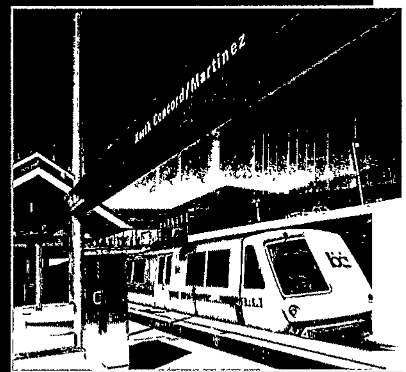
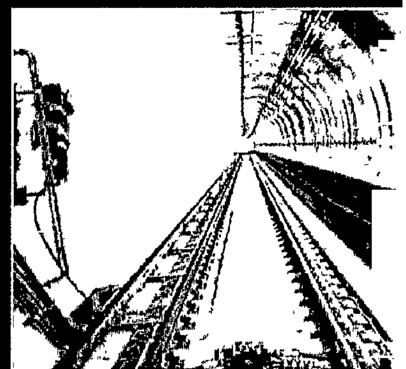
SEISMIC RETROFIT
BUILDING A STRONGER SYSTEM

BART Seismic Vulnerability Study





San Francisco Bay Area Rapid Transit District

BART

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The Bechtel/HNTB Team

BECHTEL HNTB

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Executive Summary

Executive Summary

In September 2000, the Bay Area Rapid Transit (BART) District launched a comprehensive Seismic Retrofit Program. Its goal: to strengthen the BART system ahead of a highly probable future major earthquake. The BART Seismic Vulnerability Study, including a seismic risk analysis, is a critical early stage of this program. This document presents a summary of the results of this study, highlighting items relevant to policy decisions regarding appropriate funding levels for the BART Seismic Retrofit Program.

BACKGROUND

The original BART system was constructed approximately 30 years ago using cutting-edge design and engineering techniques of the day. The original system consisted of 34 stations and about 72 miles of track. Since then, approximately 30 miles of extensions (including 9 stations) have been added.

While BART's original design criteria were advanced for their time and helped the system survive the 1989 Loma Prieta earthquake intact, it has been recognized that a larger seismic event could take place in the Bay Area. Recent U.S. Geological Survey statistical analysis indicates that there is a 70 percent probability that a major earthquake will hit the Bay Area before the year 2030. The level of anticipated impacts and damage that a major earthquake would have on the heavily populated Bay Area is projected to be significant, crippling a large portion of the state's economy for years to come.

Despite the system's reliable performance since its inception, BART initiated a variety of studies following the Loma Prieta earthquake to evaluate the system's earthquake safety. As a result, particular vulnerabilities were found to exist in aerial structures and the Transbay Tube, which could cause the system to become non-operational for a period of time in the event of a large earthquake.

Through the 1990s, BART continued to update its seismic criteria, and much of what was learned was applied to the extensions, making them substantially less vulnerable to earthquakes than the original system. Additionally, and in conjunction with Caltrans, a number of BART aerial structures that crossed local or state highways were retrofitted between 1996 and 1998.

The combination of these studies and actual retrofits led to the conclusion that many original system components probably require retrofit to ensure functionality following a major seismic event, particularly aerial structure foundations. A special feature of the Transbay Tube – its "seismic joints" – also requires adjustment to increase seismic safety.

RESOURCES AND METHODOLOGIES EMPLOYED

Over the past 10 years, new understanding of the science of seismic motions and structural and soil response to these motions has significantly altered our understanding of earthquake behavior and potential damage scenarios. To take advantage of this new knowledge and verify earlier studies, BART initiated a Vulnerability Study to perform the most comprehensive evaluation of BART facilities since the system was originally constructed.

The Vulnerability Study represents extensive and detailed engineering and statistical analyses and review by the BART management and staff, BART's General Engineering Contractor Bechtel/HNTB, the Bechtel/HNTB Design Review Board, G&E Engineering Systems, Inc., an independent Peer Review Panel, Caltrans, and the California Seismic Safety Commission.

All known active and potentially active faults in the Bay Area were examined. From these, four scenario earthquakes were selected for evaluation of the seismic risk analysis of the BART system because they represent a bounding set of events that could cause the most damage to the BART system.

The four scenario earthquakes selected, their magnitude on the Richter Scale, and their locations are listed in Table ES-1.

Table ES-1
Four Scenario Earthquakes

Earthquake Source	Magnitude (M_w)	Location	Fault Rupture Location
Hayward Fault	7.0	North and South segments	Richmond to Fremont
San Andreas Fault	8.0	North Coast northern and North Coast southern segments	Fort Ross to the south
Calaveras Fault	6.8	North segment	North segment
Concord Fault	6.8	Through Concord	Concord, South Greenville, North Greenville simultaneously

The methodologies included developing scenario earthquakes, retrofit options, and other key inputs to a System Earthquake Risk Assessment (SERA) computer model; obtaining key SERA model output; and benefit-cost analysis/recommendations.

The seismic risk analyses presented in this report are based on probabilistic methods that quantify the randomness and uncertainties in ground motions and structures. For each retrofit option, a Monte Carlo simulation using SERA was run 100 times on each of the 15,078 components in the model. Each run varied earthquake forces and component behavior randomly within the standard deviations defined in the SERA input data. The results are a statistical distribution of outcomes.

VULNERABILITIES

The vulnerability study analyses indicate that the elements of the existing BART system (called the "Status Quo" system) that are most susceptible to earthquake damage include:

- Aerial structures, including 24 miles of aerial guideway and 15 aerial stations, which, based on computer models, have potential for collapse of the bent. However, such failures have not been observed in past earthquake damage investigations, and the extent of likely damage is uncertain; less extensive damage states would result in limited operability so that trains could traverse a damaged location at slow speeds.

- The Transbay Tube, where backfill surrounding the tube is prone to liquefaction. Assuming a worst case, liquefaction could cause excessive movement of the seismic joints and structural stress that could cause the tube to fail. However, due to the mix of different soils originally used to backfill the tube and changes from sedimentation over the last 30 years, it is impossible to predict definitively how these soils will react. It is possible that, if hydraulic pressure were to be relieved through the backfill, no damage to the tube would result. The criticality of the tube and the uncertainty of the consequences of liquefaction require that the worst-case scenario be considered for this study.
- The Berkeley Hills Tunnel, which crosses the Hayward fault and would be seriously damaged by any significant offset of the fault at that location.
- Administrative buildings, yard buildings, parking structures, and other buildings, which are likely to be damaged and possibly unusable following the earthquake.
- Various kinds of equipment (substations, ventilation equipment, etc.), some of which could cause functional outages to train operations if dislodged from their anchorages.
- At-grade and underground trackways and stations, which could be damaged but most of which are not expected to become critical to safety or BART operability.

IMPACTS

The immediate impact of damage to the system from a major earthquake can be quantified in terms of ridership effects during any repair period. The Status Quo BART system subjected to a large earthquake on the Hayward Fault, with its epicenter in Oakland, is expected to be able to:

- Transport 27 percent of pre-earthquake ridership within 3 days after the earthquake
- Transport 50 percent of pre-earthquake ridership within about 475 days
- Transport 97 percent of pre-earthquake ridership at about 730 days

This represents a drastic reduction in service levels, below that which is considered acceptable for a transit system whose mission is to serve the Bay Area public. Retrofits to mitigate these impacts are discussed below.

RETROFITS

Two retrofit options for the BART system have been analyzed for this vulnerability report:

- **Systemwide Safety, Core System Operability**. Safety retrofits would be made as required throughout the original BART system, particularly the aerial structures and the Transbay Tube, such that the risk of collapse is minimized. Aerial structure retrofits include foundation strengthening, column jacketing, and additional shear keys. In addition, operability retrofits consisting of enlarged footings and possibly additional piles would be made from the west portal of the Berkeley Hills Tunnel through the Daly City Yard (defined as the "Core System") such that retrofitted structures would not experience significant damage in a scenario earthquake and, with some repairs, trains could run within a reasonable period of time after the earthquake. Transbay Tube retrofits would consist of strengthening the seismic joints, stabilizing the tube to resist forces from all directions, and stabilizing the supporting ventilation structures. Retrofit of the Berkeley Hills Tunnel, which sits across the Hayward Fault, has been evaluated as being impractical.

- **Systemwide Safety, Systemwide Operability.** This would include all of the retrofits in the previous option, plus operability retrofits (primarily for aerial structures) that would put the entire original system back in operation much sooner than would otherwise be the case.

The estimated costs for these two options are shown in Table ES-2.

Table ES-2
Retrofit Cost Estimates
(2002 dollars, in millions)*

Description	Systemwide Safety, Core System Operability	Systemwide Safety, Systemwide Operability
Aerial Guideways & Stations	491	775
Transbay Tube & Vent Structures	251	251
At Grade & Underground Stations	43	51
Administrative & Other Buildings	38	38
Systems & Equipment	4	4
Total	827	1,118

* Excludes escalation and finance costs

SERVICE IMPACTS

Figure ES-1 shows a graph of the service restoration periods for the Systemwide Safety, Core System Operability option; Systemwide Safety, Systemwide Operability option; and Status Quo (no retrofit), derived from the simulation of the Hayward 7.0 scenario earthquake for median ground motions throughout the BART system.

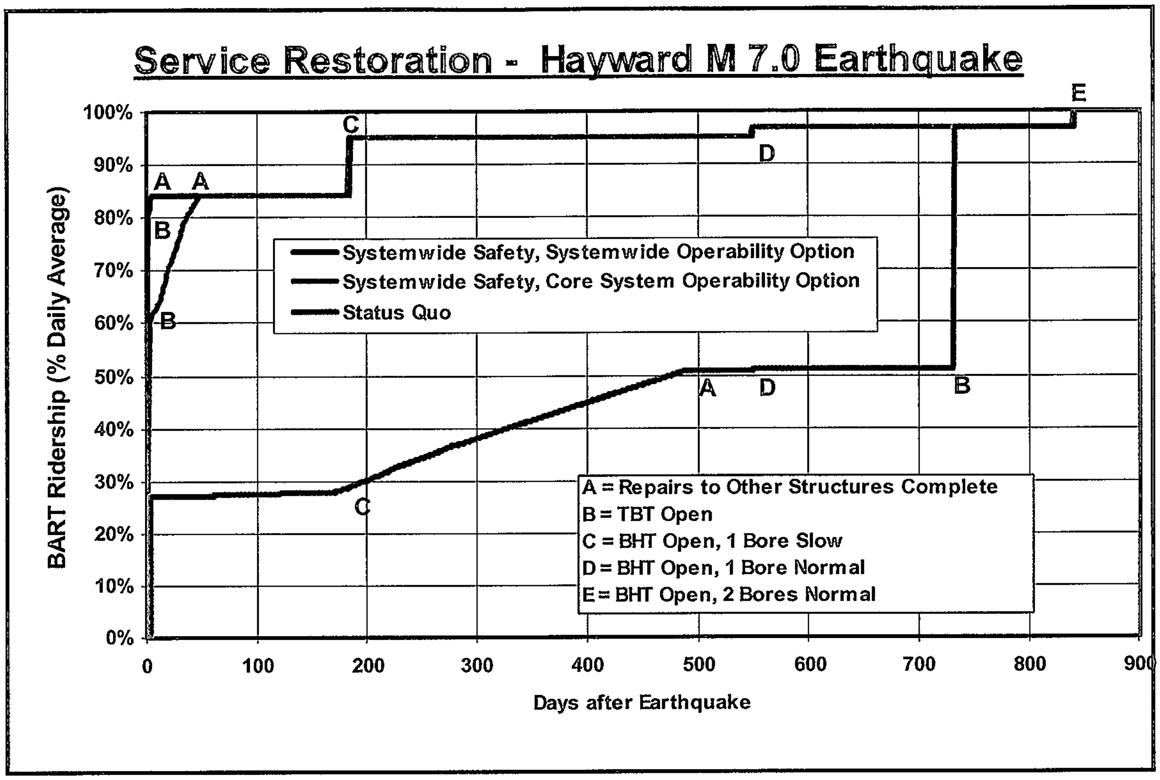


Figure ES-1 Service Restoration Curve – BART Retrofit Options

BENEFIT-COST ANALYSIS

The benefit-cost analysis of the BART retrofit options measures the benefit of each retrofit option relative to the cost of the retrofit based on net present values. The estimated costs of the retrofits are already in present (2002) dollars.

The benefit-cost analysis based on total benefits and costs is shown below in Table ES-3. This analysis indicates that either of the proposed retrofit options is economically justified.

Table ES-3
Benefit-Cost Analysis of BART Retrofit Options
Total Benefits and Costs Basis
(2002 dollars, in millions)

BART Option	Estimated Retrofit Cost	Net Present Value of Benefits	Benefit-Cost Ratio
Systemwide Safety, Core System Operability	828	2,619	3.2
Systemwide Safety, Systemwide Operability	1,118	2,747	2.5

The total benefit-cost ratios shown above are useful for comparing each option with the Status Quo. Either of the retrofit options provides more benefit to BART, compared to doing nothing, than the retrofit costs. For purposes of comparing the two retrofit options with each other, a marginal benefit/cost ratio can be calculated by comparing the additional benefits achieved under the Systemwide Safety, Systemwide Operability option ($128 million) to the additional retrofit cost ($290 million). The resulting marginal benefit-cost ratio is less than one, suggesting that the additional cost of the Systemwide Safety, Systemwide Operability option is not economically justified.

However, it is important to consider other, intangible factors that suggest additional benefits to the Bay Area due to the Systemwide Safety, Systemwide Operability option. These potential benefits cannot be precisely calculated. They include:

- Broader economic impacts to the Bay Area from the extended loss of a vital, established, public transportation system, which might include loss of business, lowered real estate values, reduced consumer spending, etc. were not included in the analysis. Since the Systemwide Safety, Systemwide Operability option returns more of this vital transportation system to operation sooner, these broader impacts would be reduced, compared to the Systemwide Safety, Core System Operability option.
- Although Caltrans and many cities are conducting retrofit programs of their own, the possibility of road closures and disruptions to other forms of transportation after a large earthquake remains. Experience following the Loma Prieta earthquake suggests that BART system ridership would increase as a result. Again, since the Systemwide Safety, Systemwide Operability option brings more of the BART system back into operation sooner, the additional benefit accrued would be greater than for the Systemwide Safety, Core System Operability option.
- The impact of post-earthquake repairs on local communities near the BART alignment will be less if the Systemwide Safety, Systemwide Operability option is carried out, since there will be fewer repairs required.

