CUSTOMER ENERGY EFFICIENCY PROGRAM

# ENERGY EFFICIENCY ASSESSMENT

**OF**

# Bay Area Rapid Transit (BART) Train Cars

**San Francisco Bay Area**

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(B A S E)

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**Report No. BASE-PGE-05-09**
**March 2007**
**Revised: November 2007**

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# 1. INTRODUCTION

The work presented in this report is a service of the **Pacific Gas & Electric Company** (PG&E) to its large commercial and industrial customers under its Customer Energy Efficiency Program, which has been contracted to BASE Energy, Inc. This work has been supported by the Integrated Energy Audit and Non-Residential New Construction Programs as PG&E's continuing commitment to provide energy efficiency, energy cost reduction services and technical solutions to its customers. The Integrated Energy Audit is intended to identify, analyze, and serve as a "roadmap" for defining and implementing cost effective energy efficiency and modernization measures, demand response opportunities, as well as any potential for self-generation (including renewables and cogeneration) for PG&E's customers. Implementing the Integrated Energy Audit recommendations will result in avoided energy, maintenance and capital costs that will assist in financing the cost of the energy efficiency improvements. Data are gathered through site visits, measurements and collection of information from customers, and energy conservation and efficiency as well as demand response opportunities are identified. When a measure is attractive and involves engineering design and capital investment, and engineering services are not available in-house, it is recommended that a consulting engineering firm be engaged to do the detailed engineering design and cost estimation for implementing the measures.

The scope of the work in this energy assessment includes:

1 - Field survey of energy consuming equipment
2 - Evaluation of as built plans and other energy related documentation
3 - Identification of energy conservation and efficiency opportunities and modernization needs
4 - Analysis of existing conditions and alternative energy efficiency, modernization and demand response opportunities
5 - Implementation analysis of major energy efficiency, modernization and demand response opportunities

The assumptions used to arrive at the energy consumption and cost savings for the recommended measures are provided in the report. These assumptions are intended to be conservative and are often arrived at in consultation with Customer (audited facility) personnel.

Three important factors that affect energy consumption and savings are operating hours, utility factor of the equipment (actual hours of operation of a device divided by the hours of operation of the department), and load factor (actual energy draw divided by the nominal draw). The numbers used in this report are based on the information provided by the customer and should be taken as average. Cost estimates have been done based on common cost estimation manuals, contacts with equipment manufacturers and contractors to the extent possible. We **recommend** that the customer consult various suppliers for competitive bids for implementation of measures whenever deemed appropriate.

We have not evaluated these measures for other factors that could impact the ultimate implementation of each measure, such as future expansion capability, regulatory compliance and permitting, ease and cost of maintenance, etc.

The assessment team would like to thank PG&E Customer Energy Efficiency managers and staff, Genrick Gofman, Michael Juniphant, and Charlie Middleton in particular, for supporting and encouraging this work. Also our sincere thanks go to Henry Kolesar of BART for his diligent attention and help in the course of developing this study.

Please feel free to contact BASE Energy, Inc. at (415) 543-1600, Rod Lee, PG&E Account Manager at (415) 973-4830, Charlie Middleton, PG&E Senior Chemical Engineer at (415) 973-4008 or Michael Juniphant at (415) 973-2983 if there are any questions or comments related to this report.

# 2. EXECUTIVE SUMMARY

This report includes the results of a limited energy efficiency evaluation of the train cars of Bay Area Rapid Transit (BART) of San Francisco Bay Area, California.

BART service territory covers the San Francisco Bay Area – from Millbrae to Pittsburg and Richmond to Fremont. Due to the vast distance covered by the transit system, there are several electric substations throughout the Bay Area that supply electricity to BART cars and facilities. However, this study focuses exclusively on energy efficiency improvements of BART cars, thus it was determined that the annual electrical consumption from billing data would not be appropriate to establish a baseline for the cars' electrical energy consumption. Instead, it was proposed that test results from the *Energy Consumption Test on Test Track* (for both C and A/B cars) be used as a baseline. Results are presented as the electrical consumption of one car per mile (kWh/car-mi). Once the yearly distance covered by each car type is determined, it is possible to determine the annual electrical energy consumption in the more conventional kilo-watt-hour per year (kWh/yr). Since not all cars operate continuously, it has been estimated that during BART's peak period, a total of 500 cars would be operating (50 trains, 10 cars per train). It is assumed that the 500 cars will be composed of: 112 C1 cars, 60 C2 cars, 44 A cars and 284 B cars. These numbers are derived from a proportional relationship between the total number of cars of a specific type to the total number of cars and the estimated 500 cars that would be operating during BART's peak period. The table below summarizes the baseline energy consumption, demand and electric costs for operating the BART cars.

| ANNUAL CAR OPERATION AND ENERGY SUMMARY | | | | | | |
|---|---|---|---|---|---|---|
| **Car Type** | **Number of Cars** | **Mileage** (mi/car-yr) | **Car Energy Consumption** (kWh/car-mi) | **Maximum Demand** (MW) | **Total Energy Consumption** (kWh/yr) | **Energy Cost** |
| C1 | 150 | 116,435 | 3.6170 | 16.8 | 63,171,946 | 6,633,054 |
| C2 | 80 | 127,020 | 3.6122 | 8.9 | 36,705,269 | 3,854,053 |
| A | 59 | 122,275 | 3.3708 | 6.1 | 24,317,710 | 2,553,360 |
| B | 380 | 137,605 | 3.3708 | 39.7 | 176,258,795 | 18,507,173 |
| **Totals** | **669** | | | **71.6** | **300,453,720** | **31,547,641** |
| | | | | Average Unit Costs | | $0.105/kWh |

Application of energy efficient technologies to the current BART fleet (considered as retrofit) and to new cars (considered non-residential new construction, NRNC) has been evaluated in this report.

**Retrofit**

The energy efficiency opportunities (EEMs) included in this report could save an estimated 129,629,488 kWh of electrical energy each year, or 43.1% of the BART cars' total electrical energy usage. This estimated electrical energy savings would translate into a cost savings of $13,632,650 per year. Total estimated implementation cost is $156,891,233 giving an average simple payback of 11.5 years. A summary for the savings and costs for these EEMs are listed in Table ES-1A. Detailed information on these recommendations and calculations of savings are in Section 5.1, Energy Efficiency Opportunities (EEMs).

**TABLE ES-1A SUMMARY OF SAVINGS AND COSTS FOR RETROFITTED BART CARS (RETROFIT)**

| EEM No. Description | Potential Energy Conserved | Maximum Demand Savings* (kW) | Potential Savings ($/yr) | Savings per car type per mile (kWh/car-mi) | Installed Project Cost ($) | Simple Payback (yr) |
|---|---|---|---|---|---|---|
| **Investment Grade Measures** | | | | | | |
| 1. High Efficiency Lighting for C1 Cars and New Cars | 156,872 kWh/yr | 42 | 37,891 | 0.009 (C1) | Included in EEM No. 4 | Included in EEM No. 4 |
| 2. Direct Cooler Air to the Inlet of HVAC Condensers | 1,717,819 kWh/yr | 409 | 180,370 | 0.019 (C1, C2)<br>0.020 (A, B) | 200,000 | 1.1 |
| 3. Install Higher Efficiency HVAC Units on C Cars and New Cars | 413,021 kWh/yr | 107 | 43,367 | 0.015 (C1, C2) | 690,000** | 15.9 |
| 4. Optimize Outside Air Intake into Cars | 1,444,334 kWh/yr | 0 | 151,791 | 0.016 (C1, C2)<br>0.017 (A, B) | 1,050,000 | 6.9 |
| 5. Install Daylight Controls on the Fluorescent Lamps | 837,433 kWh/yr | 0 | 87,930 | 0.011 (C1, C2)<br>0.009 (A, B) | 2,869,985 | 32.6 |
| 6. Install Variable Frequency Drives on HVAC Supply Fans | 3,206,292 kWh/yr | 0 | 336,661 | 0.047 (C1, C2)<br>0.032 (A, B) | 2,950,000 | 8.8 |
| 7. Use Permanent Magnet (PM) Motors for Car Propulsion | 38,905,029 kWh/yr | 9,424 | 4,085,028 | 0.663 (C1, C2)<br>0.346 (A, B) | 54,456,600 | 13.3 |
| 8. Use Ultracapacitors for Regenerative Braking Energy Storage | 82,948,688 kWh/yr | 19,733 | 8,709,612 | 0.952 (All Cars) | 94,674,648 | 10.9 |
| **Total Electrical Energy Savings** | **129,629,488 kWh/yr** | | | | | |
| **Total Demand Savings** | | **29,715** | | | | |
| **Total Cost Savings** | | | **13,632,650** | | | |
| **Total Installed Project Cost** | | | | | **156,891,233** | |
| **Simple Payback** | | | | | | **11.5** |

* The demand savings considers that at most 500 cars will be operating during BART's peak period. Additionally the demand savings does not consider the interaction between the regenerated energy and the electric grid.
** The implementation cost for these measures consider the cost premium for installing the proposed system as older systems come to their end-of-life (i.e on a replacement basis).

PG&E offers incentives for energy efficiency and/or demand response opportunities under the Non-Residential Retrofit – Demand Response (NRR-DR) program. The incentives for energy efficiency projects are subject to the following limitations:

- A measure's incentive cannot exceed 50% of the measure's cost, and
- The total incentives for all measures cannot exceed the project site cap of $3,600,000.

The total implementation cost of the EEMs recommended in this project is estimated to be $156,891,233. The total potential incentives and rebates for these measures (in using both incentive/rebate programs) are estimated to be $3,600,000 shown in Table ES-2. The total cost savings of $13,632,650 per year will pay for the adjusted total implementation cost (including incentives) of $153,291,233 in approximately 11 years.

**TABLE ES-2A SUMMARY OF ENERGY EFFICIENCY OPPORTUNITY INCENTIVES FOR EXISTING CARS (RETROFIT)**

| EEM No. Description | Energy Savings | Incentive or Rebate Program and Amount | Potential Incentive ($) | Installed Project Cost with Incentive ($) | Simple Payback Period w/ Incentive (yrs) |
|---|---|---|---|---|---|
| 1. High Efficiency Lighting for C1 Cars and New Cars | 156,872 kWh/yr | NRR-DR *$0.05/kWh* | Included in EEM 5 | Included in EEM 5 | Included in EEM 5 |
| 2. Direct Cooler Air to the Inlet of HVAC Condensers | 1,717,819 kWh/yr | NRR-DR *$0.14/kWh* | 240,495 | 100,000* | 0.6 |
| 3. Install Higher Efficiency HVAC Units on C Cars and New Cars | 413,021 kWh/yr | NRR-DR *$0.14/kWh* | 57,823 | 632,177 | 14.6 |
| 4. Optimize Outside Air Intake into Cars | 1,444,334 kWh/yr | NRR-DR *$0.14/kWh* | 202,207 | 847,793 | 5.6 |
| 5. Install Daylight Controls on the Fluorescent Lamps | 837,433 kWh/yr | NRR-DR *$0.05/kWh* | 49,715 | 2,820,270 | 22.4 |
| 6. Install Variable Frequency Drives on HVAC Supply Fans | 3,206,292 kWh/yr | NRR-DR *$0.14/kWh* | 448,881 | 1,475,000* | 4.4 |
| 7. Use Permanent Magnet (PM) Motors for Car Propulsion | 38,905,029 kWh/yr | NRR-DR *$0.08/kWh* | 3,112,402 | 51,344,198 | 12.6 |
| 8. Use Ultracapacitors for Regenerative Braking Energy Storage | 82,948,688 kWh/yr | NRR-DR *$0.08/kWh* | 6,635,895 | 88,038,753 | 10.1 |
| **Total Energy Savings** | **129,629,488 kWh/yr** | | | | |
| **Total Potential Incentives and Rebates** | | | **$3,600,000**** | | |
| **Total Installed Project Costs with Incentives** | | | | **$153,291,233**** | |
| **Simple Payback Period** | | | | | **11 years** |

* Incentive limited to 50% of measure's implementation cost.

** $3,600,000 is the maximum amount of incentive that PG&E can provide under this program.

**Non Residential New Construction (NRNC)**

The energy efficient measures (EEMs) included in this report that could be implemented in BART's new cars may save an estimated 179,038 kWh/car-yr of electrical energy each year. This estimated electrical energy savings would translate into a cost savings of $18,799 per year. Total estimated implementation cost is $220,913 giving an average simple payback of 11.8 years. A summary for the savings and costs for these EEMs are listed in Table ES-1B. Detailed information on these recommendations and calculations of savings are in Section 5.1, Energy Efficiency Opportunities (EEMs).

**TABLE ES-1B SUMMARY OF SAVINGS AND COSTS FOR NEW BART CARS (NRNC)**

| EEM No. Description | Savings per car per mile (kWh/car-mi) | Potential Energy Conserved (kWh/car-yr) | Potential Savings ($/yr) | Installed Project Cost ($) |
|---|---|---|---|---|
| **Investment Grade Measures** | | | | |
| 1. High Efficiency Lighting for C1 Cars and New Cars | 0.007793 | 1,170 | 123 | Included in EEO No. 5 |
| 2. Direct Cooler Air to the Inlet of HVAC Condensers | N / A | N / A | N / A | N / A |
| 3. Install Higher Efficiency HVAC Units on C Cars and New Cars | 0.009534 | 1,242 | 130 | 1,031 |
| 4. Optimize Outside Air Intake into Cars | 0.01677 | 2,184 | 229 | 1,570 |
| 5. Install Daylight Controls on the Fluorescent Lamps | 0.009171 | 1,194 | 125 | 4,066 |
| 6. Install Variable Frequency Drives on HVAC Supply Fans | 0.03222 | 4,196 | 441 | 4,410 |
| 7. Use Permanent Magnet (PM) Motors for Car Propulsion | 0.346 | 45,063 | 4,732 | 81,400 |
| 8. Use Ultracapacitors for Regenerative Braking Energy Storage | 0.952 | 123,989 | 13,019 | 128,436 |
| **Total Electrical Energy Savings** | | **179,038** | | |
| **Total Cost Savings** | | | **18,799** | |
| **Simple Payback Period** | | | | **220,913** |

The total implementation cost of the EEMs recommended in this project is estimated to be $220,913/car. The total potential incentives for these measures are estimated to be $14,709/car shown in Table ES-2. The total cost savings of $18,799/car per year will pay for the adjusted total implementation cost (including incentives) of $206,204 in approximately 11 years.

| **TABLE ES-2B SUMMARY OF ENERGY EFFICIENCY OPPORTUNITY INCENTIVES FOR NEW CARS (NRNC)** | | | | | |
|---|---|---|---|---|---|
| **EEM No. Description** | **Energy Savings** | **Incentive Amount** | **Potential Incentive** ($) | **Installed Project Cost with Incentive** ($) | **Simple Payback Period w/ Incentive** (yrs) |
| 1. High Efficiency Lighting for C1 Cars and New Cars | 1,170 kWh/car-y | *$0.05/kWh* | Included in EEM 5 | Included in EEM 5 | Included in EEM 5 |
| 2. Direct Cooler Air to the Inlet of HVAC Condensers | N / A | N / A | N / A | N / A | N / A |
| 3. Install Higher Efficiency HVAC Units on C Cars and New Cars | 1,242 kWh/car-y | *$0.14/kWh* | 174 | 857 | 6.6 |
| 4. Optimize Outside Air Intake into Cars | 2,184 kWh/car-y | *$0.14/kWh* | 306 | 1,264 | 5.5 |
| 5. Install Daylight Controls on the Fluorescent Lamps | 1,194 kWh/car-y | *$0.05/kWh* | 118 | 3,948 | 15.9 |
| 6. Install Variable Frequency Drives on HVAC Supply Fans | 4,196 kWh/car-y | *$0.14/kWh* | 587 | 3,823 | 8.7 |
| 7. Use Permanent Magnet (PM) Motors for Car Propulsion | 45,063 kWh/car-y | *$0.08/kWh* | 3,605 | 77,795 | 16.4 |
| 8. Use Ultracapacitors for Regenerative Braking Energy Storage | 123,989 kWh/car-y | *$0.08/kWh* | 9,919 | 118,517 | 9.1 |
| **Total Energy Savings** | **179,038 kWh/car-yr** | | | | |
| **Total Potential Incentives and Rebates** | | | **$14,709** | | |
| **Total Installed Project Costs with Incentives** | | | | **$206,204** | |
| **Simple Payback Period** | | | | | **11 years** |

* Incentive limited to 50% of the total implementation cost.
$500,000/car is the maximum amount of incentive that PG&E can provide under this program.

This study did not involve analysis of demand response opportunities for the BART system. However the following are some ideas for demand reduction during PG&E demand response events. Detailed studies of these measures are strongly recommended:

- Using more A and B cars instead of C cars.
- Reduce the acceleration rate.
- Resetting the temperature in the cars to a higher value.
- Dimming lights inside cars and stations.

**Note:**

1. Some energy efficiency and demand response projects qualify for incentives through the PG&E Customer Energy Efficiency and Demand Response Programs. The PG&E link http://www.pge.com/biz/rebates/ has complete PG&E Program information. Section 9 has an overview of these programs and incentives.

2. Please note that the final financial incentive amount will depend on the final installed project cost

**Further Steps for Implementation of the Measures**

Further steps to successfully implement the energy efficiency measures identified in this report may include the following:

1. Perform further detailed engineering evaluation of the measures that are economically and technically attractive to BART.
2. Decide whether BART would like to choose the retrofit and/or new construction path for implementation of the measures.
3. Apply for PG&E Incentives.
4. Test the measures in a prototype car or station for providing further practical insight into the implementation of the measures.
5. After trial tests, plan for further implementation on the BART system.

# 3. GENERAL BACKGROUND

## 3.1 System Description

BART has four different car types in service: C1, C2, A and B cars. The C1 cars were the first generation cars that entered service.

The propulsion systems in C1 and C2 cars consist of four direct current (DC) motors per car. There are two HVAC systems, one supplying the front and one supplying the rear of the car. C2 cars are essentially the same as C1 cars, except the interior lighting of the cars was retrofitted from T12 fluorescent lamps to T8 fluorescent lamps.

A and B cars are the first major rehabilitation project done to the BART cars. The main propulsion system was changed from DC motors to induction motors (IM). Also a higher efficiency HVAC system was used, the two larger units were replaced with six smaller units, half of them serving the front and half serving the rear of the car. The lighting system remained the same as the one used in the C2 cars, which use high efficiency T8 lamps. The main difference between A and B cars is the external shell; one has a "nose" used at the ends of the train and the other does not (thus can be used in the middle of the train).

Power is fed to the cars through a 1,000 Vdc (nominal) third rail, which runs parallel to the rail tracks. There are three main voltage busses used in a car: there is a 1,000 Vdc bus used mainly by the propulsion system; a 208 Vac bus used by the HVAC system, air compressor, hydraulic pump, propulsion blower and scavenger blower; and finally a 36.5 Vdc bus which is maintained by on-board batteries to supply critical systems like interior lighting, communications, etc. A simplified single line diagram of the electrical distribution system and loads inside a typical C car is shown in Figure 1 on the following page.

The propulsion system has the capability of recovering some of the car's kinetic energy through regenerative braking. The system is set up to redirect the regenerated energy to the third rail, where it can be used by nearby trains. If there are no nearby trains that can use the regenerated energy it is dissipated by on-board resistors.

Based on average daily operating hours provided by BART personnel, the table below summarizes the average yearly operating hours for each BART car type.

| YEARLY OPERATING HOURS BY CAR TYPE | | | |
|---|---|---|---|
| **Car Type** | **Daily Hours** (hr/day) | **Days per Year** (day/yr) | **Operating Hours** (hr/yr) |
| A | 8.1 | 365 | 2,957 |
| B | 9.1 | 365 | 3,322 |
| C1 | 7.7 | 365 | 2,811 |
| C2 | 8.4 | 365 | 3,066 |

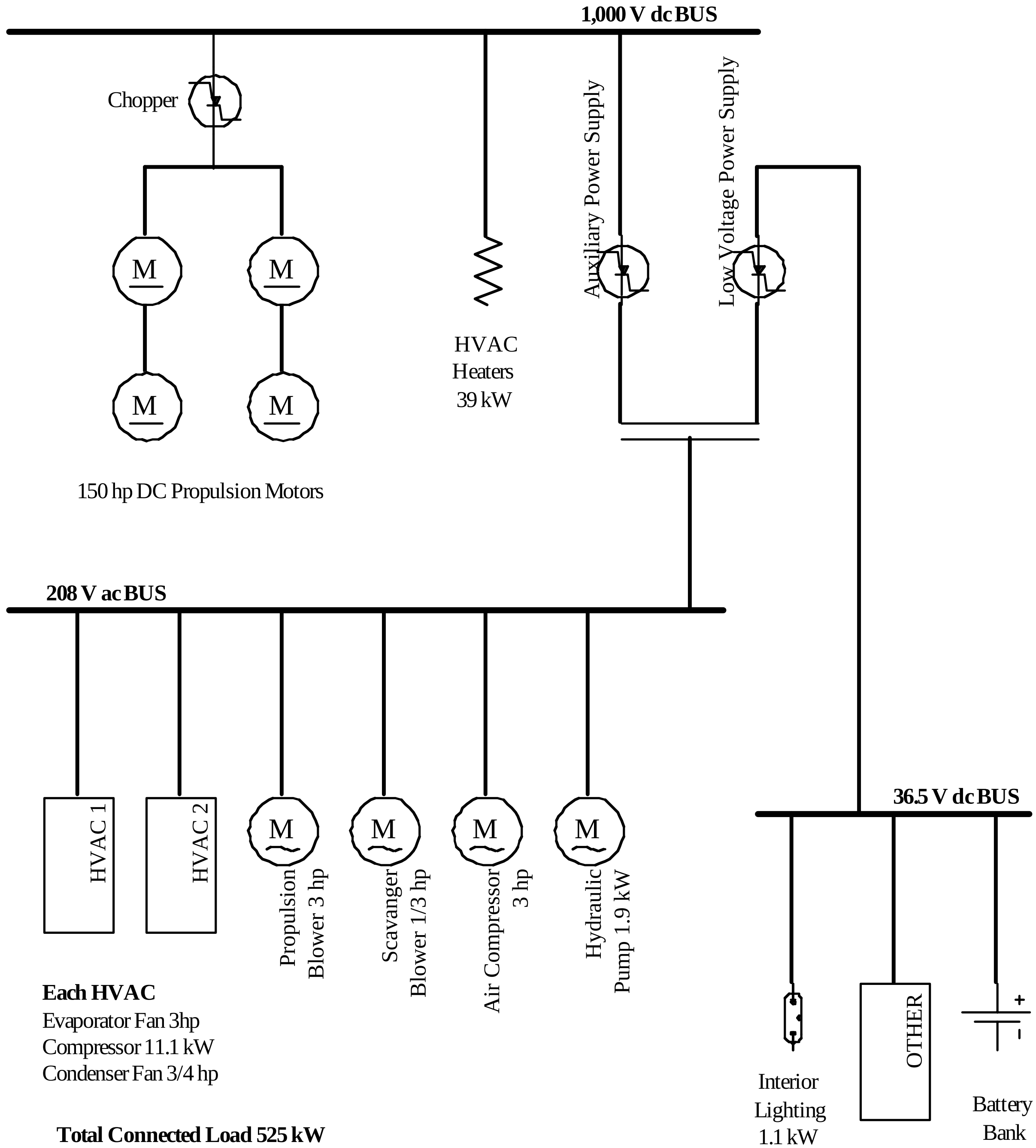



**Figure 1** Typical BART Car (C car) Electrical Distribution System and Loads

### 3.2 Major Energy Consuming Equipment Used by BART Cars

Major energy consuming devices used in the cars are shown in the following table. The power ratings listed are as read from the nameplates, or the measured power draw.

| ENERGY CONSUMING EQUIPMENT | | |
|---|---|---|
| **Energy Application** | **Quantity** | **Nominal Power** |
| **C Cars** | | |
| HVAC Indoor Fans | 2 | 2.7 kW |
| HVAC Compressors | 2 | 14.62 kW |
| HVAC Outdoor Fans | 2 | 0.6 kW |
| HVAC Heaters | 2 | 19.5 kW |
| Air Compressor | 1 | 3 hp |
| Propulsion Blower | 1 | 3 hp |
| Scavenger Blower | 1 | 0.33 hp |
| Hydraulic Pump | 1 | 1.9 kW |
| Other Equipment (e.g. communications, etc.) | 1 | 1.3 kW |
| Propulsion Motors | 4 | 150 hp |
| **A and B Cars** | | |
| HVAC Indoor Fans | 6 | 0.65 kW |
| HVAC Compressors | 6 | 5.46 kW |
| HVAC Outdoor Fans | 6 | 0.15 kW |
| HVAC Heaters* | 2 | 19.5 kW |
| Air Compressor* | 1 | 3 hp |
| Propulsion Blower* | 1 | 3 hp |
| Scavenger Blower* | 1 | 0.33 hp |
| Hydraulic Pump* | 1 | 1.9 kW |
| Other Equipment (e.g. communications, etc.)* | 1 | 1.3 kW |
| Propulsion Motors | 4 | 150 hp |

* No detail data was available for the auxiliary equipment used by the A and B cars. However it is expected that these systems will be similar to those used on the C cars.

### 3.3 Summary of Interior Lighting

The interior lighting for each car type is summarized in the following table.

Prefixes Used In Tables:

F20 = 20-Watt T12 fluorescent (with magnetic ballast), one lamp per fixture
T8-17 = 17-Watt T8 fluorescent (with electronic ballast), one lamp per fixture

| FACILITY LIGHTING SCHEDULE | | | | |
|---|---|---|---|---|
| **Car Type** | **Lamp Type** | **Number of Fixtures** | **Wattage/ Fixture** | **Total Wattage (kW)** |
| C1 Cars | F20 | 55 | 28.70 | 1.58 |
| C2 Cars | T8-17 | 55 | 20.44 | 1.12 |
| A Cars | T8-17 | 48 | 20.44 | 0.98 |
| B Cars | T8-17 | 48 | 20.44 | 0.98 |

* Each lighting fixture has only one lamp.

# 4. HISTORICAL ENERGY SUMMARY

## 4.1 Car Energy Consumption and Demand Summary

To establish a baseline for the electrical energy consumption of each BART car, we have used the following documents:

- *Qualification Test Report, Energy Consumption on Test Track, Rev C, 05/14/89*. This document presented the energy consumption of the C cars on a test track. From this document we also extracted the operational profile (how the cars were accelerated, maximum speeds as well as total distance covered).
- The result of the Energy Consumption on Test Track for the A/B cars (which were provided in an Excel spread sheet).

Based on the operational profile presented in *Qualification Test Report, Energy Consumption on Test Track, Rev C, 05/14/89* it is estimated that on average, a car will take approximately 0.024167 hours (approximately 1.45 minutes) to cover one mile. This conversion constant will be used throughout the report unless otherwise noted. The speed profile considered accelerating the train to approximately 80 mph in 45 seconds, maintaining a speed of 80 mph for 35 seconds and decelerating to a full stop in 60 seconds. A more detailed plot of the profile, which was used to derive the above constant, is included in the Appendix section at the end of the report.

From the above documents and the average daily operating hours of the cars* it is possible to estimate the annual electrical energy consumption and demand of each car type as well as the total annual electrical energy consumption of all BART cars. The results are presented in the following table.

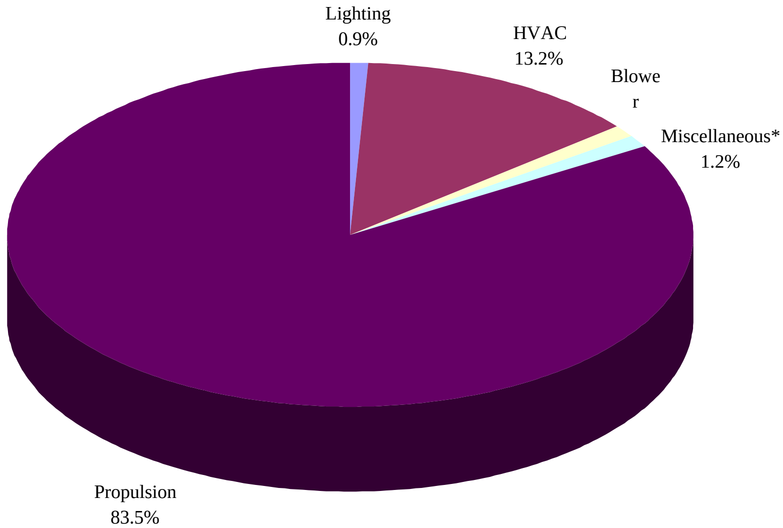
**ANNUAL ELECTRICAL ENERGY CONSUMPTION BY CAR TYPE**

| Car Type | N | H (hr/day) | D (mi/yr) | EEC (kWh/car-mi) | AEEC (kWh/car-yr) | CD (kW) | AEE (kWh/yr) |
|---|---|---|---|---|---|---|---|
| C1 | 150 | 7.7 | 116,435 | 3.6170 | 421,146 | 150 | 63,171,946 |
| C2 | 80 | 8.4 | 127,020 | 3.6122 | 458,816 | 150 | 36,705,269 |
| A | 59 | 8.1 | 122,275 | 3.3708 | 412,165 | 140 | 24,317,710 |
| B | 380 | 9.1 | 137,605 | 3.3708 | 463,839 | 140 | 176,258,795 |
| **Totals** | **669** | | | | | | **300,453,720** |

N = number of cars, H = average daily operating hours per car (provided by BART personnel), D = distance covered by each car in one year, EEC = electrical energy consumption per car per mile, AEEC = annual electrical energy consumption per car, CD = average created electrical demand per car and AEE = annual electrical consumption for all cars.

