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COMMUNICATIONS-BASED TRAIN CONTROL (CBTC) BEFORE/AFTER COST EFFECTIVENESS STUDY

March 2011

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Lea+Elliott, Inc.
785 Market Street, 12th Floor
San Francisco, California 94103</td><td>8. PERFORMING ORGANIZATION REPORT NUMBER
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Prepared by - Lea+Elliott, Inc.
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Office of Research, Demonstration and Innovation
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Foreword

The San Francisco Municipal Railway (Muni) undertook a retrofit of a fixed-block signaling system with a communications-based train control (CBTC) system in the subway portion of their light rail system in 1998. The goal of this project was to increase the throughput of the subway, improve safety, and improve reliability and availability. This study provides a narrative of that process, discusses issues particular to the Muni Metro system, and undertakes both a quantitative cost-benefit analysis (CBA) and a qualitative analysis of the project. Two cases are examined: the CBTC project as implemented and an alternative case representing a continuation of the conventional fixed-block signaling system. The audience for this report is transit system planners and operators.

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The project team wishes to extend special recognition and appreciation to the members of the SFMTA engineering and maintenance staff who assisted with this project.

Executive Summary

The San Francisco Municipal Railway (Muni) undertook a retrofit of a fixed-block signaling system with a communications-based train control (CBTC) system in the subway portion of their light rail system (Muni Metro subway) in 1998. This report presents the findings of an in-depth study of the effectiveness of implementing the project. Two forms of analysis are provided: a quantitative cost-benefit analysis (CBA) and a qualitative analysis. The CBA considers factors such as passenger wait and trip times, capital costs, and operations and maintenance (O&M) costs which can be monetized without overly onerous assumptions. The CBA is presented in 2010 dollars and is useful as a reference to evaluate potential investments in a similar CBTC application. The qualitative analysis considers additional factors which are not easily monetized. These factors are assigned a value and alternatives are ranked, providing an overview of the relative advantages of communications-based and fixed-block train control systems.

System changes including a new subway turnback, new vehicles, and a new schedule and fare structure were concurrently implemented with the addition of CBTC. Although it is difficult to completely isolate these changes, two alternative cases are considered in this analysis:

- CBTC as-designed and implemented.
- Continuation of three-speed code fixed-block signaling system.

Factors such as passenger wait and trip times, capital costs, and O&M costs are modeled for both cases assuming a 30 year life of the train control system. The CBA shows that the installation of a CBTC system provides a net benefit to the Muni Metro service area. This CBA considers both historical levels of service and a model that attempts to balance changes in service that occurred over the course of the project. The qualitative analysis indicates that CBTC is the better alternative relative to the continuation of the status quo fixed-block train control system.

Several project management issues and lessons learned from Muni's experience implementing CBTC are discussed. A list of tips and recommendations are provided for agencies considering a CBTC overlay project application. This study also allows examining the effectiveness of phased implementation, which in this case started with limited take-over of the conventional train control system and eventually phased into fully automated control under CBTC.

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Definitions

Benefit - Positive value attributed to an economic activity or project often expressed in money terms.

Capacity - The maximum number of passengers that can be moved per direction per unit time at a point along a transit route often expressed in PPHPD.

Car - see Vehicle.

Checked redundancy -A process for safety-critical functions where independent hardware and software systems perform functions on identical data. Results of these functions are compared to ensure no errors are output that may result in unsafe conditions.

Consist - Number of cars connected to make up a single unit. For example, a three-car consist could be three inseparable (married) cars, or three easily separable cars.

Cost - Negative value attributed to an economic activity or project often expressed in money terms.

Cost-benefit analysis - A methodology for evaluating the overall worth of a project by comparing total benefits with total costs.

Cost of capital - The rate of return that capital could be expected to earn in an alternative investment of equivalent risk.

Cut-Out Train - A train under full manual operation, but still communicating its location to the main CBTC computer.

Embarcadero Station - Through station (after MMT and MMX were constructed).

Embarcadero Terminal - Terminal station (before MMT was constructed) that required all trains to turn around at a diamond crossover west of the station platform.

Fixed-block signaling - Train control system where the track is electrically segmented into blocks and the speed in a given block is dependent on the occupancy of the blocks ahead.

Frequency shift keying - A method of encoding digital data where the frequency of a signal is shifted between two frequencies corresponding to either a digital zero or digital one.

Headway - Time interval between two trains traveling in the same direction past any one point.

Inbound - Eastward towards Sunnydale Station.

In-vehicle travel time - Time spent traveling inside a transit vehicle.

Market Street subway - Portion of Muni Metro system in a subway under Market Street from the Ferry Portal to Castro Station.

Muni Metro - City of San Francisco light rail system including subway and surface lines.

Muni Metro Extension (MMX) - Extension of Muni Metro from the Ferry Portal to the Caltrain Depot Station.

Muni Metro subway - Portion of Muni Metro system in a subway under Market Street and in the Twin Peaks Tunnel. This portion extends from the Ferry Portal to the West Portal.

Muni Metro Turnaround - Underground train turnaround loop east of the Embarcadero Terminal planned but never built.

Muni Metro Turnback (MMT) - Underground train storage and turnback area built east of the Embarcadero Station in 1996. Track continues through MMT out to the Ferry Portal and the MMX.

Net present value - The sum of the present values of the individual cash flows of a time series of cash flows, both incoming and outgoing. A net present value greater than zero means that an investment provides a net benefit.

Non-Communicating Train - A train not in communication with the central train control computer. This train is manually operated and tracked by the central train control computer using wayside axle counters. The train can only be located on a block level.

Outbound - Westward from Sunnydale Station.

Peak hours - As defined in this report, Muni Metro weekday service hours from 7:00-10:00 AM and 4:00-7:00 PM.

Power frequency track circuit - Train control circuitry that interfaces with the running rails to detect the presence of a train over a specific length of track.

Reverse rider - In the FBTC period, an outbound passenger that boarded an inbound train in the Muni Metro subway in the expectation that the train would turn back at the Embarcadero Terminal. This was done in order to secure a seat on the train ahead of passengers boarding at the outbound platforms.

SEL - Standard Elektrik Lorenz, subsequently acquired by Alcatel, and later by Thales.

SELTrac - Communications-based train control system developed by Standard Elektrik Lorenz (SEL).

Throughput - Number of vehicles (or trains) per hour per direction past any one point.

Train - one vehicle or series of coupled vehicles. On Muni Metro surface lines, a train can be made up of a one or two vehicle consist. In the pre-CBTC period, coupled trains in the Muni Metro subway could be made up of three or four vehicle consists. Trains currently operate uncoupled in the Muni Metro subway.

Travel time - Total time required for a single transit trip, including walk, wait, in-vehicle trip times, and transfer times.

Transit Effectiveness Project - A comprehensive review of the Muni system conducted by SFMTA in 2006-2007. Part of the TEP involved detailed study of ridership patterns on bus and rail lines.

Twin Peaks Tunnel - Portion of Muni Metro subway that runs in a tunnel underneath the Twin Peaks hills from Castro Station to West Portal Station.

Vehicle - A single vehicle for rail transport that moves along a permanent right of way and has all the equipment necessary for independent operation with an driver's operating station at each end of the vehicle.

Wait time - Time required to wait for a train at a station, understood to be half of a headway.

Acronyms and Abbreviations

APTA - American Public Transportation Association

ART - Advanced Rapid Transit (manufactured by Bombardier Transportation)

ATCS - Advanced Train Control System

ATP - Automatic Train Protection

BAH - Booze Allen Hamilton

CBA - Cost-Benefit Analysis

CBTC - Communications-Based Train Control

CCO - Central Control Operator

CPUC - California Public Utilities Commission

EB - Emergency Brake

FBTC - Fixed-Block Train Control

FSB - Full Service Brake

FTA - Federal Transit Administration

I/O - Input / Output

IATP - Interim Automatic Train Protection

ISC - Independent Safety Consultant

LRV - Light Rail Vehicle

LRV2 - Term given to the second generation of Muni Metro LRVs supplied by Breda Construzioni Ferroviarie

MMT - Muni Metro Turnback

MMX - Muni Metro Extension

Muni - San Francisco Municipal Railway

NPV - Net Present Value

NCT - Non-Communicating Train

OS/2 - Operating System/2 developed by Microsoft and IBM

O&M - Operations and Maintenance

O&SHA - Operating and Support Hazard Analysis

PCC - Presidents' Conference Committee

PHA - Preliminary Hazard Analysis

PPHPD - People per Hour per Direction

SAB - Safety Advisory Board

SCS - Station Controller Subsystem

SEL - Standard Elektrik Lorenz

SFMTA - San Francisco Municipal Transportation Agency

SLRV - Standard Light Rail Vehicle, term given to the first generation of Muni Metro LRVs supplied by Boeing-Vertol

SMC - System Management Center, a subsystem of the SELTrac CBTC system

SSHA - Subsystem Hazard Analysis

TEP - Transit Effectiveness Project

VCC - Vehicle Control Center, a subsystem of the SELTrac CBTC system

VOBC - Vehicle On-Board Controller, a subsystem of the SELTrac CBTC system

V&V - Safety Verification and Validation

1. Introduction

The objective of this report is to examine the effectiveness of the implementation of CBTC at the San Francisco Municipal Railway (Muni). The installation of communications-based train control (CBTC) in the Muni Metro subway provides a unique opportunity to study the retrofit of CBTC technology onto an existing fixed-block train control system. Inaugurated in 1998, this project is among the longest operating of its type in the world. This report identifies appropriate metrics with which to analyze changes in operations and maintenance practices as well as changes in passenger level-of-service. These metrics are input into a cost-benefit analysis in order to provide a monetary basis for comparison of the alternatives.

This report is divided into three sections. The first section, Study Background, provides the overall context for the decision to procure CBTC. The second section, Project Narrative, provides detailed historical and operational data for the before, during and post-project periods. This historical and operational data creates the foundation for the establishment of metrics. The third section, Alternatives Analysis, defines metrics and evaluates the project alternatives using both a cost-benefit analysis and a qualitative evaluation. The appendices contain detailed descriptions of assumptions, methodology and calculations that support the analysis of the report.

2. Study Background

2.1 History of the Muni Metro Subway

The San Francisco Municipal Transportation Agency (SFMTA) was established in 1999 to consolidate the management of San Francisco's transportation services, including: the San Francisco Municipal Railway (Muni), the Department of Parking and Traffic, and the Division of Taxis and Accessible Services. Muni began operations in 1912 as a single municipal line competing with several available commercial lines. Since then, Muni has absorbed and continued to operate the formerly commercial cable car and historic street car lines and expanded service to include diesel and electric-trolley buses and light-rail vehicles (LRV). The Muni LRV lines are collectively called the Muni Metro. These Muni transportation modes, in conjunction with Bay Area Rapid Transit (BART), provide a crucial means of moving people throughout the City of San Francisco (City).

The Muni Metro operates both at the surface level and below ground. The main underground section (Muni Metro subway) is made up of the combination of the 2.3-mile Twin Peaks Tunnel, completed in 1918, and the 3.5-mile Market Street subway section which opened for passenger service in 1980.[1] There are about 65 miles of above ground surface track and about seven miles of subway and tunnel track.[2] Market Street subway is a two level structure with BART trains running in the lower level tunnel and Muni LRVs in the top level tunnel. The transition from surface level to subway occurs at three portals. Convergence of three surface level LRV lines from the far south, west, and southwest areas of the City takes place at the West Portal (see Figure 2-1 and Figure 2-2). In addition, two mid-city surface level lines join the West Portal lines at the Duboce Portal. A surface level line, operating along the eastern waterfront of the City, transitions into the subway at the Ferry Portal. Several LRV lines originating from the

West or Duboce Portal turn-back in the subway before the Ferry Portal at a crossover east of the Embarcadero Station instead of continuing out to the waterfront (see MMT below). All subway LRV passenger station platforms are designed to accommodate four-vehicle trains. All surface running LRV stations consist of boarding islands designed for two-vehicle trains.

Before the Muni Metro subway was built, street operating Presidents' Conference Committee (PCC) streetcars ran from the Ferry Building down the length of Market Street until they diverged west and south near Duboce and Church Streets or entered the Twin Peak Tunnel at a portal located close to the current location of Castro Station. The surface operating streetcars utilized a circular turnaround located in front of the Ferry Building (at the North end of Market Street) which could accommodate 50 second headways.[3] As the BART system was being installed in the City in the late 1970s, planners/designers of the subway conceived of a double decker tunnel with the BART facilities located below the Muni facilities underneath Market Street. All surface running Market Street streetcar operations were moved into the subway. The Twin Peaks Tunnel was connected to the west opening of the Muni Metro subway while the BART tunnel veered south toward the Mission District west of Civic Center Station. The surface circular turnaround was demolished once the trains were moved belowground. From 1980 forward, all inbound Muni Metro trains utilized an underground diamond crossover just west of the Embarcadero Terminal to turn around (see Figure 2-3). The Muni Metro Turnback (MMT), built east of Embarcadero station to provide additional operational flexibility, would not open for revenue service until 1998.

At the surface level LRVs are operated in manual control, primarily mixed with auto-traffic, and with "line-of-sight" rules meaning that the train operator has complete responsibility for controlling the speed and braking of a train. Wayside signal lights direct train operators when to move across intersections and show the alignment of switches and routes. Before the application of CBTC in 1998, trains in the subway were operated in manual control under fixed-block signaling protection.

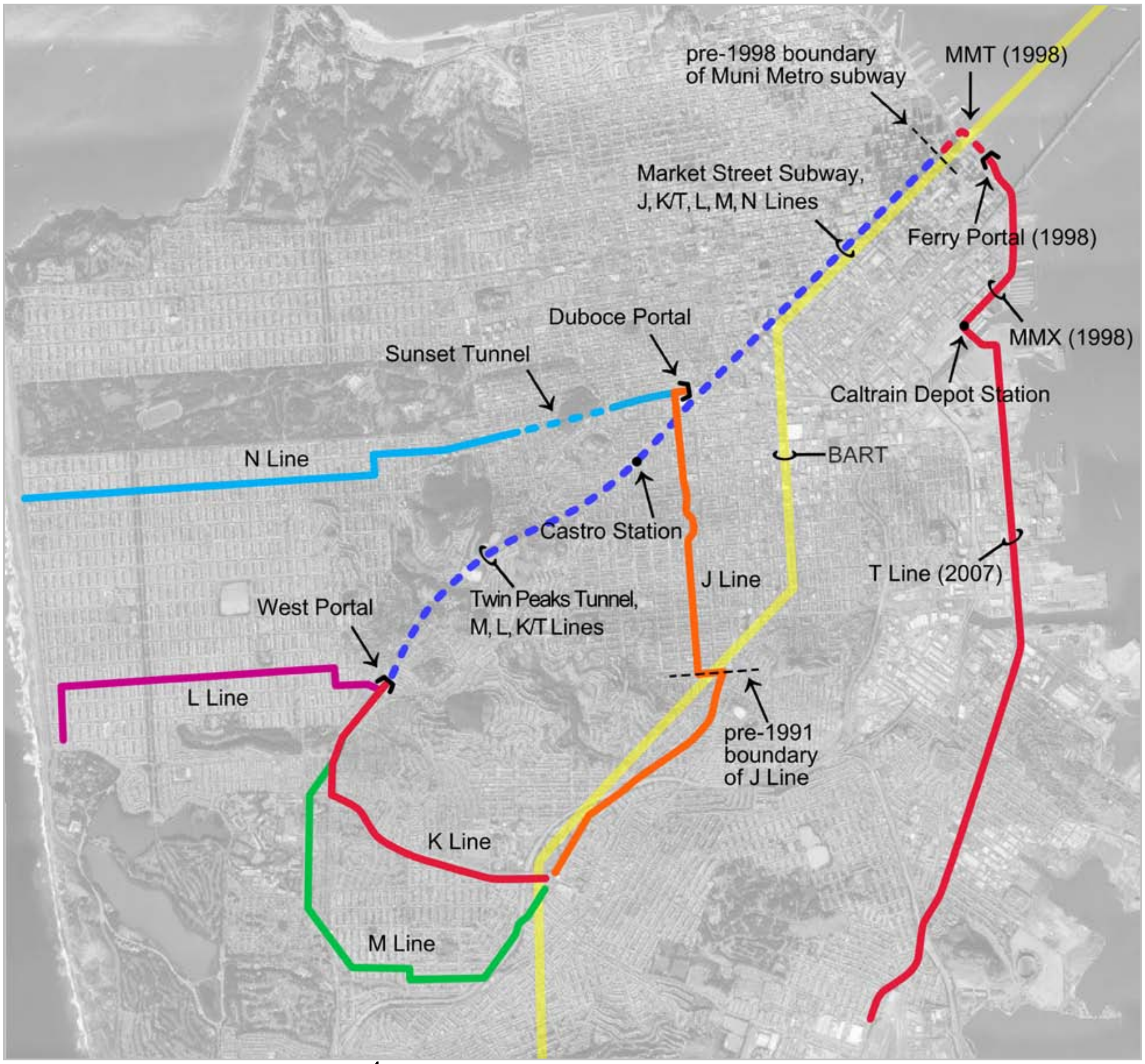

Figure 2-1 Muni Metro, 2010[4]