CONCLUSIONS

Since its inauguration in 1972, the BART system has become the backbone of commuting to downtown San Francisco, and to a lesser extent, downtown Oakland and Berkeley, from most East Bay origins. It is the lifeline for businesses and commerce in its service areas. As such, shutting down all or a portion of the BART system for an extended period of time will have a severe impact on the Bay Area economy as a whole.

Although the Vulnerability Study cannot establish the precise damage to the BART system from a large earthquake, it is clear from the analysis that the damage could be significant. Given the high probability that a large earthquake will occur in the Bay Area within the next few years, a retrofit of BART facilities is essential.

The Systemwide Safety, Core System Operability option is the minimum retrofit that should be considered. In addition to improving the seismic safety of the system, this option provides significant improvements in the ability of BART facilities to return to service after a major earthquake, and allows the resumption of BART operations in the most critical portions of the system relatively quickly. However, this option results in some portions of the system being non-operational for a lengthy period of time, requiring substantial repair before being returned to service.

The Systemwide Safety, Systemwide Operability option improves the performance of the BART system enough so that nearly the entire system can be returned to service quickly, for a cost of $290 million more than the Systemwide Safety, Core System Operability option. Because the Systemwide Safety, Systemwide Operability option retrofits the same BART facilities as does the Systemwide Safety, Core System Operability option (to a higher level of performance), the additional impact to local communities from the retrofit work is minimal. The importance of the BART system to the overall Bay Area suggests that the additional expenditure to achieve the Systemwide Safety, Systemwide Operability retrofit is prudent.

In light of the 70 percent probability that a major earthquake will hit the Bay Area by 2030, BART clearly needs to move ahead as rapidly as the resources available to it will allow.

Section 1
Introduction

In September 2000, the Bay Area Rapid Transit (BART) District launched a comprehensive Seismic Retrofit Program to strengthen the BART system in the event of a future major earthquake. The BART Seismic Vulnerability Study, including a seismic risk analysis, is a critical early stage of this program. This section describes the background of the BART Seismic Vulnerability Study as well as the purpose and plan of this report.

1.1 BACKGROUND

The original BART system was constructed approximately 30 years ago, using cutting-edge design and engineering techniques of the day.

The first real test of the system's seismic capability came on October 17, 1989, when the 7.1-magnitude Loma Prieta Earthquake, emanating from the San Andreas Fault nearly 60 miles south of San Francisco, rocked the Bay Area. The earthquake was only 10 seconds in duration, but caused devastating damage: 60 fatalities, thousands of secondary injuries, over $5.6 billion in property damage, collapse of the Cypress Freeway and parts of the Oakland Bay Bridge, and disruption to other transportation systems across the region. However, the BART system suffered only minor damage. Some service continued and the remainder needed minor repairs. Within hours after the earthquake, BART's engineering and maintenance personnel accomplished a full system inspection of its 34 stations, 21 miles of subway/tube, 24 miles of aerial guideways, and 27 miles of at-grade line. By the following morning, the repairs had been made to all crucial system components, and BART was declared operational in time for the beginning of scheduled passenger service runs. This performance has been largely attributed to BART's superior seismic design criteria, which were developed in the 1960s and applied throughout the system.

While BART's original design criteria were advanced for their time and helped the system survive intact after Loma Prieta, it was recognized that an even larger seismic event could take place in the Bay Area. Further, because portions of the BART system lie near to or cross the Hayward, Calaveras, Concord, and San Andreas faults, BART could be affected by an event on any one of them.

Recent U.S. Geological Survey (USGS) statistics have indicated that there is a 70 percent probability that a major earthquake will hit the Bay Area by 2030. The level of anticipated impacts relative to loss of life and property damage that a major earthquake would unleash upon the heavily populated Bay Area is projected to be catastrophic, crippling a large portion of the state's economy for years to come. According to an evaluation by the California Geological Survey (formerly Division of Mines and Geology) of the California Department of Conservation, using the HAZUS model, the expected losses to the five Bay Area counties would be about $1.43 billion in annualized losses for damage to buildings, inventory, and associated income (not including damage to airports or most lifelines).

The mission of the BART Seismic Retrofit Program is to seismically retrofit the entire original system, using state-of-the-art standards and methodologies to enhance the safety of passengers and personnel, and to enable the BART system to return to operation within reasonable limits after an earthquake.

1.1.1 BART Vulnerability

The BART system is located in the heart of one of the most seismically active regions in the world – on the east side of and immediately adjacent to the San Andreas Fault, and within the major faults in the region, as shown in Figure 1-1.

BART's alignment runs between the Hayward, San Andreas, Calaveras, and Concord-Green Valley faults. It crosses the Hayward Fault twice and the Calaveras and Concord-Green Valley faults once each. Because so many major faults are present, the probability of a large-magnitude earthquake occurring in the region and having a major effect on the BART system is high. The probabilities of occurrence of major earthquakes between 2000 and 2030 have been estimated by the USGS Working Group on California Earthquakes. The USGS estimates of probabilities and the magnitude are:

- Hayward Fault: 32 percent probability of a 6.7 or larger earthquake occurring on the combined Hayward and Rodgers Creek fault system
- San Andreas Fault: 21 percent probability of a 6.7 or larger earthquake on the San Francisco Peninsula segment
- Calaveras Fault: 18 percent probability of a 6.7 or larger earthquake
- Concord-Green Valley Fault: 6 percent probability of a 6.7 or larger earthquake

Overall, USGS estimates that there is a 70 percent probability of at least one magnitude 6.7 or greater earthquake hitting the Bay Area by the year 2030.

Furthermore, because of the close proximity of the BART system to the major faults in the region, the potential of the BART system being subjected to severe ground shaking and ground movement generated by a large earthquake at any one of the major faults is also high.

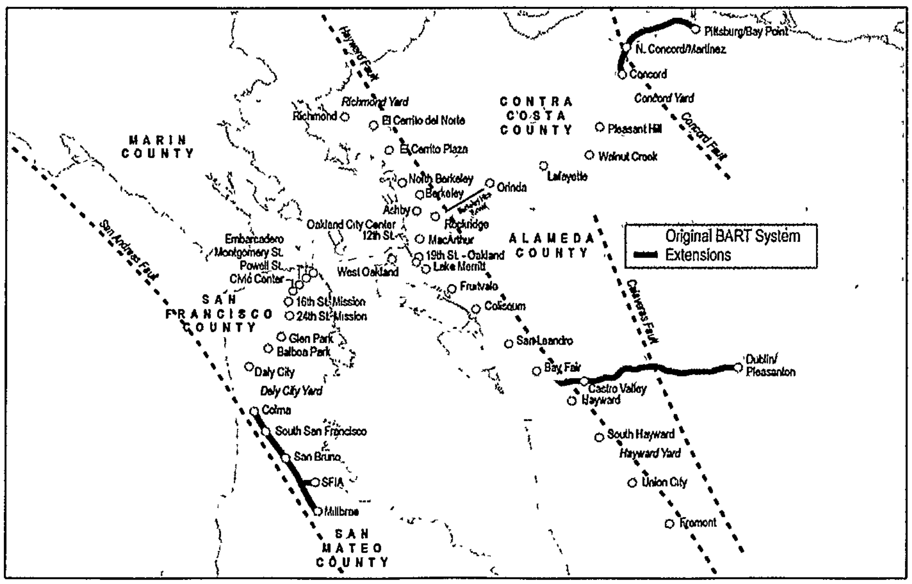


Figure 1-1 BART System in its Seismological Setting

Today, from a structural viewpoint, the BART system consists of the original system, built to the design standards of the 1960s, and several extensions built to more recent, and more robust, standards.

- **Original System.** Completed in 1976, the original BART system consisted of 72 miles of rapid transit lines and included 34 stations. There were:
  - 21 miles of subway and twin-bore tunnels (including the 3.6-mile Transbay Tube; and the 3.2-mile tunnel through the Berkeley Hills)
  - 24 miles of aerial line
  - 27 miles of at-grade track
- **Extensions.** In the 1990s, BART began a massive program to add 30 miles of extensions and nine stations to the original system.
  - The Pittsburg-Antioch Extension, 7.8 miles, opened in 1996
  - Dublin-Pleasanton Extension, 14 miles, opened in 1997
  - Colma Extension, 1.7 miles, opened in 1996
  - An extension to the San Francisco International Airport and three other stations will soon be completed

1.1.2 BART Actions Since Loma Prieta

After the Loma Prieta earthquake in October 1989, BART commissioned or participated in several efforts to better understand its risk from a major earthquake centered in the Bay Area. These efforts are summarized in Table 1-1.

Table 1-1
Seismic Studies, Reports, and Designs Following Loma Prieta Earthquake

Date	Study/Report	Developed/ Prepared By	Details
July 1990	Preliminary Summary Report – Proposed Seismic Design Criteria for Structural Design of the BART Extensions	Bay Area Transit Consultants (BATC)	A typical existing standard aerial structure was analyzed using the proposed seismic design criteria; found that the structure might suffer substantial damage but would not collapse.
May 1991	Seismic Performance Investigation of the Hayward-BART Elevated Section Instrumented under CSMIP	International Civil Engineering Consultants, Inc.	Portion of the aerial structure north of the Hayward station has motion sensors installed by the California Division of Mines and Geology under its Strong Motion Instrumentation Program (CSMIP). This paper presented, among other things, the recorded ground motions and the structure's responses during the Loma Prieta earthquake. One finding is that, in the longitudinal direction, the girders are strongly coupled by the rails and they behave essentially as a unit with almost no relative motions across the joints. The maximum relative displacement experienced at the instrumented joint was about 0.08 inch (about 10% of the joint gap).
May 1991	Extensions Seismic Criteria	BATC and BART Engineering	Work on the Extensions seismic design criteria started before the Loma Prieta Earthquake, around 1988. The goal then was for safety as specified in the FTA design seismic design guidelines in effect at the time. After the quake of 1989, the criteria was upgraded to that of functionality, as recommended by BART staff and the foremost seismic experts in the U.S., including Dr. George Housner and Dr. Joseph Penzien – respectively Chair and Vice Chair of the Governor's Board of Inquiry for the Loma Prieta Earthquake.
November 1991	Transbay Tube Seismic Joints Post-Earthquake Evaluation	Parsons Brinckerhoff Quade & Douglas, Inc.	Among the major findings: "the joints will likely remain intact and functional after the next earthquake." However, rehabilitation of the joints was recommended to restore as close as possible to the original design capacities.
February 1998	SFO Extensions Seismic Criteria	BATC & West Bay Extensions (BART)	The criteria was further updated to reflect the latest seismic design requirements.
January 2000	Caltrans Analysis of the Aerial Structure at 29th Avenue	Caltrans Office of Earthquake Engineering and Design Support	Standard aerial structure was analyzed and found that the pier footing was adequate.
March 2000	Seismic Retrofit Strategy Report – Aerial Structure at 29th Avenue	Sverdrup Civil, Inc. and MGE Engineering, Inc.	Standard aerial structure was analyzed using the functionality criteria and found that only the footing needed to be strengthened.
October 2000	BART Seismic Retrofit Program Vulnerability Study / Design Criteria	Being developed by TSD, M&E, and Bechtel	The goal was to upgrade the original BART system to the latest seismic design standards for functionality.

In addition BART has retrofitted several structures. These retrofits are summarized in Table 1-2.

Table 1-2
BART System Retrofits since Loma Prieta Earthquake

Date	Retrofit	Performed By	Scope of Work
1996	BART Standard Aerial Structure over Melrose Avenue on the A-Line	Caltrans in cooperation with BART	Three pier footings were enlarged and thickened with top mat reinforcing and CIDH piles added.
1996	BART Standard Aerial Structure over Martinez Avenue on the A-Line	Caltrans in cooperation with BART	Two pier footings were enlarged and thickened with top mat reinforcing and CIDH piles added.
1997	BART Aerial Structure (DOT-type bridge) over Peralta Blvd on the A-Line	Caltrans in cooperation with BART	Restrainers were added to girders.
1997	BART Aerial Structure over I-680/24 on the C-Line	Caltrans in cooperation with BART	Five pier footings were enlarged and thickened with top mat reinforcing and CIDH piles added. Shear key was added at one abutment. Girders diaphragms were strengthened by adding cross bracings and top and bottom chords.
1998	BART Standard Aerial Structure over I-880 (Cypress) on the M-Line	Caltrans in cooperation with BART	Construction of 4 new support structures that replaced the original pier columns which were removed to allow clearance for the new freeway lanes.

Note: BART bridge (DOT-type) over Jackson Street on the A-Line was originally included in Caltrans seismic retrofit program but was found to need no retrofitting by Caltrans' evaluations

1.1.3 Seismic Retrofit Program

In the late 1990s, because of BART's criticality to Bay Area transportation, the BART management and board of directors decided that the system – in particular, the segments built before 1989 – should be evaluated and upgraded to meet more current seismic standards. Out of this initiative grew the BART Seismic Retrofit Program.

The Program began in earnest in September 2000, when BART hired the consulting team of Bechtel Infrastructure Corporation and its principal subconsultant, HNTB Corporation (the Bechtel/HNTB team) to lead a comprehensive Seismic Retrofit Program to strengthen the BART system in the event of a major earthquake.

1.1.4 The BART Seismic Vulnerability Study

The seismic vulnerability study is one of the first key elements and one of the most critical undertakings of the program. It comprises a comprehensive assessment process examining the seismic performance of BART's representative components and system elements.

The overall objective of the BART Vulnerability Study is to analyze the BART system, determine its vulnerability to earthquakes, and recommend reasonable and prudent retrofits to address the vulnerabilities.

1.1.5 Risk Analysis

On the recommendation of a peer review panel requested by the California State Seismic Safety Commission, BART initiated a seismic risk analysis to:

- Create earthquake scenario studies that would provide realistic representations of the effects of single-scenario earthquakes
- Initially assume in the scenarios that the BART system is unretrofitted so that the existing safety and functionality risks could be clearly identified
- Subsequently assume increasing levels of retrofit and performance enhancements so the trade-offs between retrofit costs and performance beyond safety can be determined.