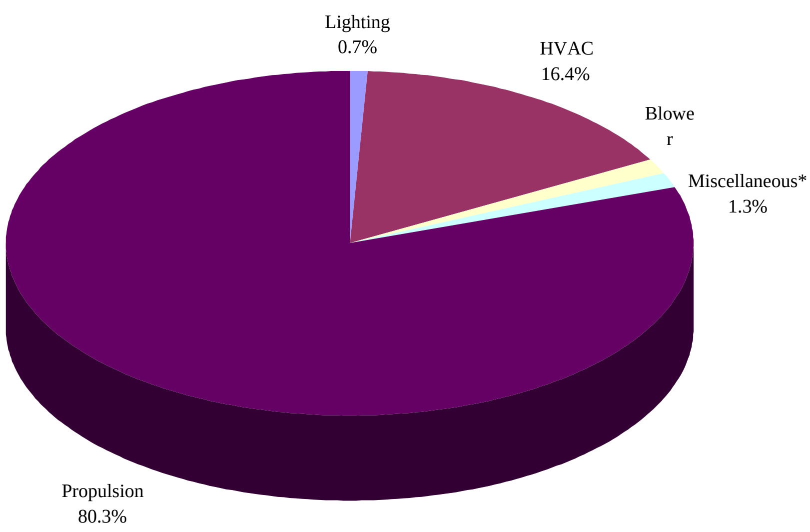
A pie chart illustrating the percentage of electrical energy usage for various functions is shown for C and A/B cars in Figures 2 and 3 respectively.

* Information provided by BART personnel through an Excel spread sheet.




* Unaccounted for, which also includes equipment not covered by the shown categories.

**Figure 2 –** C Cars Electricity Consumption by Function




* Unaccounted for, which also includes equipment not covered by the shown categories.

**Figure 3 –** A/B Cars Electricity Consumption by Function

# 5. DESCRIPTION OF ENERGY CONSERVATION AND EFFICIENCY MEASURES

This section summarizes the opportunities for energy efficiency for BART cars. The recommendations suggest methods of implementing energy efficiency measures. Implementation cost estimates are compared with energy cost savings to obtain simple payback periods. Detailed analysis for each proposed measure is presented in Section 6 – Detailed Analysis of the Measures.

Please note that the analyses presented here are preliminary and very limited in scope, which can serve as a guideline for further detailed analysis and engineering work. The assessment team has strived to utilize as much measured data, from present and past projects, as possible. Wherever assumptions were made, they have been clearly stated.

Tables ES-2A and ES-2B summarize the energy efficiency measures as elaborated in this section, in the respective categories of no-cost, low-cost, and investment grade.

**TABLE ES-2A SUMMARY OF ENERGY EFFICIENCY OPPORTUNITY INCENTIVES FOR EXISTING CARS (RETROFIT)**

| EEM No. Description | Energy Savings | Incentive or Rebate Program and Amount | Potential Incentive ($) | Installed Project Cost with Incentive ($) | Simple Payback Period w/ Incentive (yrs) |
|---|---|---|---|---|---|
| 1. High Efficiency Lighting for C1 Cars and New Cars | 156,872 kWh/yr | NRR-DR *$0.05/kWh* | Included in EEM 5 | Included in EEM 5 | Included in EEM 5 |
| 2. Direct Cooler Air to the Inlet of HVAC Condensers | 1,717,819 kWh/yr | NRR-DR *$0.14/kWh* | 240,495 | 100,000* | 0.6 |
| 3. Install Higher Efficiency HVAC Units on C Cars and New Cars | 413,021 kWh/yr | NRR-DR *$0.14/kWh* | 57,823 | 632,177 | 14.6 |
| 4. Optimize Outside Air Intake into Cars | 1,444,334 kWh/yr | NRR-DR *$0.14/kWh* | 202,207 | 847,793 | 5.6 |
| 5. Install Daylight Controls on the Fluorescent Lamps | 837,433 kWh/yr | NRR-DR *$0.05/kWh* | 49,715 | 2,820,270 | 22.4 |
| 6. Install Variable Frequency Drives on HVAC Supply Fans | 3,206,292 kWh/yr | NRR-DR *$0.14/kWh* | 448,881 | 1,475,000* | 4.4 |
| 7. Use Permanent Magnet (PM) Motors for Car Propulsion | 38,905,029 kWh/yr | NRR-DR *$0.08/kWh* | 3,112,402 | 51,344,198 | 12.6 |
| 8. Use Ultracapacitors for Regenerative Braking Energy Storage | 82,948,688 kWh/yr | NRR-DR *$0.08/kWh* | 6,635,895 | 88,038,753 | 10.1 |

* Incentive limited to 50% of measure's implementation cost.

| **TABLE ES-2B SUMMARY OF ENERGY EFFICIENCY OPPORTUNITY INCENTIVES FOR NEW CARS (NRNC)** | | | | | |
|---|---|---|---|---|---|
| **EEM No. Description** | **Energy Savings** | **Incentive Amount** | **Potential Incentive** ($) | **Installed Project Cost with Incentive** ($) | **Simple Payback Period w/ Incentive** (yrs) |
| 1. High Efficiency Lighting for C1 Cars and New Cars | 1,170 kWh/car-y | *$0.05/kWh* | Included in EEM 5 | Included in EEM 5 | Included in EEM 5 |
| 2. Direct Cooler Air to the Inlet of HVAC Condensers | N / A | N / A | N / A | N / A | N / A |
| 3. Install Higher Efficiency HVAC Units on C Cars and New Cars | 1,242 kWh/car-y | *$0.14/kWh* | 174 | 857 | 6.6 |
| 4. Optimize Outside Air Intake into Cars | 2,184 kWh/car-y | *$0.14/kWh* | 306 | 1,264 | 5.5 |
| 5. Install Daylight Controls on the Fluorescent Lamps | 1,194 kWh/car-y | *$0.05/kWh* | 118 | 3,948 | 15.9 |
| 6. Install Variable Frequency Drives on HVAC Supply Fans | 4,196 kWh/car-y | *$0.14/kWh* | 587 | 3,823 | 8.7 |
| 7. Use Permanent Magnet (PM) Motors for Car Propulsion | 45,063 kWh/car-y | *$0.08/kWh* | 3,605 | 77,795 | 16.4 |
| 8. Use Ultracapacitors for Regenerative Braking Energy Storage | 123,989 kWh/car-y | *$0.08/kWh* | 9,919 | 118,517 | 9.1 |

## EEM No. 1 - High Efficiency Lighting for C1 Cars and New Cars

In summary for this measure:

| | | |
|---|---|---|
| <u>Retrofit</u> | | |
| **Savings per car** | | |
| Electrical Energy Savings for C1 Cars | = | 0.008982 kWh/car-mi |
| | | 1,046† kWh/car-yr |
| | | |
| **Savings for whole BART fleet** | | |
| Electrical Energy Savings | = | 156,872 kWh/yr |
| Demand Reduction | = | 42 kW |
| Electrical Cost Savings | = | $16,472/yr |
| Maintenance Cost Savings | = | $21,419/yr |
| Total Cost Savings | = | $37,891/yr |
| Implementation Cost | = | Included in EEO No. 4 |
| Simple Payback Period | = | Included in EEO No. 4 |
| | | |
| <u>New Construction</u> | | |
| **Savings per car** | | |
| Electrical Energy Savings per Car | = | 0.007793 kWh/car-mi |
| | | 1,170‡ kWh/car-yr |
| Demand Reduction | = | 0.32 kW |
| Electrical Cost Savings | = | $123/yr |
| Implementation Cost | = | Included in EEO No. 4 |
| Simple Payback | = | Included in EEO No. 4 |

### Retrofit

Currently only C1 cars use old 20-Watt T12 fluorescent lighting with magnetic ballasts. The retrofitted C cars (C2) as well as the A and B cars use the more energy efficient 17-Watt T8 fluorescent lighting with electronic ballast, which has an equivalent light output to the 20-Watt fluorescent lamp. In addition to lighting energy savings, retrofitting the T12 fluorescent lamps with T8 fluorescent lamps will result in HVAC energy savings since heat generated by lighting must be removed by the HVAC system. Based on the test profile presented in the *Energy Consumption Test On Test Track*, the difference in input wattage (including lamp and ballast power) and the energy efficiency ratio (EER) of the HVAC system, it is estimated that replacing the existing T12 fluorescent lamps with T8 fluorescent lamps will save approximately 0.013209 kWh/car-mi (or 230,695 kWh/yr) resulting in a demand reduction of 62 kW. These electrical savings will result in an avoided cost of approximately $24,223/yr.

† Based on average miles per year for C1 Cars.
‡ Based on average miles per year for all cars.

Please note that if EEO No. 4 *"Install Daylight Controls on the Fluorescent Lamps"* is implemented, the potential electrical savings will slightly decrease due to the lower operating wattage of the lamps. It is estimated that the savings would be reduced by 32%. The new electrical savings would be:

EES = 0.008982 kWh/car-mi
AEES = 156,872 kWh/yr
DS = 42 kW
EECS = $16,472/yr

To avoid overlap of savings this reduced electrical savings will be used unless otherwise noted.

This recommendation will also reduce annual maintenance cost of lighting due to longer life of T8 fluorescents lamps. It is estimated that this recommendation will reduce the annual maintenance cost by $21,419. The total cost savings will be the sum of the annual electrical energy cost savings and the maintenance cost savings, which is estimated to be $37,891 per year.

The implementation cost for this recommendation is included in EEO No. 4 - *Install Daylight Controls on the Fluorescent Lamps*.

**NRNC**

*The IESNA Lighting Handbook Reference and Application* recommends that seating areas in transit systems be illuminated at 30 footcandles (fc). However, the logged light level data inside a BART car shows that the minimum light level in the train car is approximately 50 fc. Based on the train car square footage, fixture efficiency, number of light fixtures in each car and a light level depreciation factor, it is estimated that to maintain 50 fc inside a train car will require that each fluorescent lamp output 948 lumens. The T12 and T8 fluorescent lamps that can output this light level are 20- and 17-Watt lamps, respectively.

Since there are no lighting energy efficiency standards for transportation vehicles it is proposed that the present light level of 50 fc be considered as baseline.

- Based on the number of fixtures inside each train car (55 fixtures), train car square footage (735 $ft^2$) and the input power rating of a standard efficiency 20-Watt fluorescent lamp (28.7 Watts), the baseline lighting power density ($LPD_B$) for high efficiency lighting should be 2.1 $W/ft^2$.

The annual electrical energy savings (for one car) for using high efficiency T8 lighting would be 1,170 kWh/yr.

## EEM No. 2 - Direct Cooler Air to the Inlet of HVAC Condensers

Directing cooler air to the inlet of the HVAC condensers will reduce the energy consumption of the HVAC system. In summary for this measure:

Retrofit

**Savings per car**

| | | |
|---|---|---|
| Electrical Energy Savings for A/B Cars | = | 0.01995 kWh/car-mi<br>2,704 kWh/car-yr |
| Electrical Energy Savings for C Cars | = | 0.01921 kWh/car-mi<br>2,307 kWh/car-yr |

**Savings for whole BART fleet**

| | | |
|---|---|---|
| Electrical Energy Savings | = | 1,717,819 kWh/yr |
| Peak Demand Reduction | = | 409.29 kW |
| Electrical Cost Savings | = | $180,370/yr |
| Implementation Cost | = | $200,000 |
| Simple Payback Period | = | 1.1 years |

New Construction

**Savings per car**

| | | |
|---|---|---|
| Electrical Energy Savings per Car | = | N / A |

### Retrofit

Table 2-1 summarizes the HVAC system for various BART cars as well the nominal rating of the various HVAC system components. The HVAC units are controlled based on the return air temperature.

**TABLE 2-1 SUMMARY OF BART CAR HVAC SYSTEM**

| HVAC Component | Number of Units per Car | Nominal Rating per Unit* (kW/unit) |
|---|---|---|
| **A & B Cars** | | |
| HVAC Compressor | 6 | 5.46 |
| Evaporator (Supply) Blower | 6 | 0.65 |
| Condenser Fan | 6 | 0.15 |
| **C1 & C2 Cars** | | |
| HVAC Compressor | 2 | 14.62 |
| Evaporator (Supply) Blower | 2 | 2.7 |
| Condenser Fan | 2 | 0.6 |

Currently the heat generated by the resistor banks due to regenerative braking affects the temperature of the inlet to the condensers. Generally, the higher the temperature at the inlet of the condensers, the more energy the HVAC system will consume to cool the air.

To evaluate how the heat absorbed from the regenerative braking by the resistor bank affects the temperature of the inlet to the condensers, the audit team requested for temperature measurements of the inlet to the condenser heat exchanger and the outside ambient temperature to be performed. The audit team borrowed two temperature probes and a datalogger from the Pacific Energy Center’s Tool Lending Library and sent this equipment to BART personnel to install on a BART car. The measurement was first performed on BART’s test track to ensure that the equipment was set-up properly and the datalogger was recording the desired measurements. Since the regenerative braking system does not work on the test track, the inlet temperature to the condensers was found to be close to ambient conditions. BART personnel were able to schedule the measurements to be performed on a live track run, where passengers were not allowed on the car in which the equipment was installed. Figure 2-1 shows where the temperature probes were placed on the C cars to measure the temperature of the inlet to the condensers and the outside ambient temperature.

**Figure 2-1** (*Left*) Temperature Probe Mounted on Inlet to Condenser Heat exchanger. (*Right*) Temperature Probe Mounted on Car Door to Measure Outdoor Ambient Temperature

Figure 2-2 below shows the results of the live track run for a roundtrip run from Hayward to Richmond. The measurements show that the temperature of the inlet to the condenser was (for most cases) significantly higher than ambient outdoor conditions.

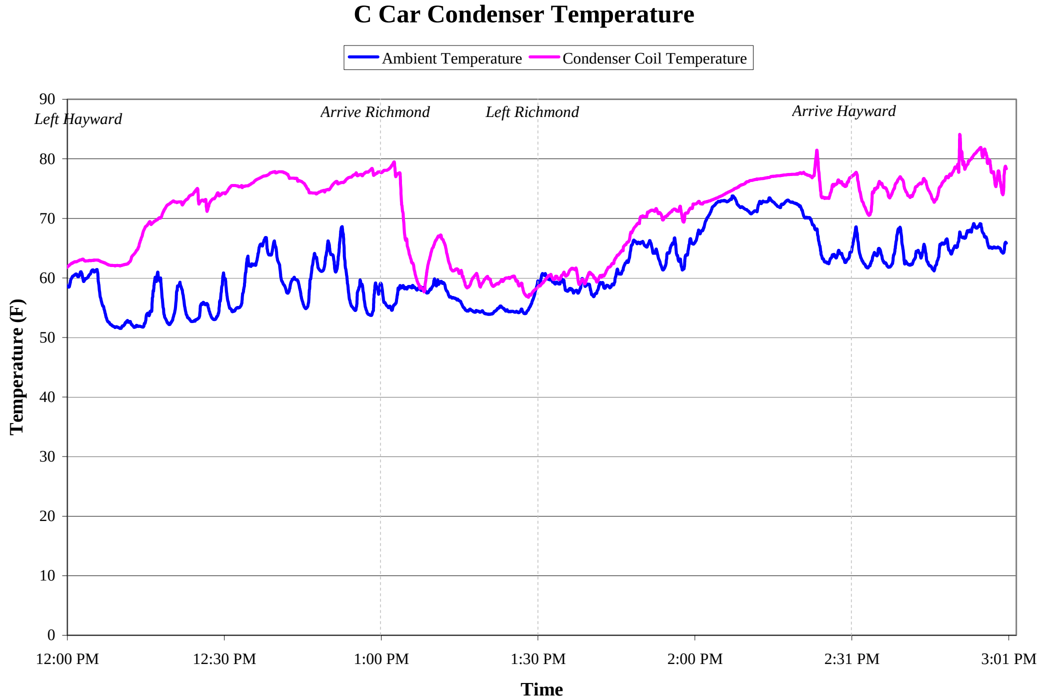



**Figure 2-2** C Car Condenser and Ambient Temperature Measurements from Live Track Run

It is recommended that cooler outside air be directed to the inlet of the condenser heat exchanger, thereby reducing the amount of work required by the compressors to cool the air. The details of the methodology and analysis of this measure is included in the Section 6 of this report. Table 2-2 summarizes the potential electrical energy, demand and cost savings that may be realized by directing cooler air to the inlet of the condenser.

| TABLE 2-2 SUMMARY OF ELECTRICAL AND COST SAVINGS | | | | | | |
|---|---|---|---|---|---|---|
| **Car Type** | **Number of Cars** | **Savings per car per mile** (kWh/car-mi) | **Annual Distance Covered** (mi/yr) | **Energy Savings** (kWh/yr) | **Peak Demand Savings** (kW) | **Total Cost Savings** ($/yr) |
| A | 59 | 0.01995 | 122,275 | 143,924 | 36.50 | 15,112 |
| B | 380 | 0.01995 | 137,605 | 1,043,184 | 235.52 | 109,534 |
| C1 | 150 | 0.01921 | 116,435 | 335,507 | 89.52 | 35,228 |
| C2 | 80 | 0.01921 | 127,020 | 195,204 | 47.75 | 20,496 |
| **Totals** | **669** | | | **1,717,819** | **409.29** | **180,370** |

From Table 2-2, directing cooler air to the intake of the condenser heat exchanger will reduce the electrical energy consumption of the HVAC compressors by approximately 1,717,819 kWh/yr resulting in a peak demand reduction of 409.29 kW. These electrical savings will result in an avoided electrical cost of approximately $180,370 per year.

Implementing this recommendation will require installing pathways to bring outside air from the sides of the cars to the inlet of the condenser heat exchanger. It has been estimated that installing pathways to direct outside air to the inlet of the condenser heat exchanger will result in an implementation cost of roughly $200,000.

Please note that the implementation cost includes only the typical installed cost of pathways. This cost does not include the engineering costs associated with the design of such a system. The total cost savings of $180,370 will pay back for the implementation cost of $200,000 in approximately 1.1 years.

**Note:** Detailed engineering will be needed to implement this measure, which is beyond the scope of this project.

**NRNC**

Since this recommendation deals with directly modifying an existing system (with no newer energy efficient equipment), this recommendation does not apply to new construction.

**EEM No. 3 - Install Higher Efficiency HVAC Units on C Cars and New Cars**

Replace the existing packaged air conditioning units on the C cars with higher efficiency units.

| | | |
|---|---|---|
| <u>Retrofit</u> | | |
| **Savings per car** | | |
| Electrical Energy Savings for C Cars | = | 0.01495 kWh/car-mi<br>1,796 kWh/car-yr |
| **Savings for whole BART fleet** | | |
| Electrical Energy Savings | = | 413,021 kWh/yr |
| Peak Demand Reduction | = | 106.83 kW |
| Electrical Cost Savings | = | $43,367/yr |
| Implementation Cost Premium | = | $690,000 |
| Simple Payback Period | = | 16 years |
| <u>New Construction</u> | | |
| **Savings per car** | | |
| Electrical Energy Savings per Car | = | 0.009534 kWh/car-mi<br>1,242 kWh/car-yr |
| Demand Reduction | = | 0.39 kW |
| Electrical Cost Savings | = | $130/yr |
| Implementation Cost Premium | = | $1,031 |
| Simple Payback | = | 7.9 years |

**Retrofit**

The C cars (C1 and C2 cars) utilize two HVAC units per car to provide heating and cooling. Each HVAC unit is equipped with a 14.6 (nominal rating) kW reciprocating R-22 compressor, 2.7 kW evaporator blower and a 0.6 kW condenser fan. The HVAC units are controlled based on the return air temperature.

The HVAC systems for the C cars have been installed in the 1980s. More efficient technologies are currently available that are more efficient than the existing HVAC units. According to the "*Qualification Test Report: Performance of HVAC System (Energy Consumption) Installed on BART C Car*" provided to the audit team by BART, the energy efficiency ratio (EER) of the existing HVAC units while in cooling mode is approximately 8.4. EER is a measure of an air conditioning unit's cooling capacity (in Btu/hr) per electrical energy input (power draw in watts). The higher a HVAC unit's EER, the less electricity the unit uses to provide the same amount of cooling. Based on data provided by StoneAir, a manufacturer of HVAC units for the transit industry, higher efficiency HVAC units currently available have an EER of about 9.1.

Another benefit with the higher efficiency HVAC units is that the new HVAC system utilizes scroll-type compressors instead of the existing reciprocating compressors. Scroll compressors are lighter, more reliable and less maintenance intensive compared to reciprocating compressors. Other benefits of the higher efficiency HVAC units as presented by StoneAir is included in the appendix of this report.

The details of the methodology and analysis of this measure is included in the Section 6 of this report. Table 3-1 on the following page summarizes the potential electrical energy, demand and cost savings that may be realized by replacing the existing HVAC units with higher efficiency units.

**TABLE 3-1 SUMMARY OF ELECTRICAL AND COST SAVINGS**

| **Car Type** | **Number of Cars** | **Savings per car per mile** (kWh/car-mi) | **Annual Distance Covered** (mi/yr) | **Energy Savings** (kWh/yr) | **Peak Demand Savings** (kW) | **Total Cost Savings** ($/yr) |
|---|---|---|---|---|---|---|
| C1 | 150 | 0.01495 | 116,435 | 261,105 | 69.67 | 27,416 |
| C2 | 80 | 0.01495 | 127,020 | 151,916 | 37.16 | 15,951 |
| **Totals** | **230** | | | **413,021** | **106.83** | **43,367** |

From Table 6-1, replacing the existing HVAC units with higher efficiency units will reduce the electrical energy consumption by approximately 413,021 kWh/yr resulting in a peak demand reduction of 106.83 kW. These electrical savings will result in an avoided electrical cost of approximately $43,367 per year.

The implementation cost premium for this measure is taken to be the cost differential between a high efficiency HVAC unit and a standard efficiency HVAC unit. The costs of the existing HVAC units and the proposed higher efficiency units were not available to BASE, thus we have taken the cost differential between a typical standard 7-ton HVAC unit and a high efficiency 7-ton HVAC unit to be the implementation cost premium for this case. The total implementation cost premium for this measure has been roughly estimated to be $690,000. The estimated total cost savings of $43,369 per year would pay for the estimated implementation cost premium of $690,000 in about 16 years.

**Notes:**

1. It should be noted when purchasing higher efficiency HVAC units, they should be specified to be equipped with the capabilities as recommended in EEOs No. 2, 4, and 6. This will increase the initial cost of the new HVAC system, however this may be less costly than retrofitting the existing units if plans are eventually made for replacing the entire HVAC system with more efficient units.
2. This recommendation only considers the HVAC system for the C cars because these were the cars that BART personnel were more focused in upgrading the HVAC system. C cars are much older than the A and B cars. As mentioned previously, the EER for the C car HVAC system was estimated to be approximately 8.4. The A and B cars are estimated to have an EER of 8.7. Since BART personnel were concerned mainly with the C cars' HVAC system, we have based our analyses on these cars in this project.

**NRNC**

For new cars, the baseline considered for a high efficiency HVAC system is the existing HVAC system in the newer A/B cars. This includes six 5.46 kW HVAC compressors (motor efficiency of 0.918) and an energy efficiency ratio (EER) value of 8.7 Btu/W-h. Using the A/B car HVAC system as baseline, and comparing the energy consumption of the proposed, more energy efficient, HVAC system (with an EER value of 9.1 Btu/W-h), the potential energy savings would be 0.009534 kWh/car-mi, resulting in an annual electrical energy savings of approximately 1,242 kWh/car-yr.

**EEM No. 4 - Optimize Outside Air Intake into Cars**

Optimize the amount of outside air intake into the cars based on the outside air temperature. In summary for this measure:

Retrofit

**Savings per car**

| | | |
|---|---|---|
| Electrical Energy Savings for A/B Cars | = | 0.01677 kWh/car-mi |
| | | 2,273 kWh/car-yr |
| Electrical Energy Savings for C Cars | = | 0.01616 kWh/car-mi |
| | | 1,941 kWh/car-yr |

**Savings for whole BART fleet**

| | | |
|---|---|---|
| Electrical Energy Savings | = | 1,444,334 kWh/yr |
| Peak Demand Reduction | = | 344.16 kW |
| Electrical Cost Savings | = | $151,791/yr |
| Implementation Cost | = | $1,050,000 |
| Simple Payback Period | = | 6.9 years |

New Construction

**Savings per car**

| | | |
|---|---|---|
| Electrical Energy Savings per Car | = | 0.01677 kWh/car-mi |
| | = | 2,184 kWh/car-yr |
| Demand Reduction | = | 0.69 kW |
| Electrical Cost Savings | = | $229/yr |
| Implementation Cost | = | $1,570 |
| Simple Payback | = | 6.8 years |

**Retrofit**

Fresh outside air should to be used directly for space cooling whenever outdoor temperature and humidity levels are favorable. By using cool **outside** air whenever possible, the energy usage by the cars' HVAC compressors can be reduced. Table 4-1 summarizes the HVAC system for various BART cars as well the nominal rating of the various HVAC system components. The HVAC units are controlled based on the return air temperature.

| **TABLE 4-1 SUMMARY OF BART CAR HVAC SYSTEM** | | |
|---|---|---|
| **HVAC Component** | **Number of Units per Car** | **Nominal Rating per Unit*** (kW/unit) |
| **A & B Cars** | | |
| HVAC Compressor | 6 | 5.46 |
| Evaporator (Supply) Blower | 6 | 0.65 |
| Condenser Fan | 6 | 0.15 |
| **C1 & C2 Cars** | | |
| HVAC Compressor | 2 | 14.62 |
| Evaporator (Supply) Blower | 2 | 2.7 |
| Condenser Fan | 2 | 0.6 |

Based on documents provided and conversations with BART personnel regarding the operation of the HVAC units, outside air is drawn into the cars through 'grilles in the sides on feature line'. The air then passes through ducts to inlet mixing plenums upstream of the air treatment units where it is mixed with recirculated air. The amount of outside air drawn into the cars does not vary, regardless of outdoor temperature conditions. Optimizing the usage of outside air will reduce the electrical energy consumption of the HVAC compressor motor. The air distribution fan in each unit must still be used.

The details of the methodology and analysis of this measure is included in the Section 6 of this report. The results for potential electrical energy, demand and cost savings are summarized on Table 4-2 on the following page.

| **TABLE 4-2 SUMMARY OF ELECTRICAL AND COST SAVINGS** | | | | | | |
|---|---|---|---|---|---|---|
| **Car Type** | **Number of Cars** | **Savings per car per mile** (kWh/car-mi) | **Annual Distance Covered** (mi/yr) | **Energy Savings** (kWh/yr) | **Peak Demand Savings** (kW) | **Total Cost Savings** ($/yr) |
| A | 59 | 0.01677 | 122,275 | 120,983 | 30.69 | 12,839 |
| B | 380 | 0.01677 | 137,605 | 876,902 | 197.98 | 92,075 |
| C1 | 150 | 0.01616 | 116,435 | 282,238 | 75.32 | 29,635 |
| C2 | 80 | 0.01616 | 127,020 | 164,211 | 40.17 | 17,242 |
| **Totals** | **669** | | | **1,444,334** | **344.16** | **151,791** |

From Table 4-2, bringing in outside air when outdoor temperature and humidity levels are favorable will reduce the electrical energy consumption by the HVAC compressors by approximately 1,444,334 kWh/yr, resulting in a peak demand reduction of 344.16 kW. These electrical savings will result in an avoided electrical cost of approximately $151,791 per year.

Implementing this recommendation will require installing motorized dampers onto the existing HVAC units that will bring in outside air when outdoor ambient conditions are favorable and temperature sensors to measure the ambient conditions. It has been estimated that the total implementation cost of this measure is roughly $1,050,000.

Please note that the implementation cost includes only the typical installed cost of the motorized damper and outdoor temperature sensor. This cost does not include the cost to interface the damper and sensor to the HVAC control system, nor the engineering costs associated with the design of such a system. The total cost savings of $151,791 will pay back for the implementation cost of $1,050,000 in approximately 6.9 years.

**Notes:**

1. It must be noted that the HVAC run hours and the temperature ranges used in this EEO was estimated from an annual average weather condition database taken from the Oakland area, and is subject to change depending on the location of the BART car. Moreover, the EEO does not account for possible changes in the relative humidity.
2. This measure may require increasing the size of the outside air duct, which will be determined from the detailed engineering of this measure.
3. Detailed engineering will be needed to implement this measure, which is beyond the scope of this project.