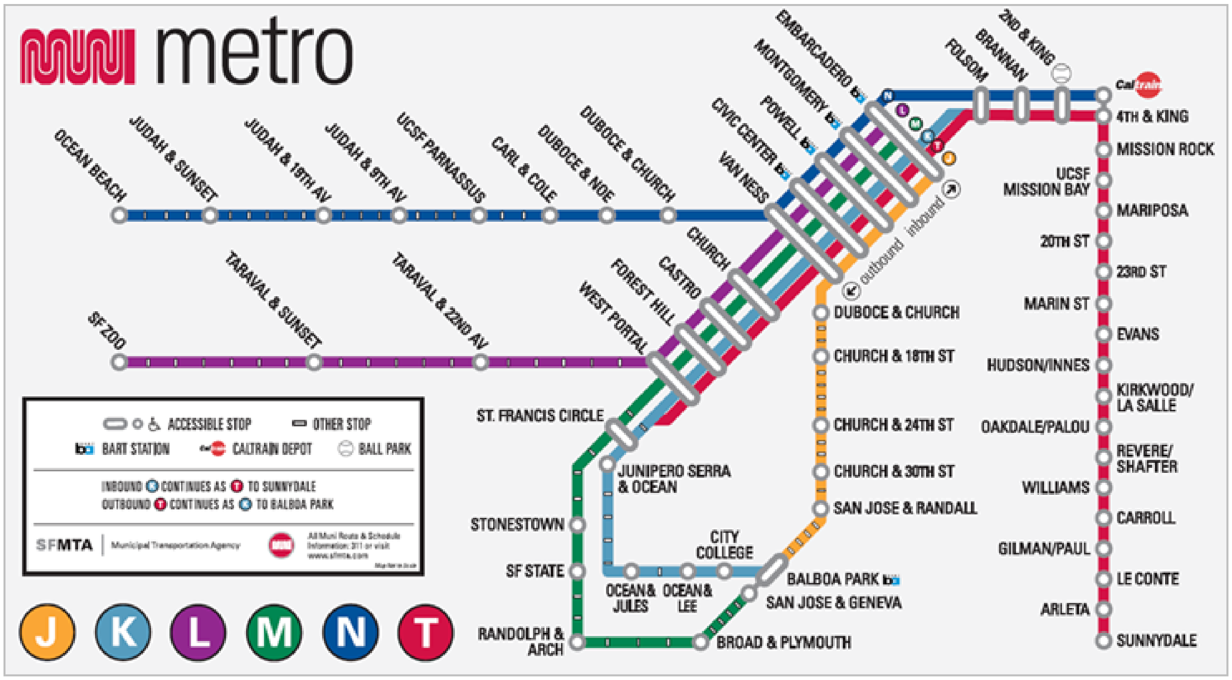

Figure 2-2 Muni Metro Schematic Map, 2010 (not to scale)

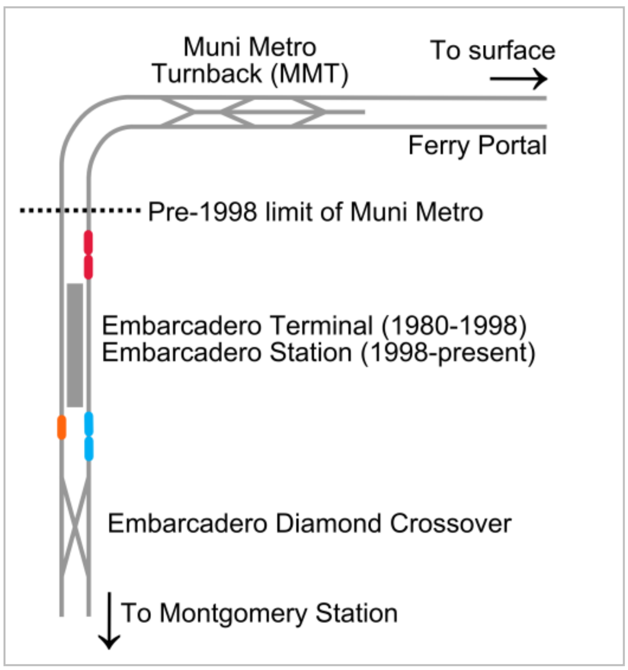

Figure 2-3 Embarcadero Station/Terminal and Muni Metro Turnback (not to scale)

2.2 Decision to Upgrade Train Control

The three-speed code fixed-block signaling system was designed to allow for a maximum throughput of forty (40) trains per hour. However, the reality of operations demonstrated that the highest throughput achieved was actually closer to 23-26 trains per hour.[5] As demand increased, system capacity was limited by the peak three-minute headways provided by the fixed-block design in the Muni Metro subway where all lines converged. To provide sufficient capacity, inbound trains were scheduled to couple at the entrance to the West and Duboce Portals. Outbound trains would uncouple at portals and continue on their respective routes.

In addition to the subway throughput limitations and unpredictable nature of arrival times due to street level operation, delays incurred turning around at the stub-end Embarcadero Terminal Station were recognized as a significant bottleneck. Reversing direction at the Embarcadero Terminal took two to three minutes from pull-in to pull-out.[6] SLRVs were required to key down on one end of the train and key up on the other, contributing to delays. Switches designed for a diverging speed of 17 mph were limited to 10 mph or below by the limited number of available speed codes (10, 27, and 50 mph).[7] At first, a circular underground turnaround east of Embarcadero Terminal was envisioned to eliminate delays related to reversing direction. Cost and other considerations scuttled the circular turnaround which was later redesigned as a turnback and pocket track just east of Embarcadero Station and named the Muni Metro Turnback (MMT) (see Figure 2-3).[8] Muni estimated that this arrangement would reduce manual reversal times to between 90 seconds and two minutes. Further studies, however, indicated that increasing throughput to just 30 trains per hour would require that trains reverse direction in much less time.[9] Although the pocket tracks would significantly improve management of disabled trains at the Embarcadero Station, considerable uncertainty existed as to whether building the MMT would offer any significant improvement over existing throughput without an upgrade of the train control system.[10]

Two viable options for upgrading the train control system were examined. The first option considered reconfiguring the fixed-blocks within the subway and designing two additional speed codes into the system. A typical fixed-block reconfiguration would include additional sectioning of the running rail and extensive modification to the existing train control system. This option would require considerable interruption in passenger services. A formal study of this option was never conducted, although a contemporary report suggested throughput of 30-35 trains per hour might be attainable.[11]

The second option was to overlay a CBTC system. CBTC systems do not rely on segmenting the running rail into isolated sections or blocks. Preliminary engineering studies conducted in the mid-1980s demonstrated that CBTC trains could turn around in under 10 seconds and provide a throughput of sixty trains per hour in the Muni Metro subway.[12] In addition, it was predicted that this system could be overlaid on top of and co-exist with the existing fixed-block train control up until CBTC system cutover with minimal interruption.

2.3 Procurement of CBTC

Upgrading to a CBTC system provided an opportunity to improve subway, and consequently, systemwide throughput while minimizing interruption to passenger service. Muni formulated four basic criteria with which to judge any proposed communications-based train control system:[13]

1. Two years of service proven operation.

2. Capable of fully driverless operation.
3. Throughput of 60 trains per hour.
4. Seamless cutover from the existing system.

Engineering consultant Booz Allen Hamilton provided lead engineering services and technical assistance to Muni.[14] The first round of bidding in 1991 attracted two fixed-block train control suppliers and one CBTC supplier. Muni, concerned that none of the respondents had adequately addressed the cutover process, conducted a second round. A sole source contract was subsequently negotiated with the CBTC supplier (SEL Division of Alcatel Canada, now a division of Thales) and signed in 1992. The $104 million dollar bid (2010 dollars) included:[15]

1. Installation, test, and safety certification of all equipment.
2. All central control equipment and software.
3. All station and wayside equipment.
4. Installation of CBTC equipment and consoles in LRVs.
5. Crossover and portal switch control.
6. Training simulator.
7. Training for central, wayside, and operations supervisors.
8. One year warranty.
9. Spare parts and maintenance manuals.
10. Diagnostic test equipment.
11. CBTC ‘Automatic Mode’ operation in the Market Street subway.
12. CBTC ‘Cab Signaling Mode’ operation in the Sunset Tunnel.
13. CBTC protection against loss of train location.
14. Dual mode operation (capable of simultaneous conventional fixed-block signaling and CBTC ‘Automatic Mode’ operation).

2.4 Muni Metro SELTrac Technology Overview

SELTrac evolved from an early digital inductive loop based train control system developed for German railways in the 1960s. One of the first implementations of the SELTrac system within an urban transit environment occurred in Vancouver for the 18-mile Skytrain driverless metro, which opened in 1985. The four-mile Scarborough RT line of the Toronto Metro, which opened in 1986, and the three-mile Detroit Downtown People Mover, which opened the following year, also featured SELTrac CBTC. All of these systems utilized Bombardier vehicles and linear induction propulsion systems.

The Alcatel SELTrac CBTC system installed at Muni is divided into three parts: wayside, central control, and vehicle subsystems. The interoperation of these subsystems provides overall management and control of trains in the Muni Metro. The central control subsystem is comprised of the Vehicle Control Center (VCC) and the System Management Center (SMC) housed in the central control facility. The VCC, which is the “brains” of the system, provides automatic train protection (ATP) functions. These functions include vital monitoring of train locations, checking trains into the system, establishing routes, maintaining safe train separation, and enforcing speed restrictions. Safety related VCC functions are performed via a checked redundant configuration. All VCC equipment is housed in several racks in the central control equipment room. The VCC transmits frequency shift keyed binary data to antennas mounted on the center truck of the vehicle, inductively coupled over an 18-inch air gap, via the twenty-five inductive loops laid between tracks along the length of the system. Schedule and routes can be programmed and system conditions monitored through the SMC interface located on computers in the central control operations room. The VCC utilizes a triple checked-redundant set of Intel 486 based computers and proprietary logic and I/O modules. The SMC software is operated on networked Intel based PCs running the OS/2 operating system.

The wayside subsystem provides the interface between the VCC and wayside. It is composed of the Station Controller Subsystem (SCS), the inductive loops, axle counters, and wayside intrusion sensors. SCS logic and I/O racks are usually located in a separate equipment room in proximity to a passenger station. SCS hardware monitors wayside sensors and switch positions and interfaces though a checked-redundant electronic interlocking. The SCS monitors the platform and portal for intrusion and signals the VCC to shut down sections of track if any unusual activity is detected. The axle counters provide detection of non-communicating trains as well as over-switch protection and axle counts of trains entering the system.

The vehicle subsystem is composed of the Vehicle On-Board Controller (VOBC), antennas, tachometers, driver’s display, on-board digital voice announcement system, and interfaces to vehicle propulsion and doors. The VOBC is responsible for speed regulation, determining train location, rollback protection, station stopping and door operation. Safety related VOBC functions are performed via a checked redundant configuration. The VOBC is located on an equipment rack in a cabinet within the passenger cabin. The VOBC communicates with the VCC digitally through the inductive loop by way of truck mounted send and receive antennas. Data communications between the VOBC, SCS, and the VCC occur via a proprietary error-corrected communications protocol.

The VOBC installed in Muni LRVs is designed to operate in four modes: Automatic Mode, Cab Signaling Mode, Cut-Out Mode, and Street Mode. Automatic, Cab Signaling, and Cut-Out Modes are designed for subway and tunnel operation. Street-Mode and Cab Signaling Modes are limited to 30 mph by onboard speed limiting hardware (see CMSL below).

Street Mode is designed for street running operations outside of CBTC territory and gives the train operator control over vehicle propulsion and braking. Upon entering CBTC territory, the VOBC is checked into the system in Cab Signaling Mode and switched into Automatic Mode by the train operator. The VOBC sends data packets to the VCC indicating its speed, position, brake status, and overall vehicle status. The VCC responds to the VOBC with a commanded speed, target point, travel direction, and door commands. The routing of a train through CBTC territory is determined by the VCC according to the portal a train enters at, and a unique numeric identifier entered by the train operator in his console at the start of the run.

Although there is always a train operator in the driver’s cab, train propulsion, braking, and doors are under full control of the VCC while the train is in the Muni Metro subway. Several other transit systems provide computer controlled propulsion and braking of vehicles while also assigning door operation to the train operator. These automatic modes where the train operator is always required to remain in the driver's cab can be considered a form of semi-automatic or attended train operation.

In Cab Signaling Mode, the train operator has control over propulsion and braking given speed restrictions communicated to his train by the VCC. Full service braking (FSB) is immediately applied in an overspeed condition. Emergency braking (EB) is immediately applied if the train does not meet the required braking profile in 3 seconds. In Cut-Out Mode the train is under the full control of the train operator. The VOBC is bypassed entirely ("cut-out") and not subject to VCC imposed speed restrictions but is still in communication with the VCC. The VCC continues to maintain the precise location of the train in its database and routes other trains accordingly. In Cut-Out Mode, properly equipped trains could utilize the existing carborne fixed-block signaling equipment from the original train control system. Trains in Cut-Out Mode without fixed-block signaling hardware are restricted to line-of-sight rules. In the event of a complete VOBC failure, the train operates under line-of-sight rules and is tracked by the VCC using wayside axle counters. This train is considered a non-communicating train (NCT). An NCT train can only be located on a block level and nearby trains must be routed a safe distance away by the VCC.

2.5 Additional Issues Moving Into Implementation

Concurrent with the procurement of a CBTC system, Muni was replacing their entire fleet of 128 original Boeing-Vertol light rail vehicles (SLRV) with vehicles manufactured by Breda Construzioni Ferroviarie (LRV2). The Boeing vehicles, built by the helicopter division Vertol in the late 1970s, experienced reliability problems, and were being retired ahead of the end of their 25 year service life.[16] The LRV2s, which were larger and had additional doors, began to be phased into service in 1996. These two projects (CBTC and LRV2) were to be executed under two separate contracts, with each contract requiring interfaces to be provided to the other's equipment. The LRV2s were scheduled to be delivered once the CBTC system had been installed and service proven with the SLRVs. As the schedule of the CBTC project was extended beyond the expected LRV2 delivery date, the carborne CBTC equipment of a limited number of LRV2s (10-15) was reprogrammed to operate under the fixed-block signaling system.[17] This temporary modification was dubbed Interim ATP (IATP). At the time of the implementation of CBTC, there was a total fleet of 136 vehicles consisting of approximately 77 SLRVs and 59 LRV2s.[18] The majority of SLRVs were retrofit with CBTC carborne equipment and could operate in either fixed-block or CBTC; LRV2s could operate in either fixed-block mode under the conventional system (during the IATP period) or in CBTC, but not both. Once the SLRVs were phased out of service and all LRV2s were programmed to operate under CBTC, no vehicles in Muni's fleet were able to utilize the fixed-block train control system.