1.2 PURPOSE AND PLAN OF THIS REPORT

The purpose of this report is to present the results of the BART Seismic Vulnerability Study for policy decisions by BART management and the Board with respect to determining the appropriate funding level for the BART Seismic Retrofit Program.

This report is organized as follows:

Section 2. Resources and Methodologies Employed. This section describes the resources and methodologies employed in preparing the vulnerability study for the BART Seismic Retrofit Program.

Section 3. BART Vulnerability. This section describes the key structural features of the BART system, the seismic hazards it is exposed to, and the types of damage that could occur to the key structural features in the event of a major earthquake

Section 4. Status Quo. This section describes the potential earthquake damage to the BART system if there is no retrofit, the cost to repair the system, the impact on ridership due to loss of service until repairs can be made, and the potential cost impacts to BART, BART's riders, and the San Francisco Bay Area commuters.

Section 5. Systemwide Safety, Core System Operability Option. This section describes an option in which operability retrofits are made from the West Portal of the Berkeley Hills Tunnel through Daly City Yard and safety retrofits are made throughout the original system.

Section 6. Systemwide Safety, Systemwide Operability Option. This section describes an option in which retrofits are made throughout the original BART system, with the exception of the Berkeley Hills Tunnel and other fault crossings.

Section 7. Benefit-Cost Analysis. This section summarizes the cost impacts of the retrofit options and presents benefit-cost analyses as input to policy decisions with respect to determining the appropriate funding level for the BART Seismic Retrofit Program.

Section 2
Resources and Methodologies Employed

This section describes the resources and methodologies employed in preparing the vulnerability study for the BART Seismic Retrofit Program.

2.1 RESOURCES EMPLOYED

This vulnerability study represents extensive and detailed engineering and statistical analyses and review by the Bechtel/HNTB team, the Bechtel/HNTB Design Review Board, G&E Engineering Systems, Inc. (G&E), a Peer Review Panel, and BART management and staff. Each is discussed briefly below.

2.1.1. The Bechtel/HNTB Team

The Bechtel/HNTB team is providing the lead to the BART vulnerability study and developing input in seismology and geotechnical engineering; structural engineering, including failure analysis and retrofit design concepts; and cost and schedule estimates for repair of damage to the BART system and for retrofit concepts.

The Bechtel/HNTB team is comprised of:

- Bechtel, an international firm with capabilities in engineering/design, program management, and construction management for transportation projects
- HNTB, a firm with extensive expertise in transit engineering, with particular strength in seismic engineering and Caltrans bridge seismic retrofit
- International Civil Engineering Consultants, Inc. (ICEC), a local consultant with internationally recognized expertise in seismic criteria and analysis
- MGE Engineering, who updated and developed the seismic design criteria, including seismic demands and structural design requirements for the aerial and underground structures for the BART SFO Extension
- Geomatrix Consultants, Inc., providing ground motion and geotechnical expertise
- Other team consultants in various fields of expertise

The Bechtel/HNTB team is augmented by the specialist firms of Structural Earthquake Analysis and Design (SEQAD), and Seismic Systems and Engineering Consultants.

2.1.2 Bechtel/HNTB Design Review Board

The Bechtel/HNTB design review board provided technical oversight. The board includes:

- Professor Ben C. Gerwick, Jr. has 55 years of structural engineering experience, including the original BART system, and has been heavily involved in the seismic retrofit of seven major Bay Area bridges as consultant to Caltrans
- Dr. Joseph Penzien, an internationally recognized expert in earthquake engineering. Dr. Penzien established seismic design criteria for the BART Extensions and founded the University of California, Berkeley's Earthquake Engineering Research Center

- Dr. Bruce Bolt, an internationally known expert in strong motion seismology and dynamics, has 33 years' experience on BART, Caltrans, and other large infrastructure engineering programs
- Dr. Frieder Seible has 20 years of experience in seismic engineering and bridge design, including 16 years experience with Caltrans Seismic retrofitting project
- Dr. Stuart Werner has 35 years of earthquake engineering experience, with specialization in seismic risk analysis for public infrastructure projects
- Matt Hsiao has 40 years of civil/structural engineering experience and comprehensive knowledge of the BART systems. Having served as Chief Structural Engineer for Bay Area Transit Consultants, he is familiar with Caltrans Non-Collapse and BART Serviceability Standards
- Dr. Ignacio Arango, Manager of Geotechnical Engineering for Bechtel Corporation, has 42 years of experience in earthquake engineering studies related to seismic design criteria, soil stability, and liquefaction evaluation
- Dr. Wayne Clough is President of the Georgia Institute of Technology and an internationally renowned authority in geotechnical engineering; his 37 years' experience include both San Francisco Muni Metro and BART projects

2.1.3 G&E Engineering Systems, Inc.

G&E, of Oakland, California, was selected to perform the seismic risk analysis with the use of its System Earthquake Risk Assessment (SERA) software.

G&E is an internationally recognized leading consulting firm in the field of lifeline earthquake engineering. John Eidinger, a principal of G&E, has published more than 40 papers and written two books on the topic. Mr. Eidinger has visited and documented earthquake impacts for numerous lifeline and utility and transportation agency operators that have been affected by great earthquakes, including 1989 Loma Prieta, 1994 Northridge, 1995 Kobe Japan, 1999 Izmit Turkey, 2001 Bhuj India, 2001 Atico Peru, and others. Mr. Eidinger has been chairman of various American Society of Civil Engineers (ASCE) committees, including various subcommittees of the Technical Council on Lifeline Earthquake Engineering.

The SERA program is G&E software, and has been used for evaluations of many types of utilities/transportation networks, including: water systems (East Bay Municipal Utilities District, San Diego Water Department), electric transmission systems (Southern California Edison, Pacific Gas and Electric), and highway bridges (Caltrans).

2.1.4 The Peer Review Panel

The Peer Review Panel, comprised of a distinguished group of specialists in seismology and risk analysis, provided additional review and guidance. The panel is co-chaired by Dr. Jack Moehle, of the University of California at Berkeley Pacific Earthquake Engineering Research Center, and Craig Comartin, S.E., of Comartin-Reis Consultants. They are joined by experts in aerial structures, buildings, and underground structures, including Dr. Roy Imbsen, Dr. Po

Lam, Professor Steve Mahin, Dr. Norm Abrahamson, William Holmes, and Steve Thoman; as well as soils and liquefaction experts to focus on the Transbay Tube, Dr. Edward Idriss of UC Davis and Dr. Jim Mitchell of Virginia Polytechnic.

2.1.5 BART Management

BART management personnel provided leadership and direction. They included:

- BART Seismic Program Manager and staff
- BART Chief Engineer and staff

2.2 METHODOLOGIES EMPLOYED

The methodologies included developing scenario earthquakes, retrofit options, and other key inputs to a System Earthquake Risk Assessment (SERA) computer model; obtaining key SERA model output; and benefit-cost analysis/recommendations. Each of these aspects is summarized in the following subsections.

2.2.1 Scenario Earthquakes and Retrofit Options

All known active and potentially active faults in the Bay Area were examined. From these, four scenario earthquakes were selected for evaluation of the seismic risk analysis of the BART system on the basis that they represent a bounding set of events that could cause the most damage to the BART system.

The four scenario earthquakes selected, their magnitude on the Richter Scale, and their locations are listed in Table 2-1.

Table 2-1
Four Scenario Earthquakes

Earthquake Source	Magnitude (M_w)	Location	Rupture Location
Hayward Fault	7.0	North and South segments	Richmond to Fremont
San Andreas Fault	8.0	North Coast northern and North Coast southern segments	Fort Bragg to the south
Calaveras Fault	6.8	North segment	North segment
Concord Fault	6.8	Through Concord	Concord, South Greenville, North Greenville simultaneously

Retrofit options were defined to represent alternatives available to BART management, and were based on the current state-of-the-art of seismic design. No retrofit has been identified for the Berkeley Hills Tunnel (which crosses the Hayward fault) that would be more cost-effective than repairing the unretrofitted tunnel after an earthquake.

The long-term disruption of service and safety impacts that could occur on the existing system (Status Quo) was found to be unacceptable. Several retrofit options were evaluated to reduce disruption of service and mitigate safety impacts.

The minimum goal of BART's Seismic Retrofit Program is to mitigate safety risks for potential earthquakes. Ground motion prediction is not an exact science and there is a wide range of uncertainty. The general practice is to use higher ground motions (lower probability) and be more conservative in assessing and mitigating safety risks than for operability. However, the level of damage allowed to mitigate safety is greater (generally non-collapse) than for operability (generally limited such that continuous occupancy is not precluded). This common practice was used for the analysis of this study. Several retrofit options were studied including safety retrofits only and four options that gave incremental increases in operability. Two of the five options evaluated are presented in this report. In many cases, safety retrofits will achieve desired operability goals, but not always.

It was found that with a relatively small increment in cost over the safety package, restoration of the critical link between the East Bay and San Francisco to normal service could be achieved relatively quickly. This "Systemwide Safety, Core System Operability" option is one of the two options presented below.

Because the cost differential between increased operability options was relatively small, it was decided to present the option that would allow rapid restoration of all segments of the system. This option is "Systemwide Safety, Systemwide Operability."

The Status Quo and two retrofit options are described as:

- **Status Quo.** The BART system as it is with no retrofits
- **Systemwide Safety, Core System Operability**. Safety retrofits would be made as required throughout the original BART system, particularly the aerial structures and the Transbay Tube, such that the risk of collapse is minimized. Aerial structure retrofits include foundation strengthening, column jacketing, and additional shear keys. In addition, operability retrofits consisting of enlarged footings and possibly additional piles would be made from the west portal of the Berkeley Hills Tunnel through the Daly City Yard (defined as the "Core System") such that retrofitted structures would not experience significant damage in a scenario earthquake and, with some repairs, trains could run within a reasonable period of time after the earthquake. Transbay Tube retrofits would consist of strengthening the seismic joints, stabilizing the tube to resist forces from all directions, and stabilizing the supporting ventilation structures. Retrofit of the Berkeley Hills Tunnel, which sits across the Hayward Fault, has been evaluated as being impractical. The Core System is shown in Figure 2-1.

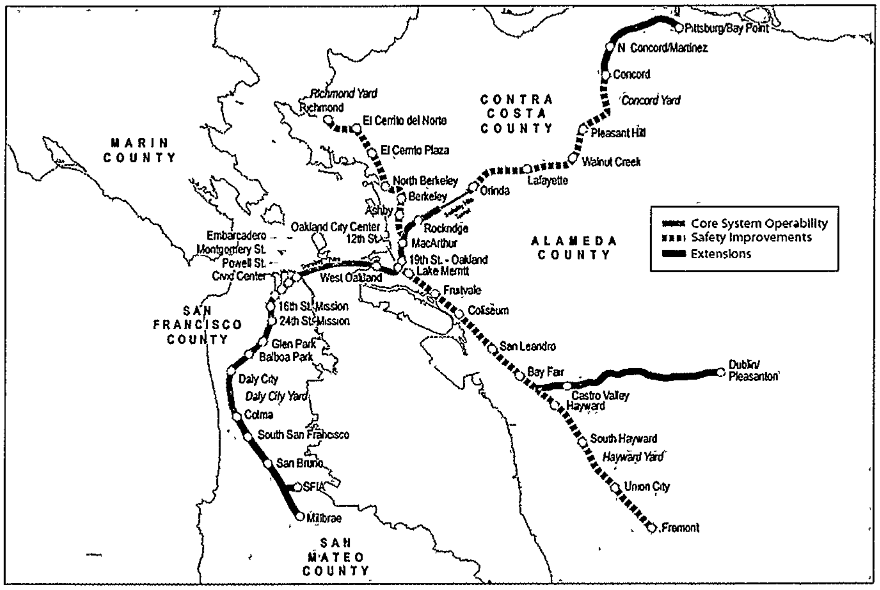


Figure 2-1 Core System Operability

- **Systemwide Safety, Systemwide Operability Option.** This would include all of the retrofits in the previous option, plus operability retrofits (primarily for aerial structures) that would put the entire original system back in operation much sooner than would otherwise be the case. Systemwide Operability is mapped in Figure 2-2.

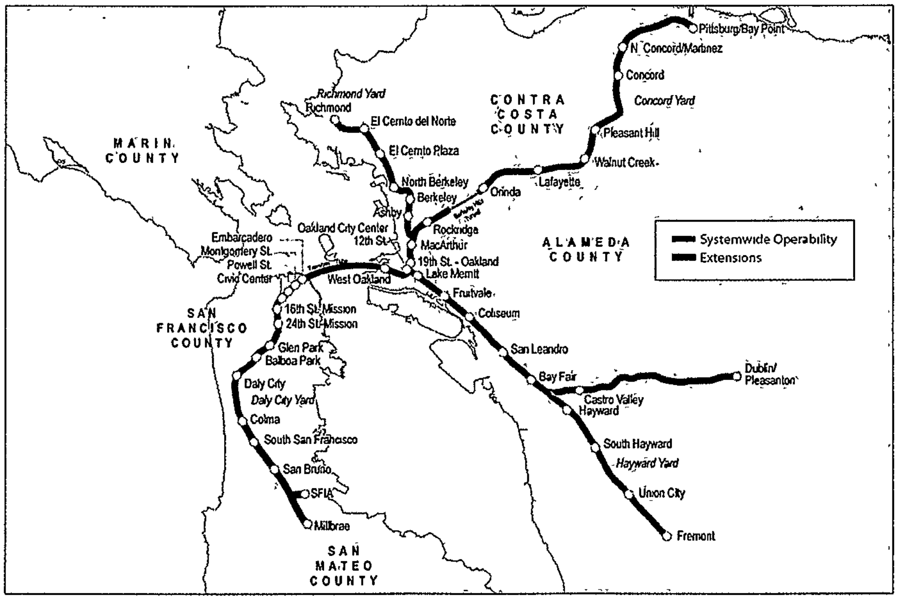


Figure 2-2 Systemwide Operability

2.2.2 Key Inputs to the SERA Model

To perform the seismic risk analysis for the BART system, the SERA software was provided the following key inputs:

- **Geotechnical Models.** The SERA model for the BART system was developed so that each component could be evaluated for the four primary seismic hazards:
  - Ground shaking
  - Surface faulting
  - Liquefaction
  - Landslide

  These models include standard deviations in earthquake forces to reflect uncertainty in the actual intensity of earthquake forces that will be encountered.

