the details of the train motion had to be inferred from this data with the aid of the BART track plans and speed limit codes.[6] The recorded locations of the lead train were used to determine track speed codes which would affect the motion of the rear train as a function of time. These speed codes were then applied at the measured locations of the rear train. By this method, we determined the effective speed limit at the position of the rear train as a function of time.

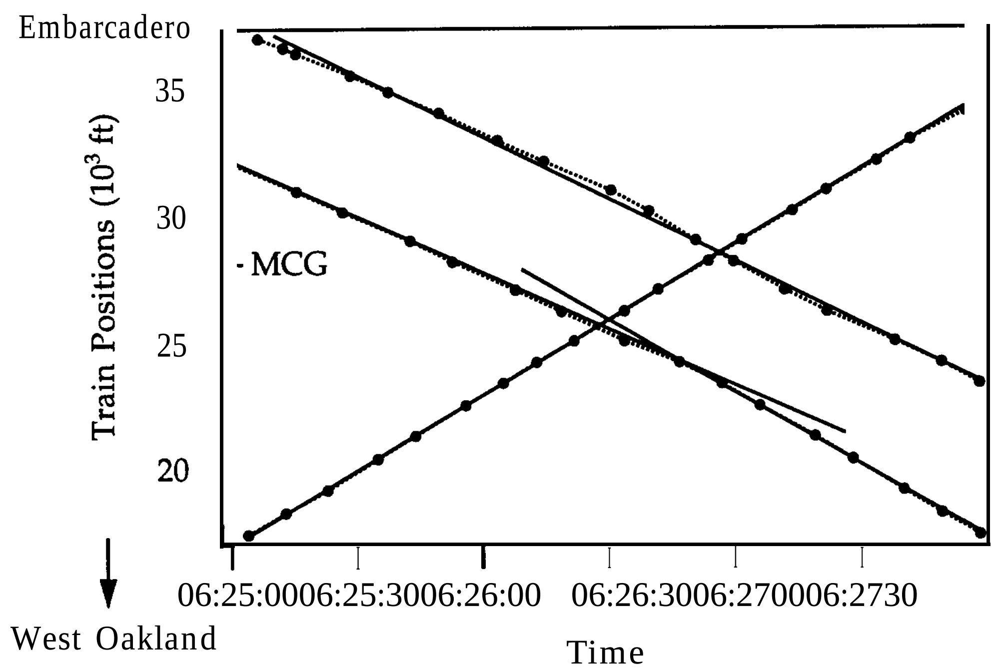

Figure **1.2.** Train motion[5] during theinterference event on Friday 8/2O/93. Each data point corresponds toameasured train location. Straight solid lines are drawn with the average speed of each train. The lead eastbound train (the lower line moving down on the graph) was traveling slowly and causing interference.

The measured voltage sags[1] are shown in Figure 1.3, along with the inferred speed limit as a function of time for the rear train. Each time the speed limit dropped, the train braked to slow down; and each time the speed limit recovered, the train accelerated and caused the voltage to drop. The four sags between 6:26:20 and 6:27:00 could only be explained by assuming a maximum speed of 78 mph, rather than the typical 68 mph. This indicated the trains were operating under Performance Level 1 (PL1), which is used when trains are behind schedule.

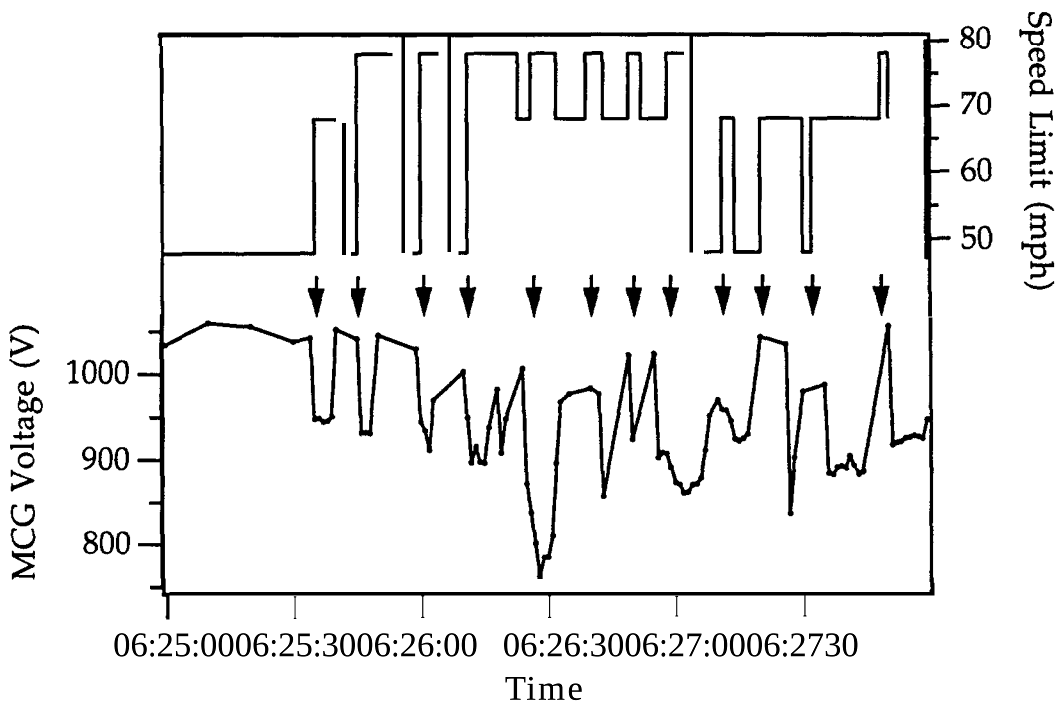

Figure 1.3. Theinferred speed limit fortheinterfering train andthe series of sags measured on 8/20/93 as a function of time. Arrows indicate times when the speed limit increased, causing the train to accelerate. The speed limit data was shifted by 8 seconds to synchronize the two clocks.

All but one of the voltage sags remained well over 800 V. However, the worst of these sags dropped almost to 750 V. This was caused by something of a coincidence: as the two interfering trains passed the middle of the tunnel (MCG), a train passed by MCG traveling in the opposite direction. In addition, the slow lead train accelerated up to full speed, as shown by the discontinuity in slope in Figure 1.2. So three trains were simultaneously in the center of the tunnel, and two of these were accelerating. Although this was the deepest recorded sag event, this set of circumstances was unlikely and does not represent a typical cause of sags.

In the voltage sag caused by interference described above, the voltage remained below 850 volts for only 6 seconds. However, the other four recorded sags that dropped below 800 V had durations on the order of 20 seconds; these occurred on 8/2, 8/9, 8/31, and 10/1. Although there was no indication of a problem in the train occupancy records at the time of the sag on 10/1, the other three cases were clearly due to SORS resets[8] that occurred while two or three trains were present in the tunnel. The deepest of these sags involved two trains that were about 1000 ft east of MCG when they attempted to accelerate. As can be seen in the train occupancy records, shown graphically in Figure 1.4, the trains in the tunnel temporarily slowed down. The two trains that happened to be in the center of the tunnel when the speed limit was raised attempted to simultaneously draw full power (-7.5 MW) for acceleration up to the increased speed limit. This large power demand had to be supplied by substations over 1.6 miles away, so a severe voltage sag resulted. Any SORS reset which occurs while more than one train is in the middle of the tunnel will cause a severe voltage sag, and this type of event is not unlikely. This occurred at least seven times during the four month measurement period, and will become more frequent if traffic density increases.

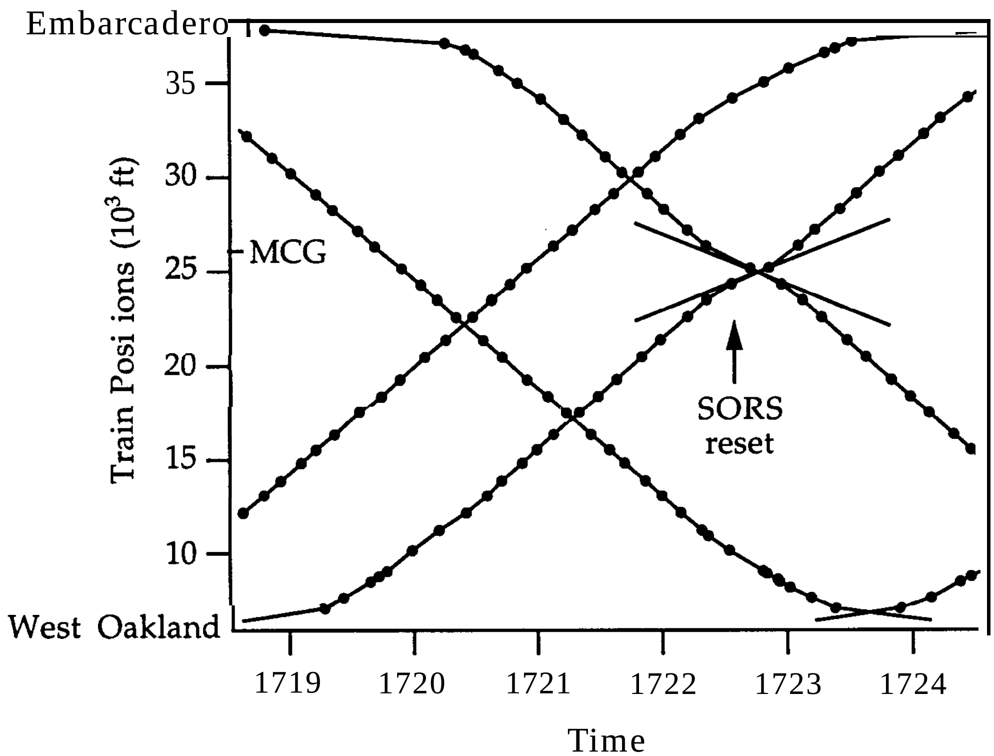

Figure 1.4. Train motion during the worst SORS reset event, which caused a voltage sag on Monday 8/9/93 at 17:22:56 (5:22:56 pm). At 17:22:13, the master control was switched to Restricted Speed, reducing the speed limit in the tunnel to 25 mph and causing two trains near MCG to brake. At 17:22:35, the normal speed limit was restored and both trains simultaneously accelerated.

Since the power demand of the trains themselves cause the voltage to sag, when the motors shut off in response to low voltage, the voltage recovers and the motors turn back on, causing the voltage to drop again. Thus, this type of event is expected to exhibit voltage fluctuations. We suspect that the SORS reset on 8/9 caused the only measured sag event in which the train voltage dropped below 75o V and train propulsion cut out, because on this occasion the voltage at MCG did fluctuate. As will be discussed in section 4, we modeled this propulsion cut-out event, and used it as a test case to compare the benefits of several potential solutions to the voltage sag problem in the tunnel.

2. The Solution: Energy Storage?

The majority of the measured severe voltage sags resulted from multiple trains simultaneously accelerating at full power in middle of the tunnel. Thus, the most obvious solution to the problem would be to change the nature of the train control to avoid this behavior; however, this solution may not be the most straightforward or cost-effective. BART's present train control system is not sufficiently capable to do this, nor are the control systems of other transit agencies. BART is developing an advanced automatic train control (AATC) system[7] which may be able to prevent such simultaneous accelerations. However, the tactic of reducing power demand through train control is limited, and improvements to the power supply system may still be required. In addition, this may not be an effective solution to the problem of substation outages, which can lead to low voltage even during nominal train operations. As alternatives, we analyzed the efficacy of three types of traction power system upgrades to improve the power supply: the addition of energy storage at MCG, substation modifications, and rail upgrades.

2.1. Energy Storage

In the mode being considered for application in the tunnel at BART, energy storage technology[16, 17] simply collects energy from the power system at times when it is available so that it may be used at times when energy is scarce. (Storage has other modes, such as allowing recovery and delayed re-use of braking energy, but this is outside the scope of this study.) As shown generically in Figure 2.1, in this mode storage is integrated into the power system between the power source and the user. In the absence of storage, the power lines must provide all the energy demanded by the user at all times. However, the user may occasionally wish to exceed the limits of the power delivery system. Energy storage systems may be employed to allow the user this flexibility by charging while power demand is low and discharging when extra power is required.

As indicated in Figure 2.1, a power conversion system (PCS) is situated between the power source and the storage device. The PCS is designed for the type of input power, the type of storage device, and the required output power. Energy may be stored in many forms, some of which are summarized in Table 2.1. A familiar form of energy storage is battery storage. In order to meet the voltage and capacity (megajoule) requirements of a particular application, hundreds of battery units may be connected in series and in parallel, and controlled by a single PCS unit.