The Muni Metro Turnback (MMT), completed in late 1997, was a series of crossovers and pocket tracks built as a continuation of the Muni Metro subway east of the Embarcadero Station (see Figure 2-3). A 1.5- mile extension of the Muni Metro (MMX or E-line), surfacing out of the MMT at the new Ferry Portal, opened as a temporary shuttle service between the Embarcadero Station and the Caltrain Depot Station in January

1998. The temporary E-line was intended to be connected and integrated with the N-line later in the year.

3. Project Narrative

Three phases of the CBTC project are studied: the period prior to CBTC, during the implementation of CBTC, and post CBTC substantial completion. While the system has been operating since the 1980s, computer generated data studied for the period prior to CBTC begins on January 1, 1996. January 10, 1998, the day that CBTC service began only on the MMX/MMT extension is chosen as the transition date to the period of CBTC implementation. January 1, 2001 is chosen as the transition date to the period post CBTC substantial completion. This narrative has been reconstructed from interviews with Muni staff, examination of historical records, computer generated data of system operation, and contemporary news accounts.

3.1 Prior to CBTC (1996-1998)

3.1.1 Train Control System

Prior to CBTC, the Muni Metro subway utilized a power (100 Hz.) frequency fixed-block train control system installed when the Market Street subway opened for revenue service in 1980. The system was divided into approximately 100 blocks and used three speed codes: 10, 27, and 50 MPH. Track occupancy was determined by the shunting of power frequency train detection currents across the rail. Impedance bonds isolated train detection signals between adjacent blocks. Speed code rates were regulated by hardwired vital relay logic and transmitted to trains via a signal coded onto the train detection current. The speed code was picked up by carborne antennas, filtered, and demodulated. This speed was electronically compared to the actual velocity of the train as measured by tachometers mounted to the propulsion motors. Train operators had full control over propulsion and braking given the limits of the maximum speed permitted. When the train moved into a zone with a more restrictive speed code, or the operator inadvertently exceeded the coded speed, the train would sound an alarm. The operator was required to move the master controller into the full service brake position in order to silence the alarm and avoid imposition of automatic full service braking to near zero speed (two mph). Regardless of operator action, an automatically service braked train that did not meet the required three mph per second deceleration rate would be irrevocably emergency braked to zero speed.

There was limited data logging and train monitoring equipment available for central control management. A mimic board display in the central control room could only show block occupancy and could not identify individual trains.

3.1.2 Operations and Maintenance

The Muni Metro subway system, which opened in 1980, was originally designed to allow coupling at portals in order to provide sufficient throughput.[19] The M, L, and K lines met at the West Portal where they were intended to couple together to form an M-L-K train. The N and J lines met at the Duboce Portal where they were intended to couple to form an N-J train. As planned, the trains would operate at the surface at peak four-minute headways. Alternating these trains would produce M-L-K / N-J / M-L-K / N-J trains in the subway at two-minute headways. All of the trains would turnback using the diamond crossover just west of the Embarcadero Terminal. This well choreographed operation was at the mercy of street level interruptions, failed couplings, and turnback time at the Embarcadero Terminal. By the late 1980s, peak operations had been relaxed to 12-minute headways on the K and L; six-minute headways on the M, and five-minute headways on the J, and N lines.[20] At the West Portal, every two-vehicle K train would couple with either a two-vehicle M train or a two-vehicle L train (see Figure 3-1). At the Duboce Portal, the two-vehicle N train would couple with the one-vehicle J train. This produced M-K, L-K, and N-J coupled train configurations in the subway at peak three-minute headways with three- and four-vehicle consists.[21]

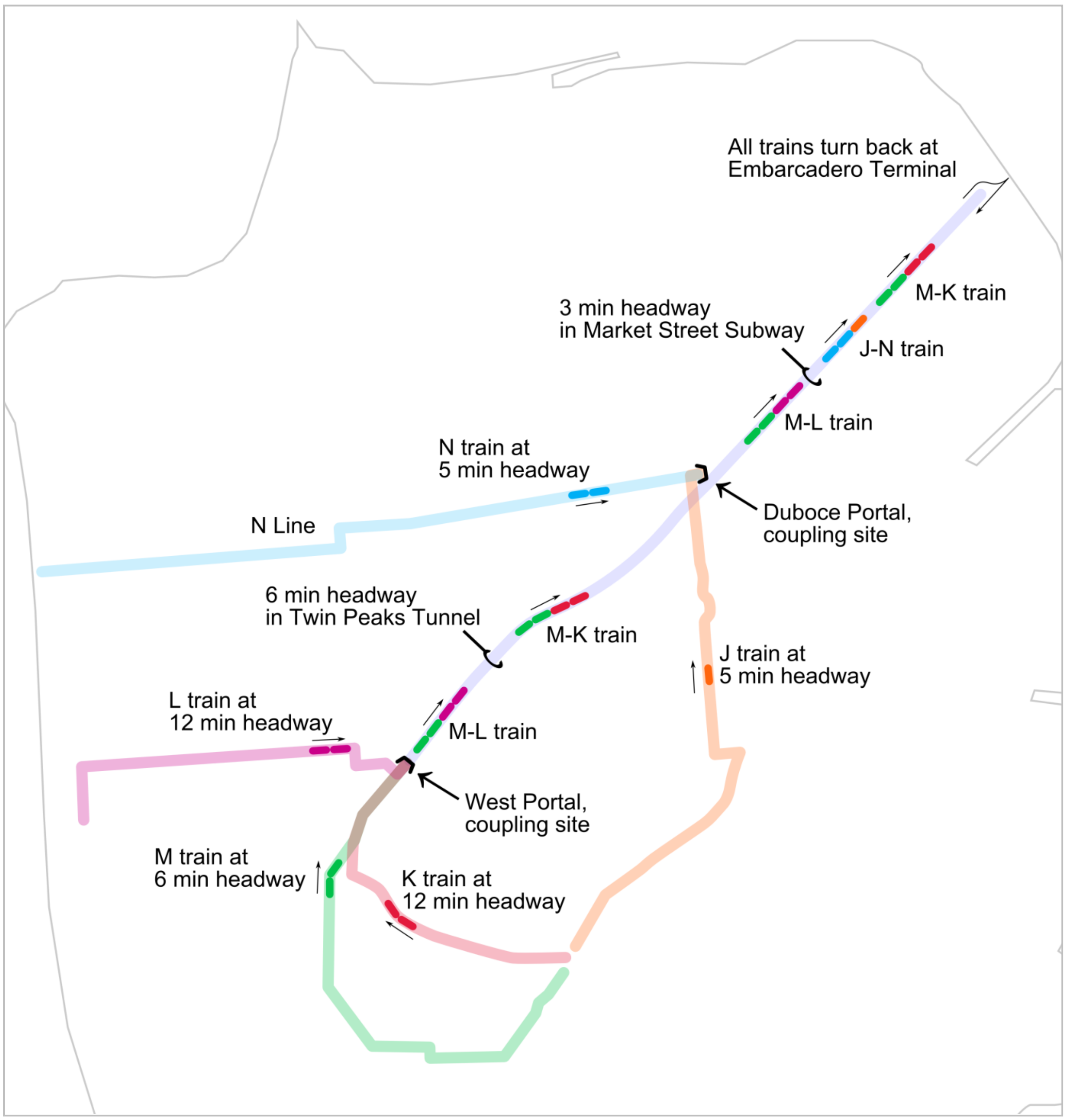

Figure 3-1 FBTC Coupling Operations, Inbound Service Toward Embarcadero

This arrangement limited the responsiveness of the system to service demands on different lines. Since each train had to meet a coupling partner, change in one line's service had a direct effect on the coupling partner's line.

In the operations control center, one staff member was dedicated to monitoring and maintaining radio contact with the entire fleet of 128 LRVs. Two full-time operations staff, located at the West and Duboce portals, were required in order to assist the coupling and uncoupling of vehicles as they entered and exited the subway. An additional full time rail supervisor was required at the Embarcadero Terminal.

In general, maintenance tasks were divided into wayside and carborne activities, with separate teams attending to each category. Signal maintainers were responsible for system-wide maintenance, including the Muni Metro subway, street running LRV and trolley bus signaling equipment. The subway portion was divided into one hundred power frequency track circuits. Over 1,000 vital relays controlled train movements within these track circuits.

3.1.3 Subway Service Levels

In practice, only 23-26 trains could be routed in a sustained manner through the subway per hour. Therefore, if all trains were coupled at portals into four-vehicle trains, about 100 vehicles per hour could travel through the subway. In reality, during peak hours, approximately 70 vehicles per hour traveled through the subway in a mix of three- and four-vehicle trains. Every peak period train was composed of a coupled one and two-vehicle train or two coupled two-vehicle trains. Given the vagaries of street running operations, even with high vehicle availability, passengers often experienced inconsistent headways in the Muni Metro. Frequent coupling at the portals caused intensive wear to the vehicle couplers and delays would occur when vehicles either failed to couple after several attempts or were not able to uncouple. In the period before the MMT, a malfunctioning switch at the diamond crossover west of the Embarcadero Terminal could halt subway operations completely. Vehicle breakdowns, although not related to the fixed-block signaling system, contributed to passenger perceptions of low quality of service. As recorded in the months prior to full CBTC implementation, and shown in Chart 3-1, subway throughput could vary by 20% during peak periods.

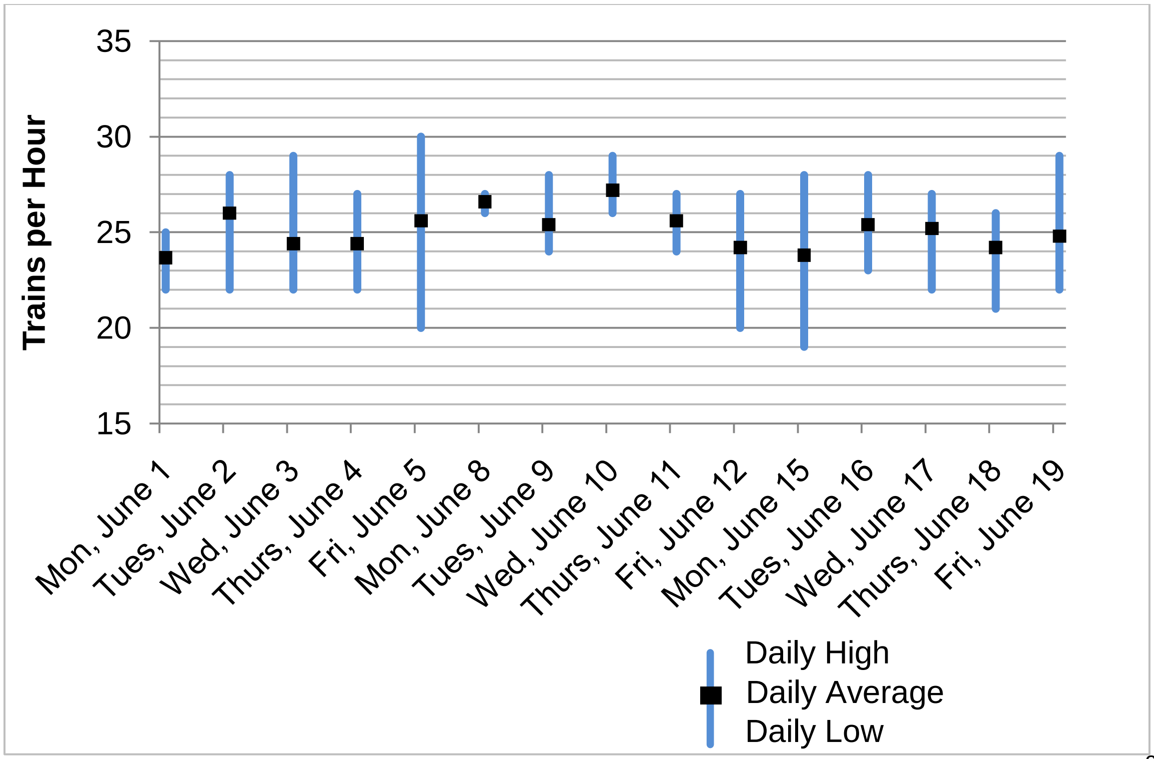

Chart 3-1 FBTC, Avg. Subway Throughput, ***Trains,*** Peak Hours Only, June 1998[22]

3.1.4 Safety Incidents

The original train control system design in the subway presented several significant safety issues. Instances of loss-of-shunt (non-detection) of unpowered trains were of particular concern to Muni officials. This problem, not unusual with conventional fixed-block track circuits, was difficult to replicate and diagnose. The lack of a zero speed code and trip stop mechanisms allowed unrestricted train movements at speeds under 10 mph in the subway. The limited number of speed codes hindered train operator flexibility and resulted in an excessive number of penalty stops with possible injury to passengers. There were approximately 19 emergency braking (EB) incidents per year leading to passenger injury under the fixed-block signaling system.[23] There were occasional incidents with manually operated train doors and steps, where, for example, doors opened on the wrong side of vehicles. These safety issues, overwhelmingly the result of train operator error, pointed to the need for significant improvement of the train operator-train control interface.[24]

Two incidents, in particular, exemplify safety issues relating to the fixed-block signaling system. On April 4, 1993 two SLRVs collided in the area near the Castro Station, causing fifteen injuries. An operator in an out-of-service train had disconnected the on-board fixed-block signal train control system and rear-ended an in-service train. On June 8, 1998, outside of the Van Ness Station, an in-bound K train traveling at less than 10 mph collided with a two-vehicle N train, resulting in 14 injuries.[25]

3.2 Implementation of CBTC (1998-2000)

3.2.1 Subway Service Levels (Jan. 1998-Aug. 1998)

The upgrade to CBTC presented several unique challenges at the time. Previous installations of SELTrac had occurred at new transit systems based on the Advanced Rapid Transit (ART) rapid transit system manufactured by Bombardier Transportation. Toronto, Vancouver, and Detroit all shared similar vehicles and propulsion systems. The Muni Metro had wholly different vehicles, propulsion technology, and infrastructure. The Muni LRV had been manually operated for more than fifteen years and the system had ingrained institutional and operational patterns. The new ART systems had provided transit agencies with an opportunity for extensive pre-revenue service testing. Vancouver Skytrain required fifteen months of operation before obtaining approval of the British Columbia government.[26] The Muni CBTC project was intended to be tested at night while maintaining daytime fixed-block signaled LRV operation. The ART system had been installed in exclusively grade-separated systems while Muni Metro interfaced with extensive street running operations. In addition, operations during the implementation of CBTC were affected by other concurrent system changes:

1. Introduction of the MMT and the temporary E-line shuttle out of the Ferry Portal to the Caltrain Depot Station,
2. Later replacement of the E-line with an extension of the N-Line service,
3. Introduction of a new proof-of-payment system on the E-line and eventually N-line,
4. Elimination of ‘reverse riders’ at the Embarcadero Station (explained below), and
5. Elimination of coupling at portals.

The temporary E-line service was inaugurated in January 1998 and was the first test of CBTC. Trains operated as a shuttle between the Embarcadero Station and the Caltrain Depot Station. Within the MMT and the Embarcadero Station, a distance of a few hundred feet, the trains operated under CBTC control. They checked into and out of the CBTC system at the Ferry Portal. All other subway lines (M, L, K, J, N) remained under control of the fixed-block signaling system and turned back westbound at the Embarcadero Station. In June 1998, all Muni Metro trains were put under CBTC control during weekends only with separate E-line shuttle service continuing. During this period, a pattern of failed check-ins at portals and loss of communication in the subway was becoming evident. Attempts were made to address these issues with VCC and VOBC software revisions.

Fully integrated continuous CBTC operation commenced on Saturday, August 22, 1998. E-line service was eliminated and replaced with N-line service from the Ocean Beach Station through to the Caltrain Depot Station. Proof-of-payment was introduced along the entire N-line. Twenty non-CBTC equipped SLRVs were also placed into operation during implementation to augment the fleet and controlled by the conventional signal system in the “dual-mode” configuration with ATCS. ‘Reverse riding’, a common practice in which westbound riders at Montgomery or Powell Station would get on an eastbound train in the expectation that that train would turn around at the Embarcadero Station and continue outbound, was eliminated. Now all passengers were required to exit all inbound trains at the Embarcadero Station, unless that train was continuing out through the Ferry Portal (N-line). These changes were not adequately communicated to passengers in the preceding weeks, and caused significant passenger confusion and frustration.