**NRNC**

For new cars, the baseline considered for a high efficiency HVAC system is the existing HVAC system in the newer A/B cars. The potential energy savings would be 0.01677 kWh/car-mi, resulting in an annual electrical energy savings of approximately 2,184 kWh/car-yr.

**EEM No. 5 - Install Daylight Controls on the Fluorescent Lamps**

In summary for this measure:

| | | |
|---|---|---|
| Retrofit | | |
| **Savings per car** | | |
| Electrical Energy Savings for A/B Cars | = | 0.009171 kWh/car-mi |
| | | 1,243 kWh/car-yr |
| Electrical Energy Savings for C Cars | = | 0.010560 kWh/car-mi |
| | | 1,268 kWh/car-yr |
| | | |
| **Savings for whole BART fleet** | | |
| Electrical Energy Savings | = | 837,433 kWh/yr |
| Demand Reduction | = | 0 kW |
| Electrical Cost Savings | = | $87,930/yr |
| Implementation Cost | = | $2,720,330 |
| Simple Payback Period | = | 31 years |
| | | |
| New Construction | | |
| **Savings per car** | | |
| Electrical Energy Savings per Car | = | 0.009171 kWh/car-mi |
| | | 1,194[§] kWh/car-yr |
| Demand Reduction | = | 0.0 kW |
| Electrical Cost Savings | = | $125/yr |
| Implementation Cost | = | $4,066 |
| Simple Payback | = | 16.4[**] years |

**Retrofit**

Currently C1 cars use 20-Watt T12 fluorescent lighting with magnetic ballasts, while A/B and C2 cars use high efficiency 17-Watt T8 fluorescent lighting with electronic ballasts. These lamps remain fully on, although 64% of BART tracks are above ground. Figure 5-1 below shows the light level inside a BART car starting on the Daly City Station and ending on the Pittsburg/Bay Point Station as measured by light sensors installed by the assessment team.

Figure 5-1, in the following page, shows the following interesting trends:

- The minimum light level required inside a BART car is about 50 fc.
- Approximately 62% of the track covered by the Daly City – Pittsburg/North Point line is on the surface. This is very close to the fraction of tracks that are on the surface for all BART lines, which is 64%.

[§] This is with the assumption that new train cars will use high efficiency lighting.
[**] Considers the electrical cost savings from EEM No. 1 - High Efficiency Lighting

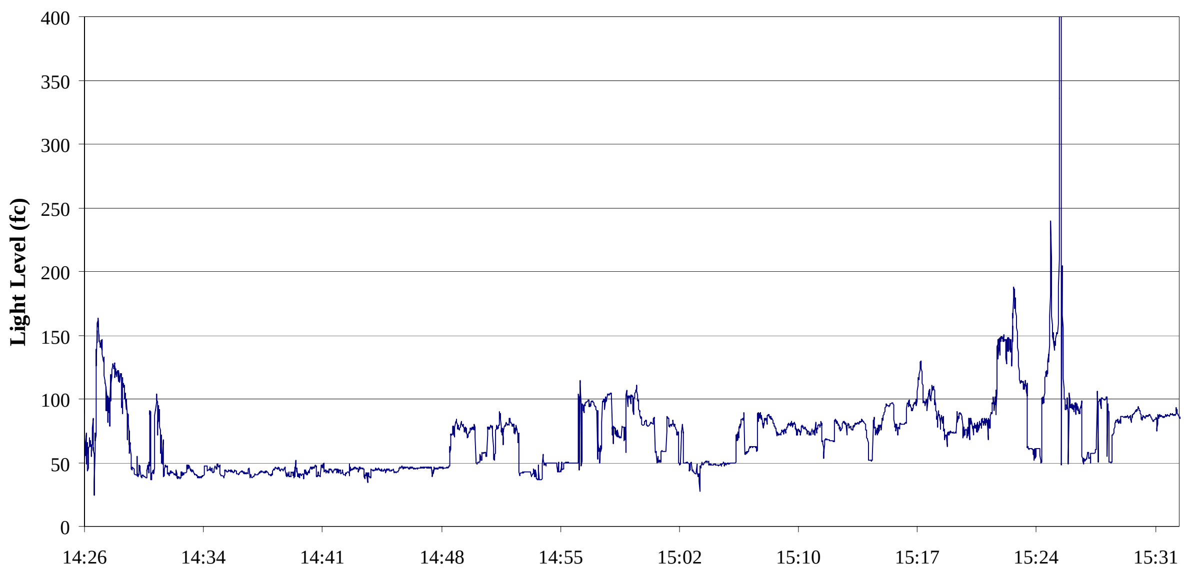



**Figure 5-1 Light Level inside a BART Car during June 9 2006 (Daly City – Pittsburg/Bay Point)**

Based on the logged light level data, the fraction of surface track of all BART lines, and a computer simulation of the light levels from sunrise to sun set for each month of the year, it is estimated that on average, the fluorescent lamps could be dimmed to 55% of its nominal light output during daytime (with the added restriction that the lamps output should never go below 25%, even when there is enough daylight available from windows).

Table 5-1 summarizes the potential electrical energy and cost savings for the A/B and C cars.

**TABLE 5-1 SUMMARY OF ELECTRICAL ENERGY AND COST SAVINGS**

| Car Type | Number of Cars | Number of Fixtures | IW (W) | EES (kWh/C-mi) | AEES (kWh/yr) | CS ($/yr) |
|---|---|---|---|---|---|---|
| A | 59 | 48 | 20.44 | 0.009171 | 66,160 | 6,947 |
| B | 380 | 48 | 20.44 | 0.009171 | 479,540 | 50,352 |
| C1 | 150 | 55 | 20.44* | 0.010560 | 184,428 | 19,365 |
| C2 | 80 | 55 | 20.44 | 0.010560 | 107,304 | 11,267 |
| **Totals** | **669** | | | | **837,433** | **87,930** |

* C1 cars currently use standard efficiency T12 lamp. However it is assumed that these lamps will be replaced with the more energy efficient T8 lamps. Thus saving estimates are based on the more energy efficient T8 lamp.
IW = lamp input wattage, EES = electrical energy savings, AEES = annual electrical energy savings and CS = cost savings.

From Table 5-1, dimming the fluorescent lamps could save approximately 837,433 kWh/yr. Since the lights would have to come to full brightness when the train goes underground, it is expected that this recommendation will not result in demand savings. The total avoided electrical cost would be approximately $87,930.

Implementing this recommendation will require installing 277 V dimmable fluorescent ballasts (2-lamp ballasts), a daylight sensor, a daylight controller, a power pack and a 1.8 kW inverter to transform DC voltage (from the battery system) to AC voltage. Based on a manufacturer's quote and RS Means Electrical Cost Data 2006, the implementation cost can be itemized as follows:

| | |
|---|---|
| (16,976) 2-lamp dimmable ballasts | $ 1,188,320 |
| (669) Daylight sensors | $ 73,590 |
| (669) Daylight controllers | $ 267,600 |
| (669) Power Packs | $ 120,420 |
| (669) 1.8 kW inverters | $ 869,700 |
| Installation Costs | $ 200,700 |
| **Total Cost** | **$ 2,720,330** |

Therefore the total cost savings of $87,930 will pay back for the implementation cost of $2,720,330 in approximately 31 years.

**NRNC**

Installing daylight controls on new BART car lighting fixtures will result in electrical energy savings. The proposed baseline for estimating the electrical savings of daylight controls on new train cars is the lighting system in the A/B cars without daylight controls. From the above, the potential electrical energy savings per car mile for installing daylight controls in the A/B cars will be 0.009171 kWh/car-mi resulting in an annual electrical energy savings of 1,194 kWh/car-yr ( at an average distance covered by one car in one year of 130,241 mi/yr).

## EEM No. 6 - Install Variable Frequency Drives on HVAC Supply Fans

Install variable frequency drives (VFD, the same as adjustable speed drive) on the HVAC supply fan motors in all car units. A VFD will reduce the power consumption of the supply fans depending on the cars' return air temperature.

| | | |
|---|---|---|
| Retrofit | | |
| **Savings per car** | | |
| Electrical Energy Savings for A/B Cars | = | 0.03222 kWh/car-mi |
| | | 4,367 kWh/car-yr |
| Electrical Energy Savings for C Cars | = | 0.04666 kWh/car-mi |
| | | 5,604 kWh/car-yr |
| **Savings for whole BART fleet** | | |
| Electrical Energy Savings | = | 3,206,292 kWh/yr |
| Peak Demand Reduction | = | 0.0 kW |
| Electrical Cost Savings | = | $336,661/yr |
| Implementation Cost | = | $2,950,000 |
| Simple Payback Period | = | 8.8 years |
| New Construction | | |
| **Savings per car** | | |
| Electrical Energy Savings per Car | = | 0.03222 kWh/car-mi |
| | = | 4,196 kWh/car-yr |
| Demand Reduction | = | 0.0 kW |
| Electrical Cost Savings | = | $441/yr |
| Implementation Cost | = | $4,410 |
| Simple Payback | = | $10.0 years |

### Retrofit

Table 6-1 summarizes the HVAC system for various BART cars as well the nominal rating of the various HVAC system components. The HVAC units are controlled based on the return air temperature.

**TABLE 6-1 SUMMARY OF BART CAR HVAC SYSTEM**

| HVAC Component | Number of Units per Car | Nominal Rating per Unit* (kW/unit) |
|---|---|---|
| **A & B Cars** | | |
| HVAC Compressor | 6 | 5.46 |
| Evaporator (Supply) Blower | 6 | 0.65 |
| Condenser Fan | 6 | 0.15 |
| **C1 & C2 Cars** | | |
| HVAC Compressor | 2 | 14.62 |
| Evaporator (Supply) Blower | 2 | 2.7 |
| Condenser Fan | 2 | 0.6 |

Based on conversations with BART personnel regarding the operation of the HVAC system, the operation of the HVAC compressors are controlled based on the return air temperature, however the air supplied to the cars are constant with only damper control. It is recommended that variable frequency drives (VFDs) be installed on the evaporator (supply) blowers to replace damper control. A VFD will control the airflow provided to the cars based on the cars' return air temperature, which varies based on the occupancy level of the cars. The hourly passenger loading variation for the BART system was not available to BASE. Thus, we have taken a typical transit passenger loading profile shown in Figure 6-1 on the following page, extracted from Vuchic (2005).

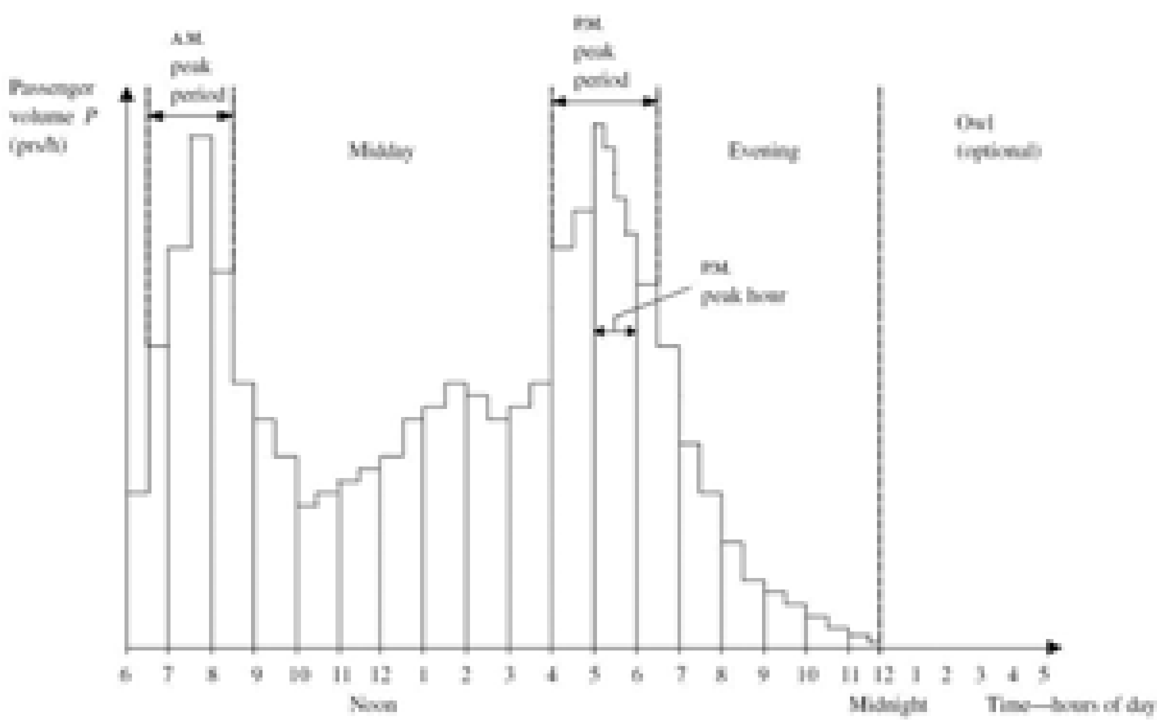



**Figure 6-1** Hourly Variation of Passenger Volume for a Typical Transit Line

By installing a VFD on each HVAC supply fan, energy savings can be obtained due to the fact that the fan motors will no longer be consuming 100% of its rated power during a majority of the cars' running hours.

The details of the methodology and analysis of this measure is included in Section 6 of this report. The results for potential electrical energy, demand and cost savings are summarized on Table 6-2 below.

**TABLE 6-2 SUMMARY OF ELECTRICAL AND COST SAVINGS**

| **Car Type** | **Number of Cars** | **Savings per car per mile** (kWh/car-mi) | **Annual Distance Covered** (mi/yr) | **Energy Savings** (kWh/yr) | **Total Cost Savings** ($/yr) |
|---|---|---|---|---|---|
| A | 59 | 0.03222 | 122,275 | 232,442 | 24,406 |
| B | 380 | 0.03222 | 137,605 | 1,684,781 | 176,902 |
| C1 | 150 | 0.04666 | 116,435 | 814,929 | 85,568 |
| C2 | 80 | 0.04666 | 127,020 | 474,140 | 49,785 |
| **Totals** | **669** | | | **3,206,292** | **336,661** |

From Table 6-2 installing VFDs on the HVAC supply fans will reduce the electrical energy consumption by 3,206,292 kWh/yr. There is not expected to be any demand savings due to implementation of this measure since the fans are expected to operate at or near full load during peak hours. The electrical energy savings will result in an avoided electrical cost of approximately $336,661 per year.

Implementing this recommendation will require installing VFD control units onto the existing supply fans and removing the existing dampers. The VFD will be controlled based on the car units' return air temperature. It has been estimated that installing VFD control units on all of the BART car HVAC supply fans will result in an implementation cost of roughly $2,950,000.

Please note that the implementation cost includes only the typical installed cost of the VFD control units. This cost does not include the cost to interface the VFDs to the HVAC control system, nor the engineering costs associated with the design of such a system. The total cost savings of $336,661 will pay back for the implementation cost of $2,950,000 in approximately 8.8 years.

**Note:** Detailed engineering will be needed to implement this measure, which is beyond the scope of this project.

**NRNC**

For new cars, the baseline considered for HVAC fan control is the existing HVAC fan control in the newer A/B cars. For installing VFD control on HVAC fans in new train cars, the potential energy savings would be 0.03222 kWh/car-mi, resulting in an annual electrical energy savings of approximately 4,367 kWh/car-yr.

**EEM No. 7 - Use Permanent Magnet (PM) Motors for Car Propulsion**

In summary for this measure:

<u>Retrofit</u>

| | | |
|---|---|---|
| **Savings per car** | | |
| Electrical Energy Savings for A/B Cars | = | 0.346 kWh/car-mi |
| | | 46,898 kWh/car-yr |
| Electrical Energy Savings for C Cars | = | 0.663 kWh/car-mi |
| | | 79,637 kWh/car-yr |
| **Savings for whole BART fleet** | | |
| Electrical Energy Savings | = | 38,905,029 kWh/yr |
| Demand Reduction | = | 9,424 kW |
| Electrical Cost Savings | = | $4,085,028/yr |
| Implementation Cost Premium | = | $54,456,600 |
| Simple Payback | = | 13.3 years |

<u>New Construction</u>

| | | |
|---|---|---|
| **Savings per car** | | |
| Electrical Energy Savings per Car | = | 0.346 kWh/car-mi |
| | | 45,063 kWh/car-yr |
| Demand Reduction | = | 14.32 kW |
| Electrical Cost Savings | = | $4,732/yr |
| Implementation Cost Premium | = | $81,400 |
| Simple Payback | = | 17.2 years |

**Retrofit**

Currently the C1 and C2 cars use direct current motors (DC) while the A and B cars use induction motors (IM) for propulsion. Replacing these motors with permanent magnet (PM) motors could result in significant electrical energy and maintenance cost savings. Based on test data provided by BART personnel and with the help of *DRS ELECTRIC POWER TECHNOLOGIES, INC*. (a PM motor manufacturer) a computer model was developed to compare the electrical energy consumption as well as potential electrical energy regeneration capability of an IM and a PM propulsion system. The results of the computer model for the IM and PM motors were then scaled to the results of the Qualification Test Report: Energy Consumption Test on Test Track performed for the A/B cars. For the C cars, which use DC motors, the results were obtained based on the comparison of actual test track data of C cars and the scaled data for the PM motors.

The details of the methodology and analysis of the computer model is included in the Appendix of the report. The results from this study are summarized on Table 7-1 below.

| TABLE 7-1 SUMMARY OF ELECTRICAL AND COST SAVINGS | | | | | | |
|---|---|---|---|---|---|---|
| **Car Type** | **Number of Cars** | **Savings per car per mile** (kWh/car-mi) | **Distance Covered** (mi/yr) | **Energy Savings** (kWh/yr) | **Demand Savings** (kW) | **Total Cost Savings** ($/yr) |
| A | 59 | 0.346 | 122,275 | 2,496,122 | 631 | 262,093 |
| B | 380 | 0.346 | 137,605 | 18,092,305 | 4,071 | 1,899,692 |
| C1 | 150 | 0.663 | 116,435 | 11,579,461 | 3,079 | 1,215,843 |
| C2 | 80 | 0.663 | 127,020 | 6,737,141 | 1,642 | 707,400 |
| **Totals** | **669** | | | **38,905,029** | **9,424** | **4,085,028** |

From Table 7-1, replacing the existing induction motors and DC motors with permanent magnet motors will reduce the electrical energy consumption by 38,905,029 kWh/yr resulting in a demand reduction of 9,424 kW. These electrical savings will result in an avoided electrical cost of approximately $4,085,028 per year.

Besides the overall increase in energy efficiency, PM motors will result in significant annual maintenance cost savings. The non-energy efficiency benefits that PM motors could provide to BART are:

1. The possibility of completely eliminating gear boxes since PM motors can provide the required torque throughout its rpm range.
2. Since PM motors are synchronous machines, each motor will have to be powered from independent motor drives to prevent damage to the machine from uneven ware of the steel wheels; however this can be used to an advantage by preventive maintenance personnel since it will be possible to track defects and worn out steel wheels electronically.

Implementing this recommendation will require a major retrofit to the existing BART cars. The essential required components will be four permanent magnet motors and new electronic drives for each motor. Based on a **very preliminary quotation** by the PM motor manufacturer, the implementation cost could be itemized as follows[††]:

| | |
|---|---|
| (2,676) 175 hp PM motor plus cooling pack.......................................... | $ 66,900,000 |
| (2,676) 450 hp water cooled electronic drives ....................................... | $ 133,800,000 |
| Non-refundable engineering costs ......................................................... | $ 8,697,000 |
| **Total Cost.......................................................................................** | **$ 209,397,000** |

If it is opted to install the permanent magnet motors as the existing AC (or DC) systems come to their end-of life, then the implementation cost will be the cost premium for choosing a PM drive system instead of an AC or DC drive system. Based on RS Means Electrical Cost Data 2007, the cost for purchasing the 150 hp AC motors and 400 hp variable frequency drives can be estimated as follows:

[††] These are off-the-shelf product prices.

| | | |
|---|---|---|
| (2,676) 150 hp AC TEFC motor | $ | 30,238,800 |
| (2,676) 400 hp variable frequency drives | $ | 124,701,600 |
| **Total Cost** | **$** | **154,940,400** |

The cost premium will be the cost difference between replacing the existing units with PM units instead of replacing them with new AC (or DC) systems. Therefore, the total cost savings of $4,085,028 would pay for the cost premium of $54,456,600 in approximately 13 years.

Notes:

1. This cost estimate does not consider installation costs.
2. For calculation of cost premium, it is assumed that the cost of DC motors and choppers is similar to the cost of the AC motors and variable frequency drives.

**NRNC**

Installing permanent magnet motors on new BART cars will result in electrical energy savings. The proposed baseline for estimating the electrical savings of permanent magnet motors on new train cars is the existing AC motor system in the A/B cars. From the above, the potential electrical energy savings per car mile for installing permanent magnet motors in the A/B cars will be 0.346 kWh/car-mi resulting in an annual electrical energy savings of 45,063 kWh/car-yr ( at an average distance covered by one car in one year of 130,241 mi/car-yr).

**EEM No. 8 - Use Ultracapacitors for Regenerative Braking**

In summary for this measure:

| | | |
|---|---|---|
| Retrofit | | |
| **Saving per car** | | |
| Electrical Energy Savings per car mile | = | 0.952 kWh/car-mi |
| | | 123,989 kWh/car-year |
| | | |
| **Savings for whole BART fleet** | | |
| Electrical Energy Savings | = | 82,948,688 kWh/yr |
| Demand Reduction | = | 19,733 kW |
| Electrical Cost Savings | = | $8,709,612/yr |
| Implementation Cost | = | $94,674,648 |
| Simple Payback Period | = | 10.9 years |
| | | |
| New Construction | | |
| **Saving per car** | | |
| Electrical Energy Savings per Car | = | 0.952 kWh/car-mi |
| | | 123,989 kWh/car-year |
| Demand Reduction | = | 39.39 kW |
| Electrical Cost Savings | = | $13,019/yr |
| Implementation Cost | = | $128,439 |
| Simple Payback | = | 9.9 years |

**Note: Please refer to Appendix B – Ultracapacitor Implementation Addendum for details on reference and application of this technology**

**Retrofit**

The ultracapacitor is a new electrical energy storage device. Its working principle is a combination of traditional batteries and capacitors. A typical double layer ultracapacitor uses a very porous material (like carbon), which is immersed in an electrolyte solution. When an electric field is applied across the ultracapacitor terminals, the electrodes and electrolyte polarize forming a double layer of ions. These ions (electrical energy) are stored in the pores of the electrodes.[‡‡] Due to the electrochemical properties of the electrodes, no electrons are transferred between the electrode and electrolyte.

Because of the large effective surface area of the porous electrodes (500 – 2,000 $m^2$/g) and the and small pore diameter (in the range of nanometers), ultracappacitors are able to store a large amount of energy (e.i. a very high capacitance relative to traditional capacitors). Additionally,

[‡‡] Bruke, Andrew, "Ultracapacitors: Why, How, and Where is the Technology," Institute of Transportation Studies (University of California, Davis), http://repositories.cdlib.org/itsdavis/UCD-ITS-REP-00-17.

since energy is stored as a separation of charge (electric energy storage), ultracapacitors are capable of releasing the stored energy very quickly (i.e. high output power).

The ultracapacitor energy density (Wh/kg) is about ten times smaller than that of conventional chemical batteries, however its power density (W/kg) is similar to the conventional capacitor, which is one thousand times larger than conventional batteries[§§]. Destraz et.al. (2004) compare the energy storage performance of ultracapacitors and conventional batteries; the following table is taken form Destraz et.al. (2004) paper.

| COMPARISON OF ACCUMULATOR AND ULTRACAPACITOR PERFORMANCE | | |
|---|---|---|
| **Performance Parameter** | **Accumulator (Batteries)** | **Ultracapacitors** |
| Specific Energy (Wh/kg) | 10 – 100 | 1 – 10 |
| Number of Cycles | 1,000 | > 500,000 |
| Specific Power (W/kg) | < 1,000 | < 10,000 |

Currently BART cars regenerate electrical energy while braking. Regenerated energy is transferred to the third rail, where nearby trains can utilize the regenerated electricity while accelerating out of a station. If the regenerated energy cannot be used by nearby trains, it is dissipated through on-board resistors. Installing ultracapacitors to store the regenerated energy instead of transferring it to the third rail will ensure that electrical energy is regenerated, stored and used to the extent possible.

With help from BART personnel, the voltage across one of the two energy dissipation resistors (both resistors are in parallel and have the same resistance) in a C car was monitored for a round trip between the South Hayward and Richmond Stations[***]. The monitoring was done during a weekday between noon and 3:00 p.m. The round trip should have taken about 2 hours, however the train was stuck at the Oakland Y for some time. From the data recorded by BART, it is estimated that during the trip from South Hayward Station to Richmond the resistors dissipated approximately 34.8 kWh. For the trip from Richmond to South Hayward, the resistors dissipated approximately 32.3 kWh. The average dissipation between both trips was approximately 333.5 kWh.

If the dissipated energy of on-board resistors is utilized, significant energy and cost savings could be realized. We have made the following assumptions in this analysis:

- The same dissipation resistors are used in all car types (A, B and C cars).
- All cars have a similar energy regeneration capability.
- All BART tracks have approximately similar line receptivity.
- Enough capacitance will be installed in each car to store all the dissipated energy.
- The added weight of the capacitors will not greatly affect the performance of the cars.

---

[§§] Destraz, B., Barrade, P., Rufer, A., Power Assistance for Diesel – Electric Locomotives with Supercapacitive Energy Storage," 2004 35th Annual IEEE Power Electronics Specialists Conference.

[***] BASE Energy engineers were granted access only to detail design schematics of C cars. For the purpose of analysis, it has been assumed that the dissipation resistors used by the A and B cars are the same as those used in the C cars.

- Losses due to interfacing electronics between ultracapacitors and BART electrical system have not been considered.

The details of the methodology and analysis of this measure is included in the appendix of the report. The results for potential energy, demand and cost savings are summarized on Table 8-1 below.

| TABLE 8-1 SUMMARY OF ELECTRICAL AND COST SAVINGS | | | | | | |
|---|---|---|---|---|---|---|
| **Car Type** | **Number of Cars** | **Savings per car per mile** (kWh/car-mi) | **Distance Covered** (mi/yr) | **Energy Savings** (kWh/yr) | **Demand Savings** (kW) | **Total Cost Savings** ($/yr) |
| A | 59 | 0.9520 | 122,275 | 6,867,942 | 1,736 | 721,134 |
| B | 380 | 0.9520 | 137,605 | 49,779,985 | 11,208 | 5,226,898 |
| C1 | 150 | 0.9520 | 116,435 | 16,626,918 | 4,420 | 1,745,826 |
| C2 | 80 | 0.9520 | 127,020 | 9,673,843 | 2,368 | 1,015,754 |
| **Totals** | **669** | | | **82,948,688** | **19,733** | **8,709,612** |

From Table 8-1, installing ultracapacitors (on-board electrical energy storage devices) will reduce the electrical energy consumption by 82,948,688 kWh/yr resulting in a demand reduction of 19,733 kW. These electrical savings will result in an avoided electrical cost of approximately $8,709,612 per year.

*On-Board Implementation*
Implementing this recommendation will require retrofitting the braking system with ultracapacitors. This may be accomplished by incorporating an ultracapacitor interface within the electric drive system. The essential required component is the ultracapacitor modules for storing the energy currently dissipated by the resistor. Based on the data collected by BART personnel and conversation with Maxwell Technologies (an ultracapacitor manufacturer) it is estimated that it will require 28 modules (28 Farad total) to store all the energy dissipated by the resistors. From a **very preliminary quotation** by the ultracapacitor manufacturer, the implementation cost could be itemized as follows:

(18,732) Ultracapacitor power modules ................................................$53,948,160
(669) DC/DC Boost Converters.............................................................$7,425,900
Installation Costs........................................................................$24,549,624
**Total Cost...............................................................................$85,923,684**

*Rail-Side Implementation*
An alternative to installing the ultracapacitors on-board is to install them close to the rail tracks at strategic locations throughout BART lines. A more detailed analysis of the implementation strategy is described in Appendix B - Ultracapacitor Implementation Addendum.

Under the assumption that at most two 10-car trains arrive at a station at any given time, then 24,080 modules and 86 DC/DC boost converters will be required, reducing the implementation cost and simple payback to $94,674,648 and 14.2 years respectively.

**NRNC**

Installing ultracapacitor modules for energy storage on new BART cars will result in electrical energy savings. The proposed baseline for estimating the electrical savings of on board ultracapacitor modules on new train cars is the existing regenerative braking system (without energy storage). From the above, the potential electrical energy savings per car mile for installing ultracapacitor modules in the train cars will be 0.952 kWh/car-mi resulting in an annual electrical energy savings of 123,989 kWh/car-yr ( at an average distance covered by one car in one year of 130,241 mi/car-yr).