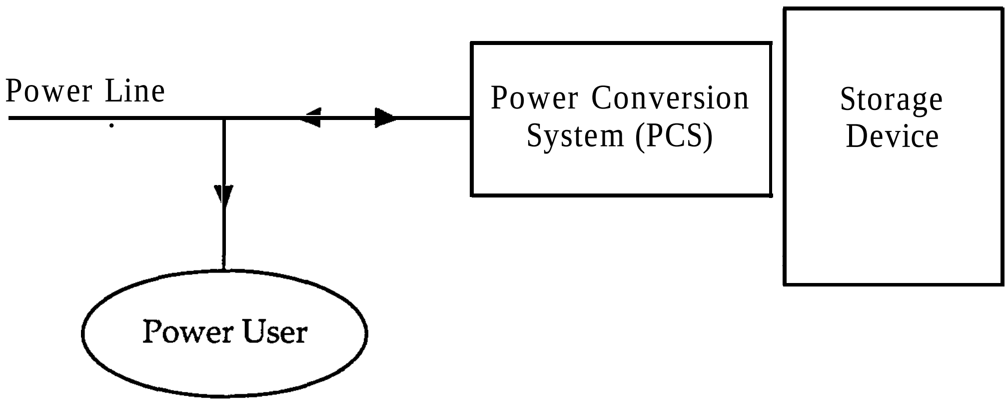

Figure 2.1. Generic energy storage integration into a power delivery system.

Table 2.1. Examples of Energy Storage Media

Storage Unit	Form of Energy
Battery	Chemical
Superconducting Magnet (SMES)	Magnetic Field
Capacitor	Electric Field
Flywheel	Mechanical
Compressed Air	Thermodynamic
Fuel Cell	Chemical

Energy may also be stored in a magnetic field by a superconducting magnetic energy storage (SMES) system. 1'Ig'19 This form of energy storage basically consists of a coil of superconducting material. A superconductor does not have any resistance, so a current injected into it will remain there with no loss. A current loop creates a magnetic field, and this is where the energy is stored. A SMES system typically has either a solenoid or a toroid of superconductor, and the magnetic field may or may not be shielded. The device may consist of one large coil, or may be constructed in smaller units and strung together, as for batteries.

Energy storage devices may be located on each train (on-board storage) or fixed in one location on the track (wayside storage), as shown in Figure 2.2. This study considers only wayside storage; specifically, storage located in the middle of the East Bay-San Francisco transbay tunnel. The "BART SMES Application Scoping Study" prepared by PG&E[1] considered both batteries and SMES, as well as the non-storage alternative of a pulsed rectifier. The functional specifications for these units included an energy capacity of 8 MJ, a maximum current of 4000 A, a pulse duration of 5 seconds, and a delivery voltage of approximately 800 V. The corresponding peak power is approximately 3 MW. In the proposed concept, the storage unit is connected between the contact and running rails at MCG, and resides in the confined space of the gallery in the tunnel. Using these criteria, a SMES system was estimated to cost approximately $1.9 million initially in capital costs, and $240k annually for operations and maintenance; a battery system $1.3 million initially and $130k annually; and a rectifier $2.3 million initially and $220k annually. The cost of SMES was projected to drop below the costs of the other options 5 years in the future, because it is presently a new technology and prices will drop with increased manufacturing experience.[20]

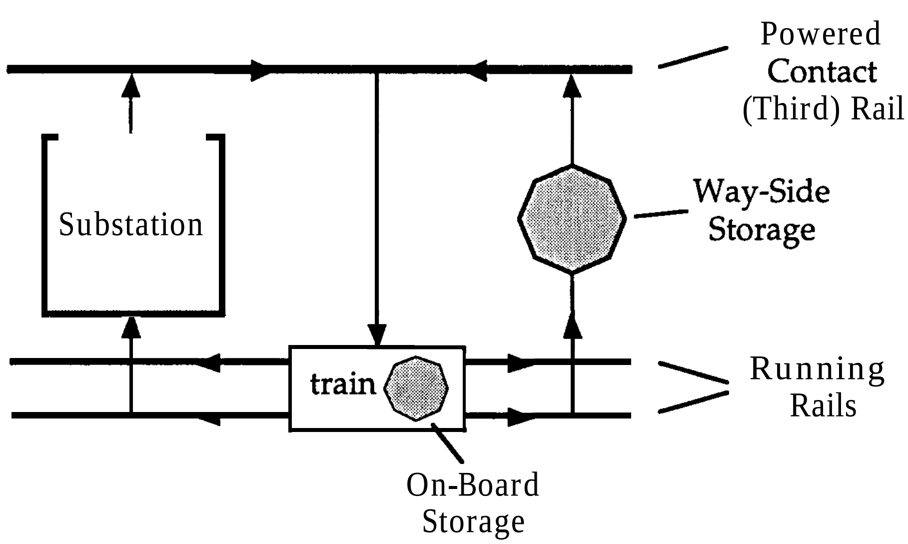

Figure 2.2. Potential energy storage locations on the BART system. Energy storage may be located on a train (on-board) or fixed on the track (wayside). Arrows indicate the direction of DC current flow during storage discharge.

As was discussed in section 1, voltage sags in the tunnel are frequently a result of accelerating trains. A train must accelerate for over 20 seconds to reach full speed from a stand still, so any voltage sag associated with a train accelerating from a low speed is expected to last approximately this long. In addition, an accelerating train draws on the order of 5 MW of power;[4] so the characteristic energy associated with train start-ups is 20 seconds times 5 MW, or 100 MJ. Although it is probable that an energy storage device used to alleviate such sags would not need to supply all the power required by a train, this is the order of magnitude of the energy required for each additional train start-up during a sag event and gives an indication of the potential energy needs. For instance, a sag event simulated by Parsons, Brinkerhoff, McQuade, and Douglas for the PG&E study - where a modeled train was stopped at MCG for six minutes, causing a back up, and three trains subsequently attempted to accelerate in the middle of the tunnel – required a total of 124 MJ of energy to support the voltage. Since this was an extremely severe event involving trains starting up, this large energy requirement is to be expected. It may be possible to handle some voltage sag events with a storage device which is much smaller, such as the 8 MJ device proposed in the PG&E study. However, most voltage sags deep enough to cause propulsion cut-outs would overwhelm a device of this size, since 100 MJ energies are involved in these events.

2.2. Alternatives to Storage

In addition to storage, we considered substation and rail upgrades as solutions to the voltage sag problem. The substations in the tunnel may be modified in several ways to support the voltage during train accelerations. The most obvious, but perhaps not the most practical or effective modification would be to increase the power ratings of the substations in the tunnel. The tube substations KTE and MTW presently have separate connections to each contact rail, each with a 5 MW rating, for a total of 10 MW at each substation.[14] We considered the possibility of increasing this rating to 10 MW on each rail, which would require additional rectifier/ transformers (R/Ts). Adding to the power capacity in this way is the most common solution to low voltage on the system. Neglecting the fact that there is not sufficient room for more R/Ts in the existing substations, this would cost in excess of $1 million per R/T. Making space for the installation could significantly increase this cost. Another possibility would be to raise the output voltage by changing transformer taps. This would be inexpensive, but would raise technical questions such as the effect of higher voltage on equipment.

A substation modification which has high promise for significantly improving transit traction power systems is the installation of thyristors to improve the regulation and to control output voltage. Thyristors are used by many transit traction power systems worldwide and have many advantages over the standard rectifiers used by BART and throughout the US.[21,22] Thyristor systems can actively control the substation output voltage to provide any desired voltage as a function of power demand or of any other parameters such as train locations or acceleration commands. In this analysis, we only consider the possibility of "stiff" substations, meaning that the substation voltage is held at the no-load voltage independent of power load. Other voltage control strategies may be even more beneficial. Although thyristor systems cost more than standard rectifiers, they can be retrofit to existing R/Ts more cheaply than adding additional R/Ts, particularly if there is no existing space for the addition and the building must be expanded or a new substation built. To upgrade the four 5 MW units in the tunnel would cost approximately $1.2 million.[23]

As will be shown in section 4, a large percentage of voltage sag in the tunnel is often attributable to rail losses, so we also considered upgrades to the contact and /or running rail conductivity. The present system has contact rail in the tunnel with a resistivity of approximately 1.9 $\mu\Omega$/ft.[24] We considered upgrading this rail to 1.0 $\mu\Omega$/ft. This could be accomplished by adding a 2 $\mu\Omega$/ft conductor in parallel with each contact rail. Assuming the conductor was aluminum, it would need a cross section of about 7 square inches. Assuming $1/pound for aluminum yields a material cost of less than $50 k/mile for the additional conductor material. Upgrading both 3.6 mile-long contact rails in the tunnel would presently cost BART about $100k/mile or about $1 million in material costs. Adding the ancillary materials and labor may raise the cost to about $2 million in capital costs.[25]

We also considered a decrease in return rail resistance. The present system has approximately 8.7 $\mu\Omega$/ft running rails[24], or 4.35 $\mu\Omega$/ft rail pairs. This resistance could be reduced by connecting an additional conductor in parallel. The two pairs of running rails (one pair for each train direction) are connected approximately every 2000 ft by crossbones. Thus, a single conductor could serve both pairs of rails. The materials required to reduce the effective running rail pair resistance from 4.35 to 2.5 $\mu\Omega$/ft would cost approximately $200k.[26] Upgrading the running rails is considerably cheaper than upgrading the contact rail, because it only requires a single installation, rather than dual-track installation, and fewer materials are required since the rail will not be at high voltage. However, this system may require additional track circuit shunts and /or impedance bonds that would increase these costs.

Additional study would be necessary to further quantify the costs of the various possible system upgrades.

3. The Traction Power Model: Transbay Tunnel Simulations

We developed a model of the traction power system in the transbay tunnel to quantify the voltage sag problem and evaluate the possible solutions. The model was verified with simulations of the measured voltage sag events. A brief description of the model is provided here, as well as a description of the cases used for verification. More detailed information about the model may be found in the appendices.

3.1. Model Overview

The traction power model of the BART system developed at Sandia National Laboratories[4] consists of two main parts – a train power model and a system model. The train power model calculates the power required by a train based on its load and trajectory. This model requires the following input information: train speed, acceleration, number of cars, passenger loading, and track grade. (No integration of acceleration or speed is performed to check train trajectories; the input information is assumed to be correct.) Based on this information, the model calculates the force required for the train to follow the input trajectory, and then uses characteristic motor curves to calculate the corresponding power requirement. The maximum power is not allowed to exceed physical limits on motor current. The trains are included in the system model as power sinks, or power sources during regenerative braking. Since trains actually draw power at each car and are typically 10 cars or 700 ft long, the trains are modeled as two point power sources, one at each end of the train. This approximation produces voltage predictions within a few volts of the predictions for a fully distributed power source, and allows much faster model run times. Although actual train motors shut off if the voltage drops below 750V, our model does not account for this and allows the train voltage to become arbitrarily low. In braking, the train voltage is not allowed to exceed 1150 V.

The system model calculates the power that is delivered by each substation, the corresponding substation voltage, and the voltage at each train in the system based upon train locations and power loads. As shown in Figure 3.1, it models a section of the BART system near the transbay tunnel that includes four substations: Powell Street (MPS), Tube West (MTW), Tube East (KTE), and Oakland West (KOW) substations.[6, 14, 27] The substations in the tunnel, KTE and MTW, have separate supplies for each contact rail, while KOW and MPS are connected to both rails. The substations have a nominal no-load voltage of 1055 V and 5.3% regulation (i.e., the substation voltage drops 5.3% at 100% of the rated load). The running rails are grounded at the substations. Diodes prevent power from flowing into the substations from the contact rail, or out of the substation ground onto the running rail. The nominal track resistances are 1.9 μΩ/ft contact rail and 4.35 μΩ/ft running rail pairs. The model includes all crossbones between running rails, and the gap breaker MCG between contact rails. The 'system' circuit is solved in steady state (DC) for each time step.

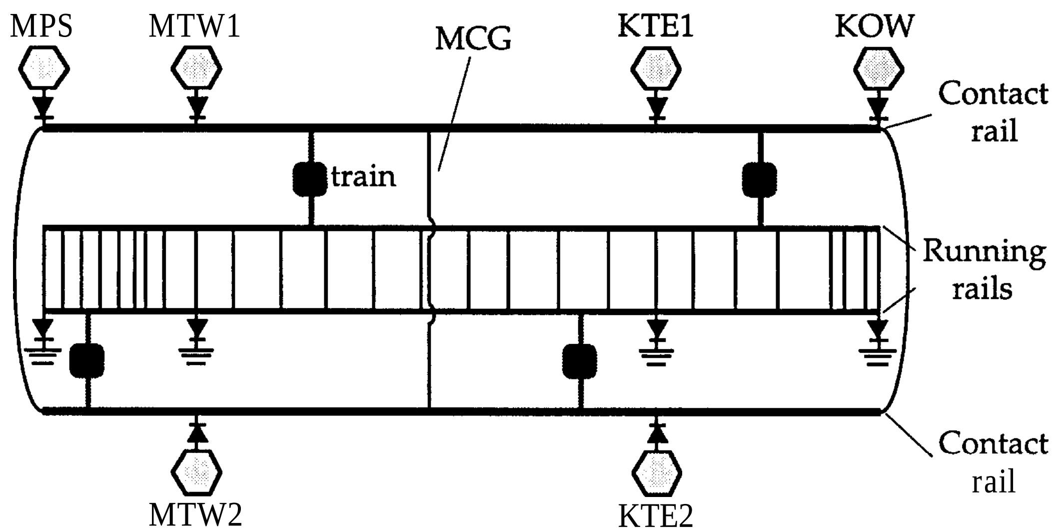

Figure 3.1. Diagram of the electrical circuit used in the traction power model. The thick parallel lines on the top and bottom of the diagram represent the powered contact (third) rails for each train direction. The thin parallel lines in the middle are the pairs of running rails, which serve as return conductors for the current. The connecting lines between running rail pairs are the crossbones, and the line between contact rails is the gap breaker MCG. The hexagons represent substations.