During this first week of full operation, a portion of vehicles, both CBTC-equipped SLRVs and LRV2s, had difficulty communicating with the VCC, resulting in VOBC time-outs. Consequently, timed-out SLRVs operated under the old fixed-block signaling system and timed-out LRV2s operated in Cut-Out Mode. Each failed check-in or communications timeout required the train operator to contact central control, exacerbating any delays caused by street running traffic. In some rare incidents, passengers, delayed in the subway, opened vehicle emergency doors and evacuated themselves onto the subway catwalk. Some doors operated improperly at station stops, or did not operate at all. [27] On occasion, trains that had been dispatched at regular headways from terminals would back up several deep at a portal. Trains were sporadically routed incorrectly. For example, some outbound trains expected to surface at the Duboce Portal (N or J line) continued in the subway to the Church Street Station.[28] Drivers had little indication other than ‘Auto’ mode on their consoles when this occurred and were not able to prepare passengers. Communications were hampered by having only one radio voice channel and one dispatcher at central control.[29] Muni maintenance staff found it difficult to separate vehicle and CBTC related problems.[30]

The cumulative effect of the conditions during the cutover to CBTC was a significant drop in passenger service level-of-quality, lasting about two weeks. In an effort to improve performance, the 20 non-CBTC equipped SLRVs were removed from service on Thursday, September 3rd. Peak train throughput in the subway overtook FBTC levels (23-26 trains per hour) by the week of September 7th and continued to increase thereafter (see Chart 3-2).

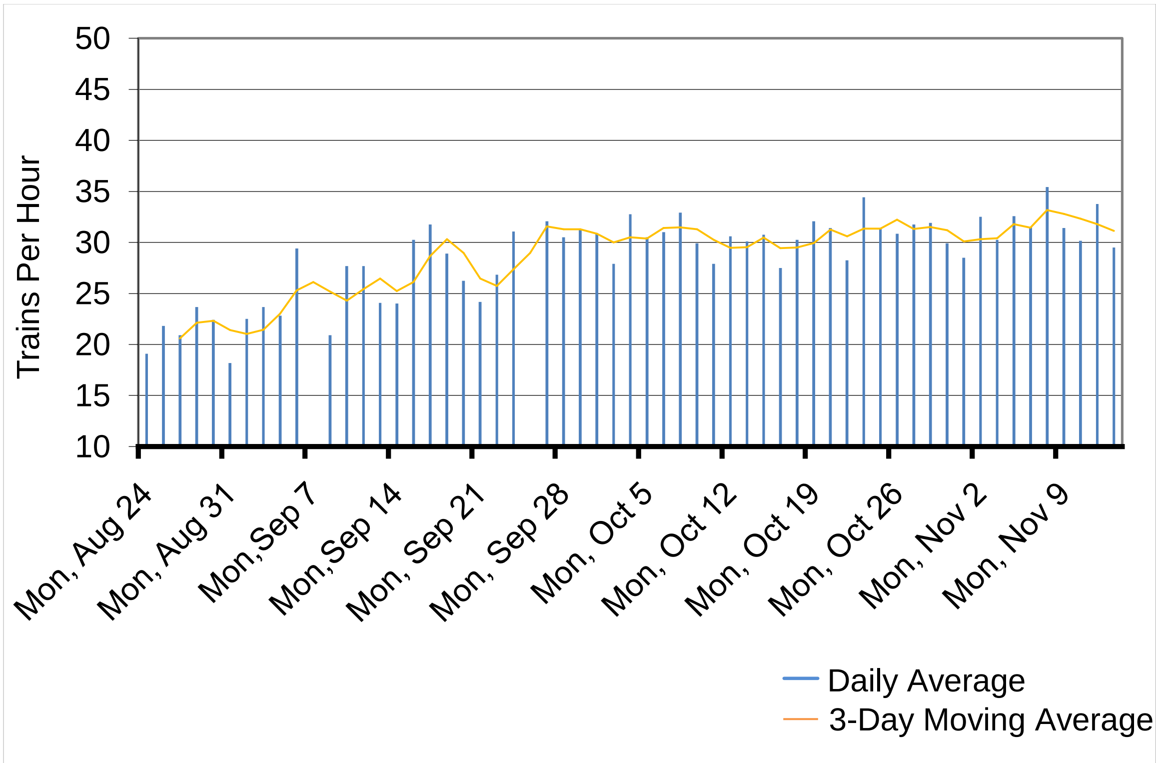

Chart 3-2 CBTC, Avg. Subway Throughput, ***Trains***, Peak Hours Only (Aug.-Nov. 1998)

3.2.2 Subway Service Levels, (Aug. 1998-Dec. 2000)

Subway throughput, measured in trains per hour, steadily increased for about six months after complete cutover to CBTC (see Chart 3-3). Coupling operations had created three- and four-vehicle coupled trains in the subway. Now, without coupling at the portals, all of the trains running in the subway were either one or two vehicles in length (see Figure 3-2). Two-minute headways with one- and two-vehicle un-coupled trains produced a throughput of roughly 50 vehicles per hour (see Chart 3-4). Analysis undertaken for this report suggests that three- and four-vehicle coupled trains at FBTC headways had produced an estimated throughput of 70 vehicles per hour in the subway. Although *train* throughput had increased, an apparent decrease of about 30% in *vehicle* throughput had occurred. Given that Muni Metro ridership remained stable through the CBTC implementation period and beyond (see Chart 3-7), it is inferred that operational efficiencies of CBTC allowed for more efficient utilization of vehicle passenger space than was possible with the fixed-block signaling system.

Several factors underlie the improvement in operational efficiency. Under the fixed-block signaling system, underutilized lines may have been over scheduled in order to match the headway of a coupling partner. In addition, due to the tendency of trains to “bunch” in the subway, additional capacity overhead was required in order to accommodate sudden surges of passengers waiting to board after delays.

Figure 3-2 Market Street subway train traffic, one direction (not to scale)

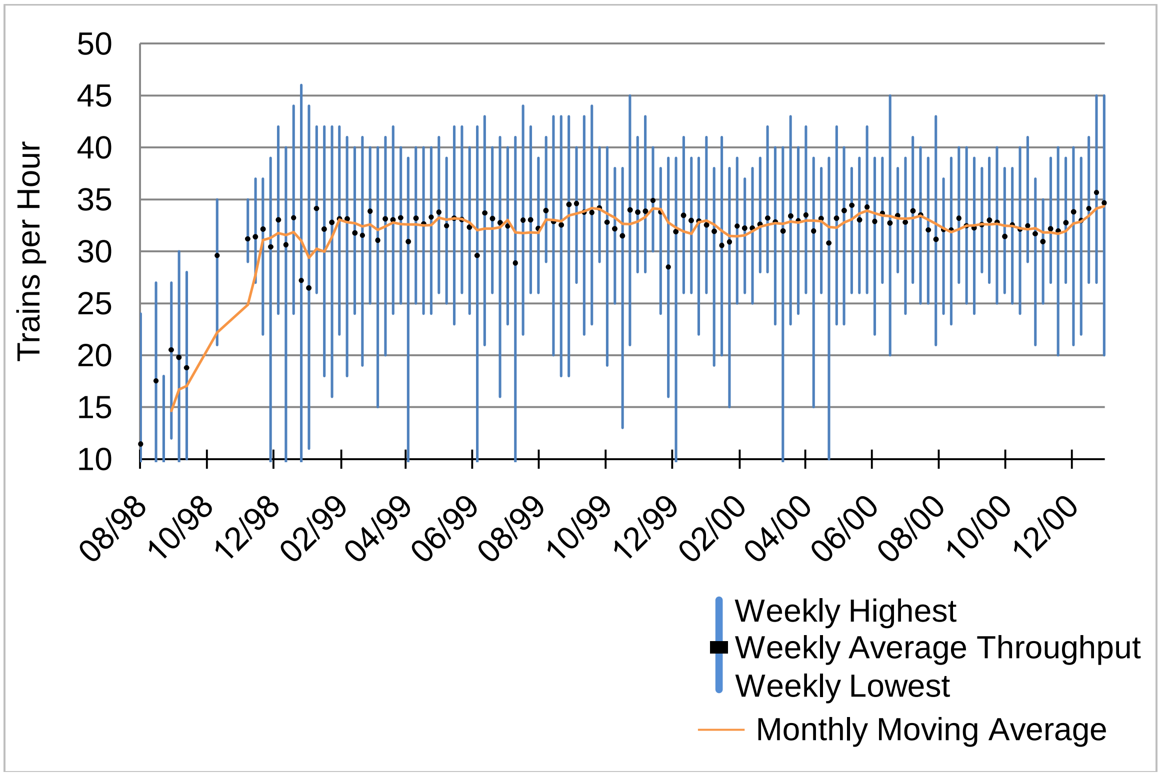

Chart 3-3 CBTC, Avg. Subway Throughput, ***Trains***, Peak Hours Only (Aug. 1998-Jun. 2000)

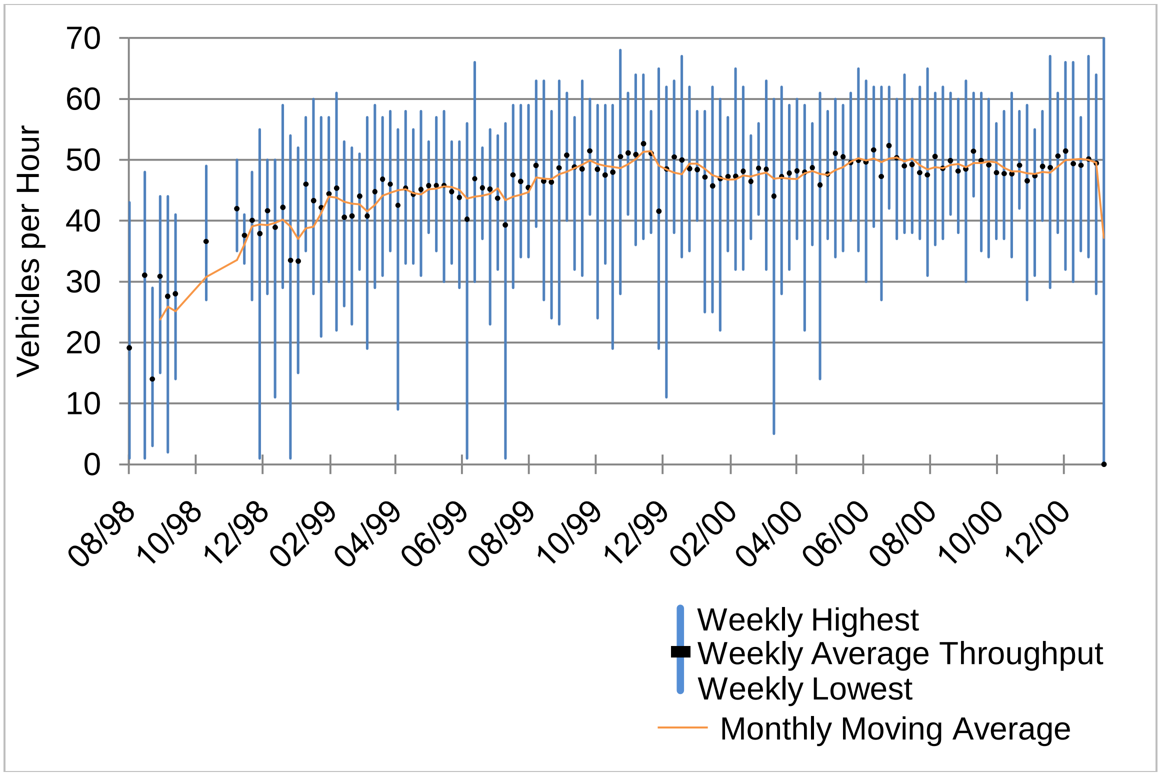

Chart 3-4 CBTC, Avg. Subway Throughput, ***Vehicles***, Peak Hours Only (Aug. 1998-Jun. 2000)

3.2.3 Safety Issues

Although it was hoped that CBTC would substantially reduce the frequency of EB events, the first few months of operation saw the system experiencing approximately five to six EBs per day due primarily to overspeeds and timeouts.[31] Approximately three to five percent of trains continued to experience difficulty checking into the CBTC system at portals, and four to six percent of trains lost communication with the VCC in the subway.[32] These trains would revert to NCT mode, limiting subway throughput and denying full CBTC protection to the vehicle. Anytime a train lost contact with the VCC in CBTC territory the train immediately applied the emergency brakes. Addressing this and other safety issues required modifications to VCC and VOBC software. Each software update potentially introduced other subtle safety or operational issues and required separate safety verification and validation testing.

3.2.4 Safety Certification Process

The safety certification process began with the formation in 1993 of a safety advisory board (SAB) chaired by an independent safety consultant (ISC). Members of the SAB included: Muni staff (projects, operations, maintenance, and safety), the project manager/technical consultant (Booz Allen Hamilton), the ISC (Lea+Elliott, Inc.), and the CBTC contractor (Alcatel Transport Automation), along with representatives from regulatory agencies.

Booz Allen Hamilton (BAH) established the safety certification plan which governed all certification data for revenue readiness. BAH had the lead in preparing the safety certification package of certificates.

Starting with the technical specifications of the CBTC system and an operations plan (which was developed jointly by the system contractor, Muni and Muni's consultants) a set of Muni specific design requirements were defined. Since Muni had specified a service-proven CBTC system, the Muni specific requirements were in addition to the generic requirements embodied in the SELTrac technology.

The final Muni CBTC design was developed by integrating the generic SELTrac design requirements and the new, Muni specific requirements. Along the way, this final design was subjected to several hazard analyses, including a preliminary hazard analysis (PHA), and subsystem hazard analyses (SSHA) of all safety-critical subsystems, including the VCC, VOBC, SCS, and data communication subsystems. These hazard analyses took the form of a fault tree analyses for the PHA, failure mode effects analyses for safety-critical subsystems, and signal interface hazard analyses to address failure mode effects among the interfaces between the elements within a subsystem and between the subsystems. Final safety requirements for use in the safety verification and validation process were derived from the overall CBTC design requirements and from outputs of the various hazard analyses.

Once the baseline safety case was established, the ISC assumed the role of principal reviewer of the documentation confirming the safety of all subsequent releases of safety-critical software. The ISC's approval of this documentation was a necessary prerequisite to Muni approving the software for use in revenue service.

Tests were conducted for all safety-critical changes to verify not only that the fix/change was properly implemented, but also that associated existing functions/routines were not corrupted by the change. All test reports/results where independently reviewed and approved by Alcatel safety engineers prior to being packaged and sent to the ISC for its review.

Other significant activities within the overall CBTC safety certification process included the verification of contract specification conformance, the conduct of an operating and support hazard analysis (O&SHA), and the verification that requirements derived from the O&SHA had been properly incorporated into the operating and maintenance plans, rulebooks and procedures, and into the maintenance and operator training programs.

The safety verification and validation (V&V) process was conducted within the framework of the overall safety certification process. The safety V&V process was completed by the CBTC contractor, with oversight and support from the ISC.

The primary objective of the safety V&V process was to verify that all of the defined safety requirements were carried out. The safety V&V process was documented in a series of reports which presented, in tabular form, the complete listing of all safety requirements by subsystem (VCC, SCS, and VOBC) and identified the means by which verification of each requirement was accomplished; that is, by reference to a specific design document, analysis report, and/or test result(s). Over 150 distinct safety requirements were defined, all of which were ultimately verified by multiple means (design documentation, analyses, and/or test). All but a few of the safety requirements were verified by tests at multiple levels, including software unit tests, engineering integration tests, field integration tests, and/or field commissioning tests.

A significant task of the safety V&V process was the effort to assure that the safety-critical functions performed by software were correctly implemented. For the project, this software consisted largely of standard SELTrac software, developed previously and installed on other projects. Modifications to this “baseline” software (for example, to change design, add or delete functions or fix problems) were therefore carried out as changes, not as new development. Changes were managed and controlled under Alcatel’s Engineering Change Control Process, which mandates that requirements definition, internal design review, coding, code review, and verification testing (regression, unit, integration, stress and/or field) all be successfully accomplished and documented before any changed software is released to the field.