**Notes:**

1. A more detailed cost savings estimate will require measurement of the energy dissipation on each line in a 24-hour period during weekdays and weekends.
2. Detailed engineering will be needed to implement this measure, which is far beyond the scope of this work.
3. The approximate total volume and mass required by 28 ultracapacitor modules is 1.8 $m^3$ and 1,400 kg (3,080 lb). Each module has a volume and mass of 0.063 $m^3$ and 50 kg.

# 6. DETAILED ANALYSIS OF THE MEASURES

## EEM No. 1 - High Efficiency Lighting for C1 Cars and New Cars

### Retrofit

The electrical energy savings due to replacing the T12 fluorescent lighting with T8 fluorescent lighting, EES, per car-mile can be estimated as follows:

$$EES = N \times (IW_C - IW_P) \times H \times [1 + C_1 \times LF / EER] / C_2$$

Where,

| | | |
|---|---|---|
| N | = | number of lamps in one car, 55 no units |
| $IW_C$ | = | current lamp input wattage, 28.70 W |
| $IW_P$ | = | proposed lamp input wattage, 20.44 W |
| H | = | average number of hours covered in one mile, 0.024167 hr |
| $C_1$ | = | conversion constant, 3.4122 Btu/W-h |
| LF | = | fraction of heat generated by lighting that must be removed by HVAC system, 0.5 no units |
| EER | = | HVAC energy efficiency ratio, 8.4 Btu/W-h |
| $C_2$ | = | conversion constant, 1000 W/kW |

Therefore the electrical energy savings, EES, per car-mile can be estimated as,

$$EES = (55)(28.70 - 20.44)(0.024167)[1 + (3.4122)(0.5)/(8.4)]/(1{,}000)$$
$$EES = 0.013209 \text{ kWh/car-mi}$$

The annual electrical energy savings, AEES, for replacing the T12 fluorescents with T8 fluorescents can be estimated as follows:

$$AEES = NC \times EES \times mi$$

Where,

| | | |
|---|---|---|
| NC | = | number of C1 cars. 150 no units |
| mi | = | is the average total distance traveled by one car during one year, 116,435 miles |

Therefore the annual electrical energy savings, AEES, for C1 cars can be estimated as,

$$AEES = (150)(0.013209)(116{,}435)$$
$$AEES = 230{,}695 \text{ kWh/yr}$$

The demand savings, DS, can be estimated as follows:

$$DS = AEES \times CF / H_{total}$$

Where all variables are the same as in the electrical energy savings, except:

CF = coincidence factor, fraction of total number of C1 cars that will run during BART's peak period, 0.75 no units
$H_{total}$ = the total number of hours per car type that will operate in one year, hr/yr

Therefore the demand savings for replacing the T12 lamps with T8 lamps will be:

$$DS = (230{,}695)(0.75)/(2{,}811 \text{ hr/yr})$$
$$DS = 61 \text{ kW}$$

The electrical energy cost savings, EECS, can be calculated as follows:

$$EECS = AEES \times (\text{average unit cost of electricity})$$
$$EECS = (230{,}695 \text{ kWh/yr})(\$0.105/\text{kWh})$$
$$EECS = \$24{,}223/\text{yr}$$

The maintenance cost savings can be estimated as follows,

$$MCS = NC \times N \times H \times mi \times [(LC_C + LC) / LL_C - (LC_P + LC) / LL_P]$$

Where all the variables are the same as in the electrical energy and demand savings except,

NC = number of C1 cars, no units
$LL_C$ = current lamp cost, \$
LC = labor cost for replacing one lamp, \$
$LL_C$ = current lamp life, hr
$LC_P$ = proposed lamp cost, \$
$LL_P$ = proposed lamps life, h

Therefore the annual maintenance cost savings can be estimated as follows,

$$MCS = (150)(55)(0.024167)(116{,}435)[(8.64 + 6.81)/(9{,}000) - (9.07 + 6.81)/20{,}000)]$$
$$MCS = \$21{,}419/\text{yr}$$

The total cost savings is the sum of the electrical energy cost savings and the maintenance cost savings, which is estimated to be $45,642/yr.

**NRNC**

The annual electrical energy savings per car, $AEES_{NRNC}$, for installing T8 fluorescents instead of T12 fluorescents in new cars can be estimated as follows:

$$AEES_{NRNC} = (1 - RF) \times EES_{NRNC} \times mi_A$$

Where,

| | | |
|---|---|---|
| $RF$ | = | reduction factor from day lighting EEM, 0.32 no units |
| $EES_{NRNC}$ | = | electrical energy savings per car mile, 0.011461[†††] kWh/car-mi, calculated through the same formulation as in the retrofit section |
| $mi_A$ | = | average annual distance covered by one train car, 130,241 mi/yr |

Therefore the expected electrical energy savings can be calculated as follows:

$$AEES_{NRNC} = (1 - 0.32)(0.011461)(130{,}241)$$
$$AEES_{NRNC} = 1{,}015 \text{ kWh/car-yr}$$

[†††] The electrical energy savings per car mile considers the A/B cars as baseline: 48 lighting fixtures per car and a higher efficiency HVAC system with an EER value of 8.7.

## EEM No. 2 - Direct Cooler Air to the Inlet of HVAC Condensers

### Retrofit

**Set-Up of Measurements**

Figure 2-1 shows where the temperature probes were placed on the C cars to measure the temperature of the inlet to the condensers and to measure the outside ambient temperature.

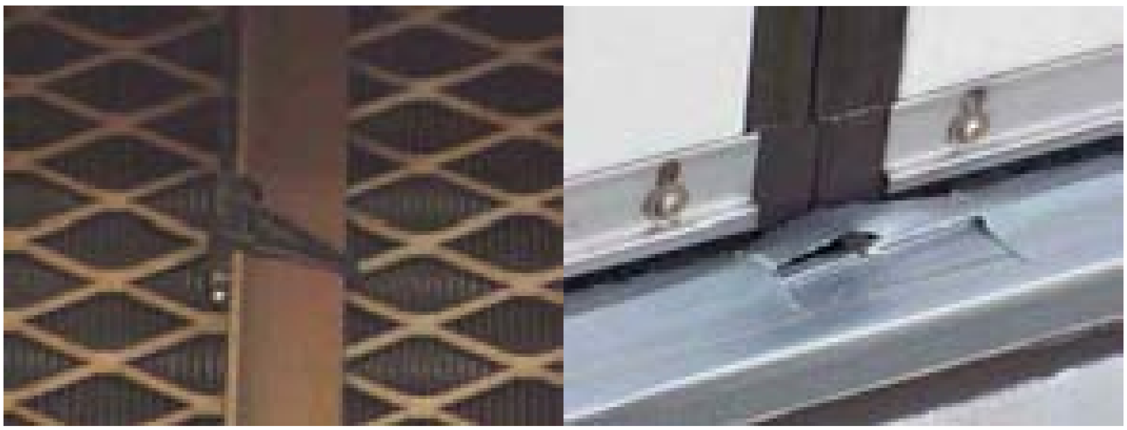


**Figure 2-1** (*Left*) Temperature Probe Mounted on Inlet to Condenser Heat Exchanger (*Right*) Temperature Probe Mounted on Car Door to Measure Outdoor Ambient Temperature

**Results from Live Track Run**

The measurements were performed on a live track run from Hayward to Richmond and returning back to Hayward on Wednesday December 20, 2006 from noon to 3 p.m. The temperatures at the inlet of the condenser heat exchanger and the ambient outdoor temperature were recorded and the results are presented in Figure 2-2 on the following page.

Based on the temperature measurements from the test run, the temperature differential between the temperature at the inlet of the heat exchanger and the ambient temperature ranged from 0ºF to 24ºF. This wide range is due to the fact that the regenerative braking system does not always produce heat in the resistors. When it does work, the heat absorbed from the regenerative braking by the resistor banks significantly increases the temperature of the inlet to the condensers. When the regenerative braking system is not producing heat in the resistors, hot air is still trapped underneath the cars, but will cool to near ambient temperature conditions. On average, the temperature at the inlet of the condenser heat exchanger was (on average) approximately 10ºF higher than the ambient outdoor temperature. Thus, we have taken a temperature differential of 10ºF between the inlet to the condenser heat exchanger and ambient conditions in all relevant calculations.

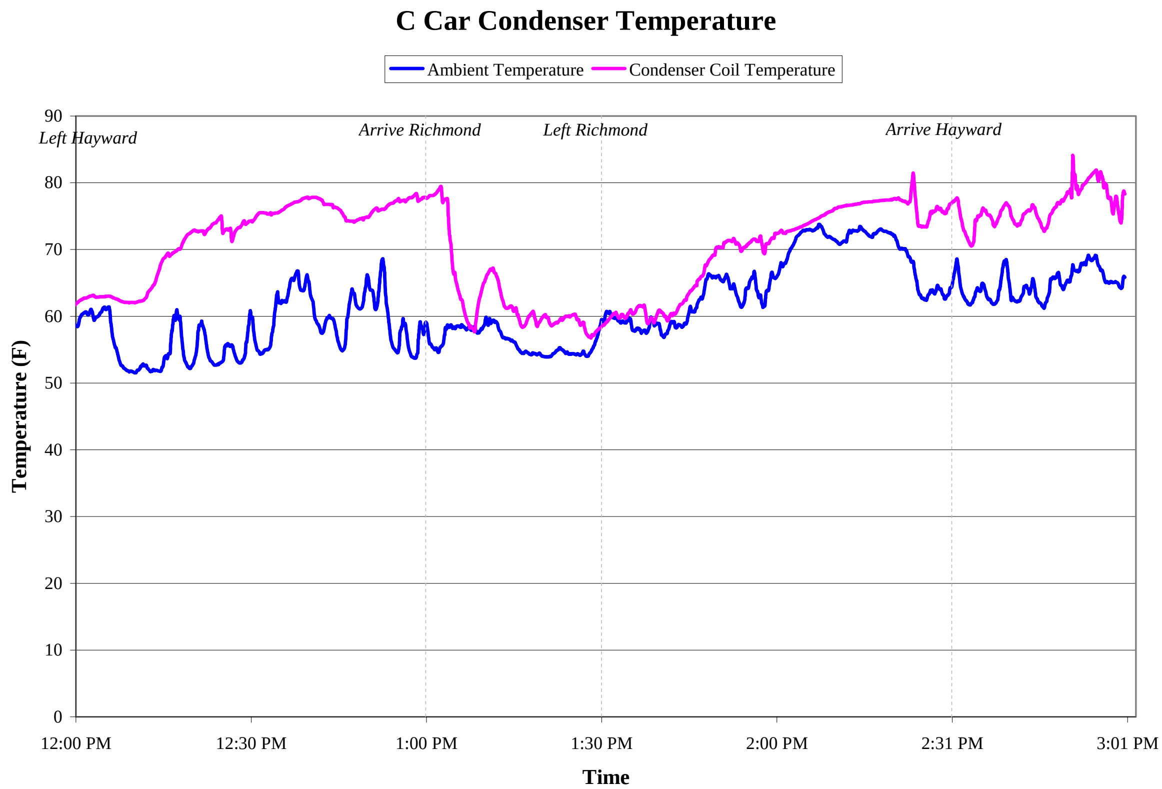



**Figure 2-2** C Car Condenser and Ambient Temperature Measurements from Live Track Run

## Electrical Energy Savings

By directing cooler air to the intake of the condenser heat exchanger, less energy will be required by the HVAC compressors to condition the air. Based on the "*Qualification Test Report: Performance of HVAC System (Energy Consumption) Installed on BART C Car*" provided to the audit team by BART, the performance curve for the HVAC compressor shows that a 10ºF drop in condensing temperature will result in a 9.7% drop in the energy consumed by the HVAC compressor. Conservatively, we have assumed that directing cooler air to the intake of the condenser heat exchanger will result in a HVAC compressor electrical energy savings of 9%.

The electrical energy savings due to directing cooler air to the intake of the condenser heat exchanger, EES, can be calculated using the following equation. It has been assumed that EEM No. 2 "*Optimize Outside Air Intake into Cars*" will be implemented simultaneously with this measure to avoid any overlapping in energy savings.

$$EES = \{[N \times (IW/Eff) \times LF \times H \times UF] - EES_{OA}\} \times FCS$$

Where,

N = total number of compressor motors per car, no units
IW = nominal input wattage of compressor motor, kW

| | | |
|---|---|---|
| Eff | = | efficiency of compressor motor, no units |
| LF | = | load factor of compressor motor (*estimated from Test Track data*), no units |
| H | = | average number of hours covered in one mile, 0.024167 hr |
| UF | = | utilization factor of compressor motor (estimated), 0.50 |
| $EES_{OA}$ | = | electrical energy savings due to implementation of EEM No. 2 "*Optimize Outside Air Intake into Cars*", kWh/car-mile |
| FCS | = | fraction of compressor energy savings due to directing cooler outside air to inlet of condenser heat exchanger, no units |

The electrical energy savings for the directing cooler air to the inlet of the C1 cars' condenser heat exchanger, $EES_1$, is estimated as:

$$EES_1 = \{(2)[(14.62)/(0.900)](0.585)(0.024167)(0.5) - 0.01616\}(0.09)$$
$$EES_1 = 0.01921 \text{ kWh/car-mi}$$

The annual electrical energy savings, AEES, due to directing cooler air to the inlet of the condenser heat exchanger can be calculated as follows:

$$AEES = NC \times EES \times mi$$

Where,

| | | |
|---|---|---|
| NC | = | number of A, B or C cars, no units |
| EES | = | total electrical energy savings for optimizing outside air usage, kWh/car-mi |
| mi | = | distance covered by each car type per year, mi/yr |

Using the same example as before, the annual electrical energy savings due to directing cooler air to the inlet of the C1 cars' condenser heat exchanger, $AEES_1$, is:

$$AEES_1 = (150 \text{ cars})(0.01921 \text{ kWh/car-mile})(116{,}435 \text{ miles/yr})$$
$$AEES_1 = 335{,}507 \text{ kWh/yr}$$

The average peak demand savings, DS, due to directing cooler air to the inlet of the condenser heat exchanger can be estimated as follows:

$$DS = AEES_i \times CF_i / H_{total}$$

Where,

| | | |
|---|---|---|
| $AEES_i$ | = | annual electrical energy savings for optimizing outside air usage for each car type (A, B or C cars), kWh/car-mi |
| $CF_i$ | = | coincidence factor, fraction of total number of cars (A, B or C cars) that will run during BART's peak period, no units |
| $H_{total}$ | = | total number of hours per car type (A, B or C cars) that will operate in one year, hr/yr |

Using the same example as in the annual electrical energy savings, the average demand savings due to directing cooler air to the inlet of the C1 cars' condenser heat exchanger, $DS_1$, is estimated to be:

$DS_1$ = (335,507 kWh/yr)(0.75) / (2,811 hr/yr)
$DS_1$ = 89.53 kW

The associated annual electrical energy cost savings, AECS, can be estimated as follows:

AECS = AEES × (average unit cost of electricity, \$0.105/kWh)
$AECS_1$ = (335,507 kWh/yr)(\$0.105/kWh)
$AECS_1$ = \$35,228/yr

Continuing the electrical energy and demand savings for the remaining BART cars yields the results shown in Table 2-2 below.

**TABLE 2-2 SUMMARY OF ELECTRICAL AND COST SAVINGS**

| **Car Type** | **Number of Cars** | **Savings per car per mile** (kWh/car-mi) | **Annual Distance Covered** (mi/yr) | **Energy Savings** (kWh/yr) | **Peak Demand Savings** (kW) | **Total Cost Savings** ($/yr) |
|---|---|---|---|---|---|---|
| A | 59 | 0.01995 | 122,275 | 143,924 | 36.50 | 15,112 |
| B | 380 | 0.01995 | 137,605 | 1,043,184 | 235.52 | 109,534 |
| C1 | 150 | 0.01921 | 116,435 | 335,507 | 89.52 | 35,228 |
| C2 | 80 | 0.01921 | 127,020 | 195,204 | 47.75 | 20,496 |
| **Totals** | **669** | | | **1,717,819** | **409.29** | **180,370** |

## EEM No. 3 - Install Higher Efficiency HVAC Units on C Cars and New Cars

### Retrofit

<u>Existing C Car HVAC Units</u> (2 HVAC units/car)

| | | |
|---|---|---|
| 7-ton HVAC Unit: | Reciprocating Compressor: | 14.62 kW |
| | Evaporator Fan: | 2.7 kW |
| | Condenser Fan: | 0.6 kW |

Overall EER: 8.4 Btu/W-hr

<u>Existing C Car HVAC Units</u> (2 HVAC units/car)

7-ton HVAC Unit: Scroll Compressor

Overall EER: 9.1 Btu/W-hr

**<u>Electrical Energy Savings</u>**

The electrical energy savings from using higher efficiency HVAC units in the C cars, EES, can be estimated as follows:

$$EES = \{[N \times (IW/Eff) \times LF \times H \times UF] - (EES_{OA} + EES_{Cond})\} \times [1 - (EER_C/EER_P)]$$

Where,

| | | |
|---|---|---|
| $N$ | = | total number of compressor motors per car, no units |
| $IW$ | = | nominal input wattage of compressor motor, kW |
| $Eff$ | = | efficiency of compressor motor, no units |
| $LF$ | = | load factor of compressor motor (*estimated from Test Track data*), no units |
| $H$ | = | average number of hours covered in one mile, 0.024167 hr |
| $UF$ | = | utilization factor of compressor motor (estimated), 0.50 |
| $EES_{OA}$ | = | electrical energy savings due to implementation of EEM No. 3 "*Optimize Outside Air Intake into Cars*", kWh/car-mile |
| $EES_{Cond}$ | = | electrical energy savings due to implementation of EEM No. 2 "*Direct Cooler Air to the Inlet of HVAC Condensers*", kWh/car-mile |
| $EER_C$ | = | energy efficiency ratio of the current HVAC units, 8.4 Btu/W-hr |
| $EER_P$ | = | energy efficiency ratio of the proposed HVAC units, 9.1 Btu/W-hr |

The electrical energy savings due to replacing the existing HVAC units on the C cars with more efficient HVAC units, EES, is estimated to be:

$$EES = \{(2)[(14.62)/(0.900)](0.585)(0.024167)(0.5) – (0.01616 + 0.01921)\} \times [1 - (8.4)/(9.1)]$$

$EES = 0.01495$ kWh/car-mi

The annual electrical energy savings, AEES, due to replacing the existing HVAC units with higher efficiency units can be calculated as follows:

$$AEES = NC \times EES \times mi$$

Where,

NC = number of C1 or C2 cars, no units
EES = total electrical energy savings for installing higher efficiency HVAC units, kWh/car-mi
mi = distance covered by each car type per year, mi/yr

As an example, the annual electrical energy savings due to replacing the existing HVAC units in the C1 cars, $AEES_1$, is:

$$AEES_1 = (150 \text{ cars})(0.01495 \text{ kWh/car-mile})(116{,}435 \text{ miles/yr})$$
$$AEES_1 = 261{,}105 \text{ kWh/yr}$$

The average peak demand savings, DS, due to replacing the existing HVAC units with higher efficiency units can be estimated as follows:

$$DS_i = AEES_i \times CF_i / H_{total}$$

Where,

$AEES_i$ = annual electrical energy savings for optimizing outside air usage for each car type (C1 or C2 cars), kWh/car-mi
$CF_i$ = coincidence factor, fraction of total number of cars (C1 or C2 cars) that will run during BART's peak period, no units
$H_{total}$ = total number of hours per car type (C1 or C2 cars) that will operate in one year, hr/yr

Using the same example as in the annual electrical energy savings, the average peak demand savings due to installing higher efficiency HVAC units on the C1 cars, $DS_1$, is estimated to be:

$$DS_1 = (261{,}105 \text{ kWh/yr})(0.75) / (2{,}811 \text{ hr/yr})$$
$$DS_1 = 69.67 \text{ kW}$$

The associated annual electrical energy cost savings for the C1 cars, $AECS_1$, can be estimated as follows:

$$AECS = AEES_1 \times (\text{average unit cost of electricity, \$0.105/kWh})$$
$$AECS_1 = (261{,}105 \text{ kWh/yr})(\$0.105/\text{kWh})$$
$$AECS_1 = \$27{,}416/\text{yr}$$

Continuing the electrical energy and demand savings for the C2 cars yields the results shown in Table 3-1 below.

| **TABLE 3-1 SUMMARY OF ELECTRICAL AND COST SAVINGS** | | | | | | |
|---|---|---|---|---|---|---|
| **Car Type** | **Number of Cars** | **Savings per car per mile** (kWh/car-mi) | **Annual Distance Covered** (mi/yr) | **Energy Savings** (kWh/yr) | **Peak Demand Savings** (kW) | **Total Cost Savings** ($/yr) |
| C1 | 150 | 0.01495 | 116,435 | 261,105 | 69.67 | 27,416 |
| C2 | 80 | 0.01495 | 127,020 | 151,916 | 37.16 | 15,951 |
| **Totals** | **230** | | | **413,021** | **106.83** | **43,367** |

**NRNC**

The annual electrical energy savings, $AEES_{NRNC}$, for installing high efficiency HVAC units in new cars can be estimated as follows:

$$AEES_{NRNC} = EES_{NRNC} \times mi_A$$

Where,

$EES_{NRNC}$ = electrical energy savings per car mile for installing high efficiency HVAC units in new cars instead of the HVAC units in A/B cars, 0.009534‡‡‡ kWh/car-mi, same formulation as in retrofit section

$mi_A$ = average distance covered by one car in one year, mi

Therefore the expected electrical energy savings can be calculated as follows:

$$AEES_{NRNC} = (0.009534)(130,241)$$
$$AEES_{NRNC} = 1,242 \text{ kWh/car-yr}$$

‡‡‡ The energy savings per car mile considers the HVAC system used in A/B cars as baseline, which includes: six 5.46 kW HVAC compressors and an EER value of 8.7 Btu/W-h.

## EEM No. 4 - Optimize Outside Air Intake into Cars

### Retrofit

Optimize the amount of outside air intake into the BART cars based on the outside air temperature. The proposed recommendation will generate savings based upon the reduced usage of the compressor motor. The air distribution fan in each unit must still be used.

**Electrical Energy Savings**

The electrical energy savings, EES, which can be realized by optimizing the outside air intake based on outside air temperature, may be estimated as follows:

$$EES = N \times (IW/Eff) \times LF \times FR \times H \times FH \times UF$$

Where,

| | | |
|---|---|---|
| N | = | total number of compressor motors per car, no units |
| IW | = | nominal input wattage of compressor motor, kW |
| Eff | = | efficiency of compressor motor, no units |
| LF | = | load factor of compressor motor (*estimated from Test Track data*), no units |
| FR | = | fraction that each unit is loaded depending on temperature (*refer to Table 3-3*), no units |
| H | = | average number of hours covered in one mile, 0.024167 hr |
| FH | = | fraction of time that each unit could be shut off for a particular temperature range, no units |
| UF | = | utilization factor of compressor motor (estimated), 1.0 |

According to the BART document (BARVE4G02571) provided to the audit team, the HVAC equipment must be able to operate without damage at a temperature as high as 120°F. Thus, the fraction that each air conditioning unit is loaded, FR, is calculated assuming that at 120°F the units are fully loaded and at 55°F, the units will shut off. A linear approximation is then used to determine the fraction of loading at temperatures between 55°F and 120° F.

The fraction of time that each unit could be shut off for a particular temperature range, FH, was estimated based on the following relationship:

$$FH = FH_i / H_{total}$$

Where,

| | | |
|---|---|---|
| $FH_i$ | = | number of hours that fall between a certain temperature range (based on weather data developed by the United States Department of Energy) for the Oakland area , hr/yr |
| $H_{total}$ | = | annual operating hours for each car type, hr/yr |

It is assumed that outdoor air can be optimized during periods of the year when the temperature range is between 55°F and 65°F (average temperature of 58°F) and at a favorable relative humidity below 50%. As an example, the fraction of time that C1 car compressors can be shut off for the temperature range of 55°F to 60°F, $FH_1$, is estimated to be:

$$FH_1 = (825 \text{ hr/yr}) / (7.7 \text{ hr/day} \times 365 \text{ day/yr})$$
$$FH_1 = 0.29$$

Using the same example, the electrical energy savings for the C1 cars' HVAC compressors at an average temperature of 58° F, $EES_1$, is estimated as:

$$EES_1 = N \times (IW/Eff) \times LF \times FR \times H \times FH \times UF$$
$$EES_1 = (2)[(14.62)/(0.900)](0.585)(0.0385)(0.024167)(0.29)(1.0)$$
$$EES_1 = 0.00512 \text{ kWh/car-mi}$$

The following table (Table 4-3) shows the fraction of loading for average temperatures for one year as well as the number of hours of operation of the C1 car HVAC units that fall within a temperature range for the A/C units. Table 4-3 also shows the electrical energy savings for the various temperature bins for the C1 cars.

**TABLE 4-3 ELECTRICAL ENERGY SAVINGS FOR C1 CARS**

| **Dry Bulb Temp. Range** (°F) | **Hours of Operation*** (hr/yr) | **A/C Fraction Loading **** (%) | **HVAC Function** | **Savings per Car per Mile** (kWh/car-mi) |
|---|---|---|---|---|
| <55 | 829 | 0 | heating | 0.00000 |
| 55-60 | 825 | 3.8 | economizer | 0.00512 |
| 60-65 | 587 | 11.5 | economizer | 0.01103 |
| > 65 | 570 | 19.2 - 100 | cooling | 0.00000 |
| **Totals** | **2,811** | | | **0.01616** |

* These hours were estimated based on data from a CD-ROM developed at the request of the United States Department of Energy. The CD-ROM contains "typical" values of dry bulb temperatures as well as average temperatures for user-defined months of the year and hours of the day. The annual operating hours were provided by BART personnel.

** The fraction that each air conditioning unit is loaded, FR, is calculated assuming that at 120 °F the units are fully loaded and at 55° F, the units will shut off.

The annual electrical energy savings, AEES, due to optimizing the amount of outside air used can be calculated as follows:

$$AEES = NC \times EES \times mi$$

Where,

NC = number of A, B or C cars, no units

EES = total electrical energy savings for optimizing outside air usage, kWh/car-mi

mi = distance covered by each car type per year, mi/yr

As an example, the annual electrical energy savings due to optimizing the amount of outside air used for the C1 cars, $AEES_1$, is:

$AEES_1 =$ (150 cars)(0.01616 kWh/car-mile)(116,435 miles/yr)
$AEES_1 =$ 282,238 kWh/yr

The average peak demand savings, DS, due to optimizing the amount of outside air used can be estimated as follows:

$$DS_i = AEES_i \times CF_i / H_{total}$$

Where,

$AEES_i =$ annual electrical energy savings for optimizing outside air usage for each car type (A, B or C cars), kWh/car-mi
$CF_i =$ coincidence factor, fraction of total number of cars (A, B or C cars) that will run during BART's peak period, no units
$H_{total} =$ total number of hours per car type (A, B or C cars) that will operate in one year, hr/yr

Using the same example as before, the total demand savings due to optimizing the amount of outside air used in the C1 cars, $DS_1$, is estimated to be:

$DS_1 =$ (282,238 kWh/yr)(0.75) / (2,811 hr/yr)
$DS_1 =$ 75.32 kW

The associated annual electrical energy cost savings, AECS, can be estimated as follows:

AECS = AEES × (average unit cost of electricity, $0.105/kWh)
$AECS_1 =$ (282,238 kWh/yr)($0.105/kWh)
$AECS_1 =$ $29,635/yr

Continuing the electrical energy and demand savings for the remaining BART cars yields the results shown in Table 4-4 below.

**TABLE 4-4 SUMMARY OF ELECTRICAL AND COST SAVINGS**

| **Car Type** | **Number of Cars** | **Savings per car per mile** (kWh/car-mi) | **Annual Distance Covered** (mi/yr) | **Energy Savings** (kWh/yr) | **Peak Demand Savings** (kW) | **Total Cost Savings** ($/yr) |
|---|---|---|---|---|---|---|
| A | 59 | 0.01677 | 122,275 | 120,983 | 30.69 | 12,839 |
| B | 380 | 0.01677 | 137,605 | 876,902 | 197.98 | 92,075 |
| C1 | 150 | 0.01616 | 116,435 | 282,238 | 75.32 | 29,635 |
| C2 | 80 | 0.01616 | 127,020 | 164,211 | 40.17 | 17,242 |
| **Totals** | **669** | | | **1,444,334** | **344.16** | **151,791** |

**NRNC**

The annual electrical energy savings, $AEES_{NRNC}$, for optimizing outside air intake in new cars can be estimated as follows:

$$AEES_{NRNC} = EES_{NRNC} \times mi_A$$

Where,

$EES_{NRNC}$ = electrical energy savings per car mile for optimizing outside air intake, 0.01677 kWh/car-mi

$mi_A$ = average distance covered by one car in one year, mi

Therefore the expected electrical energy savings can be calculated as follows:

$$AEES_{NRNC} = (0.01677)(130{,}241)$$
$$AEES_{NRNC} = 2{,}184 \text{ kWh/car-yr}$$

**EEM No. 5 - Install Daylight Controls on the Fluorescent Lamps**

**Retrofit**

A computer model was developed to estimate the light level inside a BART car. The model considered the following:

- A linear light level increase/decrease from sunrise to sunset, with the peak light level reached at midpoint between sunrise and sunset.
- Based on the Latitude and Longitude of San Francisco, the peak light level was estimated for a winter month (January) and a summer month (June). It is assumed that the light level will increase linearly from January until June and then decrease linearly form June to December.
- This model was then normalized to the light level data collected by the light level logger setup by the assessment team.
- Finally it was determined that the fraction of underground track for all BART lines was very close to the fraction of underground track for the Daly City – Pittsburg/Bay Point line (within 2%) from which data was collected.