- **An inventory of the components of the BART system** that have potential vulnerability in earthquakes, together with the sites at which they are located and the replacement cost of the structures and equipment at the site. The inventory for the BART system comprised 15,078 components at 3,089 sites.
- **Retrofit concepts for each component** appropriate to the retrofit option under study together with cost estimates for the retrofits. The cost estimates for the retrofits are based on engineers' schematic designs converted to labor and material quantities.
- **Fragility models** for each component that define the potential damage states of the item (each component may have several potential damage states, depending on the magnitude and nature of the seismic event) and the seismic levels at which the damage states would occur. The fragility models were based on Bechtel/HNTB team input from the structural analysis described above. Each retrofit concept for each component has a different fragility model. Fragility models include standard deviations to account for uncertainties in structure behaviors.
- **Repair costs and repair durations** for each damage state of each component
  - The cost estimates for repairs are based on estimated percentages of the original cost escalated to 2002 dollars.
  - The repair durations (which determine the period during which portions of the BART system are out of service and ridership is lost) are calculated from the repair costs by assuming an average cost for labor, materials, and equipment of $130 per hour. Then a repair team of 700 people working 40 hours per week is assumed for the Hayward and San Andreas scenario earthquakes and 350 people working 40 hours per week for all other earthquakes (Concord, Calaveras, etc.).
- **Current BART ridership** between various station pairs for both weekend and weekday ridership, used to estimate ridership impacts under the various earthquake scenarios and retrofit assumptions.

- **Factors for estimating cost impacts** of loss of BART services during post-earthquake repairs, including:
  - Average BART trip fare
  - Cost to provide a bus bridge between stations
  - Average commute travel time
  - Economic value of commuter's time per hour
  - Commute cost of using a car
  - Costs of major and minor injuries and deaths and casualty rates for heavy construction using FEMA methods and values

2.2.3 Key SERA Model Output

For each retrofit option, a Monte Carlo simulation using SERA was run 100 times on each of the 15,078 components in the model. Each run varied earthquake forces and component behavior randomly within the standard deviations defined in the SERA input data.. The results are a statistical distribution of outcomes which, for compactness, are described in term of the expected (mean), minimum, maximum, 16th percentile and 84th percentile estimates. For planning purposes, it is reasonable to assume the expected (mean) as the best damage estimate for each retrofit option and scenario earthquake combination, bounded by the 16th (minus one standard deviation) and 84th percentile (plus one standard deviation) estimates (the $\pm$ one standard deviation represents 68 percent probability the event will be included).

The following outputs were generated for each retrofit option:

- **Damage to BART system components**, including a breakdown by functional status immediately after the earthquake in the following categories:
  - *Total loss*. Component has suffered damage leading to complete functional loss. Significant permanent offset/drift has occurred. Collapse is possible.
  - *Part loss*. Component has suffered damage leading to partial functional loss. Trains should be able to traverse the component at slow speed.
  - *Damage, no loss*. Component has suffered damage leading to no functional loss. Trains should be able to traverse the component at regular speeds.
  - *No damage*.
- **Cost and duration to repair** the direct damage to the BART system, both short-term (temporary or emergency) repairs needed to restore all easily-fixed components to some level of (usually full) functionality and long-term repairs to restore the system to its pre-earthquake condition.
- **Link status**, the operability status of each link (segment of the physical infrastructure) in the BART system.

- **Loss of ridership** due to loss of service based on the average damage levels for each link and estimated repair times based on the following service restoration priorities:
  - Lines requiring little repair to get contiguous sections of BART operating quickly
  - The Oakland wye-core center of the system
  - The Transbay Tube
  - The individual lines with significant damage
  - The Berkeley Hills Tunnel
- **Economic impacts** due to loss of service, including:
  - Cost to BART, including loss of fare revenue and cost of providing bus bridges
  - Cost to BART riders, including cost of using automobiles or public transportation plus the economic value of lost time based on methodology used by FEMA and the USDOT
  - Cost to San Francisco Bay Area commuters, including the economic value of lost time for all Bay Area commuters

2.2.4 Benefit-Cost Analysis

The retrofit costs were summarized together with the impacts to ridership and cost impacts to BART, BART riders, and the Bay Area commuters. Retrofit costs were then compared to benefits gained to determine their relative value and implications were drawn to provide guidance for determining the appropriate funding level for the BART Seismic Retrofit Program.

2.2.5 Report Preparation

This Seismic Vulnerability Study report was prepared to summarize an extensive and detailed engineering and statistical analysis, in order to assist BART management and the Board to make policy decisions with respect to determining the appropriate funding level for the BART Seismic Retrofit Program.

Section 3
BART Vulnerability

This section describes the key components of the BART system that determine its response to an earthquake.

3.1 KEY COMPONENTS OF THE BART SYSTEM

The key components of the BART system that determine its response to an earthquake are:

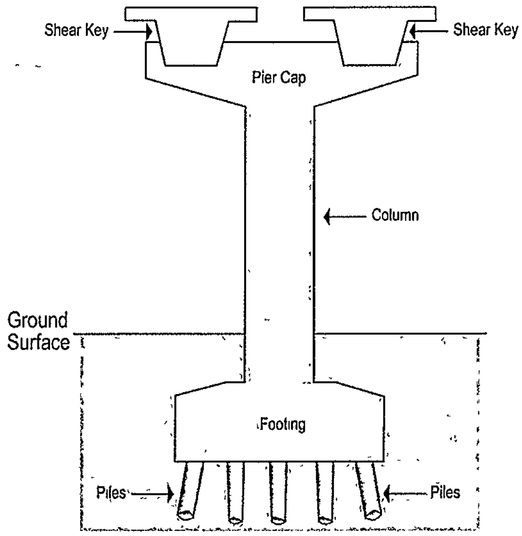
- **Aerial Guideways.** There were 24 miles of aerial (elevated) guideways in the original system; completed extensions brought that figure to 27 miles, and the San Francisco International Airport Extension will add 1.2 miles of aerial wye connector.
- **Passenger Stations**. There were 34 passenger stations in the original system; the extensions brought that figure to 39; and the SFO Extension will add 4 additional stations. There will be 15 aerial (elevated) stations, 12 at-grade stations, and 16 underground. Each station is 680-700 feet long to accommodate trains with up to 10 cars.
- **The Transbay Tube and Ventilation Structures.** The Transbay Tube is 3.6 miles long and lies at the bottom of the San Francisco Bay, at a maximum depth of 132 feet below mean sea level. The tube is constructed of 57 sections with an average section length of 330 feet. A ventilation structure is located at each end of the Transbay Tube – the San Francisco Ventilation Structure and the Oakland Ventilation Structure – and each is connected to the tube by seismic joints.
- **The Berkeley Hills Tunnel**, between Oakland and Orinda, is a 3.2-mile-long twin bore tunnel that crosses the Hayward fault.
- **Yards**. There are four yards (Concord, Daly City, Hayward, and Richmond) where trains are prepared for service, enter and exit for service, are repaired, and are stored.
- **Buildings**. There are four administrative buildings and three shops in downtown Oakland; and there are seven parking structures.

3.2 POTENTIAL EARTHQUAKE DAMAGE

Detailed structural engineering analyses by the Bechtel/HNTB team determined the damage states of the key structural elements of the BART system when subjected to earthquake forces and the seismic levels at which the damage states would be expected to occur. Some of the types of damage have the potential for severe or catastrophic consequences, but, for various reasons, the most likely consequence is a temporary reduction in functionality until repairs can be made. The potential consequences are more relevant when considering safety; the most likely consequences are more relevant when considering the impact on the operability of the system. The following paragraphs summarize the kinds of damage that could be expected.

3.2.1 Aerial Guideways

The 27 miles of aerial track are installed on guideways that are supported by columns. Depending on the severity of earthquake motions and the design of the column, an aerial column bent may suffer several damage states, including:



- Shear key failure, where the shear key attaching the girders to the column breaks, leaving the girders free to slide about on their seats. This has the potential of allowing the girders to fall off the columns; however, due to rail connectivity, the most likely result is lateral displacement of the girders, permitting trains to traverse the location at slow speeds.
- Pier cap damage, where the hammerhead beam at the top of the columns is damaged, would severely affect functionality.
- Column hinging, or permanent bending, where the column would retain limited functionality, permitting trains to traverse the location at slow speeds.
- Column shear failure, a brittle type of failure that has the potential for causing collapse of the bent, but most likely, the foundation will rock, preventing this type of failure.
- Various foundation (footings or piles) failures, which have the potential for collapse of the bent when analyzed using computer models. However, such failures have not been verified by past earthquake damage investigations, and the extent of actual damage is uncertain; less extensive damage states would result in limited operability so that trains could traverse a damage location at slow speeds.

Abutments, at each end of an aerial guideway, could have the following types of damage:

- Shear key failure, similar to that at columns.
- Pile failure and soil movements, associated with large displacements of the abutments, resulting in some loss of functionality until temporary shoring or repairs can be made, depending on the severity of the damage.

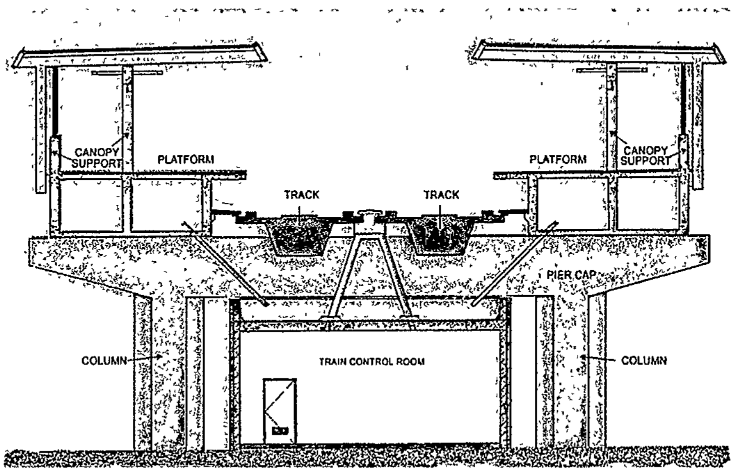
3.2.2 Stations

There are 14 aerial stations, 6 at-grade stations, and 14 underground stations in the original BART system. Each is discussed briefly in the following subsections.

3.2.2.1 Aerial Stations

Aerial stations' construction is similar to the aerial guideways, and they are expected to have similar types of damage. In addition, the aerial stations could have:

- Damage to the canopies
- Damage to the stairways and elevator shafts



3.2.2.2 At-Grade Stations

The at-grade stations could have the following types of damage:

- Sliding and dislocation of the foundations and failure of piles, resulting in partial or complete loss of operability, depending on the severity of damage
- Damage to various walls, columns, shear keys, canopies and entry structures

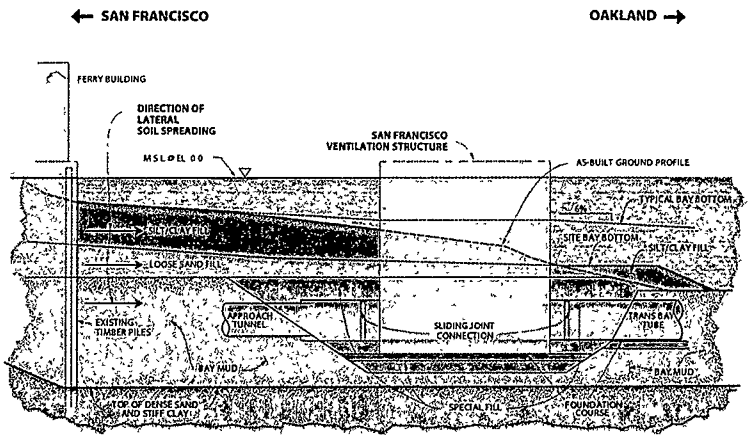
3.2.2.3 Underground Stations

In general, the long box-shape reinforced concrete shells of the underground stations are expected to undergo racking deformation during a major earthquake and sustain cracking and other forms of damage that will require minor repairs in the post-earthquake period. Some of the stations might undergo racking deformations sufficient to cause moderate damage to columns and walls.

Vertical earthquake motions could cause overstress in roof members supporting the overlying soil, but in most cases, the damage is likely to have little impact on operations. In some cases the overstress would have the potential of more severe damage and permanent deformation.

3.2.3 Transbay Tube and Ventilation Structures

The Transbay Tube is a critical link in the BART system. Satisfactory seismic performance during any future strong earthquake in the Bay Area is critical for BART to provide an adequate level of post-earthquake transportation service to the public. Furthermore, since the tube is submerged, any potential structural deficiency in it or its associated ventilation structures and seismic joints might threaten the safety of BART personnel and passengers.



SECTION OF THE SAN FRANCISCO VENTILATION STRUCTURE AND THE TUBE
LATERAL SOIL SPREADING VULNERABILITY

FIGURE 3

The overall BART system and, especially, the Transbay Tube, ventilation structures, and seismic joints performed well in the 1989 Loma Prieta earthquake. No structural damage was observed in these structures. However, the ground-shaking intensity in the Bay Area during Loma Prieta was relatively low, and the scenario earthquakes will produce much stronger ground-shaking intensity. The failure modes determined are as follows:

- The backfill surrounding the tube is prone to the phenomenon of liquefaction. The consequence of liquefaction for the tube is uncertain. Assuming a worst case combination of events, liquefaction could cause the tube to move resulting in excessive movement of the seismic joints and structural stress along the tube itself that could cause the tube to fail. However, due to the mix of different soils used to backfill the tube and changes of the past 30 years from sediment, it is impossible to definitively predict how these soils will react from the pressures developed through liquefaction. If the hydraulic pressure were to be relieved through the backfill, no damage to the tube would result. The uncertainty of the consequences and the criticality of the tube, requires that the worst case scenario be considered for this Vulnerability Study.
- Poor soil conditions adjacent to the Tube and its associated structures could result in excessive Tube movement at the seismic joints, possibly resulting in failure, or damage to the associated ventilation structures.