The train motion information that was needed as input for the electrical model was generated in two ways. Train motion related to nominal operations was generated by the train control simulator developed by BART.[28] Simulation of off-nominal train acceleration was accomplished at Sandia with a simple motor current-limited and jerk-limited train acceleration model. In either case a file containing train information for each time step was created and used as input to run the traction power model. If the input trajectory for any train exceeded the capabilities of the motors according to the train propulsion model, then the train power was limited to the maximum possible at the input train speed. There was no feedback from theelectrical model tothetrain motion simulators. Given the input file of train locations and trajectories, the model calculated voltages at the trains, at the substations, and at MCG, and the power provided by the substations, in a self-consistent manner.

Figure 3.2 shows an example of the system voltages calculated by the model during one time step as a function of position along the rails. In this case, two trains are accelerating at full power, and are located near MCG. The voltage is somewhat depressed at the substations, and continues to drop along the rails between the substations and the trains. In this paper, a single value will be given for the voltage at a train, a substation, or MCG; this will correspond to the difference between the contact rail and running rail potentials. Such differential voltages are shown at the top of Figure 3.2, where the train voltage is 762 V, the MCG voltage is 777 V, the KTE substation voltage is 1011 V, and the MTW substation voltage is 1022 V.

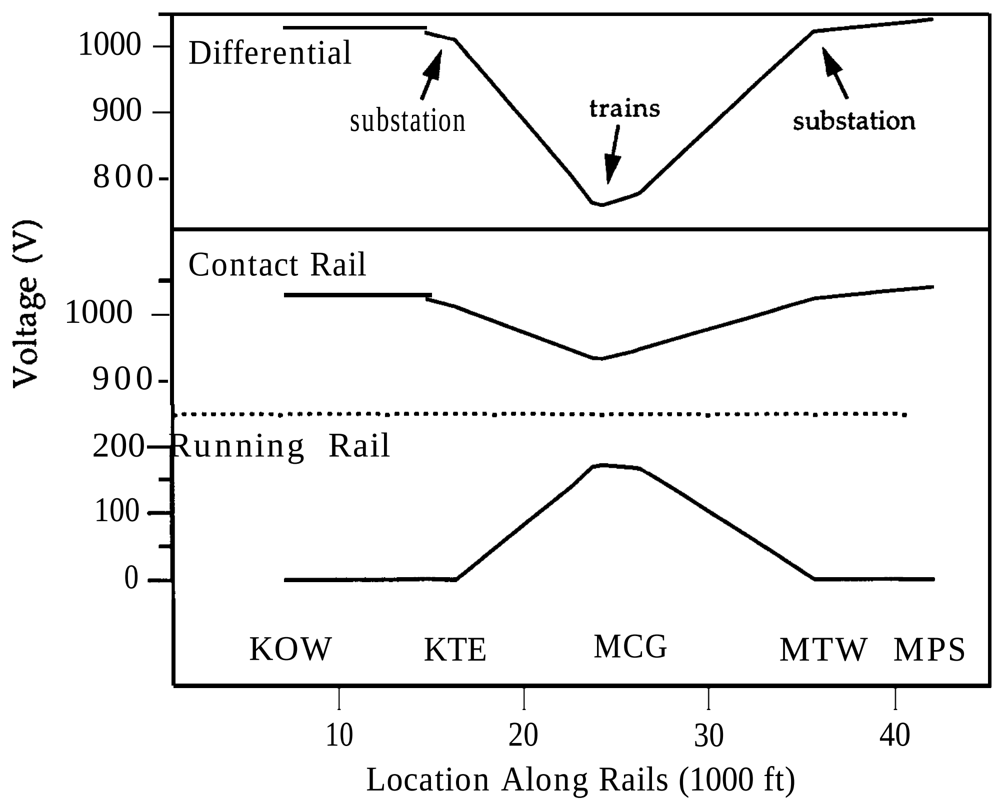

Figure 3.2. Calculated voltages as functions of rail position for two trains accelerating near MCG. The “differential” voltage is the difference between the contact and running rail voltages.

3.2. Testing the Model

The most common type of voltage sag in the tunnel is caused by trains with rush hour loads passing over the hill in the middle of the tunnel, (see Figure 1.1). These sags are not deep, with train voltages typically remaining above 950 V. Using the tunnel model, we calculated the voltage sag that would be expected if a single rush hour train passed over the hill. The predicted voltage as a function of train position as it passes over the hill is shown in Figure 3.3 for trains traveling in each direction through the tunnel. Notice that the train voltage is always lower than the voltage at MCG, since the train is the destination of the current in the circuit, and will therefore always be the lowest voltage point.

The westbound train shown in Figure 3.3a climbs a 1% grade, while the eastbound train in Figure 3.3b climbs a 2% grade, so the voltage drops more in the latter case. In both cases, after passing the backside of the hill, the train climbs a 0.3% grade, causing a secondary sag. This double dipped voltage sag structure was noted twice in the measured voltage sag data. One example is shown in Figure 3.4. The voltage sag in this case was recorded because for one second it dropped an additional 60 V, which we can not explain. Ignoring this feature, the measured voltage data closely resembles the calculations shown in Figure 3.3; however, the sag is deeper than can be explained by a single train. It was therefore deduced that this sag must have been caused by two trains, one traveling in each direction, passing simultaneously over the tunnel hill. A simulation of such a sag caused by two rush hour trains is shown with the data in Figure 3.4. After reaching this conclusion regarding the cause of this sag, we examined BART records of train motion[5] and confirmed that there were indeed two trains crossing near MCG at the time of the sag.

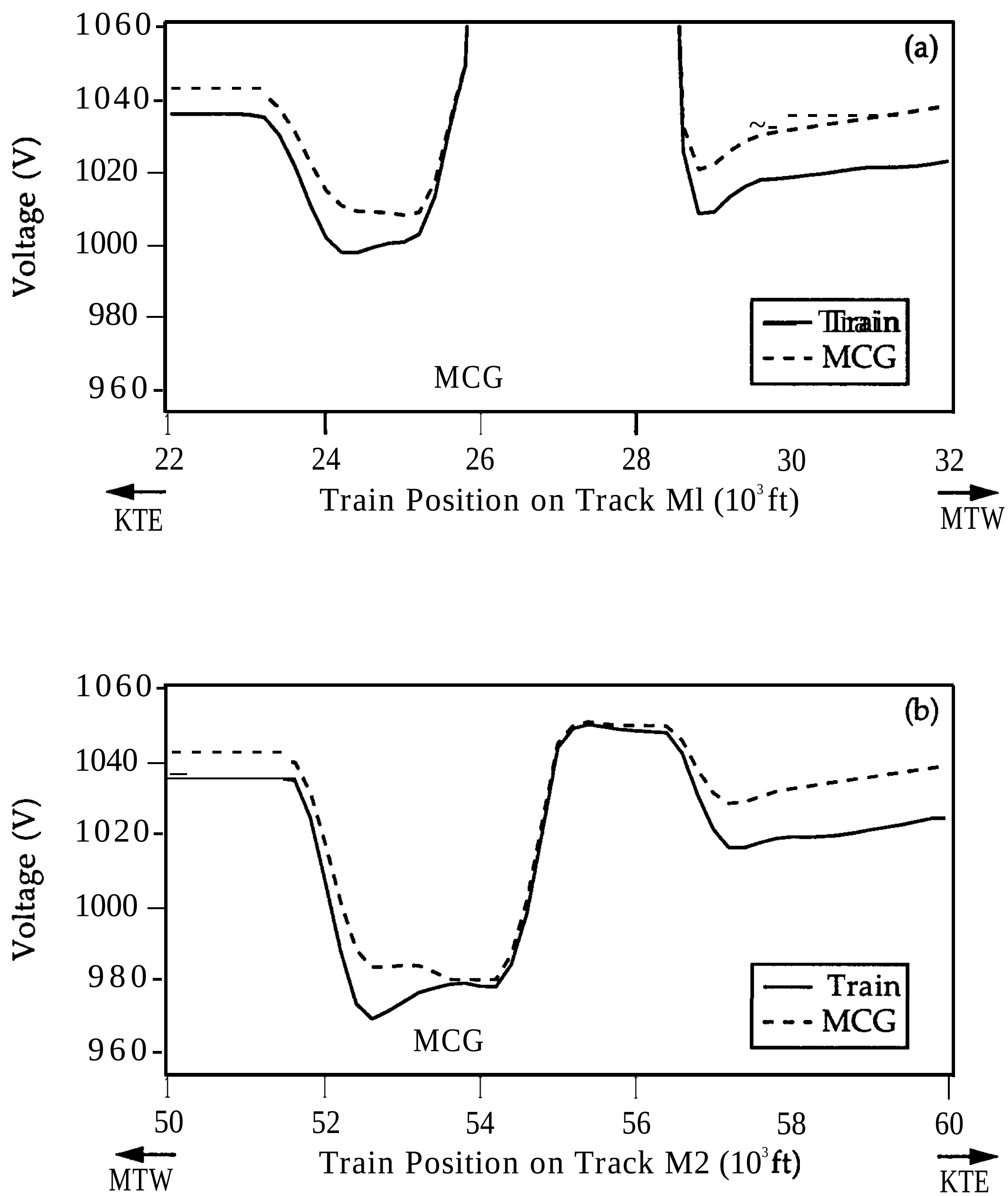

Figure 3.3. Simulated train and MCG voltages for (a) a westbound train and (b) an eastbound train traveling over the hill in the center of the tunnel at 68 mph.[4] This assumes a 10-car train with a rush hour load (120 people per car, 180 pounds each). Tracks Ml and M2 correspond to the tracks running in opposite directions through the tunnel.

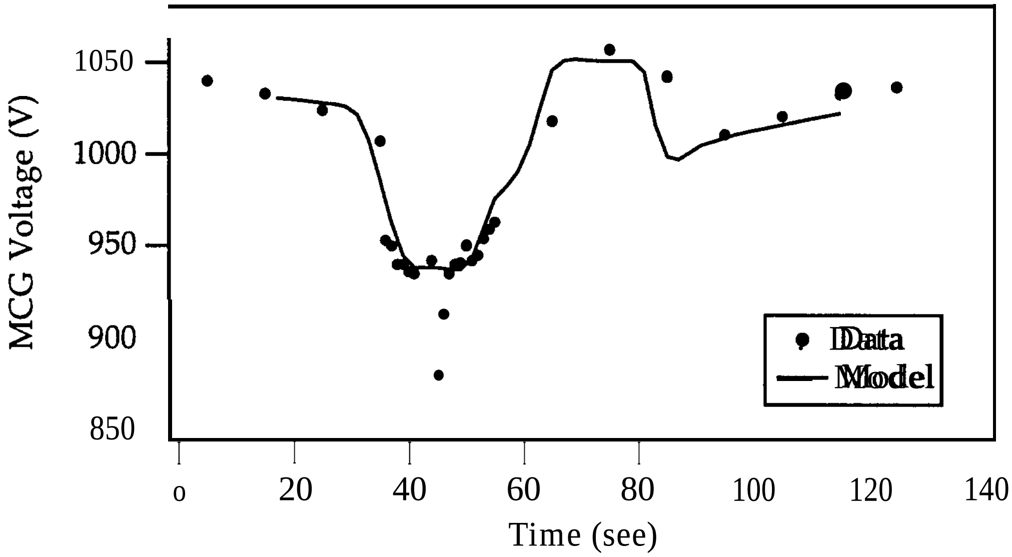

Figure 3.4. Mild voltage sag measured on Friday 6/ 18/93 at 5:28 pm.[1] From the depth and shape of the sag, it was deduced that two trains simultaneously passed over the central hill in the tunnel. The simulated voltage[4] is shown for comparison to the data.