From this computer model it was determined that on average the lights could be dimmed to 55% of the nominal output for approximately 72% of the time (based on weekday schedule) the lines are operational. The electrical energy savings, EES, can be estimated as follows:

$$EES = N \times IW \times H \times (1 - PR) \times FH \times (1 + C1 \times LF / EER) / C2$$

Where,

| | | |
|---|---|---|
| N | = | number of lamps in one car, no units |
| IW | = | current lamp input wattage, W |
| H | = | average number of hours covered in one mile, 0.024167 hr |
| PR | = | fraction of nominal power consumption of lamps at 55% light output, 0.55 no units |
| FH | = | fraction of time that lights can be dimmed, 0.72 no units |
| $C_1$ | = | conversion constant, 3.4122 Btu/W-h |
| LF | = | fraction of heat generated by lighting that must be removed by HVAC system, 0.5 no units |
| EER | = | HVAC energy efficiency ratio, 8.4 Btu/W-h for C cars and 8.65 Btu/W-h for A/B cars |
| $C_2$ | = | conversion constant, 1000 W/kW |

As an example, the electrical energy savings, $EES_1$, for C1 cars (which use the 20-Watt T12 fluorescent lamps) can be estimated as follows:

$$EES_1 = (55)(20.44)(0.024167)(1 - 0.55)(0.72)[1 + (3.4122)(0.5)/(8.4)]/(1{,}000)$$

$EES_1 = 0.010560$ kWh/car-mi

The annual electrical energy savings, AEES, for dimming the fluorescent lamps can be estimated as follows:

$AEES = NC \times EES \times mi$

Where,

NC = number of cars of a specific type, no units
mi = is the average total distance traveled by one car during one year, mi/yr

Using the same example as in the electrical energy savings, the annual electrical energy savings, $AEES_1$, for one C1 car can be estimated as,

$AEES_1 = (150)(0.010560)(166{,}435)$
$AEES_1 = 184{,}428$ kWh/yr

This recommendation is not expected to result in demand savings.

The electrical energy cost savings, EECS, can be calculated as follows:

EECS = AEES × (average unit cost of electricity)
EECS = (837,433 kWh/yr)($0.105/kWh)
EECS = $87,930/yr

**NRNC**

The annual electrical energy savings, $AEES_{NRNC}$, for installing daylight controls in new cars can be estimated as follows:

$AEES_{NRNC} = EES_{A/B} \times mi_A$

Where,

$EES_{A/B}$ = electrical energy savings per car mile for A/B cars, kWh/car-mi
$mi_A$ = average distance covered by one car in one year, mi

Therefore the expected electrical energy savings can be calculated as follows:

$AEES_{NRNC} = (0.009171)(130{,}241)$
$AEES_{NRNC} = 1{,}194$ kWh/car-yr

## EEM No. 6 - Install Variable Frequency Drives on HVAC Supply Fans

### Retrofit

Install variable frequency drives (VFD, the same as adjustable speed drive) on the HVAC evaporator (supply) fan motors in all car units.

*C1/C2 Cars* – 2 fans/car × 2.7 kW/fan
*A/B Cars* – 6 fans/car × 0.65 kW/fan

The VFDs will control the airflow provided to the car based on the car' return air temperature, which has been estimated to vary accordingly with the passenger occupancy loads of the cars.

The hourly passenger loading variation for the BART system was not available to BASE. Thus, we have taken a typical transit passenger loading profile shown in Figure 6-1 below, extracted from Vuchic (2005).

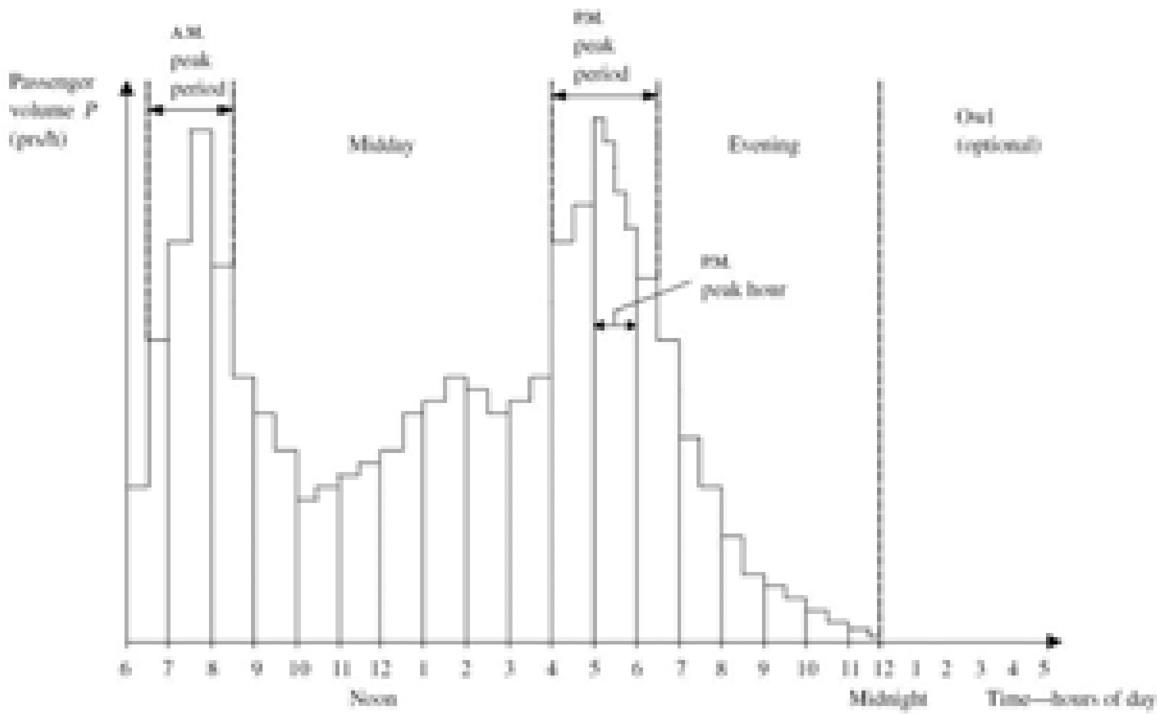



**Figure 6-1** Hourly Variation of Passenger Volume for a Typical Transit Line

Based on the above passenger volume profile, flow profiles for the various BART cars have been developed and are presented in Table 6-3 on the following page.

**TABLE 6-3 SUMMARY OF FLOW PROFILE FOR DIFFERENT BART CARS**

| Total Flow Rate Needed (%) | C1 Cars Running Hours (hr/yr) | C2 Cars Running Hours (hr/yr) | A Cars Running Hours (hr/yr) | B Cars Running Hours (hr/yr) |
|---|---|---|---|---|
| 100 | 234 | 256 | 246 | 277 |
| 90 | 234 | 256 | 246 | 277 |
| 80 | 351 | 383 | 370 | 415 |
| 70 | 117 | 128 | 123 | 138 |
| 60 | 351 | 383 | 370 | 415 |
| 50 | 468 | 511 | 493 | 554 |
| 40 | 351 | 383 | 370 | 415 |
| 30 | 351 | 383 | 370 | 415 |
| < 25* | 351 | 383 | 370 | 415 |
| **Totals** | **2,811** | **3,066** | **2,957** | **3,322** |

* Based on the passenger volume occupancy profile, the flow rate can be reduced further than 25%. However, conservatively it has been estimated that the fans would need to supply an airflow of 25% of maximum flow to the cars at low occupancy periods.

Table 6-4 shows the comparative energy consumption of an adjustable speed drive control and damper control. Energy consumption is presented in the table as the percentage of energy consumed relative to 100 % load with damper control. The present airflow is dependent on the pressure drop across the damper. For example, from Table 6-4, for a flow rate of 100%, an ASD controlled fan motor replacing dampers will have a power increase of 5%, while for a flow rate of 50%, a VFD controlled fan motor replacing the damper control will have a power savings of 53%.

**TABLE 6-4 RELATIVE POWER CONSUMPTION OF DIFFERENT CONTROL STRATEGIES AND SAVINGS**

| Total Flow Rate | Damper Control Energy | Power Consumption of Motor | | Power Savings with Application of ASD |
|---|---|---|---|---|
| | | No Flow Control | ASD Replacing Damper Control | |
| % | % | % | % | % |
| 100 | 100 | 100 | 105 | -5 |
| 95 | 96 | 100 | 90 | 6 |
| 90 | 94 | 100 | 78 | 16 |
| 85 | 93 | 100 | 66 | 27 |
| 80 | 89 | 100 | 57 | 32 |
| 75 | 86 | 100 | 48 | 38 |
| 70 | 83 | 100 | 41 | 42 |
| 60 | 79 | 100 | 30 | 49 |
| 50 | 74 | 100 | 21 | 53 |
| 40 | 71 | 100 | 14 | 57 |
| 30 | 70 | 100 | 8 | 62 |
| 20 | 70 | 100 | 5 | 65 |

The energy savings will be calculated by determining the energy usage of the air handler fan presently in use and subtracting the energy usage of the fan at reduced flow (load). The electrical energy savings per car-mile, EES, is estimated as:

$$EES = N \times (R/EFF) \times LF \times (AH_i / H_{total}) \times UF \times (CL_{DC} - CL_{VFD}) \times H$$

Where,

| | | |
|---|---|---|
| N | = | number of HVAC evaporator (supply) fan motors, no units |
| R | = | rated power of HVAC evaporator (supply) fan motor, hp |
| EFF | = | efficiency of the fan motor, no units |
| LF | = | fraction of rated load that fan motor operates, no units |
| $AH_i$ | = | annual operation hours of fan at a particular airflow, hr/yr |
| $H_{total}$ | = | total annual operation hours of fan (varies based on car type), hr/yr |
| UF | = | fraction of operating time that the fan is in use, no units |
| $CL_{DC}$ | = | controlled load fraction at which the motor will operate with damper control, no units |
| $CL_{VFD}$ | = | controlled load fraction at which the motor will operate with VFD control, no units |
| H | = | average number of hours covered in one mile, 0.024167 hr/car-mile |

As an example, the electrical energy savings for the C1 cars at an airflow of 50%, $EES_1$, can be estimated as follows:

$$EES_1 = (2)[(2.7)/(0.87)](0.70)[(468)/(2{,}811)](1.0)[(0.74) - (0.21)](0.024167)$$

$$EES_1 = 0.00928 \text{ kWh/car-mile}$$

Table 6-5 below summarizes the electrical energy savings for installing VFDs on the HVAC supply fans for the various BART cars at different flow rates.

**TABLE 6-5 ELECTRICAL ENERGY SAVINGS FOR BART CARS BASED ON FLOW PROFILE**

| Total Flow Rate (%) | $CL_{DC}$ | $CL_{VFD}$ | C1/C2 Cars No. Fans | C1/C2 Cars Rating of Fans (kW) | C1/C2 Cars EES (kWh/yr) | A/B Cars No. Fans | A/B Cars Rating of Fans (kW) | A/B Cars EES (kWh/yr) |
|---|---|---|---|---|---|---|---|---|
| 100 | 1 | 1.05 | 2 | 2.7 | -0.00044 | 6 | 0.65 | -0.00030 |
| 90 | 0.94 | 0.78 | 2 | 2.7 | 0.00140 | 6 | 0.65 | 0.00097 |
| 80 | 0.89 | 0.57 | 2 | 2.7 | 0.00420 | 6 | 0.65 | 0.00290 |
| 70 | 0.83 | 0.41 | 2 | 2.7 | 0.00184 | 6 | 0.65 | 0.00127 |
| 60 | 0.79 | 0.3 | 2 | 2.7 | 0.00643 | 6 | 0.65 | 0.00444 |
| 50 | 0.74 | 0.21 | 2 | 2.7 | 0.00928 | 6 | 0.65 | 0.00640 |
| 40 | 0.71 | 0.14 | 2 | 2.7 | 0.00748 | 6 | 0.65 | 0.00517 |
| 30 | 0.7 | 0.08 | 2 | 2.7 | 0.00814 | 6 | 0.65 | 0.00562 |
| < 25 | 0.7 | 0.065 | 2 | 2.7 | 0.00833 | 6 | 0.65 | 0.00575 |
| **Totals** | | | | | **0.04666** | | | **0.03222** |

The annual electrical energy savings, AEES, due to installing VFDs on the HVAC evaporator (supply) fans can be calculated as follows:

$$AEES = NC \times EES \times mi$$

Where,

NC = number of A, B or C cars, no units
EES = total electrical energy savings for installing VFD on supply fans, kWh/car-mi
mi = distance covered by each car type per year, mi/yr

As an example, the annual electrical energy savings due to installing VFDs on the two supply fans for the C1 cars, $AEES_1$, is:

$$AEES_1 = (150\ \text{cars})(0.04666\ \text{kWh/car-mile})(116{,}435\ \text{miles/yr})$$
$$AEES_1 = 814{,}929\ \text{kWh/yr}$$

There is not expected to be any demand savings due to implementation of this measure since the fans are expected to operate at or near full load during peak hours.

The associated annual electrical energy cost savings, AECS, can be estimated as follows:

$$AECS = AEES \times (\text{average unit cost of electricity, }\$0.105/\text{kWh})$$
$$AECS_1 = (814{,}929\ \text{kWh/yr})(\$0.105/\text{kWh})$$
$$AECS_1 = \$85{,}568/\text{yr}$$

Continuing the electrical energy savings and cost savings for the remaining BART cars yields the results shown in Table 6-6.

**TABLE 6-6 SUMMARY OF ELECTRICAL AND COST SAVINGS**

| **Car Type** | **Number of Cars** | **Savings per car per mile** (kWh/car-mi) | **Annual Distance Covered** (mi/yr) | **Energy Savings** (kWh/yr) | **Total Cost Savings** ($/yr) |
|---|---|---|---|---|---|
| A | 59 | 0.03222 | 122,275 | 232,442 | 24,406 |
| B | 380 | 0.03222 | 137,605 | 1,684,781 | 176,902 |
| C1 | 150 | 0.04666 | 116,435 | 814,929 | 85,568 |
| C2 | 80 | 0.04666 | 127,020 | 474,140 | 49,785 |
| **Totals** | **669** | | | **3,206,292** | **336,661** |

**NRNC**

The annual electrical energy savings, $AEES_{NRNC}$, for optimizing the HVAC fan controls in new cars can be estimated as follows:

$$AEES_{NRNC} = EES_{NRNC} \times mi_A$$

Where,

| | | |
|---|---|---|
| $EES_{NRNC}$ | = | electrical energy savings per car mile for installing VFD on HVAC fans, 0.03222 kWh/car-mi, same as EES for A/B cars |
| $mi_A$ | = | average distance covered by one car in one year, mi |

Therefore the expected electrical energy savings can be calculated as follows:

$$AEES_{NRNC} = (0.03222)(130{,}241)$$
$$AEES_{NRNC} = 4{,}367 \text{ kWh/car-yr}$$

## EEM No. 7 - Use Permanent Magnet (PM) Motors for Car Propulsion

### Retrofit

A computer model was developed to estimate electrical consumption of an IM and a PM motor propulsion system. The results of the computer model were then scaled so that the IM propulsion system electrical energy consumption match the results from the *Qualification Test Report, Energy Consumption Test on Test Track* (for the A/B cars) which was supplied by BART personnel. The train/track profile used was based on the train configuration as well as the speed/time plot shown in the *Qualification Test Report, Energy Consumption Test on Test Track* (Q.09.01.4.301 Rev. C) used for the C cars. The computer model considered the following:

- **Tractive losses per car.** These were estimated for each time step in the speed/time profile based on the BART car parameters using the Davis Formula.
- **Kinetic energy change.** At each time step the kinetic energy was calculated based on $\frac{1}{2} \times M \times V^2$. The rotational energy in the axles was ignored.
- **Losses in the motor.** Speed vs. efficiency models were developed for an IM and a PM motor. The model used to derive the efficiencies assumed that speed was the only variable component for efficiency (which is true for PM motors, not so for IM). This will result in a conservative estimate of savings since IM efficiency tends to also depend on torque (e.g. efficiency goes down as the torque required by the load goes down).
- **Losses in the converter.** The converter model (electronic motor drives) used for both systems was the same. It was assumed that the nominal efficiency would be 97%. The losses were divided into two categories: Fixed losses (accounting for approximately 30% of the losses in the converter), which considers voltage drops across components, gate drives, etc. and variable losses (accounting for the remaining 70% of the losses), which account for the variation in torque (current) requirements.
- Finally the total electrical consumption for the IM and PM motor propulsion system was calculated by summing up all the above components.

The results for the computer model generated by *DRS Electric Power Technologies, Inc*. that compared the electrical energy consumption and regeneration of IM versus PM motors were:

| | | |
|---|---|---|
| PM Consumption | = | 5.330 kWh/car-mi |
| IM Consumption | = | 5.580 kWh/car-mi |
| | | |
| PM Regeneration | = | 4.570 kWh/car-mi |
| IM Regeneration | = | 4.190 kWh/car-mi |

The results from the computer based model where scale to the IM consumption and regeneration reported on the Test Track Data supplied by BART personnel. The scaled down PM motor electrical consumption, $PMC_S$, can be calculated as follows:

$$PMC_S = PMC \times IMC_{TT} / IMC$$

Where,

$PMC$ = computer based model PM motor consumption, kWh/car-mi
$IMC_{TT}$ = test track IM consumption results, 4.366 kWh/car-mi
$IMC$ = computer based model IM consumption, kWh/car-mi

Therefore the electrical energy consumption of a PM propulsion system is estimated to be:

$$PMC_S = (5.330)(4.366)/(5.580)$$
$$PMC_S = 4.170 \text{ kWh/car-mi}$$

Similarly, the scaled down PM electrical energy regeneration, $PMR_S$, can be calculated as follows:

$$PMR_S = PMR \times IMR_{TT} / IMR$$

Where,

$PMR$ = computer based model PM motor regeneration, kWh/car-mi
$IMR_{TT}$ = test track IM regeneration results, 1.659 kWh/car-mi
$IMR$ = computer based model IM regeneration, kWh/car-mi

Therefore the electrical energy regeneration of a PM propulsion system is estimated to be:

$$PMC_S = (4.570)(1.659)/(4.190)$$
$$PMC_S = 1.809 \text{ kWh/car-mi}$$

Table 7-2 below summarizes the results of the study based on the results from the computer based model and the test track data for both the IM and DC propulsion system.

**TABLE 7-2 COMPARISON OF ELECTRICAL ENERGY CONSUMPTION AND REGENERATION**

| **Propulsion Type** | **Permanent Magnet** (kWh/car-mi) | **Induction** (kWh/car-mi) | **DC** (kWh/car-mi) |
|---|---|---|---|
| Motoring | 4.170 | 4.366 | 4.048 |
| Generating | 1.809 | 1.659 | 1.024 |
| Net Consumption | 2.361 | 2.707 | 3.024 |
| **Electrical Energy Savings** | | **0.346** | **0.663** |

For a graphical description of the methodology used to analyze this measure please refer to Figure 7-1 at the end of this section.

The annual electrical energy savings, AEES, that may result for retrofitting the propulsion system with permanent magnet motors can be calculated as follows:

$$AEES = N \times EES \times mi$$

Where,

N = number of A, B or C cars, no units
EES = electrical energy savings for replacing induction/DC motors with PM motors, kWh/car-mi
mi = distance covered by each car type per year, mi/yr

As an example, the annual electrical energy savings for replacing the propulsion system in the C1 cars (DC motors) with PM motors can be estimated as follows:

$AEES_1 = (150)(0.663)(116{,}435)$
$AEES_1 = 11{,}579{,}461$ kWh/yr

The demand savings, DS, for replacing the induction motor propulsion system in the C1 cars with PM motors can be estimated as follows:

$DS = AEES \times CF / H_{total}$

Where all variables are the same as in the annual electrical energy savings, except:

CF = coincidence factor, fraction of cars that run during BART's peak period, 0.75 no units
$H_{total}$ = the total number of hours per each car type will operate in one year, hr/yr

Using the same example as in the annual electrical energy savings, replacing the induction motors in the C1 cars with permanent magnet motors will result in a demand savings of:

$DS_1 = (11{,}579{,}461 \text{ kWh/yr})(0.75)/(2{,}811 \text{ hr/yr})$
$DS_1 = 3{,}079$ kW

Table 7-3 below summarizes the electrical energy and cost savings for replacing the existing propulsion system with permanent magnet motors.

**TABLE 7-3 SUMMARY OF ELECTRICAL AND COST SAVINGS**

| **Car Type** | **Number of Cars** | **Savings per car per mile** (kWh/car-mi) | **Distance Covered** (mi/yr) | **Energy Savings** (kWh/yr) | **Demand Savings** (kW) | **Total Cost Savings** ($/yr) |
|---|---|---|---|---|---|---|
| A | 59 | 0.346 | 122,275 | 2,496,122 | 631 | 262,093 |
| B | 380 | 0.346 | 137,605 | 18,092,305 | 4,071 | 1,899,692 |
| C1 | 150 | 0.663 | 116,435 | 11,579,461 | 3,079 | 1,215,843 |
| C2 | 80 | 0.663 | 127,020 | 6,737,141 | 1,642 | 707,400 |
| **Totals** | **669** | | | **38,905,029** | **9,424** | **4,085,028** |

The electrical energy cost savings, EECS, can be estimated as follows:

EECS = AEES × (average unit cost of electricity)
EECS = (38,905,029 kWh/yr)($0.105/kWh)
EECS $4,085,028/yr

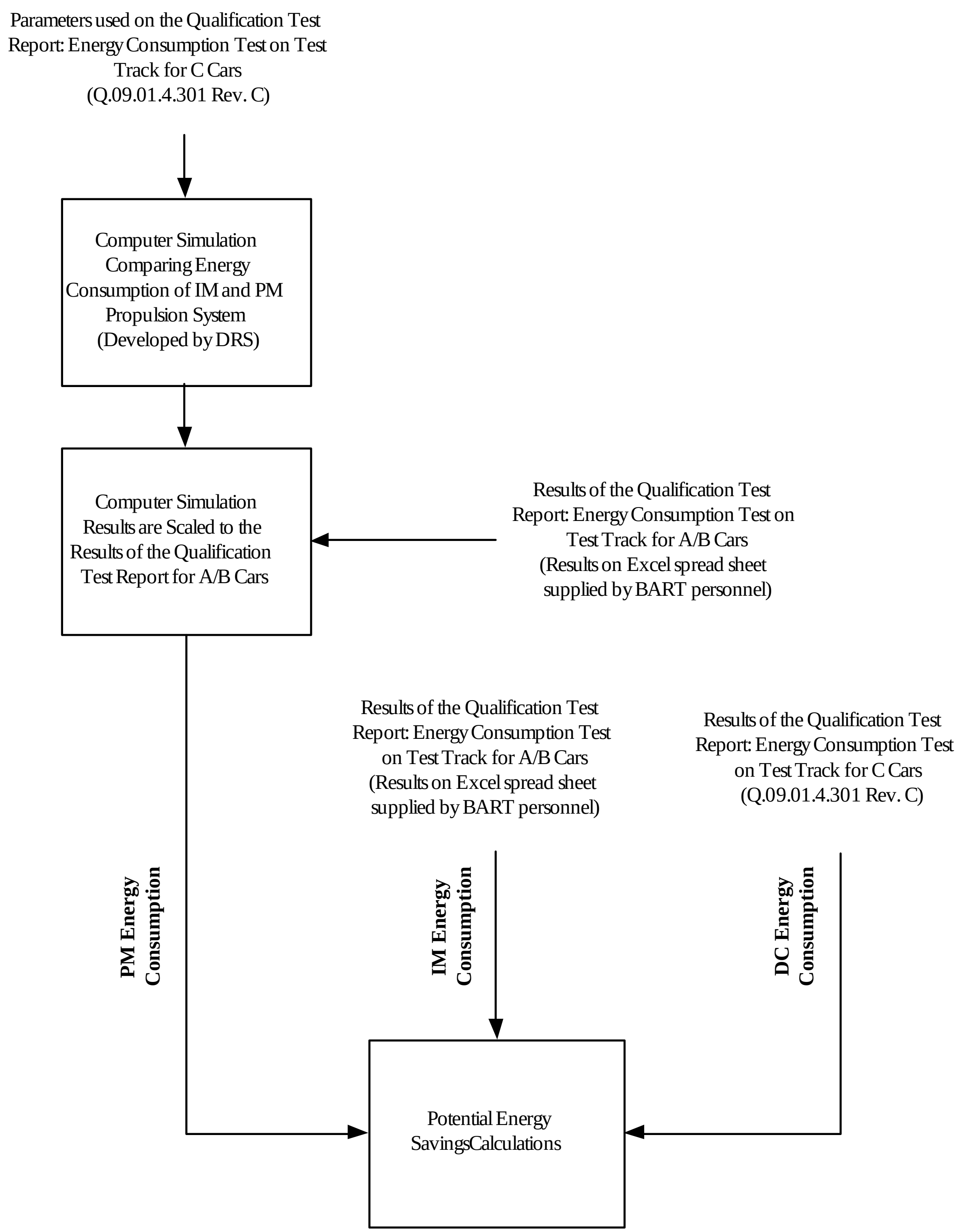



Figure 7-1 Propulsion Analysis Methodology

**NRNC**

The annual electrical energy savings, $AEES_{NRNC}$, for installing permanent magnet motors in new cars can be estimated as follows:

$$AEES_{NRNC} = EES_{A/B} \times mi_A$$

Where,

$EES_{A/B}$ = electrical energy savings per car mile for A/B cars, kWh/car-mi
$mi_A$ = average distance covered by one car in one year, mi

Therefore the expected electrical energy savings can be calculated as follows:

$$AEES_{NRNC} = (0.346)(130{,}241)$$
$$AEES_{NRNC} = 45{,}063 \text{ kWh/car-yr}$$

**EEM No. 8 - Use Ultracapacitors for Regenerative Braking**

**Retrofit**

BART helped record the following parameters with an on-board strip chart recorder:

- Capacitor Bank Voltage (third rail voltage, $V_{Rail}$)
- Dissipation Resistor Switch Duty Cycle ($D_S$)
- Dissipation Resistor Voltage Drop ($V_R$)
- Car Speed

A simplified schematic of the analyzed system along with the connections used to record the dissipated energy are shown in Figure 8-1 below.

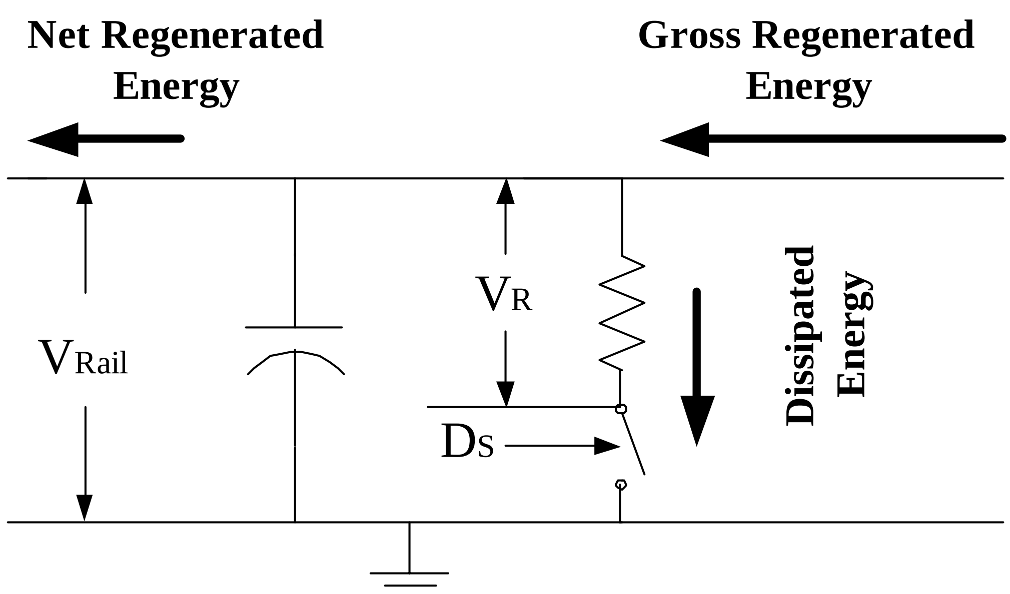



Figure 8-1 Simplified Electrical Schematic of the Regenerative Braking System

In our analysis we have used the plots for the voltage drop across one of the dissipation resistors and the car speed. Whenever there was a significant "jump" in the voltage drop across the dissipation resistor, data was considered. A total of 107 sample sets were used in our analysis (55 sample sets towards the Richmond Station and 52 sample sets coming back to the South Hayward Station). Figure 7-2 at the end of this section shows the first voltage "jump" considered in our analysis. The four plots presented are, from top to bottom: Capacitor Bank

Voltage, Switch Duty Cycle, Dissipation Resistor Voltage and Car Speed. The scales are handwritten on the left side, each horizontal division is 200 ms.