Any of these would cause a complete shutdown of the tube.

3.2.4 Berkeley Hills Tunnel

The Berkeley Hills Tunnel consists of two circular bored tunnels that pass through the Hayward Fault, and any significant rupture of the fault at this location would cause a large offset in the tunnels, resulting in serious damage to the tunnel and closure for an extended period.

3.2.5 Underground Structures and Retaining Walls

There are 21 miles of underground track in the current system, and all 21 miles are part of the original system (the SFO extension will add 6 miles of underground track). Underground structures discussed below include cut-and-cover tunnels, retaining walls, and bored tunnels.

3.2.5.1 Cut-and-Cover Tunnels

Lateral racking of the cut-and-cover tunnels is expected to cause minor damage to the walls in the form of spalling and cracking of concrete, but this is unlikely to impact operation of the system.

3.2.5.2 Retaining Walls

Some cantilever retaining walls could shift, tilt, or have structural wall damage, especially walls with sloping backfills. If the damage is severe, it could affect operations. The U-walls are expected to have only minor damage.

3.2.5.3 Bored Tunnels

The bored tunnels are typically twin circular cross-sections that are lined with steel ring liners on their inside faces. The ring liners consist typically of longitudinally segmented steel rings, which are bolted together longitudinally by high-strength bolts at their ring joints.

The structural analyses have indicated that none of the scenario earthquakes is expected to result in severe structural damage to BART's bored tunnels, with the exception of the Berkeley Hills Tunnel (discussed above). Minor damage to the tunnel liners may occur.

3.2.6 Operating Systems, Equipment, and Components

BART's operating systems, equipment, and components could be damaged where there is insufficient lateral bracing or anchorage. Heavier electrical equipment that is poorly anchored is likely to slide and possibly break connections, whereas the more fragile contents of tall cabinets that topple may be seriously damaged. The impact on operations varies, depending on the severity of the damage, the importance of the equipment, and how quickly repairs can be made.

3.2.7 Buildings at Yards, Parking Structures, and Other Sites

Buildings at the yards generally consist of steel frame structures of various sizes, ranging from small light shelters to large shop buildings; there are also some buildings constructed of other materials. In general, the older and larger yard buildings could be extensively damaged, possibly resulting in loss of use until shoring or repairs are made. The smaller and lighter buildings may be damaged, but are less likely to significantly impact operations.

Damage to parking structures is expected to vary from slight to extensive, depending on the age, type of construction, and proximity to the fault. Some of the parking structures are likely to be unusable, possibly permanently, and at least temporarily unusable until inspection, shoring, or repairs can be made.

Other buildings in the Oakland area include administrative and storage buildings of various types. In general, the older buildings are likely to suffer extensive damage and may be unusable, and in some cases may have potential for collapse. Other minor buildings throughout the system include substation and train control shelters. Damage to the minor buildings is expected to be slight and have little impact on operation of the system.

3.2.8 At-Grade Track and Embankments

There are 27 miles of at-grade track in the original system; the extensions brought the total to 47 miles at-grade; and the SFO Extension will add another 1.5 miles. At-grade track is vulnerable to settlement of supporting fills and embankments. The amount of settlement varies, depending on the soil type, embankment height, and proximity to the fault. In some cases, the settlement is expected to result in slow-speed train operation until the track is re-aligned and re-ballasted.

At one location, adjacent to gravel pits in Fremont, there is a potential for slope stability failure of the embankment supporting the track due to potential liquefaction, which could result in complete loss of this portion of track.

Section 4
Status Quo

As described in Section 2 of this report, the System Earthquake Risk Assessment (SERA) model evaluated the effect of 100 probable motions from each of four scenario earthquakes on each of 15,078 components of the BART system, for each retrofit option for the BART system. This produced over 6 million (100x4x15,078) outcomes for each retrofit option for the BART system. This section discusses the results of the analysis of the BART system in its "as-is" Status Quo condition. The discussion encompasses potential earthquake damage, cost to repair, safety loss impacts, service impacts, and cost of lost service.

4.1 POTENTIAL EARTHQUAKE DAMAGE

The primary damage from a major earthquake would be to the aerial structures (columns and bents and passenger stations), the Transbay Tube, the Berkeley Hills Tunnel, and the administrative buildings. The damage estimates produced by the SERA model are discussed below.

4.1.1 Aerial Structures

Significant damage could occur to the aerial structures (both guideways and stations) in the event of a major earthquake such as a Hayward 7.0. The other scenario earthquakes would produce lower, but still significant, levels of damage, as indicated in Table 4-1.

Potential damage to the 1,983 aerial columns and bents in the SERA model has been categorized as non-functional and partly functional damage states:

- **Non-Functional.** The column or bent suffers some permanent offset, and some may suffer partial or complete collapse. Refer to Section 3.2.1 for further discussion of potential aerial guideway damage.
- **Partly Functional.** The structure has suffered some damage which could result in some permanent offset at the track level, usually under 3 inches; and that once temporary repairs (shoring, etc.) are complete, the structure can be returned to service for normal train operations pending permanent repairs to the structure.

Table 4-1
Potential Damage – Aerial Columns and Bents

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Non-Functional after Earthquake (Major Damage)				
Average	252	66	34	31
Range*	131-372	22-109	1-66	5-56
Partly Functional after Earthquake (Minor Damage)				
Average	57	16	4	12
Range*	6-106	1-30	0-10	0-24

*Average +/- one Standard Deviation

The SERA model also indicates that, depending on the location and strength of the earthquake, as many as 10 of the 15 aerial passenger stations have at least a 15 percent chance of sustaining either total loss or partial loss of functionality, defined as:

- **Total Loss**. The station is not functional for normal train operations immediately after the earthquake, and long-term repairs are required before restoring the station to service. For aerial stations, the most likely cause of the damage is major permanent offset of one or more columns/bents.
- **Partial Loss**. The station is not functional for normal train operations immediately after the earthquake, and only temporary repairs are required before restoring the station to service. For aerial stations, the most likely cause of the damage is minor permanent offset of one or more columns/bents.

4.1.2 Transbay Tube

Under the Hayward and San Andreas scenario earthquakes the Transbay Tube would probably be closed for major repairs.

4.1.3 Berkeley Hills Tunnel

A major earthquake on the Hayward fault would probably close the Berkeley Hills Tunnel for major repairs.

4.1.4 Buildings

Table 4-2 indicates the numbers of buildings predicted to be damaged such that they would require replacement or significant structural repair before being returned to service as a result of being in complete damage or extensive damage states.

- **Complete Damage State (Red Tag).** The building has suffered significant permanent offsets and may have potential for partial or total collapse. It is assumed that buildings in the complete damage state "red-tagged" will be demolished.
- **Extensive Damage State (Yellow Tag).** The cost to repair these buildings will usually be high enough (over 50 percent of the replacement value) that the decision will be made to tear down and rebuild the "yellow-tagged" building.

Table 4-2
Potential Damage – Occupied Buildings

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Complete Damage State (Red Tag) after Earthquake				
Average	1	0	0	0
Range*	0-2	0-1	0	0
Extensive Damage State (Yellow Tag) after Earthquake				
Average	6	3	1	2
Range*	3-8	1-4	0-2	0-4

*Average +/- one Standard Deviation

4.1.5 Other Component Damage

In addition to the major damage to the structures described above, the SERA model also predicts damage in varying degrees to:

- Track sections
- Embankment sections
- At-grade and underground passenger stations
- Non-occupied buildings
- Various kinds of equipment (substations, ventilation equipment, etc.), some of which can cause functional outages to train operations

4.2 COST TO REPAIR

Repair costs are categorized as short-term and long-term, and both the average repair cost and a range of repair costs are presented for each, following the four scenario earthquakes, in Table 4-3. Short-term and long-term are defined as:

- **Short-term** repair costs include the temporary repairs to restore full operability where feasible, as well as debris removal, etc.
- **Long-term** repair costs include the costs to repair the BART system to its pre-earthquake condition.

Table 4-3
Repair Costs – Short-Term and Long-Term
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Short Term Repair Costs				
Average	22	8.5	4.7	6.0
Range*	12-31	3.3-14	0.6-8.7	1.1-11
Long Term Repair Costs				
Average	1,076	852	258	247
Range*	696-1,457	538-1,166	70-446	71-423

*Average +/- one Standard Deviation

The distribution of long-term repair costs among the key components of the BART system is shown in Table 4-4. The major costs would be for repairs to the aerial guideways and stations, the Transbay Tube, the Berkeley Hills Tunnel, and the buildings.

Table 4-4
Average Long-Term Repair Costs for Key Components
(2002 dollars, in millions)

Component Type	Hayward M 7	SanAndreas M 8	Calaveras M 6.8	Concord M 6.8
Aerials	250	70	67	89
Tunnels (inc. Transbay Tube)	557	585	112	70
Stations	164	144	49	51
Buildings	96	51	30	36
Track, Embankments, Retaining Walls	8	0.8	0.7	0.5
Equipment	1.7	0.5	0.1	0.4

4.3 SAFETY PERFORMANCE

With no retrofit, many sites are expected to be in a complete damage state after any of the scenario earthquakes, which means that there is a significant chance of causing minor or major injury or a moderate chance of causing fatality. The structures have been placed in this category because of advancements in seismology and structural analysis since the original BART system was designed. Table 4-5 indicates the number of sites expected to be in the complete damage state after an earthquake.

Table 4-5
Sites in Complete Damage State after a Major Earthquake

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Average	286	111	39	32
Range*	158-413	54-167	2-75	5-58

*Average +/- one Standard Deviation

Table 4-6 indicates the monetized value of the statistical casualties, using current FEMA values for the statistical values of human life: $2,710,000, $15,600, and $1,560 for deaths, major injuries, and minor injuries, respectively. For each scenario earthquake, the fraction of the BART system posing a significant safety risk was calculated as the fraction of BART components in the complete damage state. Average occupancy of BART was calculated from daily ridership, assuming that the average passenger spends 30 minutes in the BART system per ride, and for BART employees, assuming each employee spends an average of 9 hours per day in the BART system. Casualty rates for the fraction of occupants affected by complete damage state were taken from FEMA values for heavy construction in the complete damage state: 0.2, 0.4, and 0.4 for deaths, major injuries and minor injuries, respectively.

Table 4-6
Monetized Value of Statistical Casualties
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Monetized Statistical Casualties	296.6	115.1	40.4	33.2

4.4 SERVICE IMPACTS

With no retrofit, the damage that would be sustained from any of the scenario earthquakes would interrupt BART service for some time. Estimates of the duration of service interruption and the consequent loss of ridership are presented below.

Table 4-7 lists the number of days after the earthquake required to restore 100% of pre-earthquake passenger service at two levels of completion:

- Except through the Transbay Tube and the Berkeley Hills Tunnel
- The entire BART system (including Transbay Tube and Berkeley Hills Tunnel)

Table 4-7
Days to Restore Service to 100% of Pre-Earthquake Levels

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Except through the Transbay Tube and the Berkeley Hills Tunnel				
Average	601	267	236	262
Range*	281-921	10-545	33-438	75-449
Median Motions**	484	133	250	334
Including through Transbay Tube and Berkeley Hills Tunnel				
Average	894	754	503	408
Range*	746-1041	644-863	193-814	118-697
Median Motions**	842	732	252	335

*Average +/- one Standard Deviation

**Results for median ground motions throughout the BART system. Used to plot the service restoration curves. Note that the average restoration times are significantly greater than the restoration times for median motions, since the uncertainty in the ground motions models can occasionally cause significantly higher ground motions that have a disproportionately higher impact on restoration time.

Figure 4-1 shows a graph of the service restoration times for the Status Quo Option, derived from the simulation of the Hayward 7.0 scenario earthquake for median ground motions throughout the BART system.

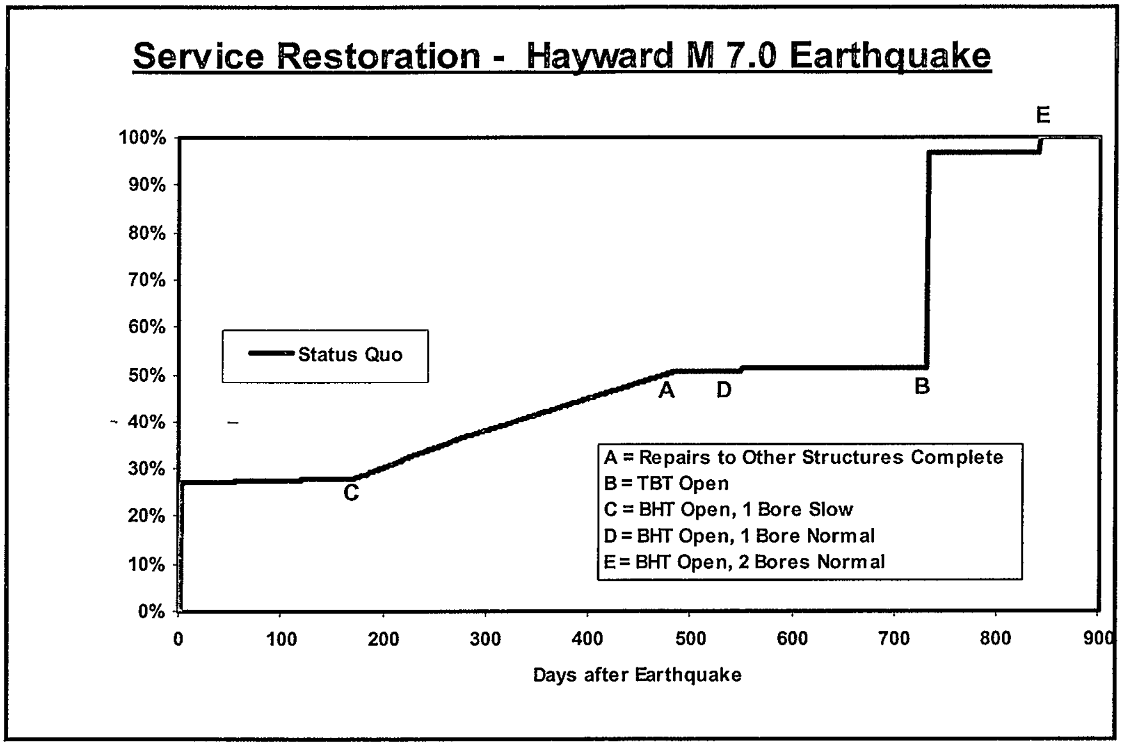


Figure 4-1 Service Restoration Curve – Status Quo Option

Table 4-8 indicates the number of passenger trips lost to the BART system due to each of the scenario earthquakes, based on a daily average of about 250,000 trips.