A series of shallow sags was noted on Friday 6/25.[1] As indicated on the train motion plot in Figure 3.5, each time a train passed over the tunnel hill, the voltage sagged. The deepest sag occurred when a westbound train climbed the hill while two other trains were in the tunnel, one of which was nearby on the opposing track. We attempted to model the deep sag, as shown in Figure 3.6. The nominal system voltage was assumed to be 1030 V in this case, because the recorded voltage seemed depressed over several minutes at the time of this sag. Although the general shape of this sag was reproduced, we were not able to replicate the deepest part of the sag while remaining consistent with the recorded train motion. The implication seems to be that a train anomalously accelerated or the power system had a problem during this event, however data is not available to check these possibilities. A two second period of acceleration may not be visible at the resolution of the recorded train position data.

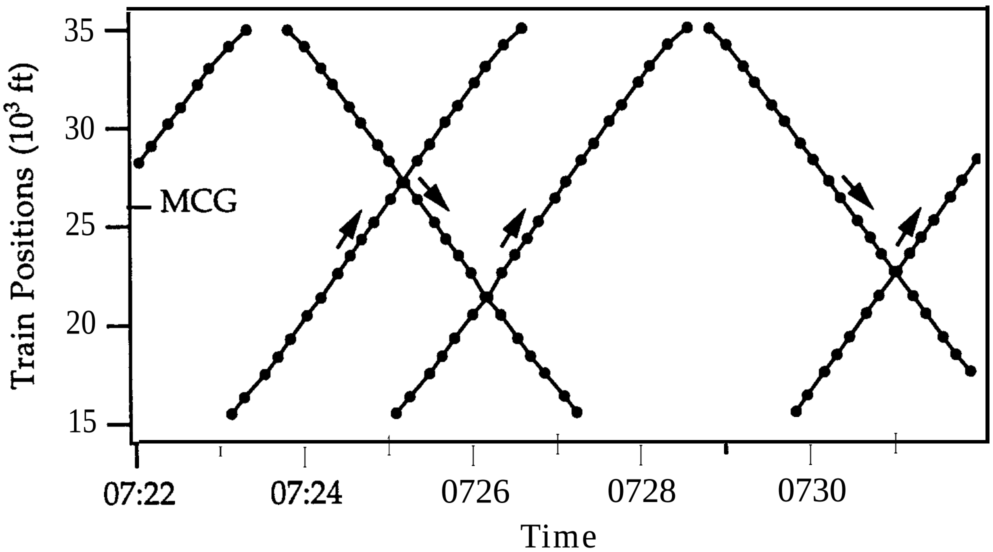

Figure 3.5. Train motion during a series of sags on Friday 6/25/93.[5] Mild sags were measured at 7:24:50, 7:25:35, 7:26:45, 7:30:35, and 7:31:30 am. At each of these times, a train was climbing the hill in the "middle of the tunnel, as indicated by arrows.

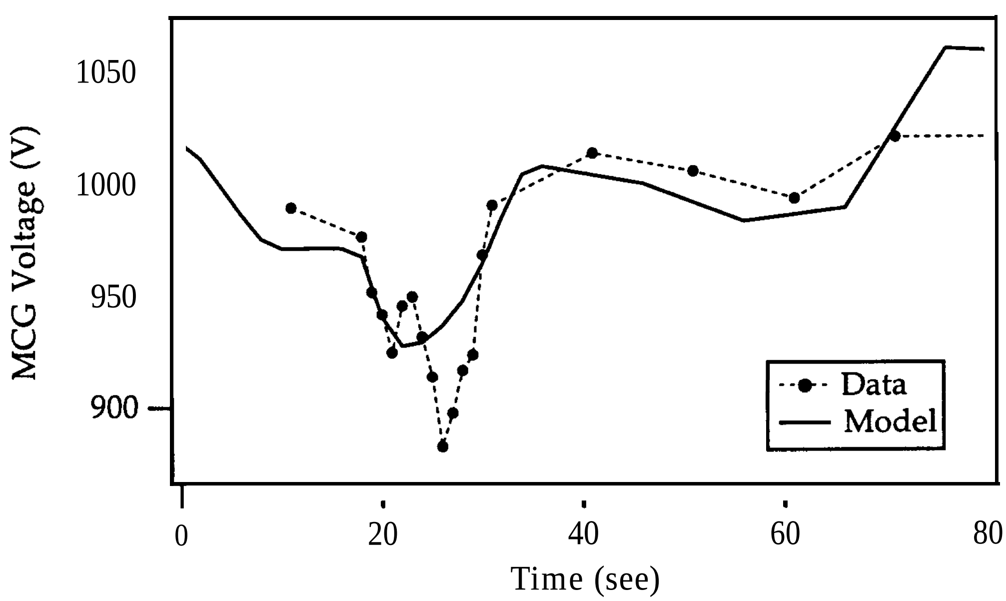

Figure 3.6. The deepest measured voltage sag on 6/25/93, which occurred at 7:25:35,[1] and the simulated voltage[4] for the same period.

Early in the morning on Thursday 6/24, two successive sags occurred. The first of these sags was caused intentionally, when an empty train was stopped near the middle of the tunnel early in the morning while no other trains were in the tunnel. When this train subsequently started up, it caused the measured sag. Using our simple train simulator and the traction power model, we approximately reproduced the depth, shape, and duration of this sag, as shown in Figure 3.7. The measured sag was a bit shallower and lasted a bit longer than the calculated sag, indicating the actual train accelerated more slowly than was predicted by the model, drawing less power and taking longer to reach full speed. The voltage was, however, reproduced to within 10 V.

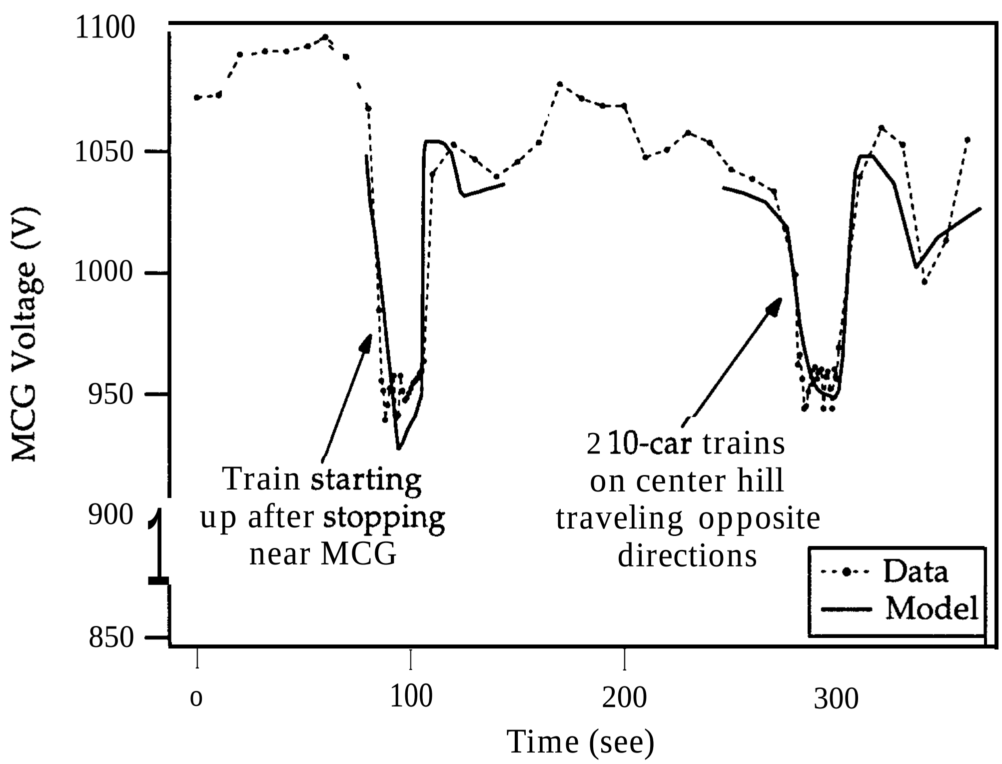

Figure 3.7. Two mild voltage sags measured on Thursday 6/24/93 at 5:18 am.[1] The first was caused by a train intentionally accelerated from a stop near MCG. From the depth and shape of the second sag, it was deduced that two trains simultaneously passed over the central hill. The simulated voltage[4] is shown for comparison to the data.

The second sag appeared to be due to a train passing over the hill at MCG; as described above, simulations of trains going over the hill had this double-dipped shape. However, this early in the morning, the trains would have carried very few people, and the sag from a train would have been much more shallow. We therefore again hypothesized the presence of two trains passing over the hill simultaneously, one in each direction. From the train schedule, this seemed possible ifoneof thetrains had been about l.5 minutes late. The calculated voltage based on this assumption is shown with thedata in Figure 3.7. Later inspection of BART's train location data for this time period confirmed this deduction.

In the next section, simulation of the propulsion cut-out event that was measured on Monday 8/9/93 will be discussed. During this sag, the voltage dropped below 800 V for approximately 20 seconds. As was shown in Figure 1.4, two trains near the middle of the tunnel slowed down temporarily, and then accelerated back up to speed. Initially, we believed that the trains decelerated as a result of the voltage sag. This belief arose because, shortly before the deceleration, the two central trains simultaneously climbed the hill, and because delays in the system caused two more trains to be present in the tunnel at the same time. However, the model did not predict a voltage sag as severe as the measured sag, even given the worst possible scenario consistent with the recorded train location data. Also, the trains decelerated at a rate more consistent with braking than with coasting. These inconsistencies led us to discover BART records that a SORS reset had occurred just before the recorded voltage sag. The trains did brake, and the sag was caused by the trains accelerating when the speed limit was restored to normal.

These successful deductions of train motion through simulations of the voltage data gave us confidence in the traction power model. This allowed us to proceed in using the model to evaluate the impact on voltage sags of the various possible system upgrades.

4. The Propulsion Cut-Out Event: Accelerating Trains

We examined in detail what we believe was the worst measured voltage sag event, which was caused by a SORS reset[8] on Monday 8/9 during the evening rush hour. Large fluctuations in the voltage during this sag indicate train motors may have been turning on and off. We used this propulsion cut-out event as a test case to size the storage device needed to eliminate such events and to investigate the efficacy of other system upgrades.

4.1. Simulation

The locations of the trains in the tunnel at the time of the sag are shown in Figure 4.1. During this event, the voltage at MCG dropped close to 750 V when the two nearby trains simultaneously accelerated. There were several other trains in the vicinity at the time, but they were drawing very little power and had minimal impact. The two trains at the ends of the tunnel were arriving at passenger stations and drawing less than 1 MW. Adding the other trains to the system only deepened the predicted sag by about 10 V; most of the sag was a result of the two trains in the middle of the tunnel. Hence, for simplicity we modeled only the two central accelerating trains.

The measured voltage data and the simulated voltage as a function of time are shown in Figure 4.2. The simulation assumed the following: both trains had 10 cars, initial speeds of 25 mph, and final speeds of 68 mph; the westbound train began 1580 feet east of MCG and carried 650 people; the eastbound train began 340 feet east of MCG and carried 1230 people; and each person weighed 180 pounds. The step in the voltage at the end of the calculated sag resulted from one train reaching full speed before the other because of the hill. The simulated train motors did not shut down, and we used only a rudimentary train motion model to simulate the trajectories of the accelerating trains. Thus, the voltage fluctuations and the exact shape of the voltage sag were not reproduced. However, we believe the depth and duration of the sag was reproduced sufficiently well to allow analysis of storage requirements and alternatives.

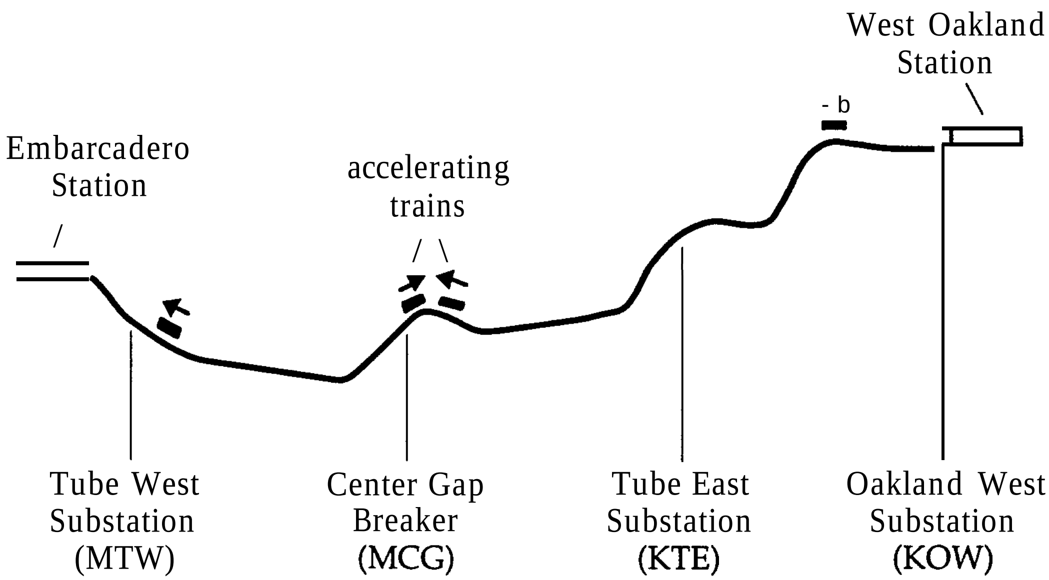

Figure 4.1. Train locations in the tunnel during the propulsion cut-out event, which was measured on Monday 8/9/93 at 5:22:56 pm. Arrows indicate the direction of motion of the trains. Acceleration of the central two trains caused the sag.