From the voltage data recorded over time and the resistance used to dissipate the excess energy we can estimate the total energy dissipated, DE, for one car on each trip:

$$DE = \sum_i \frac{V_i^2}{R} \times \Delta t \times C_1$$

Where,

| | | |
|---|---|---|
| V | = | voltage drop across the dissipation resistor during one sample, V |
| R | = | equivalent impedance for the two parallel dissipation resistors, 1.39 Ω |
| $\Delta t$ | = | sampling time interval in hours, $5.55 \times 10^{-5}$ h |
| $C_1$ | = | conversion constant, 0.001 kW/W |

Both trips had a similar amount of energy dissipated by the resistor. Table 8-3A/B at the end of this section summarizes the average voltage and dissipated energy during each braking cycle. Form Table 8-3A/B the average dissipated energy per trip was approximately 35.6 kWh. From this average dissipated energy it is possible to estimate the average energy savings, EES, per car mile that can be recovered by storing it in ultracapacitors:

EES = DE × H / HT

Where,

| | | |
|---|---|---|
| DE | = | average amount of energy dissipated by the resistors, 33.5 kWh |
| H | = | average time it takes a BART car to travel one mile, 0.024167 h/mi |
| HT | = | average time it takes to go from South Hayward to Richmond Station, 0.85 h |

Therefore the average electrical energy savings per car mile, EES, that can be realized by installing on-board electrical energy storage devices can be calculated as:

EES = (33.5)(0.024167)/(0.85)
EES = 0.952 kWh/car-mi

The annual electrical energy savings, AEES, that may result from installing on-board electrical energy storage devices can be calculated as follows:

AEES = N × EES × mi

Where,

| | | |
|---|---|---|
| N | = | number of A, B or C cars, no units |
| EES | = | electrical energy savings for installing ultracapacitors, kWh/car-mi |

mi = distance covered by each car type per year, mi/yr

As an example, the annual electrical energy savings, $AEES_1$, for installing ultracapacitors on the C1 cars to store and release all regenerated energy can be estimated as follows:

$AEES_1 =$ (150)(0.952)(116,435)
$AEES_1 =$ 16,626,918 kWh/yr

The demand savings, DS, for installing ultracapacitors in the BART can be estimated as follows:

$DS = N \times DE \times CF / HT$

Where all variables are the same as in the annual electrical energy savings, except:

CF = coincidence factor, fraction of trains that run during BART's peak period, no units

Using the same example as in the annual electrical energy savings, installing ultracapacitors in the C1 cars will result in a demand savings of:

$DS_1 =$ (150)(33.5 kWh)(0.746)/(0.85 h)
$DS_1 =$ 4,420 kW

Table 8-2 below summarizes the electrical energy and cost savings for installing on-board ultracapacitors.

**TABLE 8-2 SUMMARY OF ELECTRICAL AND COST SAVINGS**

| Car Type | Number of Cars | Savings per car per mile (kWh/car-mi) | Distance Covered (mi/yr) | Energy Savings (kWh/yr) | Demand Savings (kW) | Total Cost Savings ($/yr) |
|---|---|---|---|---|---|---|
| A | 59 | 0.9520 | 122,275 | 6,867,942 | 1,736 | 721,134 |
| B | 380 | 0.9520 | 137,605 | 49,779,985 | 11,208 | 5,226,898 |
| C1 | 150 | 0.9520 | 116,435 | 16,626,918 | 4,420 | 1,745,826 |
| C2 | 80 | 0.9520 | 127,020 | 9,673,843 | 2,368 | 1,015,754 |
| **Total** | **669** | | | **82,948,688** | **19,733** | **8,709,612** |

The electrical energy cost savings, EECS, can be estimated as follows:

EECS = AEES × (unit cost of electricity)
EECS = (82,948,688 kWh/yr)($0.105/kWh)
EECS = $8,709,612/yr

Based on the maximum energy that was dissipated while braking during the test runs, the following equation can be used to estimate the equivalent capacitance needed, $C_{eq}$, to store the maximum regenerated energy:

$C_{eq} = 2 \times E \times C_2 / V^2$

Where,

$E$ = maximum energy dissipated by the resistor during one braking cycle, 1.7 kWh
$C_2$ = conversion constant, $3.6 \times 10^6$ J/kWh
$V$ = maximum voltage drop allowed at the capacitor terminal to release all the stored energy, 666 V[§§§]

Therefore the equivalent capacitance needed to store the regenerated energy is calculated as:

$C_{eq} = (2)(1.7)(3.6 \times 10^6)/(666^2)$
$C_{eq} = 28$ Farads

Based on a conversation with Maxwell Technologies personnel (a ultracapacitor manufacturer) one of their power modules has a capacitance of 63 Farads at a nominal voltage of 125 V. The total number of modules, M, required to build a capacitor bank with 88 Farads at a nominal voltage of 1,000 V can be calculated as follows:

$M = (V_{Rail} / V_{MOD})^2 \times (C_{eq} / C_{MOD})$

Where,

$V_{Rail}$ = third rail nominal voltage, 1,000 V
$V_{MOD}$ = nominal operating voltage for one ultracapacitor module, 125 V
$C_{eq}$ = the equivalent capacitance needed to store the regenerated energy, 88 Farads
$C_{MOD}$ = the nominal capacitance of each ultracapacitor module, 63 Farads

Therefore the total number of modules required to build a capacitor bank of 156 Farads at a nominal voltage of 1,000 V is:

$M = (1{,}000/125)^2\ (28/63)$
$M = 28$ modules

The total number of modules required to have an equivalent capacitance of 28 Farads at 1,000 Volts will be 28 modules.

[§§§] Although we are sizing the capacitor bank to operate at 1,000 V (the nominal third rail voltage bus), as a conservative estimate we are requiring that the ultracapacitor does not drop its terminal voltage below 333 V to allow for proper boost converter operation.

**NRNC**

The annual electrical energy savings, $AEES_{NRNC}$, for installing on-board ultracapacitors in new cars can be estimated as follows:

$$AEES_{NRNC} = EES \times mi_A$$

Where,

$EES$ = electrical energy savings per car mile, kWh/car-mi
$mi_A$ = average distance covered by one car in one year, mi

Therefore the expected electrical energy savings can be calculated as follows:

$$AEES_{NRNC} = (0.952)(130{,}241)$$
$$AEES_{NRNC} = 123{,}989 \text{ kWh/car-yr}$$

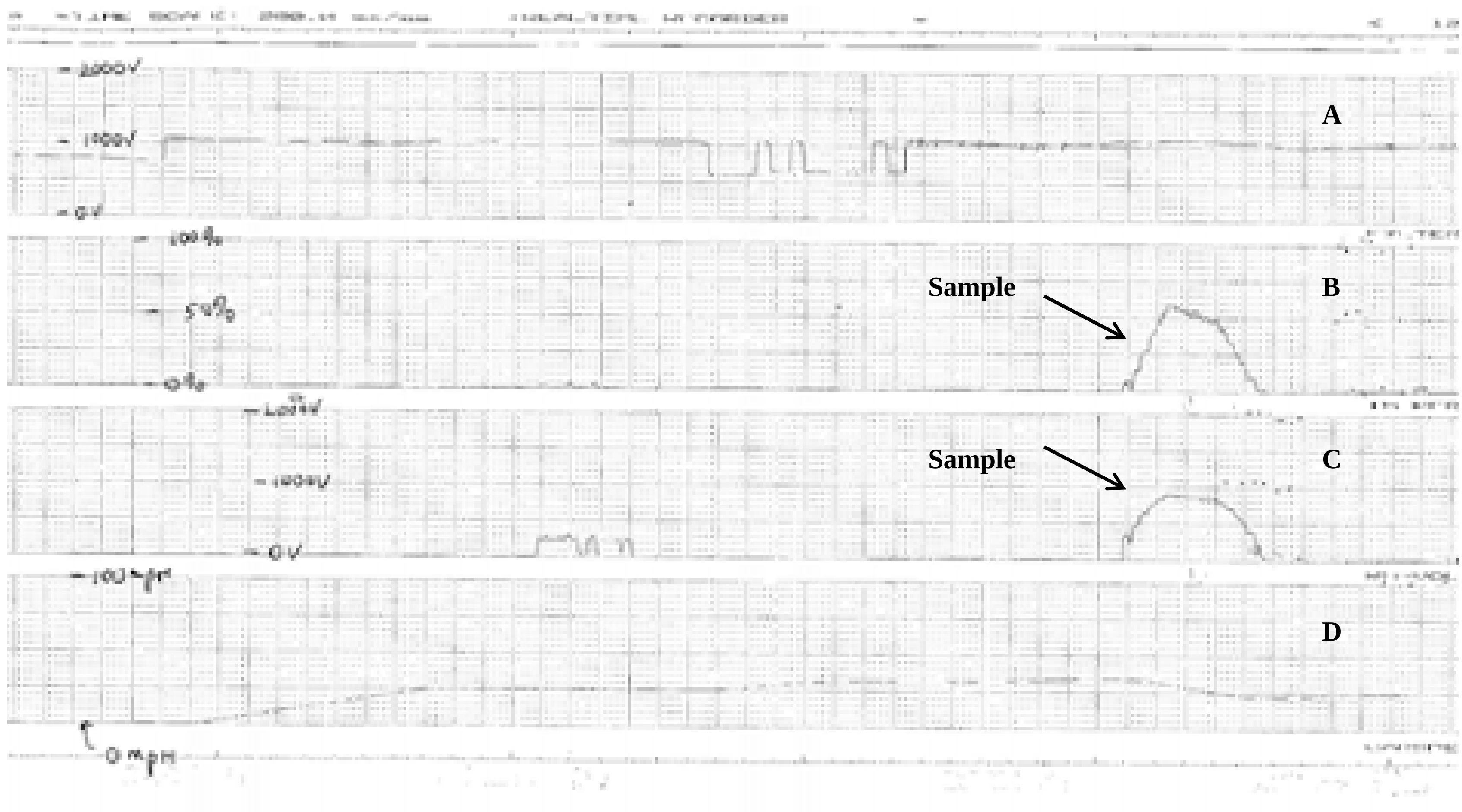



Figure 8-2 Chart Recorder Sample

(A) Capacitor Bank Voltage (third rail voltage)
(B) Dissipation Resistor Switch Duty Cycle
(C) Dissipation Resistor Voltage Drop
(D) Car Speed

| **TABLE 8-3A SUMMARY RESULTS FROM ENERGY DISSIPATION TEST – SOUTH HAYWARD TO RICHMOND STATION** | | | |
|---|---|---|---|
| **Sample Number** | **Sample Duration** (s) | **Average Voltage** (V) | **Dissipated Energy** (kWh) |
| 1 | 5 | 575 | 0.317146 |
| 2 | 4 | 695 | 0.366528 |
| 3 | 6 | 797 | 0.812163 |
| 4 | 4 | 333 | 0.079936 |
| 5 | 4 | 505 | 0.223839 |
| 6 | 5 | 817 | 0.639755 |
| 7 | 7 | 823 | 0.947174 |
| 8 | 3 | 673 | 0.271809 |
| 9 | 5 | 773 | 0.621057 |
| 10 | 4 | 732 | 0.406433 |
| 11 | 5 | 752 | 0.610016 |
| 12 | 6 | 791 | 0.799473 |
| 13 | 8 | 819 | 1.126109 |
| 14 | 5 | 748 | 0.604020 |
| 15 | 5 | 796 | 0.684267 |
| 16 | 5 | 660 | 0.435252 |
| 17 | 4 | 709 | 0.442119 |
| 18 | 9 | 644 | 0.746958 |
| 19 | 8 | 783 | 1.004474 |
| 20 | 6 | 659 | 0.502784 |
| 21 | 9 | 642 | 0.741815 |
| 22 | 5 | 454 | 0.197858 |
| 23 | 7 | 797 | 0.914480 |
| 24 | 7 | 832 | 1.024737 |
| 25 | 5 | 627 | 0.408427 |
| 26 | 11 | 564 | 0.712687 |
| 27 | 10 | 241 | 0.113574 |
| 28 | 8 | 798 | 1.016797 |
| 29 | 6 | 775 | 0.672162 |
| 30 | 9 | 636 | 0.726494 |
| 31 | 7 | 816 | 0.985201 |
| 32 | 7 | 867 | 0.990674 |
| 33 | 8 | 621 | 0.648253 |
| 34 | 3 | 680 | 0.277218 |

Continued on the following page.

| **TABLE 8-3A SUMMARY RESULTS FROM ENERGY DISSIPATION TEST – SOUTH HAYWARD TO RICHMOND STATION (CONTINUED)** | | | |
|---|---|---|---|
| **Sample Number** | **Sample Duration** (s) | **Average Voltage** (V) | **Dissipated Energy** (kWh) |
| 35 | 8 | 613 | 0.599770 |
| 36 | 6 | 803 | 0.799373 |
| 37 | 9 | 612 | 0.642918 |
| 38 | 6 | 793 | 0.754650 |
| 39 | 10 | 635 | 0.774589 |
| 40 | 6 | 328 | 0.137702 |
| 41 | 10 | 456 | 0.415540 |
| 42 | 2 | 436 | 0.083715 |
| 43 | 10 | 698 | 0.934461 |
| 44 | 11 | 606 | 0.791434 |
| 45 | 8 | 825 | 1.088129 |
| 46 | 7 | 770 | 0.781387 |
| 47 | 10 | 592 | 0.685982 |
| 48 | 2 | 382 | 0.064094 |
| 49 | 12 | 695 | 1.138750 |
| 50 | 14 | 461 | 0.611866 |
| 51 | 9 | 634 | 0.707080 |
| 52 | 11 | 787 | 1.336893 |
| 53 | 15 | 444 | 0.574751 |
| 54 | 6 | 648 | 0.487114 |
| 55 | 7 | 512 | 0.355904 |
| Total | | | 34.837792 |

| TABLE 8-3B SUMMARY RESULTS FROM ENERGY DISSIPATION TEST – RICHMOND TO SOUTH HAYWARD STATION | | | |
|---|---|---|---|
| **Sample Number** | **Sample Duration** (s) | **Average Voltage** (V) | **Dissipated Energy** (kWh) |
| 1 | 7 | 486 | 0.330022 |
| 2 | 8 | 748 | 0.893295 |
| 3 | 15 | 611 | 1.132231 |
| 4 | 5 | 419 | 0.182639 |
| 5 | 10 | 751 | 1.149582 |
| 6 | 8 | 678 | 0.753388 |
| 7 | 10 | 638 | 0.779676 |
| 8 | 9 | 768 | 1.037752 |
| 9 | 16 | 442 | 0.616221 |
| 10 | 5 | 708 | 0.520445 |
| 11 | 8 | 600 | 0.604317 |
| 12 | 5 | 704 | 0.514804 |
| 13 | 10 | 641 | 0.837988 |
| 14 | 17 | 708 | 1.704067 |
| 15 | 8 | 739 | 0.830504 |
| 16 | 10 | 598 | 0.700248 |
| 17 | 4 | 359 | 0.113382 |
| 18 | 8 | 345 | 0.180498 |
| 19 | 2 | 367 | 0.048361 |
| 20 | 7 | 676 | 0.675136 |
| 21 | 24 | 426 | 0.869708 |
| 22 | 9 | 606 | 0.690724 |
| 23 | 18 | 691 | 1.698529 |
| 24 | 9 | 615 | 0.710249 |
| 25 | 4 | 400 | 0.127898 |
| 26 | 4 | 433 | 0.135092 |
| 27 | 9 | 730 | 0.980920 |
| 28 | 9 | 613 | 0.705342 |
| 29 | 4 | 332 | 0.083491 |
| 30 | 9 | 789 | 1.119327 |
| 31 | 6 | 506 | 0.327788 |
| 32 | 9 | 609 | 0.681194 |
| 33 | 5 | 408 | 0.172723 |
| 34 | 4 | 637 | 0.307985 |

Continued on the following page.

| TABLE 8-3B SUMMARY RESULTS FROM ENERGY DISSIPATION TEST – RICHMOND TO SOUTH HAYWARD STATION (CONTINUED) | | | |
|---|---|---|---|
| **Sample Number** | **Sample Duration** (s) | **Average Voltage** (V) | **Dissipated Energy** (kWh) |
| 35 | 3 | 643 | 0.231244 |
| 36 | 12 | 649 | 1.027480 |
| 37 | 8 | 685 | 0.730585 |
| 38 | 10 | 614 | 0.753389 |
| 39 | 6 | 245 | 0.069475 |
| 40 | 12 | 631 | 0.985541 |
| 41 | 7 | 679 | 0.607708 |
| 42 | 9 | 633 | 0.735768 |
| 43 | 5 | 408 | 0.159939 |
| 44 | 10 | 775 | 1.248301 |
| 45 | 8 | 751 | 0.924763 |
| 46 | 10 | 625 | 0.811851 |
| 47 | 5 | 757 | 0.526118 |
| 48 | 11 | 465 | 0.492413 |
| 49 | 4 | 659 | 0.381967 |
| 50 | 4 | 447 | 0.151984 |
| 51 | 4 | 367 | 0.112843 |
| 52 | 6 | 279 | 0.086845 |
| **Total** | | | **32.253736** |

# 7. REFERENCES


**EEM No. 1 - High Efficiency Lighting for C1 Cars and New Cars**

Plan Layout – Lighting BART Drawing SD-0104829.

Inverter Ballast Drawing 0101921.

Plan Layout – Lighting (BART) 42DA- 110 “C” Car Drawing ICD108009.

BART REHAB “A” AND “B” VEHICLE LIGHTING INSTALATION Drawing 5D79038.

Advance electronic dimming ballasts, http://www.advancetransformer.com/.

Grainger 2005-2006 Catalog No. 396.

**EEM No. 2 - Direct Cooler Air to the Inlet of HVAC Condensers**

“BART Qualification Test Report” – C Car, 1986. (BA0401)
*A report detailing the testing of BART C Cars’ HVAC system under various conditions. The power consumption for the various HVAC system components (compressor, condenser fan, evaporator blower) was recorded for each condition.*

BART Document BARVE4G02571 Section 7: Heating, Ventilation and Cooling (C1 Car)
*Document specifying the requirements for air comfort (heating, ventilation and cooling) subsystem and equipment to be provided for C1 cars. Includes design conditions, general comfort requirements, etc.*

Soferval, “Qualification Test Report – Test Title: Performance of HVAC System (Energy Consumption) Installed on BART C Car”, Alsthom Atlantique, 1987. (BA3382)
*A report detailing the measurement of the energy consumption of BART C Cars’ HVAC system in the Environmental Test Chamber. The power consumption for the various HVAC system components (compressor, condenser fan, evaporator blower) was recorded. Performance curves of the HVAC compressor were also included in this document.*

**EEM No. 3 - Install Higher Efficiency HVAC Units on C Cars and New Cars**

"BART Qualification Test Report" – C Car, 1986. (BA0401)
*A report detailing the testing of BART C Cars' HVAC system under various conditions. The power consumption for the various HVAC system components (compressor, condenser fan, evaporator blower) was recorded for each condition.*

Soferval, "Qualification Test Report – Test Title: Performance of HVAC System (Energy Consumption) Installed on BART C Car", Alsthom Atlantique, 1987. (BA3382)
*A report detailing the measurement of the energy consumption of BART C Cars' HVAC system in the Environmental Test Chamber. The power consumption for the various HVAC system components (compressor, condenser fan, evaporator blower) was recorded. Performance curves of the HVAC compressor were also included in this document.*

**EEM No. 4 - Optimize Outside Air Intake into Cars**

"BART Qualification Test Report" – C Car, 1986. (BA0401)
*A report detailing the testing of BART C Cars' HVAC system under various conditions. The power consumption for the various HVAC system components (compressor, condenser fan, evaporator blower) was recorded for each condition.*

ABB Daimler-Benz Transportation "Qualification Test Report – Test Title: HVAC Capacity Qualification Test" – A2/B2 Cars, 1998.
*A report detailing the testing of BART A2/B2 Cars' HVAC system under various conditions. The power consumption for the various HVAC system components (compressor, condenser fan, evaporator blower) was recorded for each condition. The HVAC system performance (energy efficiency ratio) was also recorded under the various operating conditions.*

BART Document BARVE4G02571 Section 7: Heating, Ventilation and Cooling (C1 Car)
*Document specifying the requirements for air comfort (heating, ventilation and cooling) subsystem and equipment to be provided for C1 cars. Includes design conditions, general comfort requirements, etc.*

Soferval, "Qualification Test Report – Test Title: Performance of HVAC System (Energy Consumption) Installed on BART C Car", Alsthom Atlantique, 1987. (BA3382)
*A report detailing the measurement of the energy consumption of BART C Cars' HVAC system in the Environmental Test Chamber. The power consumption for the various HVAC system components (compressor, condenser fan, evaporator blower) was recorded. Performance curves of the HVAC compressor were also included in this document.*

**EEM No. 5 - Install Daylight Controls on the Fluorescent Lamps**

Plan Layout – Lighting BART Drawing SD-0104829.

Inverter Ballast Drawing 0101921.

Plan Layout – Lighting (BART) 42DA- 110 "C" Car Drawing ICD108009.

BART REHAB "A" AND "B" VEHICLE LIGHTING INSTALATION Drawing 5D79038.

Illuminating Engineering Society of North America, "The IESNA Lighting Handbook Reference & Application," 9th Edition, Illuminating Engineering Society of North America, 2000.

Astronomical Applications Department, U.S. Naval Observatory, "SAN FRANCISCO, CA Rise and Set for the Sun for 2006."

Advance electronic dimming ballasts, http://www.advancetransformer.com/.

xantrex power electronics, http://www.xantrex.com/.

WattStopper lighting controls, www.wattstopper.com/.

**EEM No. 6 - Install Variable Frequency Drives on HVAC Supply Fans**

ABB Daimler-Benz Transportation "Qualification Test Report – Test Title: HVAC Capacity Qualification Test" – A2/B2 Cars, 1998.
*A report detailing the testing of BART A2/B2 Cars' HVAC system under various conditions. The power consumption for the various HVAC system components (compressor, condenser fan, evaporator blower) was recorded for each condition. The HVAC system performance (energy efficiency ratio) was also recorded under the various operating conditions.*

BART Document BARVE4G02571 Section 7: Heating, Ventilation and Cooling (C1 Car)
*Document specifying the requirements for air comfort (heating, ventilation and cooling) subsystem and equipment to be provided for C1 cars. Includes design conditions, general comfort requirements, etc.*

"BART Qualification Test Report" – C Car, 1986. (BA0401)
*A report detailing the testing of BART C Cars' HVAC system under various conditions. The power consumption for the various HVAC system components (compressor, condenser fan, evaporator blower) was recorded for each condition.*

Electric Power Research Institute, Adjustable Speed Drives Directory, Table 3.1, p18, 1991
*Table was extracted from here which shows the comparative energy consumption of an adjustable speed drive control and damper control.*

Soferval, "Qualification Test Report – Test Title: Performance of HVAC System (Energy Consumption) Installed on BART C Car", Alsthom Atlantique, 1987. (BA3382)
*A report detailing the measurement of the energy consumption of BART C Cars' HVAC system in the Environmental Test Chamber. The power consumption for the various HVAC system components (compressor, condenser fan, evaporator blower) was recorded. Performance curves of the HVAC compressor were also included in this document.*

Vuchic, Vukan R. "Urban Transit: Operations, Planning and Economics", Wiley & Sons, 2005.
*We extracted a typical transit passenger loading profile from this report. Based on this passenger volume profile, flow profiles for the various BART cars have been developed.*

**EEM No. 7 - Use Permanent Magnet (PM) Motors for Car Propulsion**

BART Motor Replacement Performance Modeling, DRS Technologies. Mark Harris, Product Line Manager and Applications Engineering, (317) 845-8423, mharris@drs-ept.com

Power Propulsion Drawing TRR 339708

Westinghouse Type 1463BA Traction Motor (DC propulsion motor curve)

Qualification Test Report: Energy Consumption Test on Test Track, Test Set Number: Q.09.01.4.301 Revision B and C

Qualification Test Report: Car Energy Consumption Test, Test Set Number: Q.09.01.4.301 Revision B

**EEM No. 8 - Use Ultracapacitors for Regenerative Braking Energy Storage**

Maxwell Technologies, http://www.maxwell.com. Scot Thompson, Strategic Account Manager, (858) 503-3328, sthompson@maxwell.com

Power Propulsion Drawing TRR 339708

Bruke, Andrew, "Ultracapacitors: Why, How, and Where is the Technology," 2000, Institute of Transportation Studies (University of California, Davis), http://repositories.cdlib.org/itsdavis/UCD-ITS-REP-00-17.

Destraz, B., Barrade, P., Rufer, A., "Power Assistance for Diesel – Electric Locomotives with Supercapacitive Energy Storage," 2004 35th Annual IEEE Power Electronics Specialists Conference.

# 8. QUALIFICATIONS

## 8.1 Analysis Methodology

This energy assessment report is based on the site visit by BASE staff and PG&E Account Service Representative. In the course of development of this report the assessment team surveyed all energy consuming devices and the associated documentation to the extent possible. In the survey, nameplate data of equipment were extracted, and selected measurements such as the power draw of major electrical consuming equipment were made.

Based on the observations, survey and measurements, energy efficiency opportunities (EEMs) have been formulated and analyzed. These EEMs, or majority of them, were also discussed with BART personnel.

The assumptions used to arrive at the energy consumption and cost savings for the recommended EEMs are provided in the report. These assumptions are intended to be conservative and are often arrived at in consultation with Customer personnel.

Three important factors that affect energy consumption and savings are operating hours, utility factor of the machinery (actual hours of operation of a machine divided by the hours of operation of the department), and load factor (actual energy draw divided by the nominal draw). The operating hours used in this report are based on the information provided by the customer and should be taken as average. Cost estimates are based on contacts with equipment manufacturers and contractors to the extent possible. We **recommend** that the customer consult various suppliers for competitive bids for implementation of EEMs whenever deemed appropriate.

We have not evaluated these EEMs for other factors that could impact the ultimate implementation of the EEMs, such as future expansion capability, regulatory compliance and permitting, ease and cost of maintenance, etc.

### 8.2 Liability Disclaimer

PACIFIC GAS AND ELECTRIC COMPANY'S (hereinafter the "Company") AND/OR ITS CONSULTANTS' REVIEW OF THE DESIGN, CONSTRUCTION, OPERATION, OR MAINTENANCE OF THE CUSTOMER'S COMMERCIAL AND/OR INDUSTRIAL SITE, AND ANY AND ALL REPORTS PROVIDED TO CUSTOMER SHALL NOT CONSTITUTE ANY RESPRESENTATION AS TO THE ECONOMIC OR TECHNICAL FEASIBILITY, OPERATIONAL CAPABILITY, OR RELIABILITY OF THE OPTIONS PRESENTED PURSUANT TO THE ENERGY EFFICIENCY SITE SURVEY CONDUCTED ON CUSTOMER'S SITE. THE CUSTOMER SHALL IN NO WAY REPRESENT TO ANY THIRD PARTY THAT THE COMPANY'S ENERGY EFFICIENCY REVIEW OF THE CUSTOMER'S SITE, INCLUDING, BUT NOT LIMITED TO, THE COMPANY'S AND/OR ITS CONSULTANT'S REVIEW OR ANALYSIS OF THE DESIGN AND/OR THE DESIGN, CONSTRUCTION, OPERATION OR MAINTENANCE OF THE SITE, IS A REPRESENTATION BY THE COMPANY AS TO THE ECONOMIC OR TECHNICAL FEASIBILITY, OPERATIONAL CAPABILITY, AND RELIABILITY OF CUSTOMER'S SITE AND/OR THE OPTIONS PRESENTED PURSUANT TO THE ENERGY EFFICIENCY SITE SURVEY PERFORMED AT CUSTOMER'S SITE.

# 9. UTILITY INCENTIVES AND REBATES

This section provides information regarding utility incentives and rebates that are available to PG&E commercial, industrial and agricultural customers.

Section 9.1 provides the potential incentives for various eligible energy efficiency measures under the 2006 Nonresidential Retrofit – Demand Response (NRR-DR) Program.

Section 9.2 consists of a listing of the rebates for various energy efficient equipment under the 2006 Energy Efficiency Rebates for Your Business program.

Section 9.3 presents an overview of the Demand Response Programs that customers may wish to participate in to receive incentives for reducing their electric load when called for. A summary of the various demand response programs that are available and the incentives for each program are included in this section.

Section 9.4 provides an introduction to the Self Generation Incentive Program established by the California Public Utilities Commission (CPUC). This section also gives the financial incentives that are available to customers for installing qualifying self generation equipment.