Table 4-8
Passenger Trips Lost
(millions of one-way trips)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Average	82	77	46	30
Range*	68-97	60-95	13-79	0-63

*Average +/- one Standard Deviation

4.5 COST OF LOST SERVICE

The cost of temporary loss of BART service – while the BART system is being put back into operation after an earthquake – is analyzed from three perspectives: costs to BART, to BART riders, and to Bay Area commuters.

4.5.1 BART Perspective

This analysis assumes that, if BART links are closed but replaced with temporary bus bridges:

- 75% of BART riders will leave BART and 25% will use BART-supplied bus bridges.
- The average BART revenue per one-way trip is $2.15 per trip.
- The cost to BART for supplying the bus bridges is based on rental of suitable 45- to 50 passenger buses at a going rate of $400 per four-hour block, or about $100 per hour (inclusive of labor, equipment and operating costs); and the buses will be deployed in such a manner so as to average 65 passengers carried per hour.

The results of this analysis are summarized in Table 4-9.

Table 4-9
Cost of Lost Service to BART
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
BART Revenue Loss	177	166	99	65
BART Bus Bridge Cost	42	40	23	16
Total	219	206	122	81

4.5.1 BART Rider Perspective

This analysis assumes, with loss of BART service, that:

- 80% of displaced BART riders will use vehicles in lieu of BART, at average additional costs (use of vehicle, tolls, parking) of $15 to $20 per day. These extra transportation costs range from $12 to $16 per day per displaced BART rider.
- Other displaced riders may use other public transit or telecommute. For computational purposes, we use an average value of $14.00 per day per displaced BART rider.
- Following the methodology used by FEMA and the USDOT to estimate the economic value of people's time (whether remunerative or leisure), we use the Bay Area average value for wages and benefits of $32.20 per hour.

The results of this analysis are summarized in Table 4-10.

Table 4-10
Cost of Lost Service to BART Riders
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Extra Transportation Costs	577	542	322	212
Value of Lost Time	1,326	1,247	739	488
Total	1,903	1,789	1,061	700

4.5.1 Bay Area Commuter Perspective

Loss of BART service will impact commuters throughout the San Francisco Bay area because of added congestion and additional travel times on local highways. As a rough estimate, this analysis assumes that the magnitude of these economic impacts is similar to the economic value of lost time for BART riders. The results of the analysis are summarized in Table 4-11.

Table 4-11
Cost of Lost Service to Bay Area Commuters
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Total Cost of Lost Service	1,326	1,247	739	488

Section 5
Systemwide Safety,
Core System Operability Option

A minimal retrofit option was developed that would improve safety performance throughout the BART system and provide a rapid return to service for the core of the system through its most heavily used corridor. This section describes the Core Operability, Systemwide Safety retrofit, and discusses the System Earthquake Risk Assessment (SERA) model evaluation of it in terms of the physical damage, cost to repair, safety performance, and service impacts under the scenario earthquakes. For each aspect, comparisons are made to the Status Quo discussed in Section 4.

5.1 RETROFITS

Under the Systemwide Safety, Core System Operability retrofit safety retrofits would be made as required throughout the original BART system, particularly the aerial structures and the Transbay Tube, such that the risk of collapse is minimized. (Retrofit of the Berkeley Hills Tunnel, which sits across the Hayward Fault, has been evaluated as being impractical.) Operability retrofits would be made from the west portal of the Berkeley Hills Tunnel through the Daly City Yard (defined as the "Core System") such that retrofitted structures would not experience significant damage in a scenario earthquake and, with some repairs, trains could run within a reasonable period after the earthquake. Transbay Tube retrofits would consist of strengthening the seismic joints, stabilizing the tube to resist forces from all directions, and stabilizing the supporting ventilation structures.

5.1.1 Safety Retrofits (Systemwide)

Some of the key elements and potential retrofit strategies for the safety retrofits are:

- **Aerial Guideways.** Add reinforced concrete overlays on the footings, shear key/catcher blocks at girder seats, and partial height column casings. Add infill walls at multi-column bents.
- **Aerial Stations.** Add reinforced concrete overlays on the footings, shear key/catcher blocks at girder seats, and column casings.
- **Transbay Tube (including the ventilation structures).** Add micropile tiedowns in tube, and large diameter stitch piles near ends of tube. Add tunnel liner sleeve at sliding joint on San Francisco side. Add array of large diameter piles at San Francisco shoreline, and large diameter piles and collar around vent structure. Improve steel columns and bracing in Oakland vent structure.
- **At-grade Stations.** Install miscellaneous safety retrofits to entry and concourse structures.
- **Underground Stations.** Strengthen various columns, walls and roof members at Ashby, Civic Center, and Lake Merritt stations.
- **Buildings.** Improve bracing and connections of the larger yard buildings, improve lateral systems at five of the seven parking structures, and various retrofits at the administrative and other buildings to improve safety.

5.1.2 Additional Operability Retrofits (Core System Only)

In addition to the systemwide safety retrofits, there would be enhanced retrofits for BART from the West Portal of the Berkeley Hills Tunnel through the Daly City Yard.

Key elements are:

- **Aerial Guideways.** Enlarge footings, adding piles only where soil is poor or special conditions require more piles.
- **Aerial Stations.** Enlarge footings, add piles or grade beams where required, and improve stairways and canopies.
- **At-Grade Stations.** Add foundation and wall retrofits, including piles.
- **Buildings.** Provide a higher level of upgrade for the Lake Merritt Administration Building.
- **Systems and Equipment.** Improve anchorage and bracing of all poorly secured equipment that is required for operation of the system.

The estimated cost for the Systemwide Safety, Core System Operability Option retrofit is summarized in Table 5-1.

Table 5-1
Systemwide Safety, Core System Operability Retrofit Cost Estimate
(2002 dollars, in millions)*

Description	Estimated Cost
Aerial Guideways and Stations	491
Transbay Tube and Vent Structures	251
At Grade and Underground Stations	43
Administrative and Other Buildings	38
Systems and Equipment	4
Total	827

*Excludes escalation and finance costs

5.1.3 Emergency Response Plan

BART response after a major earthquake is critical to returning key components of the system to service, which will require pre-earthquake planning to be successful. As part of the Systemwide Safety, Core System Operability option, BART will develop an Emergency Response Plan that includes the following:

- Temporary repair strategies for aerial structures, including recommendations for materials and special equipment to be on-hand.
- Develop repair and reconstruction strategy for the Berkeley Hills Tunnel that will include operational plans for temporary bus bridge and single tracking during reconstruction. Plan will explore the feasibility of pre-arranged contracts with experienced tunnel constructors to expedite mobilization for repairs.

- Determine revenue vehicle repair strategies for potential shop closures due to excessive damage to one or more shops.
- Develop operational plans based upon various damage scenarios, including staffing requirements. Plan will address the level of bus bridge support for each scenario.
- Plan will develop both capital and operating cost funding needs for the period immediately post earthquake through total recovery.

5.2 POTENTIAL EARTHQUAKE DAMAGE

After the retrofit described above, there would still be significant damage from a major earthquake to aerial structures outside the core system, the Berkeley Hills Tunnel and some buildings, as discussed below.

5.2.1 Aerial Structures

As indicated in Table 5-2, significant damage could occur to the aerial columns and bents in the event of a major earthquake, such as a Hayward 7.0. However, the Systemwide Safety, Core System Operability Option would improve the safety performance systemwide and would reduce the number of columns with major damage from 252 forecast without retrofit to 81. The other scenario earthquakes now produce quite low levels of damage.

Table 5-2
Potential Damage – Aerial Columns and Bents

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Non-Functional after Earthquake (Major Damage)				
Average	81	2	4	7
Range*	11-150	0-7	0-10	0-17
Partly Functional after Earthquake (Minor Damage)				
Average	20	9	1	8
Range*	2-40	0-20	0-3	0-18

*Average +/- one Standard Deviation

The SERA model also predicts that the number of aerial passenger stations with a 15 percent or better chance of sustaining either total loss or partial loss of functionality is reduced from 10 stations under the Status Quo to 3 stations by the Systemwide Safety, Core System Operability retrofit. None of the aerial stations have over a 50 percent chance of entering a major damage or minor damage state.

5.2.2 Transbay Tube

Under all four scenario earthquakes, the Transbay Tube would probably not be closed for major repairs if retrofitted.

5.2.3 Berkeley Hills Tunnel

A major earthquake on the Hayward fault would probably close the Berkeley Hills Tunnel for major repairs, as no retrofit is provided.

5.2.4 Buildings

The proposed retrofit reduces the likelihood of any occupied buildings being in a complete damage state "Red Tag status" to practically nil, and only a few might sustain excessive damage "Yellow Tag status".

5.2.5 Other Component Damage

In addition to the reduction in major damage to the structures described above, the SERA model also predicts reductions in the likelihood of damage in:

- Track sections
- Embankment sections
- At-grade and underground passenger stations
- Non-occupied buildings
- Equipment (substations, ventilation equipment, etc.)

5.3 COST TO REPAIR

The estimated short-term and long-term repair costs for the retrofitted BART system are indicated in Table 5-3. The average cost of short-term repairs for the worst-case Hayward 7.0 earthquake is estimated to be $18 million, significantly less than the $22 million for the Status Quo. More dramatically, the average long-term repair cost has been reduced to about $290 million compared with more than $1 billion expected under the Status Quo. The repair cost estimates for the other scenario earthquakes have been similarly reduced.

Table 5-3
Repair Costs
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Short-Term Repair Costs				
Average	18	5	4	5
Range*	8-24	1-8	0-7	0-9
Long-Term Repair Costs				
Average	292	158	72	94
Range*	142-441	14-303	24-118	31-157

*Average +/- one Standard Deviation

The distribution of long-term repair costs among the key components of the BART system are shown in Table 5-4. The major costs would be for repairs to the aerial guideways, stations, buildings, and the Berkeley Hills Tunnel. The substantial cost of repairing the Transbay Tube has been eliminated, and the cost of repairing the aerial structures has been dramatically reduced. The damage to equipment has been virtually eliminated.

Table 5-4
Average Long Term Repair Costs for Key Components
(2002 dollars, millions)

Component Type	Hayward M 7	SanAndreas M 8	Calaveras M 6.8	Concord M 6.8
Aerials	86	8.8	13	27
Tunnels	39	7.8	0.3	0.1
Stations	100	104	36	37
Buildings	61.2	36.9	21.3	30.2
Track, Embankments, Retaining Walls	7.7	0.8	0.7	0.5
Equipment	0.0	0.0	0.0	0.0

5.4 SAFETY PERFORMANCE

Table 5-5 indicates that only a minimal number of sites might be in a complete damage state that would threaten injury or fatality. The estimated five sites in complete damage state for the BART system after the Hayward 7.0 scenario earthquake with the Systemwide Safety, Core System Operability retrofit is a dramatic reduction from the 295 predicted under the Status Quo.

Table 5-5
Sites in Complete Damage State after a Major Earthquake

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Average	5	2	0	1
Range*	1-9	0-6	0-0	0-4

*Average +/- one Standard Deviation

Table 5-6 indicates that the monetized value of the statistical casualties for the Hayward 7.0 scenario earthquake has been dramatically reduced to $5.2 million from the $297 million predicted for the unretrofitted BART system (Status Quo).

Table 5-6
Monetized Value of Statistical Casualties
(2002 dollars, millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Monetized Statistical Casualties	5.2	2.1	0.0	1.0

5.5 SERVICE IMPACTS

The interruption to BART service, with the Systemwide Safety, Core System Operability retrofit, would be significantly less than for the unretrofitted system. The average expected time to fully recover BART service from the Hayward 7.0 earthquake, except for service through the Berkeley Hills Tunnel, has been reduced to 207 days (7 months) from 601 days (20 months). The range of estimates has been reduced from 281 to 921 days (9 to 31 months) to 24 to 390 days (1 to 13 months).

Table 5-7
Days to Restore Service to 100% of Pre-Earthquake Levels

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Except through the Berkeley Hills Tunnel				
Average	207	112	36	67
Range*	24-390	0-339	1-95	3-164
Median Motions**	47	3	10	16
Including through the Berkeley Hills Tunnel				
Average	843	146	38	68
Range*	836-849	2-413	1-100	3-165
Median Motions**	842	3	10	16

*Average +/- one Standard Deviation

**Results for median ground motions throughout the BART system. Used to plot the service restoration curves. Note that the average restoration times are significantly greater than the restoration times for median motions, since the uncertainty in the ground motions models can occasionally cause significantly higher ground motions that have a disproportionately higher impact on restoration time.

Figure 5-1, below, shows a graph of the service restoration times for the Systemwide Safety, Core System Operability Option compared to the Status Quo, derived from the simulation of the Hayward 7.0 scenario earthquake for median ground motions throughout the BART system.