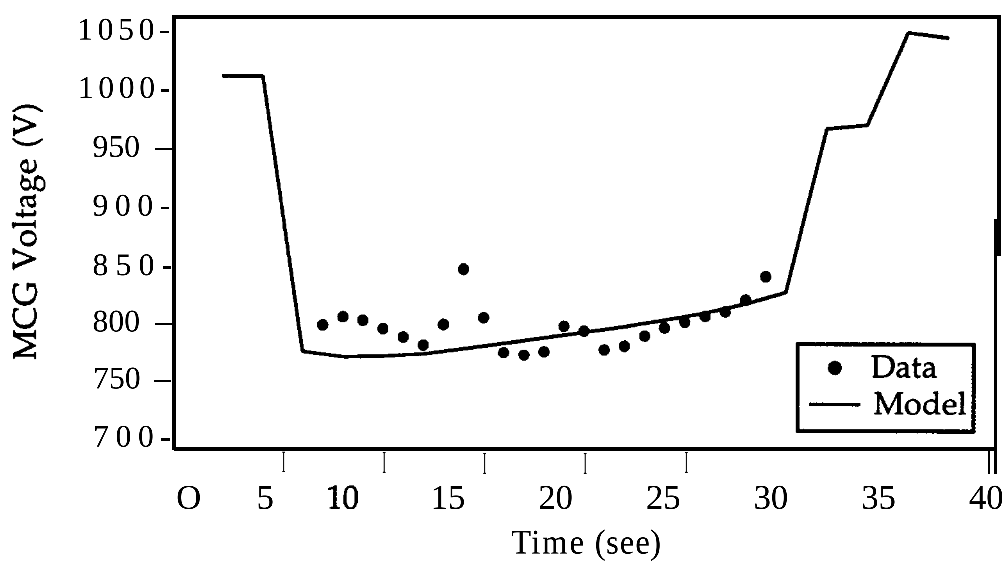

Figure 4.2. Simulated[4] versus measured[1] MCG voltage during the propulsion cut-out event.

Almost all of this sag was attributable to rail losses. Our simulations showed that the bulk of the voltage sag was in the rails, rather than at the substations. Of the nearly 300 V voltage drop, only 35 V occurred at the substations. This was an unexpected and potentially significant result, because it led to the hypothesis that an effective solution to this problem would be reduction of rail resistance. As will be discussed in section 4.3, reduced rail resistance would indeed have a large impact on the depth of such a sag.

4.2. Estimated Energy Storage Requirements

A wayside storage device located at MCG would have to maintain the voltage between the contact and running rails above about 800 V to be reasonably sure the voltage would remain above 750 V at the trains. This 50 V buffer is necessary because the lowest voltage in the system will always be at a train, and this voltage may drop 50 V below the voltage at MCG during a severe sag event, depending on the location of the trains. This principle is demonstrated in Figure 4.3, where calculated voltages are shown for the case of two trains at the same tunnel location simultaneously accelerating. The voltage at MCG, at the train with the minimum voltage, and the total power supplied by the substations are shown as a function of the location of the trains. The voltage sag is the deepest if the trains are in the center of the tunnel (near MCG). However, the difference between the train voltage and the MCG voltage is greatest for trains approximately 1 mile from MCG, nearly reaching 70 V. Although the train voltage does not drop below 750 V at this location, power demand from other nearby trains could cause the voltage to drop further. If the two trains are not located in the same position in the tunnel, then the difference between the train and MCG voltages would not be as great. If a storage device is located at MCG, then it must hold the voltage above at least 800 V in order to have a good chance of keeping all the trains above the cut-out voltage of 750 V.

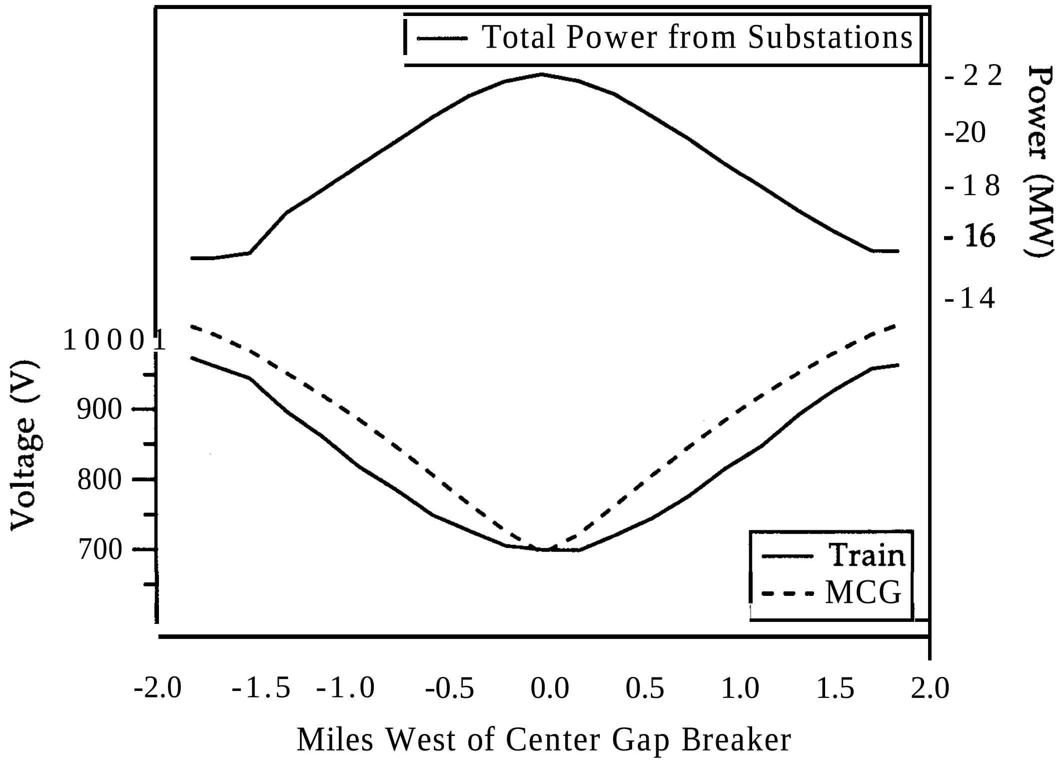

Figure 4.3. Calculated train and MCG voltages and total power consumed when two trains at the same location (one on each track) accelerate at full power, as a function of the distance between the trains and MCG. Each train is assumed to demand 7.5 MW. Notice that for a 15 MW demand in the middle of the tunnel, an additional 7 MW is wasted heating the rails.

For the measured propulsion cut-out event, a storage device at MCG would have required at least 12 MJ of capacity and a 1.1 MW peak power to maintain the voltage above 800 V, assuming the device was capable of providing the absolute minimum power at all times to maintain the voltage. The required storage size is shown graphically in Figure 4.4. The calculated storage requirement is sensitive to the voltage set-point. Maintaining the voltage above 805 V would have required 16 MJ of energy capacity, and 795 V would have required 9 MJ. In addition, the size was determined using nominal values for rail resistances, which are not well known. These values may change as the rails age, and may vary somewhat from location to location.

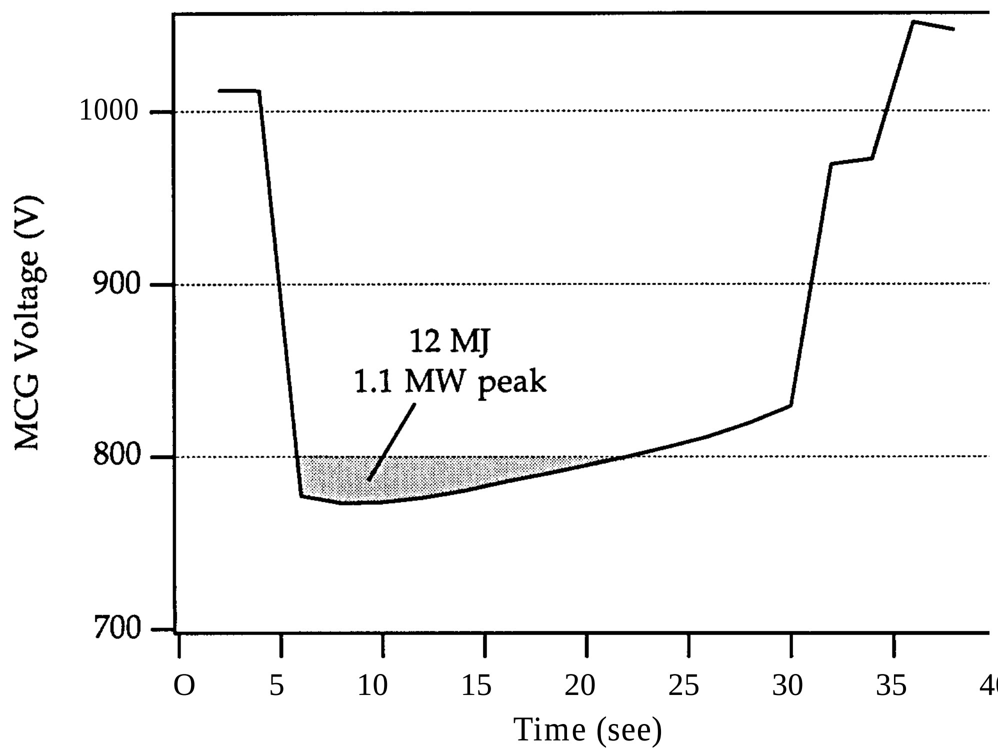

Figure 4.4. Storage required toalleviate thepropulsion cut-out event. This is the energy and power needed in this case to maintain the voltage at MCG above 800V.

The uncertainty in rail resistance andin the exact motion of the trains leads to a large uncertainty in the required storage size. The sensitivity of the depth of the voltage sag, and therefore of the storage requirement, to the rail resistance is shown graphically in Figure 4.5. The calculated storage capacity requirement for this particular event was up to 20 MJ depending on the assumptions made. When making infrastructure decisions, much more conservative values of rail resistance are sometimes used, such as in a study for BART that assumed 2.25 μΩ/ft contact rail and 4.85 μΩ/ft running rail pairs (18% and 11% above the nominal values, respectively).[3] With these values, the model predicted a voltage drop to 650 V, and implied a required storage size for this event of 3.2 MW and 50 MJ.

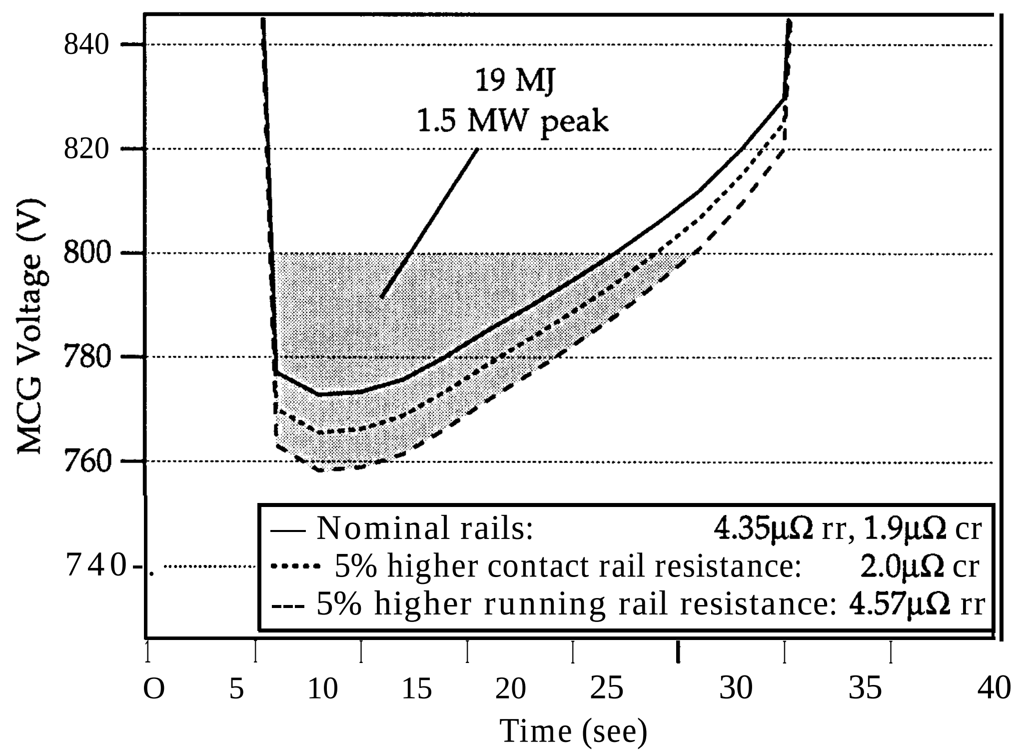

Figure 4.5. Sensitivity to assumed rail resistances. A 5% increase in running rail resistance would raise the required storage capacity in this case by 60%.