Muni, established before the jurisdiction of the state public utilities commission (CPUC) was extended beyond intercity railroads, was essentially self regulating for many years. Federal Transit Administration (FTA) rules imposed CPUC oversight in 1996. The CPUC monitored the safety certification process and ultimately gave permission for Muni to operate in revenue service under the new CBTC system.[33]

3.3 CBTC Substantial Completion (2001-2009)

3.3.1 Systemwide Service Levels

Analysis undertaken for this report suggests that under the CBTC, *average* headways, as experienced by passengers systemwide, increased slightly. This is primarily due to the fact that, overall, Muni could meet ridership demand with fewer trains due to CBTC’s scheduling and operational flexibility. In the subway, however, headways were reduced significantly due to increased throughput. Trains could be operated on as short as one-minute headways inside the subway. In reality, maximum sustained subway throughput was limited to about 45-48 trains per hour.[34] Scheduled service, dictated by ridership demand, fleet size, and budget, produced subway train throughput of approximately 33-37 trains per hour during peak hours (see Chart 3-5). Vehicle throughput stabilized to an average of 50 vehicles per hour after 2005 (see Chart 3-6). Even within the peak hours, however, significant throughput variability occurred. The most visible improvement to the public was that coupling at the portals, which had added to in-vehicle travel times and exacerbated delays, was eliminated.

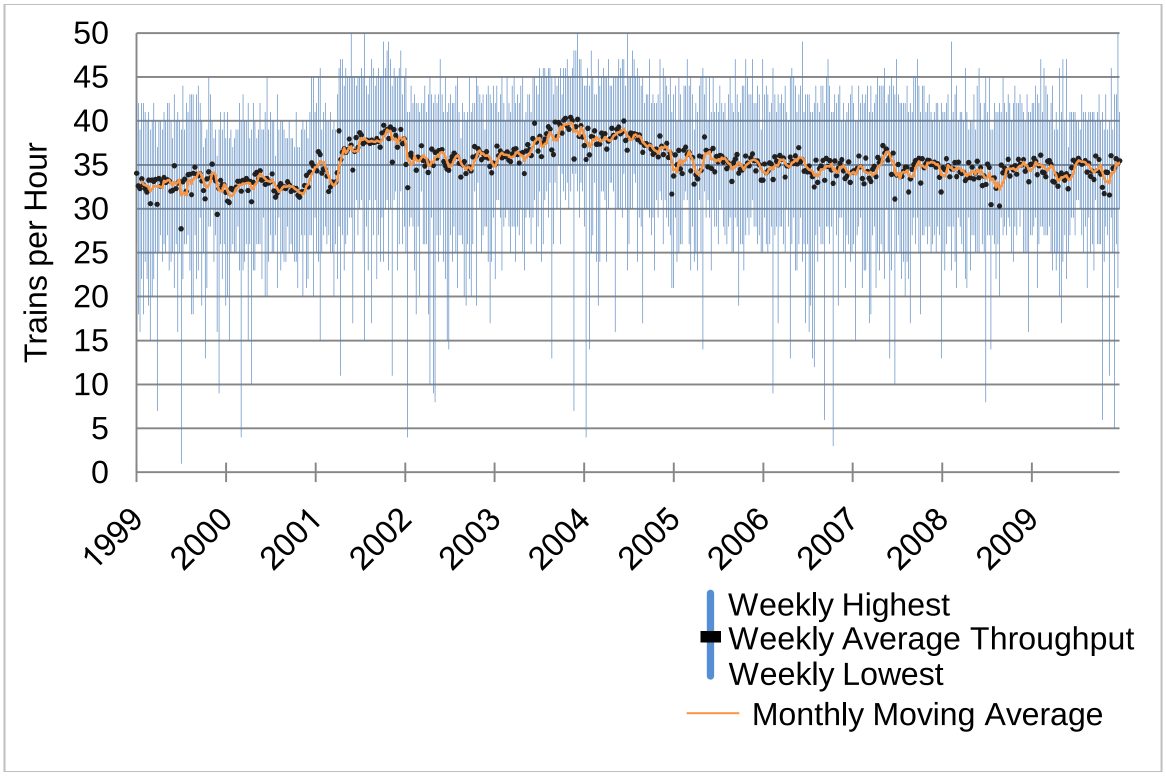

Chart 3-5 CBTC, Avg. Subway Throughput, ***Trains***, Peak Hours Only, (1999-2009)

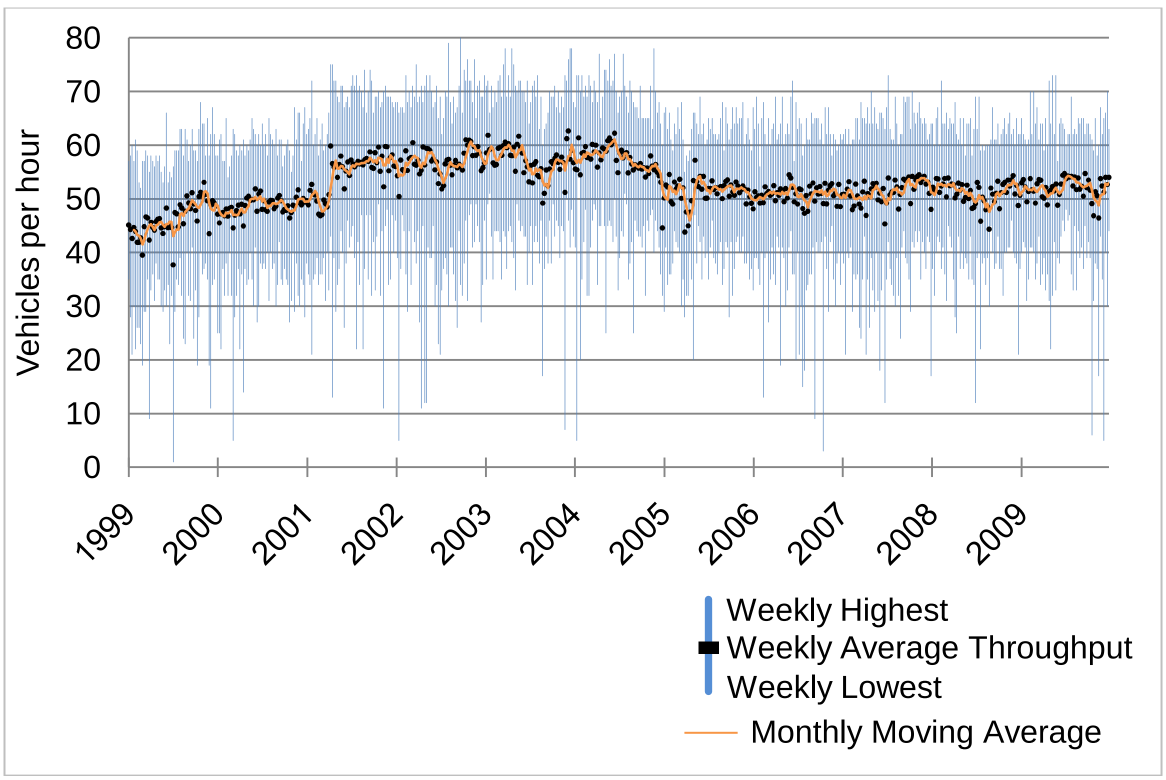

Chart 3-6 CBTC, Avg. Subway Throughput, ***Vehicles***, Peak Hours Only, (1999-2009)

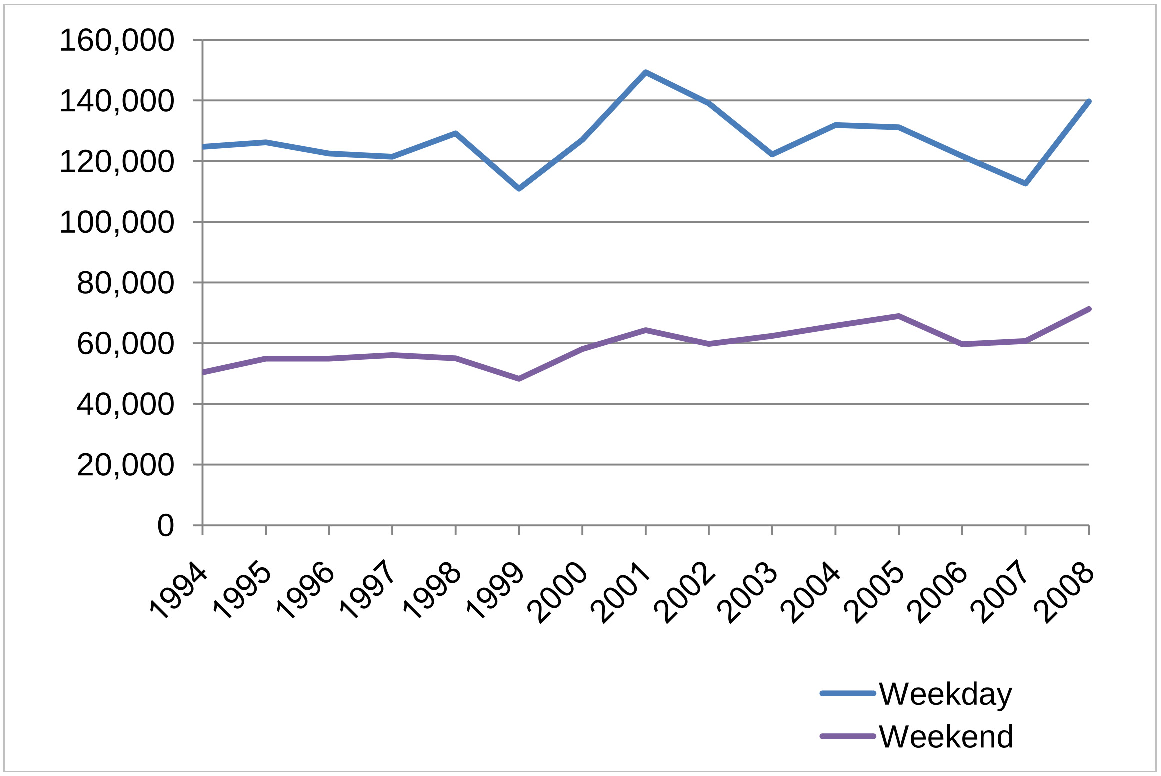

Chart 3-7 Avg. Muni Metro Daily Ridership (1994-2008)

3.3.2 Operations and Maintenance

Under CBTC, once trains were checked into the system at portals, they were routed through the Muni Metro subway according to settings input on the train operator's console. Inconsistencies in street level headways were no longer exacerbated by coupling and associated coupler breakdowns at the portals. The intensive coupler wear associated with coupling operations was eliminated. The SMC allowed central control operators (CCO) to dynamically speed up subway operation by decreasing dwells in order to make up delays. CBTC allowed for improved recovery time from bunched trains due to subway incidents. Each train was identified to the CCO by consist length, line, and status and could be individually held stationary and released if necessary. Platforms or sections of track could be bypassed if required by emergencies. Muni was free to schedule trains for lines relative to demand. In other words, trains on the lines could be scheduled independently of one another.

One specialized staff member was required to operate the SMC in the central control room. As in the FBTC era, overall LRV operations and communications, including street running trains, were handled by a separate CCO.

CBTC represented a digital, information system based technology requiring a much higher level of technical specialization to maintain than the fixed-block relay based train control. Maintenance procedures required knowledge of intermediate digital logic and computer software and hardware design principles. Although many maintenance tasks could be undertaken using tools like voltmeters and oscilloscopes, several diagnostic modes required the interpretation of hexadecimal data and the use of laptop computers.

Much of the SELTrac hardware and software was proprietary, limiting opportunities for competitive bidding for spare parts and support services. The computerized supervisory and train management system, although providing a much more granular description of the system state, created much larger amounts of data to store.

The inductive loop was laid between the running rails. This positioning made it susceptible to debris or damage from the passing LRVs. Any damage to the inductive loop cut off communication between the VOBC and VCC and required maintenance personnel to splice the cable.

4. Alternatives Analysis: CBTC and Fixed-Block Train Control

This section presents the assumptions used as the basis for the cost-benefit analysis as well as the results of the analysis.

Two alternatives are considered:

- CBTC as installed (CBTC Alternative);
- A continuation of original three-speed code fixed-block train control (FBTC Alternative).

Two forms of analysis are presented:

- A Cost-Benefit Analysis (CBA) comparing select quantifiable items;
- A qualitative analysis examining other items which are not easily quantifiable.

These forms of analysis are typically done in the planning stage of a project, not as in this case, after one alternative has been executed. This report adapts the concepts of a planning-level evaluation of alternatives to a post-project evaluation that has the benefit of historical data.

The CBA is based on spreadsheet models developed to represent the operation of the Muni Metro system. These models attempt to represent as closely as possible the historical record while isolating effects particular to the implementation of CBTC. Due to some of the assumptions inherent to this modeling, the results of this analysis should not be interpreted as an actual account of current or past Muni Metro operating conditions. Instead, this analysis evaluates the relative capabilities of a CBTC-based system against a conventional fixed-block train control system in the context of the Muni Metro system.

4.1 Definition of Analysis Alternatives

Both alternatives include construction of the MMT. Issues deemed critical to evaluating the project were developed after discussion with Muni staff and examination of the historical record.

4.1.1 CBTC as Installed (CBTC Alternative)

This alternative assumes CBTC train control equipment is installed in parallel with the existing conventional fixed-block signaling system between the Embarcadero Station and West Portal (dual mode configuration) and CBTC only equipment in the MMT (no existing conventional fixed-block signaling). Other attributes include:

1. Safety – Full moving-block automatic train control and signal system. Safe separation of trains at all times.
2. Reliability – Solid-state computer-based train control technology.
3. Throughput – Significant improvement in throughput (maximum sustained 45 trains per hour, peak one minute headways).
4. Cost – $104 million (2010 dollars, includes project management and MMT signaling).[35]
5. Disruption – Implemented alongside existing fixed-block train control. Although the project was intended to minimize effects to LRV service,

implementation contributed to a brief but moderate to severe service interruption.

6. Operational Costs – Significant retraining required for train operators and central control staff. SMC requires a dedicated computer operator in central control.
7. Maintenance Costs – Significant retraining required for vehicle and wayside signal maintenance staff. Sole source supplier for replacement parts and diagnostic test equipment. Reduction in signal maintenance effort.

4.1.2 Original three-speed code fixed-block system (FBTC Alternative)

This alternative assumes that the existing capabilities of the three-speed code fixed-block system, installed between the Embarcadero Station and West Portal, is maintained, and that the system is overhauled to extend its life to be equivalent to a newly installed CBTC system. New fixed-block system equipment will also be installed in the MMT. Throughput is limited by the original design of the train control system. Other attributes and/or changes include:

1. Safety - No improvement in safety.
2. Reliability - Continued reliance on transit industry service-proven relay based technology.
3. Throughput - No change in throughput (peak 23-26 trains per hour).
4. Cost - $116 million (2010 dollars, includes project management and MMT signaling).
5. Disruption - Minimal to moderate service interruption.
6. Operational Costs - No change.
7. Maintenance Costs - Continued maintenance of transit industry service-proven relay based technology.

4.2 Cost-Benefit Analysis (CBA)

4.2.1 Methodology

A typical transportation project CBA synthesizes as many influences of a project on the environment, society, and the taxpayer as possible. This type of analysis is used by stakeholders to determine whether a project is a wise investment and to compare a project to alternative solutions. The analysis in this report is based on TCRP Report 78 - Estimating the Benefits and Costs of Public Transit Projects.

The CBA methodology is dependent on the ability to monetize all of the costs and benefits over the lifecycle of a transportation project. The analysis in this report will focus on primary impacts over the 30 year lifecycle for both alternatives analyzed. The values of all costs and benefits over the life of a project are synthesized and summed using the dollar value of a single year, typically the present year. This single, present-time, dollar value of a time series of costs and benefits is referred to as the net present value (NPV) and is the basis for a comparison of the alternatives.

Two CBAs are performed; henceforth referred to as the Primary and Secondary CBA. Each CBA is based on a separate spreadsheet model of system operation and resulting costs and benefits.

In both CBAs, the operation of the FBTC Alternative is the same, basically operating at maximum capacity, and represented the conditions just prior to the implementation of CBTC. The CBAs only differ by the assumption of the frequency of service within the CBTC Alternative. The Primary CBA assumes the subway throughput and headways deduced from CBTC period historical records. These records suggest lower subway throughput in *vehicles* per hour and fewer trains operating systemwide after the implementation of CBTC.