## 9.1 Nonresidential Retrofit Incentives

Some energy efficiency projects may qualify for energy efficiency incentives through the PG&E Nonresidential Retrofit – Demand Response (NRR-DR) program. Please contact your PG&E account manager or visit the PG&E website at <http://www.pge.com/biz/rebates/2006_incentive_application/index.html> for details regarding this program.

The following table provides an overview of the potential incentive rates available based on the measure category.

| 2006 NONRESIDENTIAL RETROFIT PROGRAM INCENTIVES | |
|---|---|
| **Measure Category** | **Incentive Rate** |
| Lighting<br>(Fluorescent, Other Lighting or Lighting Controls) | $0.05 per kWh saved |
| Motors and Other Equipment | $0.08 per kWh saved |
| Air Conditioning and Refrigeration | $0.14 per kWh saved |
| Natural Gas | $0.80 per therm saved* |

* The incentive may range from $0.60 to $1.00 per therm.

Eligible measures are installation of new, high-efficiency equipment/systems or retrofits and replacements of existing equipment. Energy efficiency measures must exceed applicable government and/or industry minimum efficiency standards to qualify for incentives and must operate and produce verifiable energy savings for at least five years. The eligible incentive per measure is up to 50% of the measure cost, with a cap of $350,000 per project.

## 9.2 Demand Response Programs

The following table provides a general overview of the demand response programs available to customers that reward them for reducing their electric load during periods of extreme usage. More details regarding these programs can be found on the PG&E's website at http://www.pge.com/biz/demand_response/. Your PG&E account manager can also provide you with more details regarding these programs.

| SUMMARY OF DEMAND RESPONSE PROGRAMS FOR 2006 | | | | | |
|---|---|---|---|---|---|
| **Title** | **Program Requirements** | **Reduction Required** | **Reward** | **Requested Participation** | **Non-Compliance Penalty** |
| Demand Bidding Program (E-DBP) | 50 kW minimum load reduction | Voluntary | Market Price Trigger | California Independent System Operator (CAISO) Alert for the next day | None |
| Base Interruptible Program (E-BIP) | Average monthly demand > 100 kW<br><br>Minimum load reduction of 100 kW but no more than 50% of average peak load | Binding | Option A: $7/kW-month<br><br>Option B: $3/kW-month | California Independent System Operator (CAISO) Alert on day-of basis | Option A: $6/kWh (over firm service level)<br><br>Option B: $2.50/kWh (over firm service level) |
| Critical Peak Pricing (E-CPP) | Monthly maximum demand > 200 kW<br><br>No minimum load reduction | Voluntary | Lower prices during summer non-peak periods | Maximum of 12 days per summer season | Higher prices during critical peak periods* |
| Optional Binding Mandatory Curtailment Plan (OBMC) | Ability to achieve a minimum of 15% circuit load reduction from established baseline | Binding | Exemption from rolling blackouts | Price and system conditions | $6/kWh penalty |
| Scheduled Load Reduction Program (E-SLRP) | Reduction of the greater of 15% of baseline or 100 kW | Binding | $0.10/kWh | 4 hr/wk minimum during summer | No incentive or removal from program |
| Demand Reserves Partnership (CPA-DRP) | None | Binding | A capacity or reservation payment as well as an energy payment for performance | Maximum 24 hours per month or a total of 150 hours per year | Established in advance by customer/ Demand Reserves Provider |

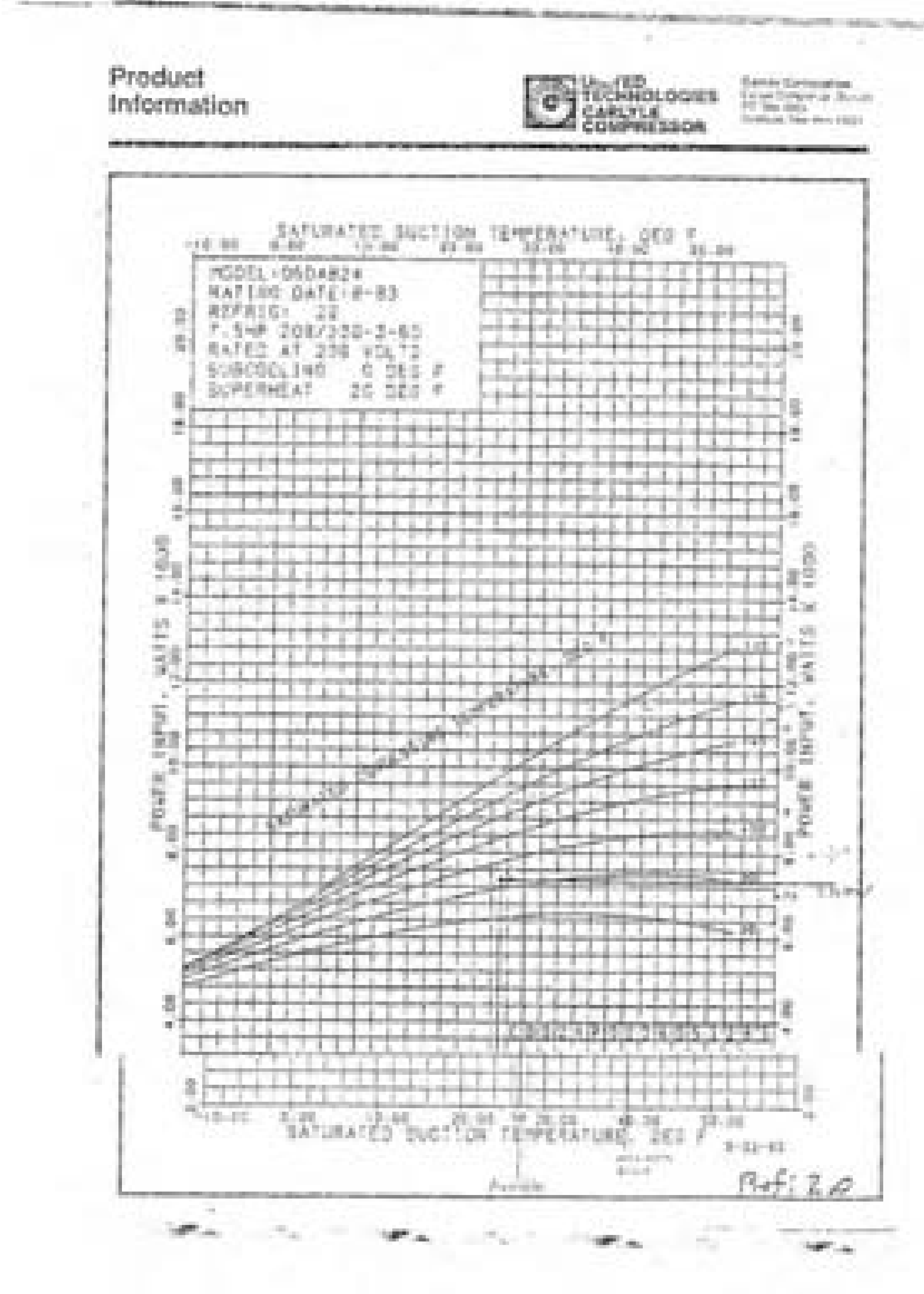
* Bill protection for new customers making participation in the program risk-free for the initial 12 months of participation

# 10. Appendix A - Selected Referenced Documents

This section contains copies of some of the documentation that have been referred to in this report. They are arranged per energy efficiency measure as follows:

- EEM No. 2 - Direct Cooler Air to the Inlet of HVAC Condensers
    - HVAC Compressor Performance Curve
- EEM No. 3 - Install Higher Efficiency HVAC Units on C Cars
    - BART C1 and C2 Cars HVAC ENERGY SAVING ANALYSIS
- EEM No. 7 - Use Ultracapacitors for Regenerative Braking Energy Storage
    - Ultracapacitor datasheet
- EEM No. 8 - Use Permanent Magnet (PM) Motors for Car Propulsion
    - Simulation methodology and results provided by DRS Electric Power Technologies personnel

## HVAC Compressor Performance Curve



**Wabtec/StoneAir, "BART C1 & C2 Cars HVAC Energy Savings Analysis", 2006.**

Stone Air

# BART C1 & C2 CARS

# HVAC ENERGY SAVING ANALYSIS

## Wabtec/Stone Air

| | | |
|---|---|---|
| Modified : | Oleg Goureev<br>Project Leader | |
| Verified : | Daniel Simounet<br>Program Manager | |
| Approved: | Daniel Simounet<br>Program Manager | |
| | Name / Title | Signature / Date |

DRAFT

| Document No. | 200610417 | Revision | 4 |
|---|---|---|---|
| | | Date (yyyy/mm/dd) | 2006/10/12 |

# Table of Contents

# HVAC THAT SAVES ENERGY

## 1 Overview

There are few ways to control and save energy in HVAC system. Mainly all methods related on hardware efficiency, reducing the losses and improving the control. The following proposal will show various ways to achieve the energy saving goal using the combination of various tools available on the market and applicable to the railroad industry. Some of the methods may require testing and prototyping prior to be implemented on revenue cars.

## 2 Improved Temperature Control Algorithm

### 2.1 HVAC operation modes cycle control

PID control logic allowing reduce energy consumption:
depending on the temperature sensor location, the temperature readings may be affected by door cycling that brings some amount of ambient air inside the car. This influence can force HVAC unit to increase heat or cooling capacity while there is no real demand to do that. The special PID algorithm will prevent waste of energy while doors are cycling.

Risk: low (software driven solution)
Advantages:

- energy saving
- increased reliability by reducing unnecessary component cycling

### 2.2 Humidity sensing

Most of the energy consumption comes from cooling operation when both passenger and solar loads does not contribute to the temperature control. While during cold season, both passenger and solar loads are positive factors contributing to energy saving, it is the opposite during the hot season operation. Therefore the proprietary Stone Air control algorithm allows managing energy consumption based on the real temperature and humidity conditions.

Reheat on demand – the reheat during cooling mode will only be activated if humidity level exceeds certain level. Therefore in case of low passenger load or/and during dry-air weather conditions there will be much less energy consumption.

Risk: low (software driven solution)
Advantages:

- energy saving
- increased reliability by reducing unnecessary component cycling
- better passenger comfort due to real humidity control

### 2.3 Flexible set points based on ASHRAE recommendations

Set points to be provided as a function of human-body filling, i.e. the humidity will cause set-point shift to colder temperature during summer while dry air will force set-point shift to warmer temperature. The bracket (range) where temperature may be changed is to be determined, but it can be in the range of ±2°F. Increasing setting point for 2 °F during summer season and reducing setting point for 2 °F during winter will results in 8324 BTUH which represent 7% of the reduction of the energy consumption.

Risk: low (software driven solution)
Advantages:

- energy saving
- better passenger comfort based on real human body requirements

### 2.4 Fresh Air Intake

Fresh air intake is usually calculated based on maximum number of passengers and on the assumption that the car has no other fresh air intake during operation. In case if number of passengers is less than the maximum car capacity or if doors are cycling every few minutes, the fresh air intake coming from fresh air duct may be reduced to avoid additional energy losses required to condition extra amount of fresh air in the system. This can be achieved by measuring temperature profile over the time along with humidity variation profile. All this allows estimate passenger load and adjust fresh air intake accordingly using motorized fresh air damper. Closing the fresh air intake during the low or less passenger requirement in during cooling operation will change the total cooling requirement from 6.08 to 3.33 tons. This reduction will reduce the cooling energy consumption down to about 50%.

Risk: medium (motorized fresh air damper installation required, cost impact)
Advantages:

- energy saving

## 3 Improved HVAC efficiency

### 3.1 Optimize Mechanical System Design

#### 3.1.1 Condenser coil design improvement.

The existing condenser coils have been in service since 1985. However, such a big coil, (5 rows, 48" finned length, and 26" high), has only 5 circuits. Based on Stone Air's experience, the refrigerant pressure drop across the coil will be very high. Theoretic analysis indicate that this very high pressure drop will result in the waste of large amount of energy, making the compressor work in difficult conditions and reducing the system cooling performance. If the number of circuits are increased, the system cooling capacity could be improved.

Changing the condenser coil from 5 circuits to 10 circuits will:

- Increase the cooling capacity for 0.5 ton, which represents 7.1% increase.
- Decrease the energy required to operate this large cooling capacity by 4.5%

- Increase EER value from 8.4 to 9.1
- Greatly reduce pressure drop across condenser coil from 31.59 psi to 2.24 psi.

It should be pointed out that the coil circuit change will only change the coil internally. The outside dimensions and connection dimensions of the 10-circuits coil are the same as the dimensions of 5-circuits coil.

### 3.2 Scroll compressor versus reciprocating compressor

Initial study shows the benefits of using scroll compressors instead of reciprocating:
- weigh reduction
- higher EER
- more reliable
- less service required
- field-proved solution

All together these factors contributes to more efficient energy distribution and additional maintenance savings.

### 3.3 Two-speed evaporator blower.

The dehumidify using the refrigeration method will follow the following two important rules
1. Reduce the amount of air flow through evaporator coil, and
2. Increase enthalpy difference between air inlet and outlet.

In the actual design there is no problem to reduce the moisture in the air during full cooling operation while there is a problem during the partial cooling operation since compressor has not enough time to remove moisture prior the temperature drops too low and force system to switch into ventilation. Stone Air's recommends select a two-speed motor for best performance and energy savings. Combining with humidity control algorithm the significant energy savings can be achieved at low extra cost.

Risk: medium-low (additional contactor required in the control box, cost impact, field-proved design)
Advantages:
- energy saving
- efficiency improvement

### 3.4 PermaFrost and other chemical materials

Some materials were developed to improve HVAC refrigerant system efficiency. One of these materials is the PermaFrost that improves system efficiency by reducing refrigerant flow restriction caused by oil attached to the inner layer of the system.

Risk: medium (requires on-car testing)
Advantages:
- energy saving

| Contract Specifications | | | BART 7 Tons (108 pass., 100% FA) | BART 7 Tons (54 pass., 0% FA) | BART 7 Tons (0 pass., 0% FA) |
|---|---|---|---|---|---|
| Fresh Air Condition | Dry Bulb | °F | 100 | 100 | 100 |
| | Wet Bulb | °F | 69 | 69 | 69 |
| | Atmospheric pressure | psia | 14.696 | 14.696 | 14.696 |
| | Relative humidity | % | 19.80% | 19.80% | 19.80% |
| | Dew point temperature | °F | 51.6 | 51.6 | 51.6 |
| | Humidity ratio | lbw/lbda | 0.0081 | 0.0081 | 0.0081 |
| | Enthalpy | Btu/lb | 33.00 | 33.00 | 33.00 |
| | Volume | cf/lb | 14.29 | 14.29 | 14.29 |
| | Fresh Air Flow Per Car | CFM | 800 | 800 | 0 |
| Return Air Condition | Dry Bulb | °F | 76 | 76 | 76 |
| | Relative humidity | % | 55% | 55% | 55% |
| | Atmospheric pressure | psia | 14.696 | 14.696 | 14.696 |
| | Wet-bulb temperature | °F | 64.79 | 64.79 | 64.79 |
| | Dew-point temperature | °F | 58.69 | 58.69 | 58.69 |
| | Humidity ratio | lbw/lbda | 0.01057 | 0.01057 | 0.01057 |
| | Enthalpy | Btu/lb | 29.82 | 29.82 | 29.82 |
| | Volume | cf/lb | 13.73 | 13.73 | 13.73 |
| | Return Air Flow Per Car | CFM | 3200 | 4000 | 4000 |
| Passenger | Number of Passengers | Qty | 108 | 54 | 0 |
| | Load per passenger | Btu/hr | 450 | 450 | 450 |
| | Sensible Heat Ratio | % | 49% | 49% | 49% |

| | | | Sensible Heat | Latent Heat | Sensible Heat | Latent Heat | Sensible Heat | Latent Heat |
|---|---|---|---|---|---|---|---|---|
| Cooling Capacity Requirement | Fresh Air | Btu/hr | 19348 | -8844 | 0 | 0 | 0 | 0 |
| | Passenger Heat | Btu/hr | 23814 | 24786 | 11907 | 12393 | 0 | 0 |
| | Lighting load | Btu/hr | 8538 | | 8538 | | 8538 | |
| | Carbody | Btu/hr | 31131 | | 31131 | | 31131 | |
| | Solar internal heat load | Btu/hr | 20800 | | 20800 | | 20800 | |
| | Blower Motor (2x2.0 HP) | Btu/hr | 12265 | | 12265 | | 12265 | |
| | Required Capacity per car | Btu/hr | 115895 | 15942 | 84641 | 12393 | 72734 | |
| | | Btu/hr | 131837 | | 97034 | | 72734 | |
| | | Tons | 9.7 | 1.3 | 7.1 | 1.0 | 6.1 | 0 |
| | | Total Tons | 10.99 | | 8.09 | | 6.06 | |
| | | 10% more Tons | 12.09 | | 8.89 | | 6.67 | |
| | Required Capacity per unit | Btu/hr | 57948 | 7971 | 42320 | 6197 | 36367 | 0 |
| | | Btu/hr | 65919 | | 48517 | | 36367 | |
| | | Tons | 4.8 | 0.7 | 3.5 | 0.5 | 3 | 0 |
| | | SHR | 0.88 | | 0.87 | | 1.00 | |
| | | Total Tons | 5.49 | | 4.04 | | 3.03 | |
| | | 10% more Tons | 6.04 | | 4.45 | | 3.33 | |

Maxwell TECHNOLOGIES

HTM Power Series 125v BOOSTCAP® Ultracapacitor Modules

P

## Series: HTM Power
### 125 Volt Module

- Ultra Low Internal Resistance
- Highest Power Performance Available
- Lowest Time Constant

**Features:**

- 125V Operating Voltage
- Monitoring provisions for temperature and voltage
- Over 1M duty cycles
- Sealed from exposure to the elements by being compliant with the IP 65 requirements as detailed in the IEC standards
- Proprietary material science and packaging technology

**Applications:**

- Heavy Duty Transportation

| Item | Performance | |
|---|---|---|
| Nominal Operating voltage (Vdc) | [illegible] | |
| Maximum Operating Voltage (Vdc) | [illegible] | |
| Surge voltage (Vdc) | [illegible] | |
| Nominal Capacitance (F) | [illegible] | |
| Tolerance Capacitance (%) | [illegible] | |
| DC Series resistance (mΩ) | [illegible] | RT |
| 100 Hz Series resistance (mΩ) | [illegible] | RT |
| Energy Available (Wh) | [illegible] | [illegible] |
| Self discharge (% of initial V) | [illegible] | [illegible] |
| Maximum Continuous Current (A) | [illegible] | [illegible] |
| Max current (A) | [illegible] | [illegible] |
| Lifetime 125V, RT (hours) | [illegible] | [illegible] |
| Cycles 125 to 62.5 Vdc, RT (cycles) | [illegible] | [illegible] |
| Isolation Voltage (Vdc) | [illegible] | [illegible] |

| Part Number | Vol (l) | Mass (kg) | Size (mm) | | |
|---|---|---|---|---|---|
| | | | L | W | H |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

DRS TECHNOLOGIES

DRS ELECTRIC POWER TECHNOLOGIES, INC.

7/18/2006

BART Motor Replacement Performance Modeling

978-353-5000
Fax 978-353-5793
http://www.drs.com

Ricardo A. Sfeir
Electrical Engineer
BASE Energy, Inc.
(415) 543-1600

Ref: BART car Efficiency Performance Test Package
1) Qualification Test Procedure Car Energy Consumption Test Q.09.01.4.301 Rev B 10/14/85
2) Qualification Test Report, Composite, Energy Consumption, Rev B 10/14/85
3) Qualification Test Report, Composite, Regeneration Efficiency, Rev 0 10/30/85
4) Qualification Test Report, Energy Consumption Test on Test Track, Rev C, 05/14/89
5) Ohio Semitronics, INC., Equipment Certifications
6) Davis Formula, Train Resistance Equations

Ricardo:

I have completed the evaluation of permanent magnet machine efficiency as compared to induction machine performance based on the information you supplied me, as referenced above. The following report lays out my analysis methods and calculations as well as conclusions.

## Basic Approach and Calculations

Since BASE and BART desired an analysis of the advantages of PM machines based on actual operating profile and allowing a direct comparison with existing equipment, the data from ref 4 above was used. The data enable the development of a system model of a BART car on the test track. Two alternate models were developed, one for a permanent magnet machine, the other for an induction machines, this enabled the results to be checked against actual test data.

The model developed is a simple physics representation of a complex system (a three car train on a real world track). The modeled results provide an indication of the differences to be expected between an induction machine based system and one using permanent magnet machines. The modeled Induction machine performance was used along with test track data to enable a preliminary estimate of the Wh per car mile savings to be expected of a PM based system.

The test profile chart from the data package was translated by hand to a data table of speed vs. time that could be used as input to the performance model. Tractive losses were calculated based on the mass of one car, the change in kinetic energy at each time step was calculated, the losses in the motor given the power required to overcome the tractive losses and the change in kinetic energy, the input energy to the motor was used to calculate the losses in the converter. Then all of these losses were summed. The regenerative energy was developed in a similar way, during deceleration the kinetic energy change at each time step less the sum of; the tractive, motor, and converter losses, is the energy available to the rail.

<u>**Test profile, speed and time:**</u>

The copy of the paper tape from the data-logger was used to generate a speed vs. time table in Excel, this was then transferred to a table in MathCad. There were 52, ½ second time steps, maximum speed achieved was approximately 78 mph. Chart 1 shows the resulting graph.

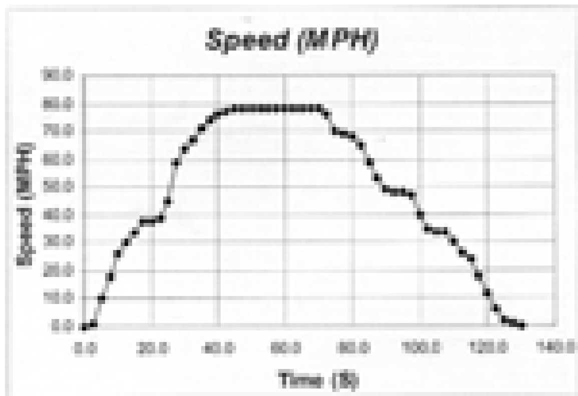



*Chart 1: Speed / Time chart from the test data*

**Tractive losses per car:**

The Davis Formula was used to generate a curve of tractive forces (losses) vs. speed. The equation used calculated tractive effort in lbs/axle.

$$1.3\frac{W}{N} + 29 + \frac{.045V\,W}{N} + \left[0.0024 + \frac{0.00034(C-1)}{C\cdot N}\right]A\cdot V^2$$

| | | |
|---|---|---|
| Weight in tons per car | W | 31.5 |
| Velocity in MPH (max of 84) | V | Speed |
| Total frontal area sq ft | A | 110.25 |
| Number of cars in the train | C | 10 |
| Number of axles per car | N | 4 |

This calculation was used to generate a tractive effort vs. speed graph, which was then used to generate a curve equation. Where Speed was in units of mph and the output in lbf.

$$38.191e^{0.0181\cdot Speed}$$

This equation was used to develop the power required to maintain a speed, and the average power of two adjacent time-steps was used to calculate the energy losses.

**Kinetic energy change:**

Kinetic energy was calculated as:

$$\frac{1}{2}MV^2$$

This ignores the rotational energy in the axles. The kinetic energy at each time step was calculated and the energy required to change the KE state was taken to be the difference between those two numbers.

**Losses in the motors:**

Basic speed vs. efficiency models for both a PM motor and an induction motor were developed. The efficiency vs. speed graph that resulted was converted to a curve in a curve fitting program.

The PM machine equation is:

x = percentage of maximum RPM (*100)

$$\frac{a \cdot b + c \cdot (x)^{d}}{b + (x)^{d}}$$

$a := 0$

$b := 633$

$c := 97.3$

$d := 3.25$

The IM equation is:

z = % max RPM

$$\frac{ai \cdot bi + ci \cdot (z)^{di}}{bi + (z)^{di}}$$

$ai := 0$

$bi := .025$

$ci := .99$

$di := 1.94$

The IM curve is particularly simplistic, assuming that speed is the only component of efficiency (true for a PM), in fact an IM is also sensitive to load, with efficiency going down with torque. Since the load is rarely anywhere near peak the IM would be significantly less efficient than estimated here.

**Losses in the Converter:**

Converter losses are made up of two principle components; fixed losses due to passive components, contacts, device drops, gate drives, control electronics, etc. and variable losses which are due primarily to the switching and conduction losses in the semiconductor devices with a small component of transient losses in capacitors and inductors. The variable losses are proportional to current, which is equivalent to torque. Converter efficiency at max power was set at 97%, a good figure for a modern converter. This 97% figure was multiplied by the power to a single axle to find the total converter losses. These were apportioned 30% fixed, 70% variable, and the variable component was modulated by the torque at the wheels. This was then multiplied by 4 to get the total losses per car.

**Total Losses:**

For the portion of the test run under acceleration and constant speed:

Total losses =Tractive losses +Motor Losses + Converter Losses + Increase in car KE

Model Losses were:

A) Permanent Magnet Machine based system model predicted ~5330Wh
B) Induction machine based system model~5580Wh

This 250 Wh difference is indicative of the performance differences between PM and IM based systems. But the numbers are significantly lower than those measured on the track (as was expected). Rotational inertia and the load variable efficiency hit in the IM machine were ignored and would have had a significant impact on the numbers.

*Test Track Performance Modeling (07-18-06).doc*
*Page 4 of 6*

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These numbers provide a basis for an estimate of system level performance improvement. The IM number and the actual test result were used to scale the PM numbers. This was then converted to a Watt hour per car mile number and finally a Watt hour per car mile savings number:

A) Actual measured energy consumption on the BART test track: 4048 Wh per car mile
B) Expected PM Motor System Energy consumption on the same track: 3860 Wh per car mile
C) **Expected savings of a PM Motor System: >180 Wh per car-mil**

**Regenerative Energy:**
For the portion of the test run under deceleration

Regenerated = Kinetic Energy - Tractive losses - Motor Losses - Converter Losses

Model regenerated energy was:
A) Permanent Magnet Machine based system model predicted ~4570Wh
B) Induction machine based system model~4190Wh

This number is a lot higher than the system test measurement of ~1940Wh; however the method of calculation is highly simplified and not well suited to calculating regenerated energy. Once more it does provide a measure of the differences to be expected between modern PM and IM based systems.

Scaled from the IM model and the actual test data, energy regeneration through a PM based machine, could be expected to be **≈ 2100 Wh a 9% improvement**. Actual equipment could well do better.

## PM Technology Advantages and Differences

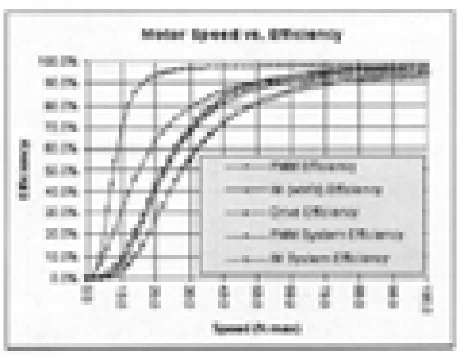


*Chart 2: Motor Speed vs. Efficiency for IM & PM motors / systems*

For traction applications the two principle attributes of PM machines are efficiency and 'torque density' i.e. comparatively modest size and weight in comparison to other machines. The efficiency advantage is shown in Chart 2, a graphical assessment of a PM machine vs. an equivalent IM machine. The efficiency of the motor drive (controller) is also graphed along with the 'system' efficiencies of a combined motor and drive. This clearly shows that the drive has a large impact on the actual efficiencies seen in operation and while a PM based system will be more efficient, the difference will not be as definitive as between the two machines. Modern drives are generally able to control a PM machine with no difficulty, often with no additional hardware (in a sensor-less configuration). Generally because of the lower current requirement in a PM (higher efficiency) the system will be able to operate above the 'normal' rating.

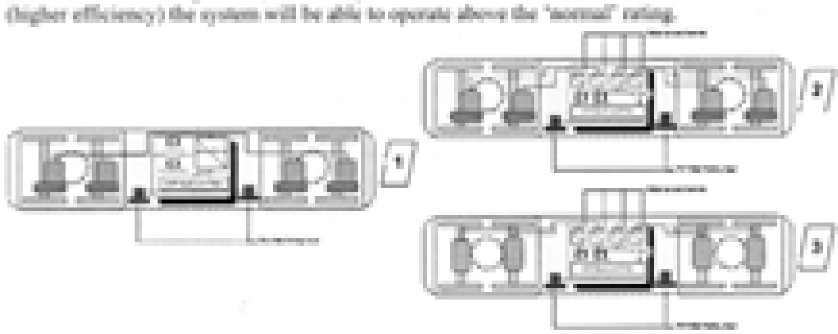


*Figure 1: Baseline Induction (or DC) light rail car configuration (1) vs. PM based (2) & (3)*

The most fundamental difference between PM machines and general purpose induction machines is that PM machine are inherently synchronous, the impact of this is shown in Figure 1, when you compare configuration 1 (induction or DC machines) to either configuration 2 or 3 (PM machines). The diameters of the steel tires on a car are not going to be exactly matched. Consequently the axles do not turn at the same speed. This has no impact on a DC or Induction machine but will cause major problems in a PM machine based system with a single drive. Efficiency would be severely compromised and damage to the components would be frequent.