For this type of voltage sag, it takes only a small perturbation in the system to go from a sag that does not drop below 750 V to a sag that requires tens of megajoules of stored energy. It should be noted here that, due to the need to hold the voltage at MCG above 800 V, sags below 800 V would discharge the storage even if the trains would not have dropped below 750 V. The measured propulsion cut-out event was extremely marginal, as the calculated train voltage dropped to only 760 V, and it would have required 10 to 20 MJ of stored capacity. The addition of any more power-hungry trains nearby would greatly increase the needed storage size.

A similar event involving three rather than two accelerating trains could easily require 100 MJ of storage. This would occur, for example, if a train stopped in the middle of the tunnel long enough for two more trains to back up behind it, and all three trains simultaneously attempted to start up. As discussed above, two trains accelerating in the middle of the tunnel draw as much power as the present system can provide, causing a voltage sag to nearly 750 V and marginal propulsion cut-outs.

Any additional power demand near MCG would have to come from a separate power source, such as a local storage device, to prevent the voltage from dropping further. If a third accelerating train were present, the entire power for that train would effectively haveto come from storage, thus requiring on the order of 100MJ of energy. This situation was modeled as part of the PG&E study, and was estimated to require 124 MJ of storage.[1]

A 10 MJ storage device may be useful for alleviating small voltage sags if it includes intelligent control that measures the voltage at nearby trains and their locations, rather than simply reacting to the voltage at the storage site (at MCG in this case). This type of control would allow the storage device to be discharged only when the voltage at a train in the tunnel drops close to 750 V. The minimum necessary amount of energy would then be used for any given sag event to hold the trains at a reasonable voltage, rather than wasting energy maintaining MCG at 800 V independent of the actual need at the trains. However, even this sophisticated type of control would handle only marginal sag events, and the 10 MJ storage capacity would still be overwhelmed by events involving more than two accelerating trains.

4.3. Substation and Rail Upgrades

We examined several alternative solutions to the sag problem, again using the propulsion cut-out event as a test case. We considered various types of substation upgrades, including increasing the power rating, improving the regulation, and raising the nominal voltage. The resulting predicted MCG voltages, in comparison to the calculation for the present system, are shown in Figure 4.6. Nominally, the substations in the tunnel are rated at 1055 V, with 5.3% regulation and 5 MW on each rail. Increasing the rated power to 10 MW on each rail improved the calculated MCG voltage during the sag by approximately 20 V. Reducing the regulation to 0%, so that the substation voltage did not sag, or increasing the nominal substation voltage to 1100 V, improved the voltage during the sag by about 50 V. These results are reasonable, because approximately 35 V of the voltage sag is due to sag at the substations. Somewhat more than 35 V may be recovered by preventing substation voltage sag because of the nonlinearity of the system. Preventing substation voltage sag or raising the nominal voltage would hold the voltage at MCG above 800 V during this event.

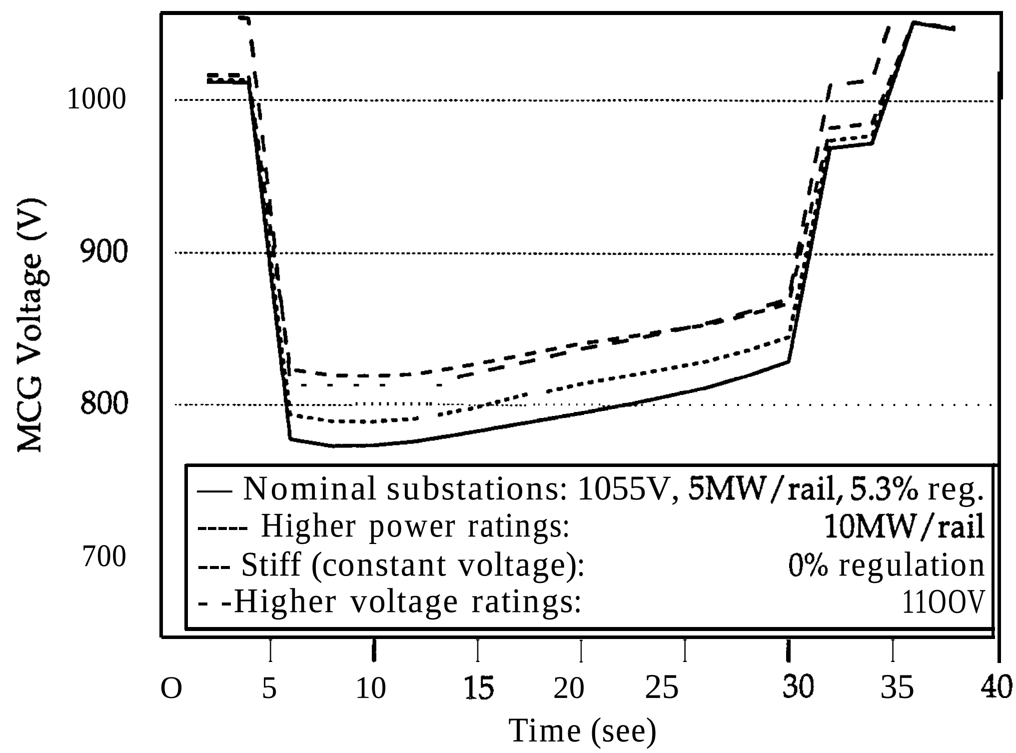

Figure 4.6. Predicted improvement in the sag voltage during the propulsion cut-out event with substation upgrades at KTE and MTW.

Since the bulk of the voltage sag was a result of rail losses, rather than voltage drop at the substations, we also considered reduction of rail resistance to be a promising solution to the sag problem. We considered upgrades to the running rails, as well as to the contact (third) rail. Nominally, the contact rail in the tunnel has a resistance of 1.9 $\mu\Omega/ft$, and the two running rails in parallel have an effective resistance of 4.35 $\mu\Omega/ft$. As shown in Figure 4.7, reducing the contact rail resistance to 1.0 $\mu\Omega/ft$ improved the calculated MCG voltage during the sag by over 50 V. Reducing the running rail pair resistance to 2.5 $\mu\Omega/ft$ improved the voltage by nearly 100 V. Either of these rail upgrades would hold the voltage well above 800 V during this event.

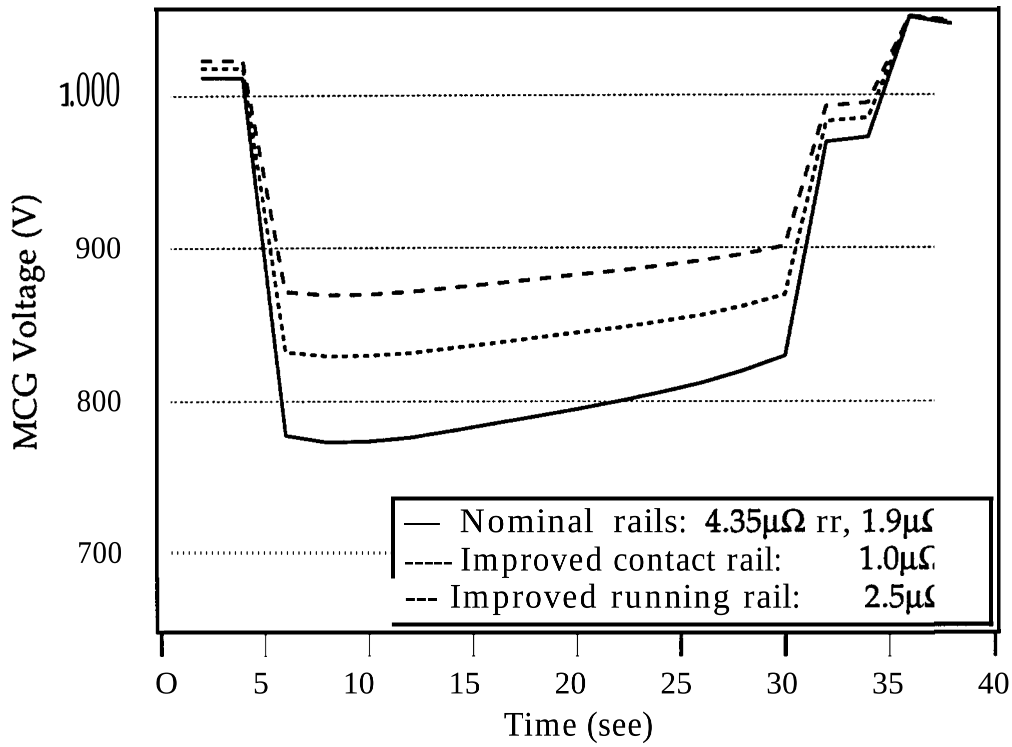

Figure 4.7. Predicted improvement in the sag voltage during the propulsion cut-out event with reduced rail resistances.

In addition, it is worth noting that the power losses associated with voltage sag in the rails can be significant, because the power lost to heat is proportional to the square of the current. During this sag, 25% of the power provided by the substations was lost to rail resistance; with 14 MW demanded by the trains, 19 MW was provided by the substations. The running rail upgrade discussed above would reduce this power loss to 17% of the substation power. Of course, this upgrade would not significantly reduce the total energy consumed by the system, because the power savings would only accrue during a deep sag such as this one, which lasts a short time compared to the trip time through the tunnel and occurs only rarely.

The results discussed above, as well as the impact of some combinations of upgrades, are summarized in Table 4.1. Notice that in the table, the minimum train voltage, rather than the MCG voltage is shown. Simultaneous upgrades to the contact and the running rails would maintain the trains above 900 V during the sag. A similar improvement would be achieved by both stiffening the substations with thyristor-controlled rectifiers and upgrading the running rails.

Table 4.1. Simulated Sag Voltages for Two Accelerating Trains*

System Upgrade:	None	Running rail	Contact rail	Running rail and Contact rail	Raised voltage	Stiff substations	Larger substations	Stiff substations and Running rail
Rail parameters:								
Running rail pairs (μΩ/ft)	4.35	2.5		2.5				2.5
Contact rail (μΩ/ft)	1.9		1.0	1.0				
Substation params:								
No-load voltage (v)	1055				1100			
Regulation (%)	5.3					0		0
MW/rail	5						10	
Predicted result:								
Minimum train voltage (V)	755	856	817	903	803	811	780	898

*For trains traveling in opposite directions near the center of the transbay tunnel, as during the propulsion cut-out event. Various types of system upgrades are shown for comparison. Substation upgrades in this table are applied to KTE & MTW only.

In addition to examining the impact of one level of upgrade to the running rails, we calculated the minimum train voltage during the sag for a range of possible resistances. This calculation is shown in Figure 4.8. As would be expected, the lower the effective running rail pair resistance becomes, the more the voltage recovers. If the resistance is reduced from the present 4.35 μΩ/ft to 1.5 μΩ/ft, this upgrade alone would maintain the voltage above 900 V during a sag caused by two accelerating trains.

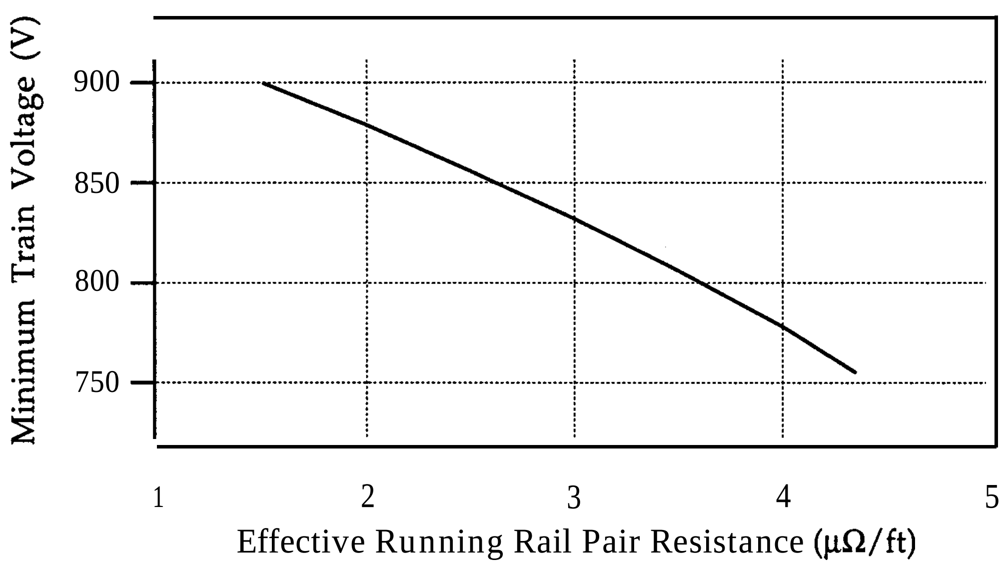

Figure 4.8. Simulated sag voltage during the propulsion cut-out event, shown as a function of the effective resistance of the running rail pairs.