The Secondary CBA assumes that subway throughput in *vehicles* per hour and the number of systemwide operating trains are consistent both before and after project implementation. The frequency of service represented in the Secondary CBA has never been implemented with CBTC, but provides a different basis for comparison of CBTC and FBTC.

A separate evaluation will compare the alternatives qualitatively from the perspective of the transit agency. Alternatives will be scored based upon how well they support the primary project objectives.

4.2.2 Types of Transit Impacts

A wide variety of criteria and metrics are available with which to assess the overall value of a transit project. The boundaries of a study can be limited to the transit agency itself or can include the municipality in which the project is located.

Typical primary impacts include:

1. Transit agency
    a. Internal planning costs
    b. Capital costs
    c. Rolling stock capital costs (change in # of vehicles and facilities)
    d. Transit vehicle accidents/collisions
    e. Transit vehicle operations costs
    f. Central control operator/dispatcher operations costs
    g. Rolling stock maintenance costs
    h. Wayside equipment maintenance costs
2. User
    a. Costs of alternative transportation such as automobile use (ownership, operation, parking)
    b. Wait time, in-vehicle time, and travel conditions for both rapid transit and automobile travel
    c. Congestion, user comfort for both rapid transit and automobile travel.
    d. Relative safety of rapid transit vs. automobiles

Typical secondary impacts include:

1. Economic
    a. Economic activity due to increased mobility
    b. Property values

2. Environmental
    a. Pollution of automobile use
    b. Fossil fuel conservation
    c. Noise
3. Societal
    a. Increased mobility
    b. Congestion
    c. Roadway (traffic services, road facilities, land value)
    d. Barrier effect

4.2.3 Impacts Used in this Cost-Benefit Analysis

This analysis is largely based on the primary impacts which could be modeled without overly onerous assumptions. The analysis boundary is the Muni Metro service area. Primary impacts addressed are Muni direct capital and O&M costs related to the train control system and user benefits. User benefits derive from changes in passenger level-of-service due to the upgrade of the train control system. The only user benefits that were monetized for the CBA were wait time and in-vehicle time.

Secondary impacts are not included in this analysis. Muni Metro represents the main artery for LRV service in San Francisco. Any changes to Muni Metro service will impact LRV operations citywide and consequently have some local effects. Given the tremendous size and complexity of the local economy, isolating the economic and social effects of a variation in an existing service, as opposed to initiation of new service, requires analysis beyond the scope of this report.

The following sections examine whether impacts to Muni and passenger level-of-service can be applied to the CBA.

4.2.3.1 Impacts on Muni Direct Costs

Changes in fleet size

Over the period of implementation, Muni's LRV fleet changed from a mix of approximately 136 SLRVs and LRV2s to 151 LRV2s in the early 2000s. Although analysis revealed changes in the theoretical number of operating trains, it is difficult to verify any actual impact CBTC may have had on the required fleet size and corresponding required vehicle maintenance and facilities requirements. Therefore, the CBA does not distinguish any cost difference between the two alternatives based on changes in fleet size.

Changes in systemwide number of operating trains

Analysis of the historical record suggests that fewer trains are operating in the post implementation period. The number of operating trains in both the pre- and post-project periods have been normalized to current (2010) round trip times. Although this does not explicitly represent FBTC conditions, it allows for better direct comparison of changes in system operating characteristics due to CBTC.

The analysis shows that the (normalized) FBTC Alternative utilizes 81 trains operating during off-peak hours and 98 trains operating during peak hours. The CBTC Alternative, due to increased scheduling flexibility and operating efficiencies, utilizes fewer operating trains while still meeting ridership demand. This alternative assumes 62 trains operated during off-peak hours and 72 trains during peak hours.

Several important additional assumptions underlie these estimates of the number of operating trains. See Appendix A for additional information.

Changes in maintenance effort

This analysis estimates that under the FBTC Alternative wayside train control maintenance for the 5.8-mile tunnel and subway portions requires approximately 950 labor-hours per mile per year. The CBTC Alternative is estimated to require 350 labor-hours per mile per year. The FBTC Alternative *vehicle* train control maintenance effort is estimated at 16 labor-hours per year. The CBTC Alternative maintenance effort is estimated at 18 labor-hours per vehicle per year.

CBTC negated the need for maintenance to couplers formerly required due to intensive coupler wear at the portals. However, data on the maintenance cost savings is not available and was not included in the analysis.

Under the fixed-block signaling system, track occupancy currents also monitored the integrity of the rail. Any break in the rail, which could cause a derailment, stopped the flow of current, and caused the indication of an occupied block. The CBTC inductive loop did not monitor the integrity of the rail. Thus Muni is required to schedule bi-yearly ultrasonic broken rail detection.

Changes in train control related incidents

Incidents such as overspeed penalty stops or collisions between trains can cause passenger injury and may damage vehicles. Possible costs from these incidents include vehicle repair, litigation, and damages paid to injury claimants.

Analysis of incident logs reveals a doubling of in-service train control related incidents from approximately 0.4 per day under fixed-block signaling to 0.9 per day under CBTC. Although the analysis can attribute incidents to the train control system (either fixed-block or communications-based), detailed descriptions of the types of incidents, their severity, or financial impact are not available. Therefore, the CBA does not distinguish any cost difference between the two alternatives based on these incidents.

Changes in operations staff

CBTC eliminates the need for coupling supervisors at both the West and Duboce Portals. In addition, one fewer supervisor is needed to oversee LRV operations at the Embarcadero Station. In the Control Center, an additional staff member is required to operate the CBTC system. Overall, two fewer staff members are used in the CBTC Alternative compared to the FBTC Alternative.

4.2.3.2 Impacts on Passenger Level-of-Service

The monetization of impacts for the CBA is dependent on data that demonstrates changes in passenger wait or in-vehicle travel times due to changes in headways during the transition to CBTC and beyond. The monetary value of in-vehicle travel and station wait time is a key assumption in the calculation of the CBA. In-vehicle travel time is defined as time spent on the LRV in transit. Wait time is defined as time spent waiting at stations. Waiting times are calculated as one half of a headway.

Changes in passenger wait times

Average passenger wait times are calculated as one-half of the headway time. Passenger wait times vary according to the assumptions inherent to either the Primary of Secondary CBA.

Changes in in-vehicle travel times

The phasing out of coupling and uncoupling operations eliminated roughly two minutes from each passenger trip into or out of the Muni Metro subway.[36] Changes in travel times due to changes in train speed and speed regulation in the subway were not available and not included in the CBA. While delays appeared to diminish under CBTC, reduction of in-vehicle travel times due to fewer delays was not monetized in the CBA. Both models assume that the FBTC passenger's in-vehicle travel time is 2 minutes longer that the CBTC passenger's if the FBTC passenger traverses a portal.

Changes in variability and arrival uncertainty

Schedule adherence in the FBTC period was affected by variability in train arrival times due to ripple effects from the coupling and uncoupling of trains at portal entrances. CBTC eliminated the need for coupling, although street running operations still significantly affected headway variability. Data indicating changes in on-time performance is not available although this was likely a significant contributing factor to changes in passenger experience.

After the implementation of CBTC, arrival uncertainty was somewhat mitigated by a passenger information system that provided arrival times for incoming trains. While differences exist, the CBA does not distinguish any monetized difference between the two alternatives based on changes in variability and arrival uncertainty.

Changes in travel conditions

User in-vehicle travel time costs can be modeled to increase in crowded transit vehicles. No data exists to demonstrate changes in passenger travel conditions and this was not considered in the CBA.

Shifts in passenger mode

Changes in ridership can indicate shifts in mode share from automobile to light rail. These shifts can occur from both automobiles and buses to light rail or vice versa and would represent public response to changes in capacity or headways. These changes can be monetized according to changes in the environmental and social impacts of automobile use. Ridership did not change in a consistent fashion attributable to CBTC over the implementation period and data on mode shifts, if any, is unavailable. Therefore, the CBA does not distinguish any cost difference between the two alternatives based on shifts in passenger mode.

4.2.4 Key Cost-benefit Analysis Assumptions

The costs and benefits of the criteria discussed in 3.2.4 and 3.2.5 are calculated over the 30 year life of the system alternatives. A NPV analysis is used to determine the present year value of the time series for each alternative. The final NPVs for each alternative are compared. Differences between the NPVs are used to determine whether one alternative provides a value (benefit) over the other.

Significant changes occurred to the Muni Metro system outside of train control over the ten year planning, engineering and installation effort for the CBTC system. In addition to modifications in service and the construction of the MMT, several rail lines were extended. This analysis endeavors to isolate effects clearly attributable to the differences in the train control systems.

Many variables influence this cost-benefit analysis. These include passenger trips patterns, Muni LRV operating schemes and headways, and economic factors such as wage inflation and the cost of capital. Reasonable generalizations and assumptions are utilized to reduce the complexity of the model. Some key assumptions are provided below:

Regarding user benefits:

1. Only benefits due to differences in passenger waiting and in-vehicle travel times are analyzed. While CBTC affords many additional benefits such as increased real-time LRV location data, such benefits are difficult to accurately monetize, and were not considered.
2. Average system wait times are derived from average system headways; the headways input into the CBA are a function of both scheduled headways and Muni Metro subway throughput. In general, headways are weighted to achieve a subway throughput target. Average wait times are also influenced by the distribution of passenger trips by origin and destination.
3. In-vehicle travel time is valued at 50% of the prevailing wage rate, wait time is valued at 100% of prevailing wage which was assumed to be $23.20 per hour per passenger (2010 dollars).[37]

Regarding service level representations in the model:

1. Only two rates of service levels are represented: peak and off-peak. While service levels vary throughout the day, an average level for all peak and off-peak hours was used to simplify the model.
2. For the purposes of this analysis, peak hours are defined as weekdays from 7:00-10:00 AM and from 4:00-7:00 PM.[38]
3. While actual service levels do vary seasonally, this is not taken into consideration in the model.

Regarding throughput:

1. For the FBTC Alternative, Muni Metro subway throughput is assumed to be 20 trains per hour off-peak and 25 trains per hour peak. All trains operating under the FBTC Alternative are coupled at portals.
2. For the CBTC Alternative, Muni Metro subway throughput is assumed to be 30 trains per hour off-peak and 35 trains per hour peak in the Primary CBA

and 40 trains per hour off-peak and 50 trains per hour peak in the Secondary CBA. After implementation of CBTC, no coupling occurred.

Regarding number of systemwide operating trains:

1. The number of system-wide operating trains are based upon round trip times for the individual lines, subway throughput, coupling configurations, and headways.
2. In general, the increased operating efficiencies due to CBTC and the elimination of coupling allowed Muni to serve the same ridership with fewer trains operating at one time as represented in the Primary CBA.
3. The Secondary CBA assumes an equal number of system-wide operating trains for both alternatives.

Regarding the system size and lines in service:

1. While several changes in the system infrastructure occurred before, after, and during the implementation of CBTC, both alternatives and both models assume the system size and lines operated in 2010.

Regarding passenger travel patterns:[39]

1. 30% of passenger trips occur wholly within the Muni Metro subway, half of which are wholly between the Embarcadero and Van Ness Stations.
2. 70% of passenger trips cross a portal threshold.
3. 50% of passenger trips occur during peak hours.

Regarding capital costs:

1. This analysis assumes that the full cost of either installing the CBTC system or overhauling the fixed-block signaling system is incurred at Year 1.
2. All cases include the cost of signaling the MMT portion of the Muni Metro.
3. Capital costs are escalated at 3% per year.

Additional assumptions:

1. The cost of capital is assumed to be five percent.
2. Muni O&M wage costs as described in the Appendix are assumed to be burdened at a multiplier of three.
3. Muni wages and the monetized value of passenger wait and in-vehicle travel time increases at a rate of three percent per year.

4.2.5 Monetization Conclusions

Two CBAs are conducted. The assumptions that underlie the Primary CBA are based upon operating characteristics derived from the historical record. The Secondary CBA assumes that the two alternatives operate with an equal number of systemwide trains and equal subway *vehicle* throughput. See Appendix B for detailed calculations of the NPV for both alternatives and additional supporting calculations.

4.2.5.1 Primary CBA

With CBTC in the subway, coupling delays are eliminated. Fewer trains are operating than under the FBTC Alternative. This is consistent with the historical record, and can be justified by the scheduling flexibility inherent to a lack of coupling and increased subway throughput due to CBTC.

Fewer operating trains mean that systemwide average wait times are slightly longer with the CBTC Alternative. Each year, FBTC Alternative passengers spent approximately 365,000 passenger-hours of in-vehicle travel due to train coupling. In the CBTC Alternative, passengers are not experiencing coupling delays but are spending approximately 300,000 additional passenger-hours waiting at stations.[40] Although wait times for trips confined to the subway are shortened considerably for the CBTC Alternative, these shortened wait times are not enough to upset the overall lengthening of wait times at surface stations.

Even though system-wide average headways within the CBTC Alternative are longer than the FBTC Alternative, Muni retains the capability of operating more trains to provide shorter headways. This is represented in the Secondary CBA. The Primary CBA demonstrates that the FBTC Alternative has a slight advantage over the CBTC Alternative when only the value of wait times are considered.

Since fewer trains are operated in the CBTC Alternative, train operations costs are much lower providing a significant savings in total vehicle operating costs over the FBTC Alternative. Fewer supervisory staff are also assumed under the CBTC Alternative. The O&M savings in year one for the CBTC Alternative are approximately $16 million. This more than makes up the approximately $2 million advantage that the FBTC Alternative holds in estimated passenger benefits.

The NPV of the CBTC Alternative relative to the FBTC Alternative for this CBA is $395 million over the 30 year life of the system. That is, CBTC provides a total net benefit of $395 million to the Muni Metro service area (see Table 4-1for summary).

NPV of maintenance benefits with CBTC:	$ 7,020,000
NPV of operations benefits with CBTC:	$ 439,640,000
NPV of capital cost for CBTC over FBTC:	$ 12,140,000
NPV for transit agency:	$ 458,800,000
NPV of travel time benefits (no coupling)	$ 97,890,000
NPV of benefits due to changes in wait times:	$ (161,650,000)
NPV for passengers:	$ (63,760,000)
Total NPV (passengers + agency):	$ 395,040,000

Table 4-1 Summary of NPV of Primary CBA

4.2.5.2 Secondary CBA

The Secondary CBA assumes that the two alternatives operate with an equal number of systemwide trains and equal subway *vehicle* throughput. Under this assumption, there is little difference in vehicle operating costs between alternatives. Without coupling and with increased subway throughput due to CBTC, scheduling of trains across Muni lines can occur in a much more evenhanded fashion. Headways for passengers riding the surface K/T and M lines decrease by four minutes. Headways in the subway reach just above one minute (50 *trains* per hour).[41] As in the Primary CBA, trip times are reduced by the elimination of coupling at portals.

As in the Primary CBA, there are some additional benefits from the lower capital cost of the CBTC Alternative and lower train control maintenance costs.

In this CBA, the overwhelming source of benefits is the reduction in wait times at stations.[42] The NPV of the CBTC Alternative relative to the FBTC Alternative for the Secondary CBA is $305 million over the 30 year life of the system (see Table 4-2). That is, CBTC provides a total net benefit of $305 million to the Muni Metro service area (see Table 4-2 for summary).

NPV of maintenance benefits with CBTC:	$ 7,020,000
NPV of operations benefits with CBTC:	$ 4,480,000
NPV of capital cost for CBTC over FBTC:	$ 12,140,000
Total NPV for transit agency:	$ 23,640,000
NPV of travel time benefits (no coupling)	$ 97,890,000
NPV of benefits due to changes in wait times:	$ 183,310,000
Total NPV for passengers:	$ 281,200,000
Total NPV (passengers + agency):	$ 304,840,000

Table 4-2 Summary of NPV of Secondary CBA

4.3 Qualitative Analysis

A qualitative analysis was used to compare the two alternatives. This type of evaluation allows for the consideration of benefits that directly impact the transit agency and system operators. This can be used, in conjunction with the CBA, to assess the overall value of a project.

4.3.1 Methodology and Evaluation Criteria

The alternatives defined in Section 3.1 were scored by the authors of this report according to a weighted evaluation methodology using criteria including safety, reliability, capacity, disruption, and cost. Individual criteria weights were determined using a criteria scoring matrix, in which the relative importance of each criteria was compared and given a numerical value. The highest scoring criteria became the most heavily weighted, and so on. See Appendix C for sample criteria weighing matrices.