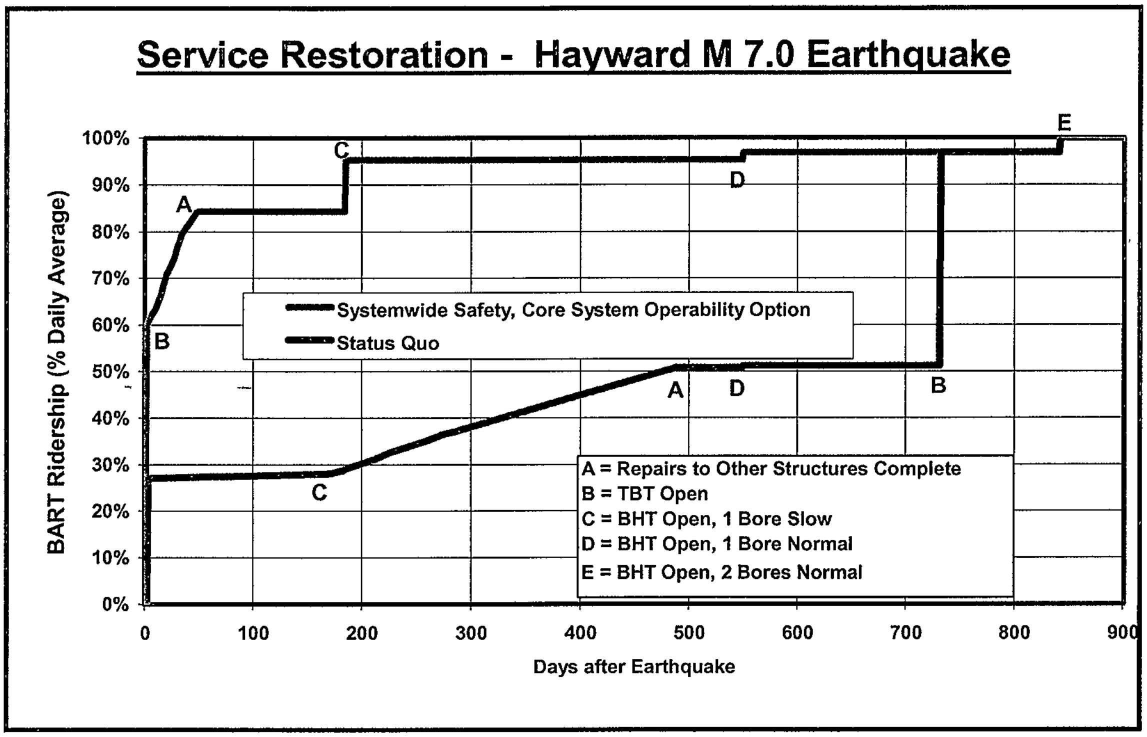


Figure 5-1
Service Restoration Curve – Systemwide Safety, Core System Operability Option

Table 5-8 indicates the number of passenger trips lost to BART due to each of the scenario earthquakes, out of a daily average of about 250,000 trips. The average trips lost of less than 1 million to 21 million is a significant reduction from the average trips lost of 30 to 82 million forecast for the unretrofitted BART system.

Table 5-8
Passenger Trips Lost
(millions of one-way trips)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Average	21	12	0.6	1.1
Range*	4-39	0-35	0-1.8	1-2.8

*Average +/- one Standard Deviation

5.6 COST OF LOST SERVICE

The following subsections describe the impact of the Systemwide Safety, Core System Operability retrofit on the cost of temporary loss of BART service (while the BART system is being put back into operation after an earthquake) from the perspectives of costs to BART, to BART riders, and to Bay Area commuters.

5.6.1 BART Perspective

The cost of lost service from BART's perspective is summarized in Table 5-9. The analysis indicates that, with the Systemwide Safety, Core System Operability retrofit this cost has been reduced to $56 million from the $219 million estimated without retrofit.

Table 5-9
Cost of Lost Service to BART
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
BART Revenue Loss	46	25	1.3	2
BART Bus Bridge Cost	11	6	0.3	1
Total	56	31	2	3

5.6.2 BART Rider Perspective

The cost of lost service from the BART riders' perspective is summarized in Table 5-10. For the Hayward 7.0 scenario earthquake, the cost is only $489 million, compared to almost $2 billion without retrofit.

Table 5-10
Cost of Lost Service to BART Riders
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Extra Transportation Costs	148	82	4	8
Value of Lost Time	341	189	10	17
Total	489	271	14	25

5.6.3 Bay Area Commuter Perspective

The cost of lost service from the Bay Area commuter perspective is summarized in Table 5-11. For the Hayward 7.0 scenario earthquake, the cost has been reduced to $341 million, compared to $1.3 billion for the unretrofitted BART system.

Table 5-11
Cost of Lost Service to Bay Area Commuters
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Total	341	189	10	17

Section 6
Systemwide Safety, Systemwide Operability Option

A retrofit option was developed that would provide a rapid return to service throughout the BART system with the exception of the Berkeley Hills Tunnel, for which an economically feasible retrofit has not been found. This section describes the Systemwide Safety, Systemwide Operability Option retrofit, and discusses the System Earthquake Risk Asessment (SERA) model evaluation of it in terms of the physical damage, cost to repair, safety performance, and service impacts under the scenario earthquakes. For each aspect, comparisons are made to the Systemwide Safety, Core System Operability Option discussed in Section 5.

6.1 RETROFITS

The Systemwide Safety, Systemwide Operability Option includes all of the retrofits in the Systemwide Safety, Core System Operability, plus operability retrofits (primarily for aerial structures) that would put the entire original system back in operation much sooner than would otherwise be the case.

Some of the key elements and potential retrofit strategies for the Systemwide Safety, Systemwide Operability retrofit are:

- **Aerial Guideways.** Enlarge footings, adding piles only where soil is poor or special conditions require more piles, shear key/catcher blocks at girder seats, and column casings. Add infill walls at multi-column bents.
- **Aerial Stations.** Enlarge footings, add piles or grade beams where required, shear key/catcher blocks at girder seats, column casings, and improve stairways and canopies
- **Transbay Tube (including the ventilation structures).** Add micropile tiedowns in tube, and large-diameter stitch piles near ends of the tube. Add tunnel liner sleeve at sliding joint. Add array of large-diameter piles at San Francisco shoreline, and large-diameter piles and collar around vent structure. Improve steel columns and bracing in Oakland vent structure.
- **At-Grade Stations.** Add foundation and wall retrofits, including piles. Install miscellaneous minor safety retrofits to entry and concourse structures.
- **Underground Stations.** Strengthen various columns, walls and roof members at Ashby, Civic Center, and Lake Merritt stations.
- **Buildings.** Improve bracing and connections of the larger yard buildings, improve lateral systems at five of the seven parking structures, and various retrofits at the administrative and other buildings.
- **Systems and Equipment.** Improve anchorage and bracing of all poorly secured equipment that is required for operation of the system.

The estimated cost for the Systemwide Safety, Systemwide Operability retrofit is summarized in Table 6-1.

Table 6-1
Systemwide Safety, Systemwide Operability Retrofit Cost Estimate
(2002 dollars, in millions)

Description	Estimated Cost
Aerial Guideways & Stations	775
Transbay Tube & Vent Structures	251
At Grade & Underground Stations	51
Administrative & Other Buildings	38
Systems & Equipment	4
Total	1,118

*Excludes escalation and finance costs

6.2 POTENTIAL EARTHQUAKE DAMAGE

The retrofit described above would provide major reductions in damage compared to the Systemwide Safety, Core System Operability retrofit, as discussed below.

6.2.1 Aerial Structures

As indicated in Table 6-2, significant damage to BART's aerial columns and bents would be minimized by the Systemwide Safety, Systemwide Operability retrofit. While in a Hayward 7.0 earthquake, there would be chances of between 0 and 28 columns/bents (out of a total of 1,983 columns and bents) with major damage, this would be a significant reduction from the prospects for a range of 11 to 150 columns/bents with major damage predicted with the Systemwide Safety, Core System Operability retrofit.

Table 6-2
Aerial Columns and Bents

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Non-Functional after Earthquake (Major Damage)				
Average	13	1	0	3
Range*	0-28	0-5	0-1	0-7
Partly Functional after Earthquake (Minor Damage)				
Average	30	7	1	8
Range*	0-67	0-18	0-3	0-19

*Average +/- one Standard Deviation

The SERA model also predicts that the likelihood of aerial passenger stations sustaining either total loss or partial loss of functionality would be practically nil.

6.2.2 Transbay Tube

Under all four scenario earthquakes, the Transbay Tube would probably not be closed for major repairs if retrofitted.

6.2.3 Berkeley Hills Tunnel

A major earthquake on the Hayward fault would probably close the Berkeley Hills Tunnel for major repairs, as an economically feasible retrofit has not been found and no retrofit is provided in this option.

6.2.4 Buildings

There is no improvement in the seismic performance of any administrative buildings with the Systemwide Safety, Systemwide Operability retrofit over the Systemwide Safety, Core System Operability retrofit, which reduces the potential damage.

6.2.5 Other Component Damage

There is no improvement in the seismic peformance of the following, for which the Systemwide Safety, Core System Operability retrofit has already reduced likelihood of damage to very low levels:

- Track sections
- Embankment sections
- At-grade and underground passenger stations
- Non-occupied buildings
- Equipment (substations, ventilation equipment, etc.)

6.3 COST TO REPAIR

The estimated short-term and long-term repair costs for the retrofitted BART system are indicated in Table 6-3. The average cost of short-term repairs for the worst case Hayward 7.0 earthquake is estimated to be $14 million, down from the $18 million for the BART system with the Systemwide Safety, Core System Operability retrofit. More significantly, the average long-term repair cost of about $290 million predicted for the Systemwide Safety, Core System Operability retrofit has been reduced to about $183 million. The repair cost estimates for the other scenario earthquakes have been similarly reduced.

Table 6-3
Repair Costs
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Short-Term Repair Costs				
Average	14	3	1	5
Range*	5-24	0-6	0-2	0-10
Long-Term Repair Costs				
Average	183	142	38	58
Range*	77-290	7-280	10-66	20-97

*=Average +/- one Standard Deviation

The distribution of long-term repair costs among the key components of the BART system are shown in Table 6-4. The major costs would be for repairs to the aerial guideways and stations, the Berkeley Hills Tunnel, and the administrative buildings.

Table 6-4
Average Long-Term Repair Costs for Key Components
(2002 dollars, in millions)

Component Type	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Aerials	39	7.3	6.4	12
Tunnels	39	7.8	0.3	0.1
Stations	38	90	13	15
Buildings	61.2	36.9	21.3	30.2
Track, Embankments, Retaining Walls	7.3	0.5	0.3	0.4
Equipment	0.0	0.0	0.0	0.0

6.4 SAFETY PERFORMANCE

Table 6-5 indicates that only a minimal number of sites might be in a complete damage state that would threaten injury or fatality. The difference from the Systemwide Safety, Core System Operability retrofit is insignificant.

Table 6-5
Sites in Complete Damage State after a Major Earthquake

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Average	4	2	0	1
Range*	0-8	0-6	0-0	0-4

*Average +/- one Standard Deviation

Table 6-6 indicates the monetized value of the statistical casualties, only slightly below those for the Systemwide Safety, Core System Operability retrofit.

Table 6-6
Monetized Value of Statistical Casualties
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Monetized Statistical Casualties	4.1	2.1	0.0	4.8

6.5 SERVICE IMPACTS

The interruption to BART service with the Systemwide Safety, Systemwide Operability retrofit would be significantly below that for the Systemwide Safety, Core System Operability retrofit. The average expected time to recover BART service from the Hayward 7.0 earthquake, except for service through the Berkeley Hills Tunnel, has been reduced to 76 days (2.5 months) from 243 days (8 months). The range of estimates has been reduced from 57 to 430 days (2 to 14 months) to 0 to 203 days (0 to 7 months).

Table 6-7
Days to Restore Service to 100% of Pre-Earthquake Levels

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Except through the Berkeley Hills Tunnel				
Average	76	113	9	19
Range*	0-203	0-295	1-39	3-52
Median Motions**	4	1	1	3
Including through the Berkeley Hills Tunnel				
Average	842	142	14	21
Range*	841-842	1-408	1-57	3-52
Median Motions**	841	2	1	3

*Average +/- one Standard Deviation

**Results for median ground motions throughout the BART system. Used to plot the service restoration curves. Note that the average restoration times are significantly greater than the restoration times for median motions, since the uncertainty in the ground motions models can occasionally cause significantly higher ground motions that have a disproportionately higher impact on restoration time.

Figure 6-1, below, shows a graph of the service restoration times for the Systemwide Safety, Systemwide Operability Option compared to the Systemwide Safety, Core System Operability and Status Quo options, derived from the simulation of the Hayward 7.0 scenario earthquake for median ground motions throughout the BART system.

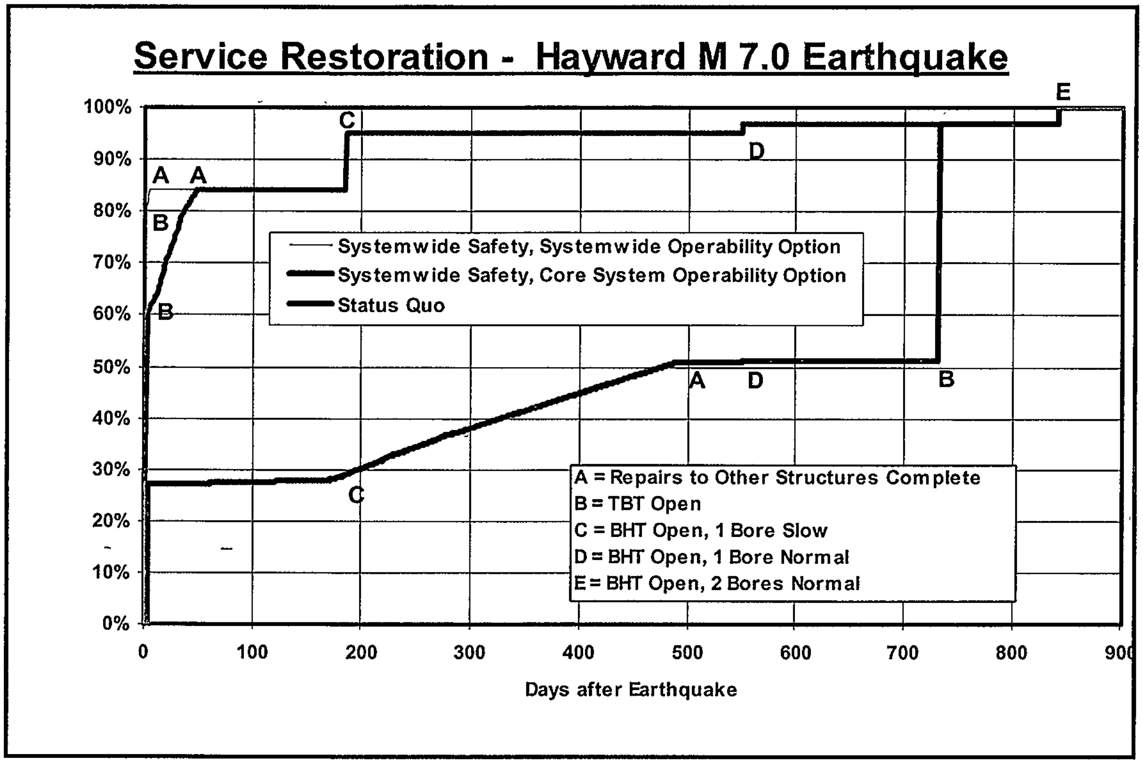


Figure 6-1
Service Restoration Curve – Systemwide Safety, Systemwide Operability Option

Table 6-8 indicates the number of passenger trips lost to the BART system due to earthquake, out of a daily average of about 250,000, for each of the scenario earthquakes. The range of averages of 0.1 to 17 million lost trips is a significant reduction from the 0.6 to 21 million million forecast for the Systemwide Safety, Core System Operability retrofit.