System upgrades such as those discussed above have the potential to eliminate all the measured voltage sags. In addition, they may be used to raise the voltage during three-train back ups. With the present system, an extremely severe sag occurs if three trains simultaneously accelerate in the middle of the tunnel after a backup. A snapshot of three trains drawing 7.5 MW each was studied in lieu of a full train motion simulation of a backup. The sag was extremely severe with the present system parameters (the simulator was unable to converge on a solution, but the voltage was below 500 V). If the return rail was upgraded to 2.5 μΩ/ft and either the contact rail was upgraded to 1.0 μΩ/ft or the substations were held stiffly at 1055 V, the calculated voltage dropped to approximately 750 V. If all three of these upgrades were assumed, the voltage remained over 800 V. Thus, even an event involving three trains could be handled by these types of system improvements.

4.4. Future Implications

The BART system is presently expanding its service area and will soon require the tunnel to accommodate more closely spaced trains. At the 97 second headways expected in the year 2010, closely spaced trains may cause SORS resets to occur more frequently. In addition, the impact of a SORS reset will be significantly worsened. Twice as many trains will occupy the tunnel compared to today's operations, causing more trains to be affected. In the present system, a SORS reset may only cause one train in the middle of the tunnel to accelerate, and poor timing is required to cause a sag severe enough to cut off train motors. However, 97 second-spaced trains will probably cause propulsion cut-outs during virtually all SORS reset occurrences. Two to four trains would simultaneously attempt to accelerate, and several other trains would also be likely to draw significant power nearby. Assuming motors do not cut out, calculations predict that 90% of SORS resets would cause the voltage to drop below 650 V with the present traction power system. A storage unit would be likely to require 50 to 100 MJ of energy to handle such severe sags. Reducing the effective running rail pair resistance to 2.5 $\mu\Omega/ft$ or stiffening the KTE and MTW substations would probably be sufficient to maintain train voltages above 750 V during most SORS resets at 97 second headways. Upgrading both the running rails to 2.5 $\mu\Omega$ and the contact rail to 1.0 $\mu\Omega$ rail would maintain the voltage above 800 V. Upgrading the running rail and stiffening the substations would maintain train voltages above 850 V. A more detailed study would be necessary to confirm these results, as only a limited set of test cases was examined.

5. The Long-term Problem: Power Outages at Reduced Headways

Maintaining the ability to operate at full capacity during a substation outage places stringent requirements on the traction power system. A system that provides adequate train voltage during normal operating conditions may not be adequate if there is a rectifier/transformer outage. The Extension Service Plan Study of Traction Power System Capability prepared by Parsons DeLeuw (PDL)[3] found that if one of the present substations in the BART tunnel failed during 97 second headway operations, a train's voltage could drop as low as 553 V (if train motors remained on at low voltage). Based on such calculations over the entire BART system, PDL recommended installation of 15 additional rectifier/transformers. Upgrades of the existing substations or of the rails, such as those considered in this report, may reduce the need to invest in this additional power capability.

Using our traction power model of the BART tunnel, we have attempted to reproduce the predictions made by PDL and to calculate the effect of system upgrades on these predictions. We used data from the 'Criteria' section of the PDL study to set the nominal rail resistances: the contact rail resistance was 2.25 $\mu\Omega/ft$, and the running rail pair resistance was 4.85 $\mu\Omega/ft$. These numbers are high according to BART engineers[24]; however, we assume PDL used them to reach conservative conclusions. We also duplicated the PDL assumption that all BART trains were fully loaded (92000 lb/car) 10-car trains.

To create an input file of train data for our electrical model, we used train trajectory information modeled by the BART train control simulator[28] and spaced identical trains at 97 second intervals. Rather than attempting a full statistical analysis of all the possible train locations and phases between the trains traveling in opposite directions, we studied a single snapshot in time that we hope represents the worst case scenario that one would expect to occur regularly during nominal 97 second headway operations. (This situation could be avoided by appropriate coordination of eastbound and westbound trains; however, even with such coordination, any deviation from the schedule could cause it to occur.) In this snapshot, every modeled train was either accelerating or going up a hill, including two trains climbing the hill in the middle of the tunnel, two trains each accelerating out of Embarcadero and Montgomery stations, and one train pulling out of Powell Street station. The locations of the trains in the tunnel are shown schematically in Figure 5.1.

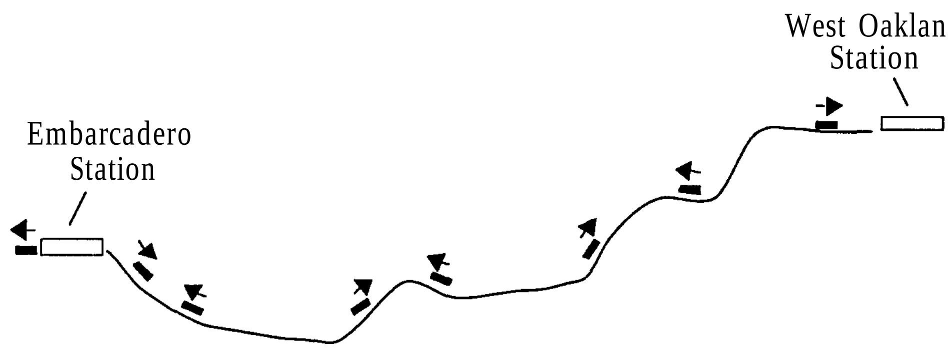

Figure 5.1. Aworst-case scenario oftrain locations inthe tunnel during nominal 97 second headway operations. Additional trains not shown here were modeled west of Embarcadero Station, including trains at Montgomery and Powell Street stations.

Table 5.1 summarizes the minimum train voltages predicted by our model for the snapshot in time described above. Included are predictions during nominal operations and during substation outages at either of the tube substations. Since we did not use the same train configuration as the PDL study, we did not reproduce their predictions exactly. However, we did predict a problem of similar magnitude. Even in this worst case scenario, the calculated train voltages remained over 750 V if all substations were functioning. Thus, aside from substation outages, the present power system could potentially handle 97 second operations.

In addition to the present (conservatively defined) system, we predicted the voltage for power systems with upgrades in the rails, in the substations, and in combinations of these. These upgrades were found to significantly improve the voltage during an outage. A failure at MTW caused the worst sag, and the voltage dropped below 600 V assuming no upgrades. Running rail upgrades raised this voltage to 650 V, contact rail upgrades raised it to over 700 V, and upgrades to all the rails increased the voltage to over 750 V, a potentially acceptable level during an outage. The most effective solution was to maintain the voltage at MPS and KTE substations independent of power load so that they could provide the additional power without sagging. This type of upgrade would maintain the voltage above 800 V and could eliminate the need for additional substations. However, it should be noted that the power demanded from the functional substations during this outage was typically over three times the rated power. During the MTW failure, the MPS substation, which has a 10 MW rating, was providing 34 MW to the system. Although substations can provide 4.5 times their rated power for 15 minutes at a time, further study of the duration and repetition rate of these sags is needed to determine if thermal loading of the substations would be a problem.

Table 5.1. Worst-Case Train Voltages with 97 Second Headways*

System Upgrade:	None	Running rail	Running rail	Contact rail	All rails	Stiff substations (MPS, MTW & KTE)	Larger substations (MTW & KTE)	All rails and Stiff substations
Rail parameters:								
Running rail pairs (μΩ/ft)	4.85	2.5	2.0		2.5			2.5
Contact rail (μΩ/ft)	2.25			1.2	1.2			1.2
Substation params:								
Regulation (%)	5.3					0		0
MW/rail	5						10	
I?redicted **result:**								
Minimum train voltage (V)	787	858	872	826	891	895	834	978
with a failure at KTE (V)	671	765	782	761	836	810	730	935
with a failure at MTW (V)	561	643	655	724	791	813	608	943

*Train voltage predictions with nominal 97 second headway conditions, normally and during substation failures, assuming conservative rail resistances. The "stiff substation" upgrade includes MI%, because if only the tube substations (MTW & KTE) are prevented from sagging, the train voltage still sags to 654V during the MTW failure.

tunnel. Thyristor-controlled rectifiers that maintain substation voltages at 1055 V independent of power output most effectively improve train voltages during substation outages. We recommend that BART consider conducting a more detailed study of these solutions rather than proceeding with testing of an 8 MJ SMES device.

We have studied the technical performance of the various possible system upgrades, but have completed only a cursory evaluation of the associated costs and have not touched on the issue of feasibility. Specifically, we have not determined whether any implementation problems exist which would lead to prohibitive costs. For example, we have not studied in detail how the effective return resistance could be reduced without interfering with the train locator system, which detects AC current flow through the running rails. Also, we have not investigated whether thyristor control would be able to handle the large power loads that would occur during an outage, including issues of thermal overload. BART should complete a detailed study of these feasibility issues, as well as investigating more thoroughly the associated costs. These should be compared to the energy storage estimates and the costs of additional rectifier/transformers. If these results look promising for the transbay tunnel, a system-wide study should be performed to quantify potential savings on other sections of the BART system that would otherwise require additional rectifier/transformers. If any of the system upgrade alternatives are feasible and more cost-effective than either energy storage or additional rectifier/transformers, the study results would benefit both BART and other US transit systems.

References

1. M. M. Reading, *BART SMES Application Scoping Study, Phase O,* Pacific Gas and Electric, 007.5-94.4 (1994).

2. BART, *Rolling Stock Maintenance Department Book 50 Vol 2A.*

3. Parsons DeLeuw, *Extension Service Plan Study: Traction Power System Capability, Operation Years - 1998, 2002, 2010,* Bay Area Rapid Transit District, (March 1993).

4. S. P. Gordon, *BART Tunnel Traction Power Model,* Sandia National Laboratories (1994).

5. BART, *Data Transmission System Log.*

6. BART, *Track Plans.*

7. E. I. Nishinaga, J. A. Evans and G. L. Mayhew, *Rail Industry Signaling Innovations via the Technology Reinvestment Program,* 1994 American Public Transit Association Rapid Transit Conference (Sacramento, 1994).

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13. ABB Traction Inc., *System Test Report for 3000 kW Transformer-Rectifier Combination Unit,* San Francisco Bay Area Rapid Transit District, Contract 15 EG-220A (October 1989).

14. BART, *Traction Power Electrification Systemwide,* Dwg. No. R-1 OO436 (revised 2/92).

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16. F. R. McLarnon and E. J. Cairns, "Energy Storage" *Annu. Rev. Energy* 14, 241-71 (1989).

17. R. B. Schainker, *Energy Storage: How the New Options Stack Up,* Electric Power Research Institute.

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23. S. D. Jacimovic, *Train Voltage Improvement and Peak Power Demand Reduction on the BART System using Thyristor Rectifiers,* presentation to BART - Oakland (1994).

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Table 5.1. Worst-Case Train Voltages with 97 Second Headways*

System Upgrade:	None	Running rail	Running rail	Contact rail	All rails	Stiff substations (MPS, MTW & KTE)	Larger substations (MTW & KTE)	All rails and Stiff substations
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Contact rail (μΩ/ft)	*2.25*			1.2	1.2			1.2
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with a failure at MTW (V)	*561*	*643*	*655*	*724*	791	*813*	*608*	*943*

*Train voltage predictions with nominal 97 second headway conditions, normally and during substation failures, assuming conservative rail resistances. The "stiff substation" upgrade includes MPS, because if only the tube substations (MTW & KTE) are prevented from sagging, the train voltage still sags to 654V during the MTW failure.

We also made a rough estimate of the storage size that would be required to handle the sag during an MTW substation outage for this train scenario. As the trains pass through this snapshot, the voltage at MCG drops below 800V for -15 seconds. Storage would require approximately 10 MW for 15 seconds, or 150 MJ of energy to hold the voltage at MCG above 800V. This requirement may be repeated every 97 seconds for the entire duration of the outage.

From these calculations, it seems likely that the need for substation additions in the transbay tunnel could be partially or totally alleviated by improvements in rail resistance or modification of substations with thyristor control to prevent voltage sag. It is possible the additional power capacity recommended by Parsons DeLeuw in other sections of the BART system could be similarly reduced, although we have not looked at other locations in this study.