The criteria include:

1. Safety - minimizes operational hazards and promotes the safe separation of vehicles.
2. Reliability - provides high level of system reliability and availability.
3. Capacity - maximizes passenger throughput and provides high level of passenger service.
4. Initial Cost - minimizes capital costs.
5. Disruption - minimizes disruption to passenger services during overhaul/implementation.

6. Operational Costs - minimizes number of supervisory personnel required to monitor and operate system.
7. Maintenance Costs - minimizes number of personnel and equipment required to maintain system.
8. Control and Diagnostic Capability - maximizes train management capability and provides high level of system status and diagnostic information.
9. Proprietary - minimizes dependence on proprietary technology.

The results of the criteria weighing exercise are shown in Chart 4-1.

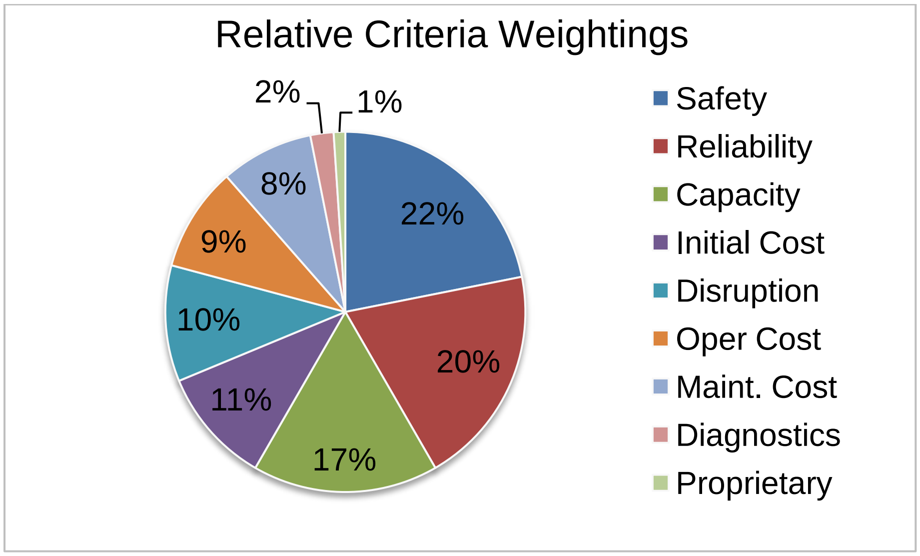

Chart 4-1 Criteria Weightings

4.3.2 Scoring and Final Result

Each alternative was scored according to extent to which it was determined to have satisfied the criteria: (1) poor, (2) fair, (3) good, (4) very good, and (5) excellent (see Table 4-3).

Criteria (weight)	CBTC	FBTC
Safety (22)	4.5	2.0
Reliability (20)	4.5	3.0
Capacity (17)	5.0	1.5
Initial Cost (11)	3.0	3.0
Disruption (10)	1.5	3.0
Operational Cost (9)	3.5	2.5
Maintenance Cost (8)	3.0	3.0
System Diagnostics (2)	5.0	1.0
Proprietary (1)	2.0	4.5
Weighted Score:	387	243
Percentage of Maximum:	78%	49%

Table 4-3 Qualitative Comparative Analysis Scoring

A perfect score would represent a train control system that allows for cost effective operation with good availability and high passenger level-of-service. The CBTC Alternative, despite some disruption during implementation, provides cost, safety, operational, and passenger level-of-service improvements that outweigh continuation of the status quo in the FBTC Alternative.

5. CBTC Implementation Projects at other Agencies

NYMTA launched a $326 million program to overlay CBTC onto the 22-mile Canarsie ‘L’ line in 1999. This represented the second ever CBTC re-signaling onto an operating railway in the United States after the Muni Metro subway. The ‘L’ line was chosen for the first implementation due the fact that it does not share track with any other subway lines. In order to ensure multiple sources for future procurements, NYMTA specified that interfaces be shared and coordinated between different carborne and wayside train control suppliers. Communications between wayside and vehicle are made with radio frequency antennas. Trains can operate simultaneously in manual mode, ATP-only cab-signaling, or in full ATO.[43] In early 2009 the Canarsie line began full ATO after several years of ATP only cab-signaling operation. Door operation is completely automatic although a operator remains on board and must operate a dead man button at regular intervals. In 2010, Thales was awarded a $343 million contract to upgrade NYMTA’s Flushing ‘7’ line from conventional fixed-block signaling system to SELTrac CBTC operating over radio frequencies. This upgrade is anticipated to be completed by 2017.[44] MTA plans to continue moving towards installation of CBTC on many of its existing lines.

The Southeastern Pennsylvania Transportation Authority (SEPTA) installed communications-based train control system in the subway portion of its Subway–Surface Trolley Lines. Five lines converge onto the subway which runs beneath downtown Philadelphia. The Bombardier CBTC system is limited to cab-signaled ATP for manual operation and does provide an automatic mode.

6. Similar Concurrent ATC Projects at SFMTA

Several projects are either underway or under development supporting the CBTC system. The SMCs in Central Control are being upgraded to a Windows-based operating system from OS/2. The VCC currently makes switch movement and routing requests through an interface to the original relay-based train control equipment throughout most of the subway. Muni has entered the design phase for final cutover to remove all elements of the original fixed-block system and allow the VCC direct control. This will reduce complexity, maintenance costs, and open up space in train control equipment rooms. In addition, a project is underway to replace the inductive loop, which has been spliced past recommended guidelines.

The Central Subway, scheduled to be completed in 2018, will run perpendicular to and underneath the Muni Metro in a tunnel from the South of Market neighborhood to the Chinatown neighborhood of San Francisco. Inductive loop based CBTC, provided by Thales, will be installed in order to maintain compatibility with the existing fleet. For additional redundancy and for ease of testing, it is anticipated that the Central Subway will be controlled by a VCC separate from the Muni Metro VCC.

7. Conclusion

Two alternatives are used as the basis for the cost-benefit analysis. The Primary CBA, based on the historical record, suggests that Muni experienced a reduction in operating costs due to a reduction in the number of operating trains required to meet demand. The Secondary CBA, in which the number of operating trains is equalized between

CBTC and FBTC, reveals significant user benefits in reduced wait times. For both CBAs, the total benefit of the CBTC Alternative offset the capital costs of CBTC and provides a net benefit to the Muni Metro service area. A qualitative analysis, focused on criteria relevant to the transit operator (Muni), also revealed an overall advantage of the CBTC Alternative.

7.1 Applicability to Other Properties

A unique set of circumstances govern Muni Metro operations. Five lines converge onto a single double track railway in the Muni Metro subway. A substantial portion of track shares the right-of-way with motor vehicle street traffic. Coupling operations were required at portals in the pre-CBTC period. Under CBTC, trains are required to electronically check into the system at portals. These characteristics limit applicability of this project to other projects when comparing operations on a system-wide level. Comparison across projects is best when standard transit project metrics such as passenger wait time, passenger travel time and vehicle loading are available and applicable. These types of metrics are independent of the type of train control technology employed and are monetized based on economic factors such as wage rates. The availability of such metrics is often limited and may or may not be employed in the planning phases to justify a project. Modes outside of heavy and light rail such as automated people movers, which are always grade separated and designed in pinched loop, loop, or shuttle configurations, benefit least from a consideration of such metrics. Such modes are limited to circulating within a particular activity area and do not interface with the public at large. Therefore, passenger level-of-service criteria based on wage rates are less applicable and other economic factors need to be taken into consideration. Direct comparison across projects would require accounting for such factors, particularly operating and implementation circumstances (such as those cited).

7.2 Lessons Learned

Although service proven on new systems with exclusive rights-of-way, integrating CBTC with an existing system of mostly a street running operation was unprecedented. At the outset of the project, passenger level-of-service was primarily impacted by street running delays, coupling at the portals, an inflexible fixed-block signaling system, LRV mechanical problems, switch malfunctions, and turn back time at the Embarcadero Terminal. An upgrade to CBTC could, at best, address the coupling and fixed-block signaling bottlenecks. Minor mitigation of street running delays could occur by computerized control of train dwell times at stations. Embarcadero turn back delays, including switch problems, were to be addressed separately with the MMT project. LRV mechanical problems were to be addressed by the complete replacement of the SLRVs with LRV2s. The simultaneous execution of these projects complicates any assessment of their individual contributions to overall service improvements.

Ultimately, the purpose of the project was to increase passenger level-of-service and provide a buffer for future increases in service. Passenger level-of-service is affected by wait time (headways), in-vehicle travel time, arrival uncertainty (schedule adhesion), and in-vehicle crowding on a system-wide level. Performance based specifications and metrics for measuring the effectiveness of any change in operations should have followed from these criteria. Monetization of these metrics, according to the generally accepted principles of a transportation cost-benefit study, provides the basis for evaluating the feasibility of any service change. A consistent increase in ridership relative to population change could have demonstrated a shift from automobile use to transit use. This increase did not occur.

Project goals were tied to increasing the throughput (trains per hour) of the subway portion of the system. The feasibility of achieving these goals was based upon theoretical civil limits of the track and switch layouts and did not necessarily take into account other sources of delays. While CBTC can support a minimum peak headway of one-minute, this does not occur in the Muni Metro subway in a sustained fashion for more than a few minutes. Actual sustained operating headways correspond to a maximum of approximately 45-48 trains per hour,[45] with the additional throughput necessary to recover from surface delays and train bunching.

While peak subway throughput in trains per hour increased, consist sizes in the subway decreased from three- and four-vehicle to one- and two-vehicle trains. The effective number of *vehicles* per peak hour through the subway decreased from about 80 to about 50. Ridership through the implementation period remained stable, however, indicating that due to the increased efficiencies of CBTC operation, fewer vehicles per hour were required to effectively move the same amount of passengers in the subway. In addition, CBTC can accommodate growth in passenger demand by allowing for an increase in tunnel throughput from 35 trains per hour today to 48 in the future, if necessary. The fixed-block train control system was at capacity.

7.3 Tips for Transit Agencies

Based on discussion with Muni staff and examination of documents related to the management and engineering of the project, several recommendations can be made to other transit agencies considering a similar CBTC implementation:

1. Define performance specifications based upon system-wide passenger level-of-service criteria including wait time (headways), in-vehicle travel time, arrival uncertainty (schedule adhesion), and capacity. Use these performance criteria to evaluate the feasibility and likelihood of success of train control modifications.
2. The implementation of several service changes concurrent with full CBTC operation caused passenger confusion and exacerbated any CBTC related issues. There should be an effort made to minimize changes to passengers' expected service patterns during implementation of any modification of train control.
3. Three capital improvement projects with a direct effect on passenger level-of-service; a new train control system, a new vehicle, and the MMT; were implemented simultaneously. Troubleshooting of train control issues was, for example, exacerbated by maintenance personnel unfamiliar with new vehicle mechanical and electrical systems. Evaluation of the effectiveness of any one project was precluded by the complex interrelationship between them. Consider staggering the implementation of capital improvement projects whose systems can have a direct impact on the functionality of others.

4. Transitioning from a fixed-block signaling based train control system to CBTC requires a dramatic shift in technological and business practices within the transit agency. Cultural challenges can represent the biggest obstacles to project success. Dedicated commitment from management at the highest levels to implement change is essential.
5. Maintaining project success beyond implementation requires effective understanding and practice of systems engineering and interface management within the transit agency.
6. Open architectures facilitate interoperability between equipment from different suppliers and maximize use of commercial off the shelf equipment. This opens up opportunities for competitive bidding not only during system procurement but later for spare parts and support services. As open train control standards mature, consider specifying open architectures in procurement documents.

Appendix A - Additional Cost-Benefit Analysis Assumptions

This appendix provides additional context for the assumptions that provided the basis for the CBA. For the purpose of this study, two alternatives were selected to be studied: CBTC and FBTC. These alternatives were input into two CBAs based upon differing CBTC operating scenarios. This section provides additional detailed information on some of the assumptions and methodology used in the analysis.

Overall, the following were considered:

1. The cost of operating and maintaining a CBTC vs. fixed-block signaling system, including portal supervisors.
2. Passenger time due to waiting at a station due to modified headways.
3. Passenger time due to elimination of coupling at the portals.
4. Cost and benefits associated with vehicle operation, specifically energy and labor expenses.

The following were not considered:

1. Any increase or decrease in farebox revenue due to changes in ridership or service.
2. Any changes in operating or maintenance costs due to non-train control related issues.
3. The costs of procuring new vehicles.
4. Savings due to vehicles not procured due to increased operating efficiencies.

Wait Time

For each year in the study, an average overall wait time per passenger is calculated from weekday, weekend, peak, and non-peak service characteristics. Although headways can vary throughout peak and non-peak service periods, a consistent headway is assumed for each service period for the purposes of this analysis. The average overall wait time, calculated for both the pre- and post-project periods, is the basic unit used to determine wait time changes and resulting user benefits. Any change in average wait time multiplied by the number of current riders is the user benefit (or cost) conferred to current riders of the system.

For the FBTC period, systemwide average passenger LRV station wait time is dependent on the ridership and headway for each line. After the implementation of CBTC, it was found that no matter the service characteristics, the average headway on the surface lines is equal to five times the subway headway.

Due to limitations in available data, several data sets are correlated in order to estimate the ridership on the lines for FBTC wait times. These data sets include historical ridership data and the Muni 2007 ‘Transit Effectiveness Project (TEP).’ Headways per line for FBTC peak hours are not well documented. Subway throughput for peak hours was measured at approximately 23-26 trains per hour several months before full implementation. Headways for FBTC non-peak hours are not available and are estimated to be just sufficient enough to ensure a maximum 12-minute headway systemwide (20 trains per hour in the subway).

Travel Time

Preliminary engineering studies for the CBTC system indicate that approximately two minutes were required per coupling operation at the portal entrances. Analysis of data collected from the TEP shows that roughly 30% of passenger trips are limited to the surface lines, 30% of passenger trips are limited to the Muni Metro subway portion of the system, and 40% of trips cross the threshold of either the Duboce or the West Portal at some point. This analysis assumes that the distribution and density of San Francisco commercial and residential development has not experienced significant change in the past 15 years.

Assuming passenger trip patterns remain relatively constant back into the FBTC period, 40% of passengers experienced coupling delays. The decrease in in-vehicle travel time due to lack of coupling multiplied by the number of riders that travel through portals is the user benefit conferred to riders of the system.

The change from fixed-block signaling to CBTC provided much finer control over the speed and distance between trains in the subway. Although it is arguable that reductions in in-vehicle travel times within the subway occurred, data is not available which quantifies this benefit.

Maintenance Costs

This analysis assumes that Muni has all the necessary resources with which to maintain the signaling system in a state of good repair. The maintenance costs described in the report do not include the hiring of additional staff or any training that may be required. At Muni, maintenance personnel are responsible for systemwide signaling equipment including street running LRV, subway LRV, and trolley bus signaling equipment. Maintenance tasks for both wayside and carborne LRV repair were developed based on APTA Recommended Practices, CBTC Maintenance Manuals and interviews with Muni staff. Specific maintenance procedures and schedules were not available for the FBTC period.

Changes In Ridership

Changes in ridership are not taken into consideration. An average of the Muni Metro ridership between 1994-2008 was used for all calculations.

Changes in Number of Operating Trains CBTC vs. Fixed-Block Signaling

Under the fixed-block signaling system, due to limitations in subway throughput, trains were required to meet a coupling partner at portal entrances. Trains had to be dispatched from terminals at headways that assured they would meet their partner at portals. This limited the flexibility to schedule headways for each line independently of each other. Consequently, some lines would be scheduled with enough operating trains to guarantee a train for its coupling partner, rather than scheduled to reflect the actual ridership demand of that line. If one line were scheduled to reflect ridership demand, its coupling partner would inevitably be over or under scheduled. After the implementation of CBTC in the subway, it was possible to schedule trains in a pattern much more responsive to ridership demand.