Table 6-8
Passenger Trips Lost
(millions of one-way trips)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Average	17	11	0.1	0.3
Range*	2-32	0-34	0-0.5	0-0.8

*Average +/- one Standard Deviation

6.6 COST OF LOST SERVICE

The following describes the impact of the Systemwide Safety, Systemwide Operability retrofit on the cost of temporary loss of BART service (while the BART system is being put back into operation after an earthquake) from the perspectives of costs to BART, to BART riders, and to Bay Area commuters.

6.6.1 BART Perspective

The cost of lost service from BART's perspective is summarized in Table 6-9. For the Hayward 7.0 scenario earthquake, the cost is only $45 million, compared to $56 million for the Systemwide Safety, Core System Operability retrofit.

Table 6-9
Cost of Lost Service to BART
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
BART Revenue Loss	36	24	0	1
BART Bus Bridge Cost	9	6	0	0
Total	45	30	0	1

6.6.2 BART Rider Perspective

The costs of lost service from the BART riders' perspective are summarized in Table 6-10. For the Hayward 7.0 scenario earthquake, the cost is 393 million, compared to $489 million for the Systemwide Safety, Core System Operability retrofit.

Table 6-10
Cost of Lost Service to BART Riders
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Extra Transportation Costs	119	79	1	2
Value of Lost Time	274	182	2	5
Total	393	261	3	7

6.6.3 Bay Area Commuter Perspective

The cost of lost service from the Bay Area commuter perspective are summarized in Table 6-11. For the Hayward 7.0 scenario earthquake, the cost is $274 million compared to $341 million for the Systemwide Safety, Core Operability Option.

Table 6-11
Cost of Lost Service to Bay Area Commuters
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
Total	274	182	2	5

Section 7
Benefit-Cost Analysis

This report has presented the System Earthquake Risk Assessment (SERA) model analyses of the performance of the BART system in its as-is condition (Status Quo, Section 4) and its performance with either of two retrofits (the Systemwide Safety, Core System Operability Option in Section 5 and the Systemwide Safety, Systemwide Operability Option in Section 6). The estimated costs of the two retrofit options are:

- Systemwide Safety, Core System Operability Option – $828 million (2002 dollars)
- Systemwide Safety, Systemwide Operability Option – $1,118 million (2002 dollars)

This section summarizes the cost impacts of the retrofit options, including repair costs to BART, the cost of lost ridership during repairs, and life-safety costs. Benefit-cost analyses are then presented as input for policy decisions by BART management and the Board with respect to determining the appropriate funding level for the BART Seismic Retrofit Program.

7.1 ANNUALIZED COST IMPACTS

The following paragraphs discuss the cost impact summaries for scenario earthquakes and annualization of cost impacts for comprehensive earthquake risk.

7.1.1 Cost Impact Summaries for Scenario Earthquakes

The following tables summarize the cost impacts of the BART Status Quo and the two retrofit options considered. First, the costs resulting from individual scenario earthquakes, as presented in earlier sections, are summarized. Then, the costs are annualized by multiplying the totals by the probabilities of an earthquake similar to the scenario earthquake occurring in any one year.

Table 7-1
Cost Impacts of BART Status Quo
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
BART Repair Costs	1,098	860	263	253
Monetized Statistical Casualties	297	115	40	33
Total Cost of Lost Service to BART	219	206	122	81
Cost of Lost Service to BART Riders	1,903	1,789	1061	700
Cost of Lost Service to Bay Area Commuters	1,326	1,246	739	488
Total Costs from Earthquake Damage	**4,844**	**4,218**	**2,225**	**1,555**
Annual Probability	0.010	0.002	0.006	0.002
Annualized Costs	**48.44**	**8.44**	**13.35**	**3.11**

Table 7-2
Cost Impacts of BART Systemwide Safety, Core System Operability Retrofit
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
BART Repair Costs	310	163	75	99
Monetized Statistical Casualties	5	2	0	1
Total Cost of Lost Service to BART	56	31	2	3
Cost of Lost Service to BART Riders	489	271	14	25
Cost of Lost Service to Bay Area Commuters	341	189	10	17
Total Costs from Earthquake Damage	**1,201**	**657**	**101**	**145**
Annual Probability	0.010	0.002	0.006	0.002
Annualized Costs	**12.01**	**1.31**	**0.60**	**0.29**

Table 7-3
Cost Impacts of BART Systemwide Safety, Systemwide Operability Retrofit
(2002 dollars, in millions)

	Hayward M 7	San Andreas M 8	Calaveras M 6.8	Concord M 6.8
BART Repair Costs	198	145	45	63
Monetized Statistical Casualties	4	2	0	1
Total Cost of Lost Service to BART	45	30	0	1
Cost of Lost Service to BART Riders	393	261	3	7
Cost of Lost Service to Bay Area Commuters	274	182	2	5
Total Costs from Earthquake Damage	**914**	**620**	**50**	**77**
Annual Probability	0.010	0.002	0.006	0.002
Annualized Costs	**9.13**	**1.24**	**0.30**	**0.15**

7.1.2 Annualization of Cost Impacts for Comprehensive Earthquake Risk

The scenario earthquakes were selected as the basis for the design of BART seismic retrofits because they represent the largest earthquakes likely to occur in the Bay Area. BART would also, however, be exposed to numerous smaller earthquakes that would cause lower levels of damage.

To obtain a more comprehensive estimate of the cost impacts of BART's ability to resist earthquake forces, annualized cost impact estimates were developed for the following nine additional scenario earthquakes:

Table 7-4
Additional Scenario Earthquakes

Scenario Earthquake	Annual Probability of Occurence
Hayward 6.4	0.004
Hayward 6.0	0.004
San Andreas 7.0	0.005
San Andreas 6.0	0.004
Calaveras 6.4	0.005
Calaveras 6.0	0.005
Concord 6.4	0.001
Concord 6.0	0.005
Rogers Creek 7.0	0.005

The sum of the annualized cost impacts for the four major scenario earthquakes and the nine smaller scenario earthquakes are shown in Table 7-5.

Table 7-5
Total Annualized Cost Impacts for BART Retrofit Options
(2002 dollars, in millions)

BART Option	Annualized Cost Impacts for 4 Major Scenario Earthquakes	Annualized Cost Impacts for 9 Smaller Scenario Earthquakes	Total Annualized Cost Impacts for 13 Scenario Earthquakes
Status Quo	73.33	71.48	144.81
Systemwide Safety, Core System Operability Retrofit	14.22	8.69	22.90
Systemwide Safety, Systemwide Operability Retrofit	10.83	6.13	16.96

The total annualized damages for the 13 scenario earthquakes listed in Table 7-5 constitute the vast majority of seismic risk for the BART system. Annualized damages for all other possible earthquakes probably constitute substantially less than 10 percent of the level of annualized damages calculated above; and were indirectly captured by assigning relatively high probabilities for the annual interval probabilities listed in Table 7-4.

7.2 BENEFIT-COST ANALYSIS

The benefit-cost analysis of the BART retrofit options measures the benefit of each retrofit option relative to the cost of the retrofit based on net present values. The estimated costs of the retrofits are in year 2002 dollars. The net present value of the benefits is the annual benefit (reduction in cost impacts) times the present value coefficient. A 4.0 percent discount rate recognizes the likely long-term risk-adjusted effective cost of borrowing for BART, excluding the effects of inflation.

For a discount rate of 4.0 percent and a 50-year useful lifetime for the retrofits, the present value coefficient is 21.48. In other words, the net present values of cost impacts are 21.48 times the annualized cost impacts shown in Table 7-5 (By using a higher discount rate such as 7 percent, which is often used for federal projects, the net present value of the annualized benefits would be lower; conversely, by using a lower discount rate, the net present value of the annualized benefits would be higher.).

A benefit-cost ratio over 1.0 indicates that the level of retrofit is economically justified. A benefit-cost analysis can be made on the basis of both total benefits and costs and marginal benefits and costs. These analyses are summarized in tables on the following page.

The benefit-cost analysis based on total benefits and costs is shown in Table 7-6.

Table 7-6
Benefit-Cost Analysis of BART Retrofit Options
Total Benefits and Costs Basis
(2002 dollars, in millions)

BART Retrofit Option	Estimated Retrofit Cost	Total Annualized Cost Impacts	Annualized Benefits over Status Quo	Net Present Value of Benefits	Benefit-Cost Ratio
Status Quo	–	144.81	–	–	–
Systemwide Safety, Core System Operability Retrofit	828	22.90	121.91	2,619	3.2
Systemwide Safety, Systemwide Operability Retrofit	1,118	16.96	127.85	2,747	2.5

The total benefit-cost ratios shown above are useful for comparing each retrofit option with the Status Quo option. Either of the retrofit options provides more benefit to BART, compared to doing nothing, than it costs.

To compare the two retrofit options with each other, a marginal benefit-cost ratio can be calculated by comparing the additional benefits achieved under the Systemwide Safety, Systemwide Operability option to the additional retrofit contained in this option. The results of such an analysis are shown in Table 7-7 below. The marginal benefit-cost ratio is less than one, suggesting that the additional cost of the Systemwide Safety, Systemwide Operability option is not economically justified.

Table 7-7
Benefit-Cost Analysis of BART Retrofit Options
Marginal Benefits and Costs Basis
(2002 dollars, in millions)

BART Retrofit Option	Estimated Retrofit Marginal Cost	Annualized Marginal Benefits	Net Present Value of Marginal Benefits	Benefit-Cost Ratio
Systemwide Safety, Core System Operability Retrofit	828	121.91	2,619	3.2
Systemwide Safety, Systemwide Operability Retrofit	290	5.94	128	0.4

However, it is important to consider other, intangible factors that suggest additional benefits to the Bay Area from the Systemwide Safety, Systemwide Operability option. These potential benefits cannot be precisely calculated, but include:

- Broader economic impacts to the Bay Area from the extended loss of a vital, established, public transportation system, which might include loss of business, lowered real estate values, reduced consumer spending, etc. were not included in the analysis. Since the Systemwide Safety, Systemwide Operability option returns more of this vital transportation system to operation sooner, these broader impacts would be reduced, compared to the Systemwide Safety, Core System Operability option.
- Although Caltrans and many cities are conducting retrofit programs of their own, the possibility of road closures and disruptions to other forms of transportation after a large earthquake remains. Experience following the Loma Prieta earthquake suggests that BART system ridership would increase as a result. Again, since the Systemwide Safety, Systemwide Operability option brings more of the BART system back into operation sooner, the additional benefit accrued would be greater than for the Systemwide Safety, Core System Operability option.
- The impact of post-earthquake repairs on local communities near the BART alignment will be less if the Systemwide Safety, Systemwide Operability option is carried out, since there will be fewer repairs required.

7.3 CONCLUSIONS

Since its inauguration in 1973, the BART system has become the commuting backbone to downtown San Francisco, and to a lesser extent, downtown Oakland and Berkeley, from most East Bay origins. It has also become a lifeline for businesses and commerce in its service areas. As such, shutting down all or a portion of the BART system for an extended period to time would have a severe impact on the Bay Area economy as a whole.

Although the Vulnerability Study cannot establish the precise damage to the BART system that would be experienced should a large earthquake occur, it is clear from the analysis that the damage would be significant. Given the high probability that a large earthquake will occur in the Bay Area within the next few years, a retrofit of BART facilities is highly desirable.

The Systemwide Safety, Core System Operability option is the minimum retrofit that should be considered. In addition to improving the seismic safety of the system, this option provides significant improvements in the ability of BART facilities to return to service after a major earthquake, and allows the resumption of BART operations in the most critical portions of the system relatively quickly. However, this option results in some portions of the system being non-operational for a lengthy period of time, requiring substantial repair before being returned to service.

The Systemwide Safety, Systemwide Operability option improves the performance of the BART system enough so that nearly the entire system can be returned to service quickly, for a cost of $290 million more than the Systemwide Safety, Core System Operability option. Because the Systemwide Safety, Systemwide Operability option retrofits the same BART facilities as does the Systemwide Safety, Core System Operability option (to a higher level of performance), the additional impact to local communities from the retrofit work is minimal.

The importance of the BART system to the overall Bay Area suggests that the additional expenditure to achieve the Systemwide Safety, Systemwide Operability retrofit is prudent.

In light of the 70 percent probability that a major earthquake will hit the Bay Area by 2030, BART clearly needs to move ahead as rapidly as the resources available to it will allow. The vulnerability study provides valuable guidance on the way forward.

7.4 ACKNOWLEDGMENTS

The risk analysis performed by G&E Engineering Systems Inc. contributed significantly to the BART Seismic Retrofit Program by:

- Assisting the Bechtel/HNTB team to refine its retrofit concepts during the course of the analysis, through identifying structures exposed to potential failure under conditions of uncertainties in ground motion and structures.
- Assisting BART to prioritize the program to focus on the structures that are most important for the safety and operability of the BART system, particularly the Transbay Tube and the aerial structures in the core system.

The independent Peer Review Panel retained by BART provided valuable oversight and advice on the risk analysis process, the likely behaviors of structures and likely earthquake scenarios.

The California Seismic Safety Commission has provided continual support for the BART Seismic Retrofit Program.

The California Department of Transportation (Caltrans) has provided program funding and technical advice regarding its seismic retrofit experiences.