6. Conclusions

In the present BART system, severe voltage sags in the transbay tunnel result when multiple trains are accelerated simultaneously far from substations. This type of behavior is caused by the Automatic Train Control (ATC) system, which commands all trains to accelerate to speed as quickly as possible following a backup or the removal of a speed limit restriction, without consideration of the capacity of the traction power system. The Advanced Automatic Train Control (AATC) system' which BART is presently pursuing could potentially be implemented in such a way as to prevent such train behavior. However, the AATC is not yet installed, and, even after installation, the capacity of the power system may still need to be increased through other means. Thus, alternative solutions should be considered.

Multiple train accelerations are most commonly caused by SORS resets in the tunnel. An 8 MJ storage device installed at MCG probably will not suffice to alleviate this voltage sag problem. Unless intelligent control of the storage is implemented which keeps track of train voltages rather than simply reacting to the local voltage, a storage device in the middle of the tunnel would require at least 20 MJ of capacity to avoid sags down to 750 V caused by two accelerating trains. Alternatively, increasing the conductivity of the rails or stiffening the substation voltages may lead to a substantial improvement in these voltage sags.

In future operations, the present voltage sag problem will become worse due to the presence of more trains in the tunnel during SORS resets. Storage capacity of 50 to 100 MJ would likely be required to maintain the tunnel voltage after a SORS reset. Rail or substation upgrades may be sufficient to avoid propulsion cut-outs during these events. In addition, nominal operations in the tunnel with 97 second headways during a substation outage would cause severe voltage sags, as was discussed in the Extension Service Plan by Parsons DeLeuw.[3] PDL recommended the installation of additional rectifier/transformers to address this problem; however, rail and substation upgrades present an opportunity to considerably reduce the need for this added power capacity, and may allow significant capital cost savings.

Improved substations, rails, or train control have the potential to be more cost-effective than energy storage for preventing critical voltage sags due to train accelerations or outages, and may substantially reduce the need for additional substations to power future operations. Reduced running rail resistance most effectively improves train voltages during multiple train accelerations in the tunnel. Thyristor-controlled rectifiers that maintain substation voltages at 1055 V independent of power output most effectively improve train voltages during substation outages. We recommend that BART consider conducting a more detailed study of these solutions rather than proceeding with testing of an 8 MJ SMES device.

We have studied the technical performance of the various possible system upgrades, but have completed only a cursory evaluation of the associated costs and have not touched on the issue of feasibility. Specifically, we have not determined whether any implementation problems exist which would lead to prohibitive costs. For example, we have not studied in detail how the effective return resistance could be reduced without interfering with the train locator system, which detects AC current flow through the running rails. Also, we have not investigated whether thyristor control would be able to handle the large power loads that would occur during an outage, including issues of thermal overload. BART should complete a detailed study of these feasibility issues, as well as investigating more thoroughly the associated costs. These should be compared to the energy storage estimates and the costs of additional rectifier/transformers. If these results look promising for the transbay tunnel, a system-wide study should be performed to quantify potential savings on other sections of the BART system that would otherwise require additional rectifier /transformers. If any of the system upgrade alternatives are feasible and more cost-effective than either energy storage or additional rectifier/transformers, the study results would benefit both BART and other US transit systems.

References

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24. H. Shaikh, BART, personal communication (1994).

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28. D. G. Lehrer and J. A. Evans, *AATC Train Simulator and Utilities,* Bay Area Rapid Transit (1994).

APPENDIX A - DETAILS OF THE TRAIN PROPULSION MODEL

We model the power demand of train motors as follows. The force (tractive effort) required to move a train includes acceleration, drag (Davis resistance) and grade:

w [lbf] = 60000 + 180 * (people/car)
where w is the weight of a car assuming 180 lb/person.

F_{accel} [lbf] = n * w/32.2* a*4.4/3,
where n is the number of train cars,
and a is the train acceleration in mph/s.

F_{Davis} [lbf] = 1.3*n*w/2000+116*n+0 .045*n*w/2000*v
+Mult*(LDrag+TDrag* (n-l))* Area*v*v,[1]
where v is the train speed in mph,
LDrag = 0.00215 is the lead car air drag coefficient,
TDrag = 0,0003 is the trailing car air drag coefficient,
Area = 100 square feet is the area of front of train,
and Mult = 2 is a multiplier for air drag in a tunnel.

F_{grade} [lbf] = n*w*g/100,
where g is the percent grade (the hill),
which is averaged over the length of the train.

F_{train} [lbf] = F_{accel} + F_{Davis} + F_{grade}.

F_m [lbf] = F_{train} / 4*n,
where F_m is the tractive effort required from each motor,
and there are 4 motors on each train car.

From F_m, we calculate the motor current. This is limited by a maximum current, which depends on the train speed. We use the motor current and train speed to calculate the motor voltage (not the rail voltage, but the internal motor voltage). Finally, the power required from the motor is calculated from the product of motor current and voltage, including an auxiliary power demand of 0.04 MW per car. This calculation is done depending on whether the motor is in full or shunted field, and whether it is in propulsion or is regeneratively braking. The equations for the these calculations are shown below, with the exception of the motor voltage which is extrapolated from a look-up table. The equations and the look-up tables were extracted from published BART motor curves.[2] These equations do not account for changes in performance due to depressed rail voltage.

rpm = v * 336.14 / wheel * ratio,[2]

where wheel = 30” is the wheel diameter

(this could be 28” to 30”, but the study assumes 30”),

and ratio = 5.5714 is the gear ratio.

I_m is the motor current.

I_{max} is the maximum allowed motor current.

V_m is the motor voltage.

<u>Braking</u>

<u>Full field</u> for v < 4447 rpm:

$I_m=0.145*F_m*(F_m+1244)/(F_m+302)$,

$V_m=V_{ff}(rpm, I_re)$.

<u>Shunted field</u> for v > 4447 rpm:

$I_m=0.162*F_m*(F_m+1670)/(F_m+312)$,

$V_m=V_{sf}(rpm, I_re)$.

Power = $(0.04 - I_m*V_m*4.0e-6)$ MW.

<u>Propulsion</u>

<u>Full field</u> for $V_m < 220$ Volts

$I_m=0.168*F_m*(F_m+977)/(F_m+135)$,

$V_m=V_{ff}(rpm, I_m) + 0.096*I_m$,

where $0.096*I_m$ accounts for motor resistance,

$I_{max}=30.4+1206*exp(-v/35.8)$ for $v<53.7mph$,

$I_{max}=132+4796*exp(-v/16.0)$ for $v>53.7mph$.

<u>Shunted field</u> for $V_m > 220$ Volts

$I_m=0.179*F_m*(F_m+1413)/(F_m+145)$,

$V_m=V_{sf}(rpm, I_m) + 0.08*I_m$,

$I_{max}=185+1050*exp(-v/38.2)$.

Power = $(0.04+ I_m*V_m*4.0e-6)$ MW

References for Appendix A

1. BART, personal communication (1994).

2. BART, *Rolling Stock Maintenance Department Book 50 Vol 2A.*

APPENDIX B - DETAILS OF THE TRACTION POWER MODEL

The traction power model of the BART transbay tunnel[1] is written in Think C on a Macintosh Quadra computer. As described in section 3, the model extends from the Powell Street substation to the Oakland West substation. The circuit is essentially as shown in Figure 3.1, with one additional detail. The tunnel substations, KTE and MTW, are connected to opposing rails on either side, as shown in Figure B.1.[2] As a train passes by the KTE substation, it switches from KTE2 to KTE1, and similarly for MTW.

A flowchart of the traction power model is shown in Figure B.2. For each time step, the circuit is solved in two main steps. Given the locations of the track features and of the trains, circuit “nodes” are numbered at each train and each feature, the connections between them are identified as trains or resistors, and for each connection the train index or the resistance is recorded. Next, this array of connection information is iteratively formed into a set of linear voltage equations and solved. Iteration is necessary because some of the voltage equations are nonlinear.

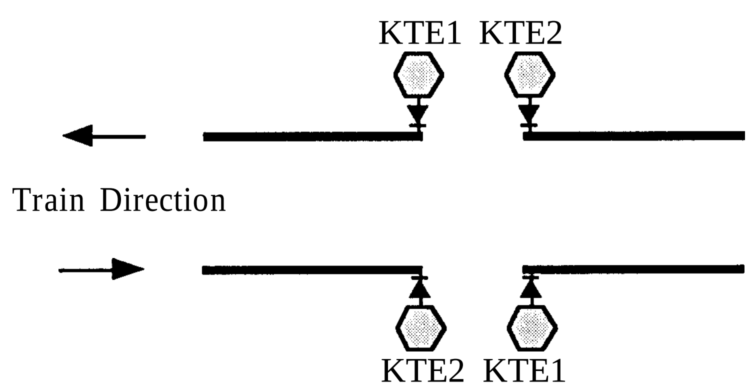

Figure B.1. Tube substation rail connections.

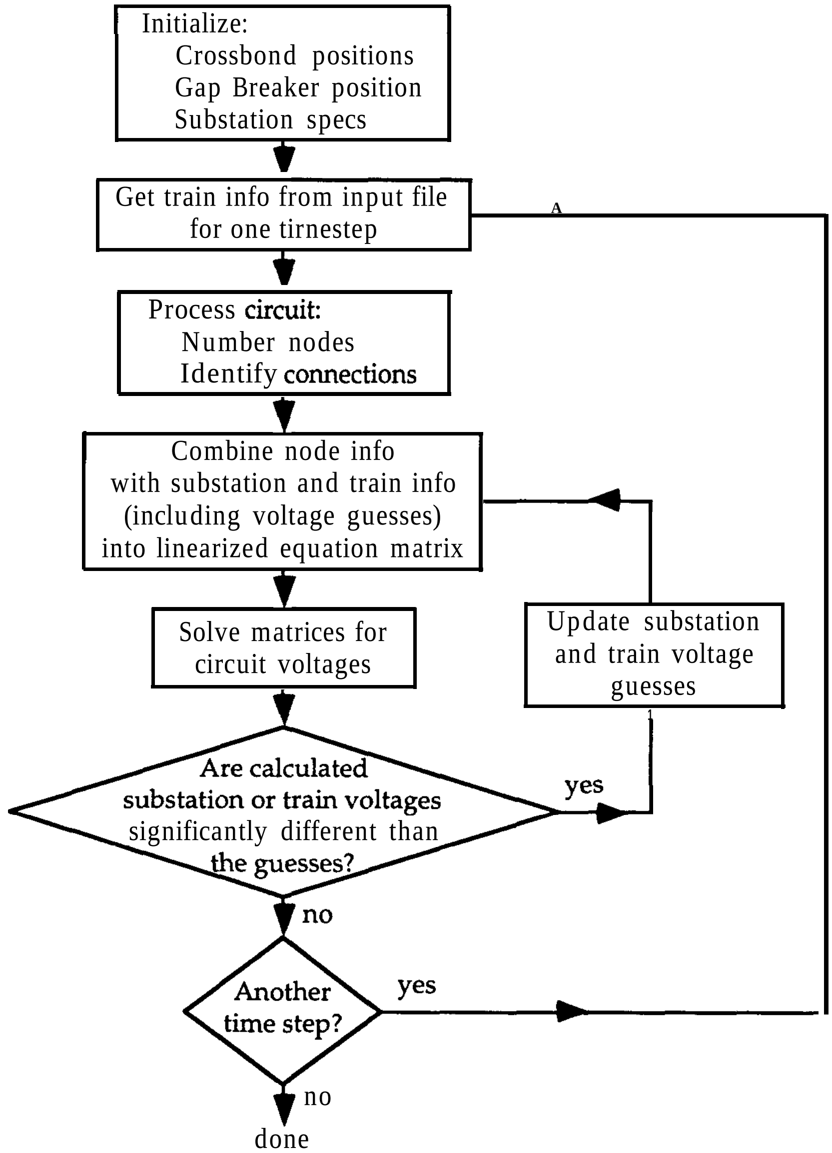

Figure B.2. Traction power model flow chart.

Conservation of current at each node is used to form the voltage equations. For lengths of rail, crossbones, and the gap breaker, these equations take the form I=V/R, where R is the resistance of the connection. For trains, however, the equations take the form I=P/V, where P is the train power, which is non-linear in V. The train equations are therefore linearized into the form

$$I = P/V_o - P/V_o^2 * (V-V_o),$$

where V. is a voltage guess. Thus, the linear equations contain a guess of the train voltage, which is compared to the calculated value after each iteration and updated. Similarly, the substation voltage is guessed, the equations are solved, the substation power is calculated, and the next voltage guess is calculated from this power ($V= 1055- 0.053*P/P_{rating}$). This process is repeated until the differences between the guessed and the calculated train and substation voltages are less than 0.1 V each.

References for Appendix B

1. S. P. Gordon, *BART Tunnel Traction Power Model,* Sandia National Laboratories (1994).

2. BART, *Traction Power Electrification Systemwide,* Dwg. No. R-1 OO436 (revised 2/92).

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