The solution to this 'synchronicity' problem is to have 4 separate sensorless motor drive output stages for the PM machine based propulsion system. This solves the problem, and has the added benefit of completely eliminating the need to match the wheel diameters between axles. In addition the drive system can monitor the wear on the tires (and identify flat spots or out of round issues) and provide this information to the maintenance staff. This will allow condition based maintenance and decrease the need for extra axle assemblies, providing large cost savings to the maintenance shop.

Figure 1 configuration 3 shows that PM motors have the potential to simplify the propulsion system even more radically. A PM machine is simply a rotating structure with powerful magnets fixed to it, that is then encased by a static (stator) structure that provides the variable electromagnetic field for drive. Currently there is a gear fixed to the axle, a PM system could have the magnets attached to the axle and the stator would fit around and support the axle, this would eliminate the need for the gearbox and simplify the mounting. While the powerful magnets of a modern PM certainly require care in handling, there are multiple ways of shielding them for those times that the axle has to be removed from the stator for servicing. This style of (PM) machine, while larger ant a geared motor, would fit easily in the BART car and would provide multiple system advantages.

## Conclusion

The energy consumption and regeneration calculations above show that a Permanent Magnet Motor based propulsion system for the BART car refurbishment program would provide large real operational savings. A <u>savings of >180Wh per car mile</u> for every one of the cars upgraded, plus an <u>improvement of 9% or better in regenerated energy</u> would have significant advantages to BART and PG&E.

PM machine prices continue to decrease, and because they are inherently smaller and lighter (using less copper, iron and aluminum) than IM machines they may well end up costing about the same as similarly rated IM machines (given that the magnet materials will always be much more expensive). By the time the BART refurbishment program begins the cost of PM machines may have come down to near parity with high quality induction machines and the drives will be common to both types of machine. The largest impediment to PM machine acceptance is a certain lingering sense of the exotic and the fact that Induction machines and their kin are common, reliable and well understood by everyone in industry. The obvious PM opportunity is the significant systemic savings that PM machines bring.

## In Closing

I regret the time it has taken to get you this report. This is a new area for me and the company and there is a lot to learn. Your help and understanding along with the data packages you have provided have been of great value. I hope that you can at least use this report as an addendum to the main report you submitted to PG&E

If you or anyone else at BASE, PG&E or BART has questions, please feel free to call at any time.

Regards

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# 11. Appendix B - Ultracapacitor Implementation Addendum

## 11.1 Introduction

### Objectives

The objective of this study as an Addendum to BART Energy Audit Report is to examine the implementation strategy for incorporating ultracapacitor energy storage devices into BART's existing regenerative braking system. The four main topics addressed in this study include:

1. Research the practical implementation of rail-side and on-board ultracapacitors for use with the regenerative braking system.
2. Economic feasibility analysis and cost estimation of the required interfacing electronics (boost converter).
3. Qualitatively identify the potential benefits and drawbacks of incorporating ultracapacitors at the rail-side, as well as quantify the costs and payback for implementing this option.
4. Qualitatively identify the potential benefits and drawbacks of incorporating ultracapacitors on-board, as well as quantify the costs for implementing this option.

Based on the above research and analysis, the best option (in terms of cost effectiveness) will be assessed based on retrofitting existing BART cars and implementation of this recommendation on a future fleet.

### Limitations

This addendum to the Energy Efficiency Assessment of Bay Area Rapid Transit (BART) Train Cars is a very preliminary study on the potential costs and benefits of retrofitting BART's existing regenerative braking system with ultracapacitors. The component sizing and cost estimate for the DC/DC boost converter represent an approximation (ball park) of what the potential capital costs may be. In no way should the initial boost converter requirements and specifications outlined in this report be treated as a design document.

The qualitative discussions presented in this addendum may serve as an outline and initial assessment of the potential impact of upgrading the existing regenerative braking system with ultracapacitors on the BART system.

### Implementation Summary

Based on the preliminary findings in this study, the following conclusions may be drawn:

1. **Ultracapacitor Life:** A rail-side system is expected to have a life cycle of 30 years, which is approximately 30% longer than the expected 23 years life cycle of an on-board system.
2. **Capital Costs:** A rail-side system may have a slightly higher initial capital cost than an on-board system. It is expected that the capital cost for a rail-side system will be approximately $94,674,648, which is approximately 10% more expensive than an on-board system ($85,923,684).
3. **On-Board vs. Rail-Side:** It is recommended to install a rail-side system if BART is considering retrofitting the existing fleet, however if ultracapacitors are only to be used in a future fleet, it is recommended to install them on-board. If ultracapacitors are used to retrofit the existing fleet there may be other costs (besides capital costs) associated with an on-board system which have not been included in this study. Some of these additional costs may include reengineering a cooling system under the car, reprogramming the automatic traffic control software, etc.

## Research Material

The following list outlines all the research material (along with a brief description) used to analyze the feasibility and economic analysis for implementing a rail-side or on-board ultracapacitor bank as electrical energy storage for regenerative braking. Original documents are attached in the Appendix at the end of this addendum.

1. ***Energy Storage: Onboard or in Substations?*, Bombardier, June 2005**
   This is a Power Point presentation on a study performed by Bombardier that compared implementing ultracapacitor based regenerative braking on-board with rail-side.

2. ***Energy Storage Devices in Railway Systems*, Martyn Chymera, Alasdair Renfrew, Mike Barnes, University of Manchester, UK, School of Electrical and Electronic Engineering , Manchester M60.**
   This journal article discusses the use of ultracapacitors to improve voltage regulation and energy efficiency in railway networks.

3. ***Energy Recuperation in Transportation*, Dr. Adrian Schneuwly, epn-online, [www.epn-online.com](www.epn-online.com)**
   This is an online article that describes Rail-Side Regenerative Braking systems that have been successfully implemented in Europe.

4. ***Energy Storage Onboard of Railway Vehicles*, Dr. Michael Steiner, Dr. Johannes Scholten, Power Electronics Specialists Conference, 2004, PESC 04.2004 IEEE 35$^{th}$ Annual, Volume 1, Issue 20-25, June 2004**
   This paper describes the energy efficiency advantages of an on-board energy storage device (ultracapacitors) for use with regenerative braking.

5. **Maxwell Technologies, [http://www.maxwell.com](http://www.maxwell.com).**
   Datasheet on a particular ultracapacitor

6. **Power Propulsion Drawing TRR 339708**
   This is the power propulsion schematic for a BART car.

7. **Bruke, Andrew, "Ultracapacitors: Why, How, and Where is the Technology," Institute of Transportation Studies (University of California, Davis), http://repositories.cdlib.org/itsdavis/UCD-ITS-REP-00-17.**
   This is a paper that details the state of the ultracapacitor technology.

8. **Destraz, B., Barrade, P., Rufer, A., Power Assistance for Diesel – Electric Locomotives with Supercapacitive Energy Storage," 2004 35th Annual IEEE Power Electronics Specialists Conference.**
   This paper examines the applicability of ultracapacitors in a diesel-electric locomotive. It also compares the ultracapacitor performance with other traditional electrical energy storage devices.


## 11.2 Implementation of Ultracapacitors for Energy Storage of Regenerative Braking

### General Implementation Requirements:

Successful interconnection of the ultracapacitor module to the BART propulsion system will require an electronic interface to interconnect the ultracapacitor bank to the third rail (if installed at the rail-side) or directly to the propulsion system (if installed on-board). The electronic interface consists of a DC/DC boost converter system capable of:

- Transferring power from the propulsion system (regenerated energy during braking) to the ultracapacitor module while in braking mode.
- Transferring power from the ultracapacitor module (stored energy) to the propulsion system while in acceleration mode (through the third rail or directly to the propulsion system).
- The ultracapacitor bank voltage should not exceed 1,000 $V_{DC}$, the third rail nominal voltage. While power is being withdrawn from the ultracapacitor bank, the voltage should not decrease below 333 $V_{DC}$ to help maintain the current and voltage ripples low while keeping the boost converter's component size to a minimum. Having smaller rating components will keep the boost converter weight and cost low.
- The boost converter should be sized to handle the maximum power transfer (equivalent to four 150 hp motors). Sizing the boost converter to transfer 448 kW (equivalent to 600 hp) will help ensure that all energy being regenerated can be safely transferred to the ultracapacitor banks, without need to dissipate "excess" energy on braking resistors.

Preliminary calculations on the boost converter design and implementation cost estimations are shown in the Appendix. It is estimated that a boost converter sized to transfer power between the propulsion system of one car and the ultracapacitor bank will cost (capital cost), approximately $11,100 per car.

### Implementation Option 1: Rail-Side Configuration

A rail-side configuration involves distributing and placing the ultracapacitor banks at strategic locations throughout the BART network. These banks may be installed at the points of PG&E interconnection close to the third rail in places where trains typically stop, or at the individual train stations. In this study, it is assumed that the ultracapacitor banks will be installed at the train stations.

A brief qualitative discussion on electrical losses, overall BART electrical system capacity, train performance and maintenance issues are presented below. Following this discussion a preliminary capital cost analysis of a rail-side system is presented.

**Electrical Losses**

Installing the ultracapacitor banks at the train stations will result in slightly lower system efficiency when compared to an on-board system. The decrease in efficiency is due to the transportation of regenerated energy from the propulsion motors to the capacitor banks located in the train station. It is estimated that the maximum distance that the energy would need to be transferred is approximately 3 miles, equivalent to approximately one half the distance between the furthest apart stations. However, since details on the third rail conductor were not available, it is not possible to estimate the potential losses. Based on a presentation given by Bombardier[****] which compares a rail-side vs. on-board system, the transmission losses in the third rail are approximately 5% of the regenerated energy.

**BART Electrical System Capacity (3rd Rail)**

Rail-side ultracapacitor banks may slightly increase the electrical load on the third rail. The increased electrical load on the third rail is due to the additional available regenerated energy, which used to be dissipated by the braking resistors, that needs to be transferred between the car propulsion system and the ultracapacitor banks in the train stations. However, this slight increase in electrical load is not expected to significantly affect BART's electrical system capacity. This is under the assumption that the third rail has been designed with enough capacity to transfer the additional regenerated energy.

**Train Car Performance**

Since a rail-side system involves installing the ultracapacitor banks off-board, the weight of the ultracapacitor banks will not be added to the train car. Based on the ultracapacitor data sheet, the required 28 modules per car would add approximately 3,000 lbs to the car's overall weight, which represents a weight increase of approximately 5%. Although implementation of a rail-side system may allow removing the existing braking resistors from the train cars (thus making it lighter), it is strongly suggested to keep them on-board for redundancy of the electrical braking system.

**Maintenance and Upgrades**

In a rail-side system it is not necessary to pull train cars out of service when there is need to maintain the electronic braking system, resulting in an increase in train car availability.

[****] *Energy Storage: Onboard or in Substations?*, a presentation by Bombardier, June 2005

Additionally, since the rail-side system is relatively independent of the train cars, as the BART fleet gets upgraded with new cars, the ultracapacitor and DC/DC converter system will remain as part of BART's infrastructure, which would result in less expensive trains.

**Cost Analysis**

Effective implementation of this recommendation will require installing two large regenerative braking systems at each train station capable of absorbing the kinetic energy of two, 10-car trains (one system per train). Therefore a total of 560 ultracapacitor modules[††††] would be required per train station, which would cost approximately $1,612,800. Additionally a rail-side system would require two large boost converters at each train station capable of transferring power between the train cars and the storage devices, costing approximately $221,980 per station. Installing a rail-side system in all 43 train stations will cost approximately:

| | |
|---|---|
| (24,080) Ultracapacitor Modules | $ 69,350,400 |
| (86) DC/DC Boost Converters | $ 9,545,140 |
| Installation Costs (20% of above costs) | $ 15,779,108 |
| **TOTAL** | **$ 94,674,648** |

The implementation cost estimation of a boost converter capable of transferring the regenerated energy from a whole train (10 cars) was estimated based on the cost of a converter sized for a single car and multiplied by a factor of ten, which is a very conservative estimate.

Based on the life expectancy of ultracapacitors and an average number of stops that the train is expected to make in the period of one year, it is estimated that a rail-side system would have an average life expectancy of approximately 30 years[‡‡‡‡].

## Implementation Option 2: On-Board Configuration

An on-board configuration involves installing a dedicated ultracapacitor bank and DC/DC boost converter under each BART train car.

A brief qualitative discussion on electrical losses, overall BART electrical system capacity, train performance and maintenance issues are discussed below. Following this discussion a preliminary cost analysis of an on-board system will be quantified.

**Electrical Losses**

Installing on-board ultracapacitor banks will result in increased system efficiency when compared to a rail-side system. The increase in efficiency is due a reduction on the electrical distance which energy must travel between the ultracapacitor bank and the propulsion motors. As stated in the Rail-Side Configuration Section, an on-board system may result in approximately 5% increase in system efficiency when compared to a rail-side system.

[††††] Please refer to the Bay Area Rapid Transit (BART) Train Cars Energy Efficiency Assessment for details.

[‡‡‡‡] Detailed calculations are shown in the Appendix under Ultracapacitor Bank Life Expectancy.

**BART Electrical System Capacity (3rd Rail)**
On-board ultracapacitor banks may significantly decrease the electrical load on the third rail. A decrease in the third rail electrical load allows for an increase on the number of car trains that may simultaneously run on the tracks by making longer trains (with consideration to station size) or by running more trains (with consideration to train scheduling).

**Train Car Performance**
Since an on-board system would require installing the ultracapacitor bank and DC/DC boost converter underneath a train car, the new system will result in a slight increase in the overall car weight (approximately 5% weight increase). As a result of the increased car weight, it will be necessary to update the automatic train operator parameters that control train acceleration and braking rates as well as the leveling the train cars with station height. This system update would need to be carried out on all 669 cars in the fleet. An additional effect of increasing the car's weight is that it will require additional power to accelerate the train.

**Maintenance and Upgrades**
Maintaining an on-board system involves pulling train cars out of service, which may reduce the overall car availability. Additionally, as old train cars are decommissioned the on-board regenerative braking system would leave along with the cars, which may result in retiring the ultracapacitor storage system too early.

**Cost Analysis**
To effectively implement this recommendation will require installing a capacitor bank under each train car (a total of 669 cars in the fleet) capable absorbing the car's kinetic energy. Therefore a total of 28 ultracapacitor modules[§§§§] would be required per car, and would cost approximately $80,640. Additionally an on-board system would require a boost converter on each train car capable of transferring power between the propulsion system and the ultracapacitor bank, costing approximately $11,100 per car. Installing an on-board system in all 669 train cars will cost approximately:

| | |
|---|---|
| (18,732) Ultracapacitor Modules | $ 53,948,160 |
| (669) DC/DC Boost Converters | $ 7,425,900 |
| Installation Costs (40% of above costs[*****]) | $ 24,549,624 |
| **TOTAL** | **$ 85,923,684** |
| **Cost per Car** | **$128,436/car** |

Based on the life expectancy of ultracapacitors and an average number of stops that the cars are expected to make in the period of one year, it is estimated that an on-board system would have an average life expectancy of approximately 23 years[†††††].

[§§§§] Please refer to the Bay Area Rapid Transit (BART) Train Cars Energy Efficiency Assessment for details.
[*****] It is expected that the installation cost of an on-board system will be at least twice as expensive as the installation cost of a rail-side system. Installing an on-board system will require retrofitting 669 different ultracapacitor systems, whereas installing a rail-side system will require installing only 86 different systems.
[†††††] Detailed calculations are shown in the Appendix under Ultracapacitor Bank Life Expectancy.

It should be noted that an on-board system may require adding an air intake system under the train cars for additional cooling purposes. Based on temperature measurements under a train car, the temperature climbed up to 20 ºF higher than ambient when the braking resistors where used. Although the braking resistors may not be used as often (once the ultracapacitors are installed), the observed temperature rise suggests that there is no adequate air circulation under the train car, which may result in inadequate ventilation for the boost converter.

**Conclusions**

Both, on-board and rail-side systems have been successfully implemented in light rail systems. References to technical journals and magazine articles that describe both implementation strategies are listed at the beginning of this document (full documents are attached to the Addendum).

When deciding between on-board or rail-side implementation of ultracapacitors, it must be determined whether the system will be installed on the current fleet or incorporated on future cars. Table 1 compares the advantages and disadvantages of implementing either a rail-side or on-board side ultracapacitor regenerative braking system.

**TABLE 1 ADVANTAGES/DISADVANTAGES OF BOTH IMPLEMENTATION STRATEGIES**

| Implementation | On-Board | Rail-Side |
|---|---|---|
| System Efficiency | X | |
| Electrical Capacity | X | |
| Train Performance | | X |
| Maintenance and System Upgrades | | X |
| Air Cooling Requirements | | X |
| System Life Expectancy | | X |
| Retrofit Implementation Costs | | X |
| New Fleet Implementation Costs | X | |

X = advantage.

From Table 1, with consideration of implementation costs and life expectancy, a rail-side system would be advantageous if BART plans to retrofit the existing fleet; however if the energy storage system is going to be implemented on a future fleet, it may be less expensive to install them on-board.

## 11.3 Appendix

### DC/DC Boost Converter (DC Transformer)

A DC-to-DC boost converter is the analog of an AC step-up transformer. Through the use of power electronics the converter is able to step-up a DC voltage. To accomplish this, the boost converter requires two passive energy storage devices, an inductor and a capacitor, as well as a thyristor (a type of transistor), which is used as a switch. A basic boost converter‡‡‡‡‡ circuit is shown in Figure 1 below.

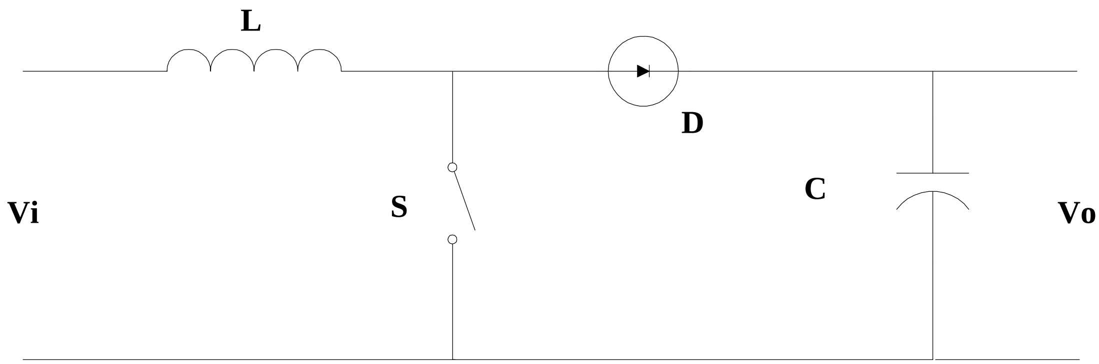


Figure 1 – Basic DC/DC Boost Converter

**Boost Converter Operation**

When Switch S is closed, the power supply feeds Inductor L at a voltage $V_i$. Once Inductor L is fully charged, Switch S opens and the inductor releases its energy through diode D to Capacitor C. As charge is accumulated in Capacitor C, voltage $V_o$ starts to increase until it settles on its steady state value. The output voltage $V_o$ is controlled by regulating the percent of time that Switch S stays on during each switching cycle. Diode D prevents the energy stored in Capacitor C to discharge back to $V_i$ or to ground (through Switch S). Instead energy can only be released to the load, which is at the higher voltage $V_o$.

**The Boost Converter, Ultracapacitor Bank and Third Rail**

To effectively use the regenerated energy from the ultracapacitor bank, it is necessary to release the energy from a lower potential (the voltage across the ultracapacitor bank, $V_i$) to the third rail ($V_o$) which is at 1,000 V dc. Since capacitor voltage decreases as it discharges, the boost converter should actively monitor and regulate the output voltage $V_o$ to 1,000 V dc by controlling the percent of time that Switch S remains closed. From Figure 1, above, the ultracapacitor bank would be connected across the terminal indicated labeled $V_i$, and the third rail would be connected across the terminal labeled $V_o$.

**First Order Boost Converter Prototype**

‡‡‡‡‡ *Power Electronics, Converters, Applications, and Design,* Mohan, Undeland, and Robbins, Second Edition, 1995

Component sizing on the boost converter shown in Figure 1 should be determined based on the boost effect requirements with consideration of the maximum electrical load (four 150 hp motors). To correctly size the inductor, capacitor, diode and thyristor (switch) it is necessary to first determine the switching frequency ($f_s$).

*Switching Frequency*

The limiting factor when determining the switching frequency depends on how fast the thyristor (switch S) can turn on and off. Based on a thyristor manufacturer's datasheet (IXYS Corporation), one of their models which is rated at 1,250 V dc which can conduct up to 600 A (equivalent to a 600 kVA load at 1,000 V dc) has a slew rate (turn-on time) of approximately 1,000 V/µs. Limiting the turn-on time to be no more than 10% of the switching frequency, the maximum switching frequency, $f_s$, can be calculated as follow:

$$f_s = \frac{Vo}{SR} \times 10\%$$

Where,

$V_o$ = third rail voltage, 1,000 V dc
SR = thyristor slew rate, 1,000 V/µs

Therefore the switching frequency is estimated as follows:

$f_s$ = (1,000 V)(0.10) / (1,000 V/µs)
$f_s$ = 100 kHz

*Inductor*

Inductor L should be sized to carry the maximum amount of current that may be required by the load while maintaining the current ripple to no more than 5%. Ignoring the voltage drop across Switch S and Diode D, then the required inductance value, L, that will keep the current ripple to less than 5% can be calculated as follows:

$$L = \frac{Vi\left(1 - \frac{Vi}{Vo}\right)}{fs \times \Delta i}$$

Where,

$V_i$ = lowest voltage across the ultracapacitor bank, 333V dc
$V_o$ = third rail voltage, 1,000 V dc
$f_s$ = switching frequency, 100 kHz
$\Delta i$ = current ripple, 24.85 A (5% of maximum load, 497 A)

Therefore the inductance is calculated as follows:

L = [(333 V dc)(1 – (333 V dc)/(1,000 V dc)] / [(100,000 Hz)(24.9 A)]
L = 89 µH (rated at 497 A, which is the maximum propulsion load)

*Capacitor*

Capacitor C should be sized to maintain the nominal third rail voltage of 1,000 V dc to within 5%. While Switch S is on and Inductor L is charging, the load will be supplied energy by Capacitor C. As Capacitor C discharges, its terminal voltage will begin to decrease. The capacitance value, C, needed to maintain the boost converter output voltage within 5% of the nominal 1,000 V dc can be calculated as follows:

$$C = \frac{\left(1 - \frac{Vi}{Vo}\right) \times Io}{fs \times \Delta Vo}$$

Where all variables are the same as in the inductor sizing, except

$\Delta V_o$ = voltage ripple, 50 V (5% of 1,000 V)
$I_o$ = maximum output current, 497 A

Therefore the capacitance at the output of the boost converter should be:

C = [(1 – (333 V dc)/(1,000 V dc)](497 A) / [100,000 Hz)(50 V dc)]
C = 66 µF (rated at 1,000 V dc)

*Diode*

Diode D should be rated to carry the maximum load current plus the current ripple and be able to withstand a peak inverse voltage of 1,250 V.

**Modified Boost Converter Prototype**

The basic boost converter configuration shown in Figure 1, due to Diode D, is unidirectional, energy can only be transferred from the ultracapacitor bank to the third rail. Adding a second thyristor (switch) across Diode D will allow the boost converter to transfer energy both ways, to and from the ultracapacitor bank. Figure 2 on the next page illustrates the modified prototype.

While in regeneration mode, the thyristor between L and C will remain closed, while the second thyristor will be open. On the other hand, when power is needed from the ultracapacitor bank, the thyristor between L and C will remain open, while the other thyristor cycles on and off as needed.

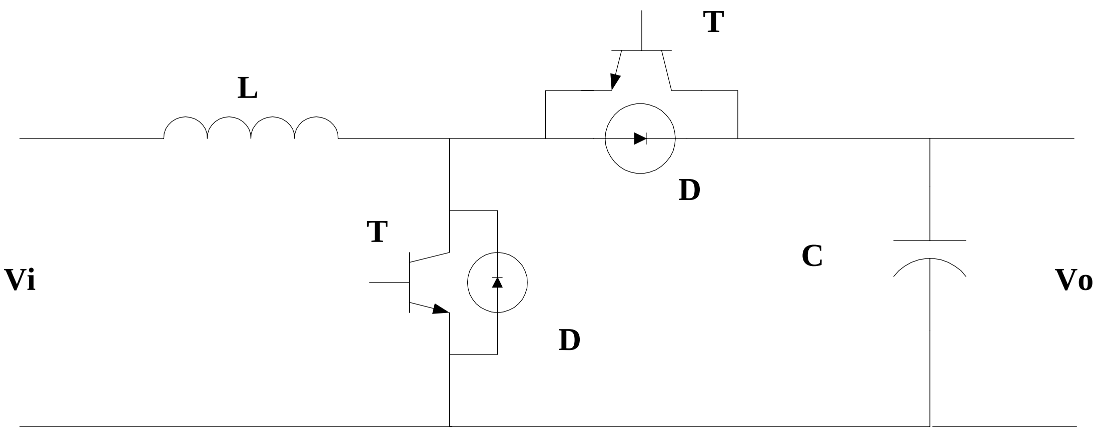


Figure 2 – Modified Boost Converter Prototype

**Boost Converter Cost Estimation**

Based on the component sized for the prototype boost converter and manufacturer's quotes, the boost converter for each car can be estimated as follows:

| | |
|---|---|
| (2) Thyristors | $ 312 |
| (1) Inductor | $ 3,500 |
| (1) Capacitor | $ 30 |
| (2) Diodes | $ 500 |
| Microcontroller and sensors | $ 2,000 |
| Protective Circuit (12% of above costs) | $ 1,586 |
| **Subtotal 1** | **$ 7,928** |
| Engineering (25% of Subtotal 1) | $ 1,982 |
| **Subtotal 2** | **$ 9,909** |
| Overhead and Profit (12% of Subtotal 2) | $ 1,189 |
| **TOTAL** | **$ 11,099** |
| **Cost per Station** | **$221,980** |

Therefore, it is estimated that a boost converter sized to transfer energy between the ultracapacitor bank and the third rail will be approximately $11,100 per car.

**Ultracapacitor Bank Life Expectancy**

Maxwell Technologies, an ultracapacitor manufacturer, rates the life expectancy of their ultracapacitor at 1,000,000 cycles (charging and discharging the ultracapacitor once is considered one cycle). Therefore, to estimate the life expectancy of an ultracapacitor bank as it applies to BART cars, it is necessary to estimate the number of times a car will accelerate and deaccelerate (or start and stop) in one year. From BART's line maps, it is estimated that on average, train stations are approximately 3 miles apart. Table 2 summarizes the total number of miles traveled by car type in a year, as well as the estimated number of stops per year.

**TABLE 2 – CAR STOPS PER YEAR**

| Car Type | Number of Cars | Car-Miles/yr | Car-Stops/yr |
|---|---|---|---|
| C1 | 150 | 116,435 | 38,812 |
| C2 | 80 | 127,020 | 42,340 |
| A | 59 | 122,275 | 40,758 |
| B | 380 | 137,605 | 45,868 |
| **Average** | | | **43,413*** |

*** This is a weighted average.**

*Rail-Side System Life Expectancy*

For a rail-side system, the life expectancy, $LE_{RS}$, for the ultracapacitor bank can be estimated as follows:

$$LE_{RS} = \frac{ULE \times NS \times SS \times TS \times CT}{N \times S}$$

Where,

| | | |
|---|---|---|
| ULE | = | ultracapacitor life expectancy, 1,000,000 cycles |
| NS | = | number of train stations, 43 stations |
| SS | = | number of ultracapacitor banks per station, 2 systems/station |
| TS | = | number of trains each system can support, 1 train/system |
| CT | = | number of cars per train, 10 cars/train |
| N | = | total number of cars in BART's existing fleet, 669 cars |
| S | = | average number of cycles per year, 43,413 cycles/yr |

Therefore the life expectancy for the ultracapacitor bank installed at the rail-side can be estimated as follows:

$LE_{RS}$ = [(1,000,000 cycles)(43 stations)(2 systems/station)(10 cars/train) (1 train/system)] / [(669 cars)(43,413 cycles/yr)]

$LE_{RS}$ = 30 years

*On-Board System Life Expectancy*

For an on-board system, the life expectancy, $LE_{OB}$, for the ultracapacitor bank can be estimated as follows:

$$LE_{OB} = \frac{ULE}{S}$$

Where all variables are the same as in the rail-side system. Therefore the life expectancy for the ultracapacitor bank when installed on-board each BART car can be estimated as follows:

$$LE_{OB} = (1{,}000{,}000 \text{ cycles}) / (43{,}413 \text{ cycles/yr})$$
$$LE_{OB} = 23 \text{ years}$$