The number of operating trains can vary on a minute by minute basis. The number of operating trains is also influenced by ridership demand, fleet size, and budget. In order to produce a workable CBA, some idealizations have been made. The model used in this analysis limits estimates of the number of operating trains to either a peak or non-peak value. The number of operating trains in both the pre- and post-project periods have been normalized to current (2010) round trip times. Although this does not explicitly represent FBTC conditions, it allows for better direct comparison of changes in system operating characteristics due to CBTC.

Specific data on the number of operating trains during the FBTC period was unavailable from Muni. Analysis of the data contained in materials that were available (historical documents and preliminary engineering studies) are used to produce estimates for the purposes of the CBA. These estimates do not necessarily reflect past Muni operating conditions. Estimates of the number operating trains for the FBTC period are based upon round trip times for the individual lines, subway throughput, coupling configurations, and headways. Post-project headways are taken from schedules posted on timetables available on the World Wide Web. Estimates of the number operating trains for the post-project period are based upon round trip times for the individual lines, subway throughput, and headways.

All estimates of the number of operating trains include layover time. Operating hour costs in 2010 dollars includes $25 per hour for electricity which assumes 250 kW average power per train and $0.10 per kWh and $130 per hour for the operator (burdened).

Appendix B - Cost-Benefit Analysis Calculations

The following spreadsheets provide a detailed view of the calculations used to determine the net present value of the alternatives.

Yr	Capital cost	Train control maintenance costs	Operations costs		
			CCO	Portal supervisors	Vehicle
1	$ 116,390,000	$ 805,000	$ 300,000	$ 900,000	$ 76,273,080
2	$ -	$ 829,150	$ 309,000	$ 927,000	$ 78,561,272
3	$ -	$ 854,025	$ 318,270	$ 954,810	$ 80,918,111
4	$ -	$ 879,645	$ 327,818	$ 983,454	$ 83,345,654
5	$ -	$ 906,035	$ 337,653	$ 1,012,958	$ 85,846,024
6	$ -	$ 933,216	$ 347,782	$ 1,043,347	$ 88,421,404
7	$ -	$ 961,212	$ 358,216	$ 1,074,647	$ 91,074,046
8	$ -	$ 990,048	$ 368,962	$ 1,106,886	$ 93,806,268
9	$ -	$ 1,019,750	$ 380,031	$ 1,140,093	$ 96,620,456
10	$ -	$ 1,050,342	$ 391,432	$ 1,174,296	$ 99,519,069
11	$ -	$ 1,081,853	$ 403,175	$ 1,209,525	$ 102,504,642
12	$ -	$ 1,114,308	$ 415,270	$ 1,245,810	$ 105,579,781
13	$ -	$ 1,147,738	$ 427,728	$ 1,283,185	$ 108,747,174
14	$ -	$ 1,182,170	$ 440,560	$ 1,321,680	$ 112,009,589
15	$ -	$ 1,217,635	$ 453,777	$ 1,361,331	$ 115,369,877
16	$ -	$ 1,254,164	$ 467,390	$ 1,402,171	$ 118,830,973
17	$ -	$ 1,291,789	$ 481,412	$ 1,444,236	$ 122,395,903
18	$ -	$ 1,330,542	$ 495,854	$ 1,487,563	$ 126,067,780
19	$ -	$ 1,370,459	$ 510,730	$ 1,532,190	$ 129,849,813
20	$ -	$ 1,411,572	$ 526,052	$ 1,578,155	$ 133,745,307
21	$ -	$ 1,453,920	$ 541,833	$ 1,625,500	$ 137,757,667
22	$ -	$ 1,497,537	$ 558,088	$ 1,674,265	$ 141,890,397
23	$ -	$ 1,542,463	$ 574,831	$ 1,724,493	$ 146,147,109
24	$ -	$ 1,588,737	$ 592,076	$ 1,776,228	$ 150,531,522
25	$ -	$ 1,636,399	$ 609,838	$ 1,829,515	$ 155,047,468
26	$ -	$ 1,685,491	$ 628,133	$ 1,884,400	$ 159,698,892
27	$ -	$ 1,736,056	$ 646,977	$ 1,940,932	$ 164,489,858
28	$ -	$ 1,788,138	$ 666,387	$ 1,999,160	$ 169,424,554
29	$ -	$ 1,841,782	$ 686,378	$ 2,059,135	$ 174,507,291
30	$ -	$ 1,897,035	$ 706,970	$ 2,120,909	$ 179,742,509
NPV:	$ 116,390,000	$ 18,530,000	$ 6,900,000	$ 20,710,000	$ 1,755,450,000

Table B-1 Costs for FBTC Alternative

This table summarizes the yearly costs for the FBTC Alternative. Applicable to both the Primary and Secondary CBA. Additional capital expenditures for signal refurbishment or additional LRVs are not included. Vehicle operations costs derive from the number of operating trains. In this case 98 peak and 81 off peak. Vehicle operations costs include both driver labor hours and traction power costs (kWh). Wages are burdened x3 and increase 3% yearly. One CBTC central control LRV dispatcher is represented under the CCO column. Coupling supervisors at both portals and one supervisor at Embarcadero Terminal are represented under the portal supervisors column.

Yr	Capital cost	Train control maintenance costs	Operations costs		
			CCO	Portal supervisors	Vehicle
1	$104,250,000	$ 500,000	$ 600,000	$ -	$ 57,770,960
2	$ -	$ 515,000	$ 618,000	$ -	$ 59,504,089
3	$ -	$ 530,450	$ 636,540	$ -	$ 61,289,211
4	$ -	$ 546,364	$ 655,636	$ -	$ 63,127,888
5	$ -	$ 562,754	$ 675,305	$ -	$ 65,021,724
6	$ -	$ 579,637	$ 695,564	$ -	$ 66,972,376
7	$ -	$ 597,026	$ 716,431	$ -	$ 68,981,547
8	$ -	$ 614,937	$ 737,924	$ -	$ 71,050,994
9	$ -	$ 633,385	$ 760,062	$ -	$ 73,182,524
10	$ -	$ 652,387	$ 782,864	$ -	$ 75,377,999
11	$ -	$ 671,958	$ 806,350	$ -	$ 77,639,339
12	$ -	$ 692,117	$ 830,540	$ -	$ 79,968,520
13	$ -	$ 712,880	$ 855,457	$ -	$ 82,367,575
14	$ -	$ 734,267	$ 881,120	$ -	$ 84,838,602
15	$ -	$ 756,295	$ 907,554	$ -	$ 87,383,760
16	$ -	$ 778,984	$ 934,780	$ -	$ 90,005,273
17	$ -	$ 802,353	$ 962,824	$ -	$ 92,705,432
18	$ -	$ 826,424	$ 991,709	$ -	$ 95,486,594
19	$ -	$ 851,217	$ 1,021,460	$ -	$ 98,351,192
20	$ -	$ 876,753	$ 1,052,104	$ -	$ 101,301,728
21	$ -	$ 903,056	$ 1,083,667	$ -	$ 104,340,780
22	$ -	$ 930,147	$ 1,116,177	$ -	$ 107,471,003
23	$ -	$ 958,052	$ 1,149,662	$ -	$ 110,695,133
24	$ -	$ 986,793	$ 1,184,152	$ -	$ 114,015,987
25	$ -	$ 1,016,397	$ 1,219,676	$ -	$ 117,436,467
26	$ -	$ 1,046,889	$ 1,256,267	$ -	$ 120,959,561
27	$ -	$ 1,078,296	$ 1,293,955	$ -	$ 124,588,348
28	$ -	$ 1,110,645	$ 1,332,773	$ -	$ 128,325,998
29	$ -	$ 1,143,964	$ 1,372,757	$ -	$ 132,175,778
30	$ -	$ 1,178,283	$ 1,413,939	$ -	$ 136,141,052
NPV:	$104,250,000	$ 11,510,000	$ 13,810,000	$ -	$ 1,329,610,000

Table B-2 Primary CBA, Costs for CBTC Alternative, Years 1-30

This table summarizes the yearly costs for the CBTC alternative. Additional capital expenditures for signal refurbishment or additional LRVs are not included. Vehicle operations costs derive from the number of operating trains. Vehicle operations costs include both driver labor hours and traction power costs (kWh). Wages are burdened x3 and increase 3% yearly. One CBTC central control operator and one LRV dispatcher at central control are represented under the CCO column. No coupling supervisors are required.

Year	Capital cost difference	Maintenance cost difference	Operations cost difference		
			CCO	Portal supervisors	Vehicle
1	$ 12,140,000	$ 305,000	$ (300,000)	$ 900,000	$ 18,502,120
2	$ -	$ 314,150	$ (309,000)	$ 927,000	$ 19,057,184
3	$ -	$ 323,575	$ (318,270)	$ 954,810	$ 19,628,899
4	$ -	$ 333,282	$ (327,818)	$ 983,454	$ 20,217,766
5	$ -	$ 343,280	$ (337,653)	$ 1,012,958	$ 20,824,299
6	$ -	$ 353,579	$ (347,782)	$ 1,043,347	$ 21,449,028
7	$ -	$ 364,186	$ (358,216)	$ 1,074,647	$ 22,092,499
8	$ -	$ 375,112	$ (368,962)	$ 1,106,886	$ 22,755,274
9	$ -	$ 386,365	$ (380,031)	$ 1,140,093	$ 23,437,932
10	$ -	$ 397,956	$ (391,432)	$ 1,174,296	$ 24,141,070
11	$ -	$ 409,894	$ (403,175)	$ 1,209,525	$ 24,865,302
12	$ -	$ 422,191	$ (415,270)	$ 1,245,810	$ 25,611,261
13	$ -	$ 434,857	$ (427,728)	$ 1,283,185	$ 26,379,599
14	$ -	$ 447,903	$ (440,560)	$ 1,321,680	$ 27,170,987
15	$ -	$ 461,340	$ (453,777)	$ 1,361,331	$ 27,986,117
16	$ -	$ 475,180	$ (467,390)	$ 1,402,171	$ 28,825,700
17	$ -	$ 489,435	$ (481,412)	$ 1,444,236	$ 29,690,471
18	$ -	$ 504,119	$ (495,854)	$ 1,487,563	$ 30,581,185
19	$ -	$ 519,242	$ (510,730)	$ 1,532,190	$ 31,498,621
20	$ -	$ 534,819	$ (526,052)	$ 1,578,155	$ 32,443,579
21	$ -	$ 550,864	$ (541,833)	$ 1,625,500	$ 33,416,887
22	$ -	$ 567,390	$ (558,088)	$ 1,674,265	$ 34,419,393
23	$ -	$ 584,412	$ (574,831)	$ 1,724,493	$ 35,451,975
24	$ -	$ 601,944	$ (592,076)	$ 1,776,228	$ 36,515,534
25	$ -	$ 620,002	$ (609,838)	$ 1,829,515	$ 37,611,000
26	$ -	$ 638,602	$ (628,133)	$ 1,884,400	$ 38,739,331
27	$ -	$ 657,760	$ (646,977)	$ 1,940,932	$ 39,901,510
28	$ -	$ 677,493	$ (666,387)	$ 1,999,160	$ 41,098,556
29	$ -	$ 697,818	$ (686,378)	$ 2,059,135	$ 42,331,512
30	$ -	$ 718,752	$ (706,970)	$ 2,120,909	$ 43,601,458
NPV:	$ 12,140,000	$ 7,020,000	$(6,900,000)	$ 20,710,000	$ 425,830,000

Table B-3 Primary CBA, Differences In Costs Between FBTC And CBTC Alternatives, Years 1-30.

Positive number represents benefit (savings) of CBTC over FBTC. In the Primary CBA, fewer trains are operating and there are significant savings in vehicle operations costs.

Year	Trip time benefit	Wait time benefit
1	$ 4,253,156	$ (7,023,649)
2	$ 4,380,751	$ (7,234,359)
3	$ 4,512,173	$ (7,451,389)
4	$ 4,647,538	$ (7,674,931)
5	$ 4,786,965	$ (7,905,179)
6	$ 4,930,573	$ (8,142,334)
7	$ 5,078,491	$ (8,386,604)
8	$ 5,230,845	$ (8,638,203)
9	$ 5,387,771	$ (8,897,349)
10	$ 5,549,404	$ (9,164,269)
11	$ 5,715,886	$ (9,439,197)
12	$ 5,887,363	$ (9,722,373)
13	$ 6,063,983	$ (10,014,044)
14	$ 6,245,903	$ (10,314,466)
15	$ 6,433,280	$ (10,623,900)
16	$ 6,626,278	$ (10,942,616)
17	$ 6,825,067	$ (11,270,895)
18	$ 7,029,819	$ (11,609,022)
19	$ 7,240,713	$ (11,957,292)
20	$ 7,457,935	$ (12,316,011)
21	$ 7,681,673	$ (12,685,492)
22	$ 7,912,123	$ (13,066,056)
23	$ 8,149,487	$ (13,458,038)
24	$ 8,393,971	$ (13,861,779)
25	$ 8,645,790	$ (14,277,633)
26	$ 8,905,164	$ (14,705,962)
27	$ 9,172,319	$ (15,147,140)
28	$ 9,447,489	$ (15,601,555)
29	$ 9,730,913	$ (16,069,601)
30	$ 10,022,841	$ (16,551,689)
NPV:	$ 97,890,000	$ (161,650,000)

Table B-4 Primary CBA, Wait And Trip Time Benefits, Years 1-30

Positive numbers represents benefit (savings) of CBTC over FBTC. See Table B-5 through Table B-8 for summary of wait and trip time benefits for year 1. Monetization of wait and trip times is based on the prevailing wage which increases 3% a year. In the Primary CBA, fewer trains are operating and wait times are slightly longer after the cutover to CBTC. Trip times are shorter due to lack of coupling delays.

Passenger trip characteristics	Weekday Ridership	Non-peak periods			Peak periods			All
		Headway	Ridership	Wait time	Peak headway	Ridership	Wait time	Average weekday wait time
Embarc. to Van Ness only	19,100	2.00 min	9,550	1.00 min	1.71 min	9,550	0.86 min	0.93 min
Van Ness to West Portal only	19,100	3.33 min	9,550	1.67 min	2.86 min	9,550	1.43 min	1.55 min
J,K,L,M,N through portal	89,132	10.00 min	44,566	5.00 min	8.57 min	44,566	4.29 min	4.64 min
							Average wait time for all riders:	3.62 min

Table B-5 Primary CBA, Wait Time Calculations, Weekdays

Passenger trip characteristics	Weekend Ridership	Headway	Wait time
Embarc. to Van Ness only	8,911	2.00 min	1.00 min
Van Ness to West Portal only	8,911	3.33 min	1.67 min
J,K,L,M,N through portal	41,583	10.00 min	5.00 min
		Average wait time for all riders:	3.90 min

Table B-6 Primary CBA, Wait Time Calculations, Weekends

Passenger trip characteristics	Weekday daily pass. on would-be coupling trains	Averted coupling delay	Yearly averted coupling delay	Weekend daily pass. on would-be coupling trains	Weekend daily averted coupling delay	Yearly weekend averted coupling delay
Embarc. to Van Ness only	-	-	-	-	-	-
Van Ness to West Portal only	-	-	-	-	-	-
J,K,L,M,N through Portal	89,132	1,188 hrs	308,880 hrs	16,633	554 hrs	57,616 hrs

Table B-7 Averted Coupling Delay (Applicable To Both Primary And Secondary CBA)

Total hours of coupling time averted:	366,651 hrs
Benefit of coupling time averted:	$4,253,156
FBTC weekday wait time:	3.13 min
FBTC weekend wait time:	3.58 min
FBTC average wait time:	3.20 min
CBTC weekday wait time:	3.62 min
CBTC weekend wait time:	3.90 min
CBTC average wait time:	3.67 min
Difference in wait time:	-0.47 min
Yearly ridership:	39,284,076
Total difference in wait time :	-302,743 hrs
Benefit of wait time change this year:	$ (7,023,649)

Table B-8 Primary CBA, Summary Of Trip And Wait Time Benefits, Year 1

FBTC Non-Peak

Line	Round trip time	Scheduled Headway	Modified Headway	# Cars per train	Train/hr subway	Cars/hr subway	Operating Trains	Operating Cars
J	90.9	6.0	6.0	1.5	10.0	15.0	16.0	24
K/T	184.7	12.0	12.0	1.5	5.0	7.5	16.0	24
L	91.6	12.0	12.0	1.5	5.0	7.5	8.0	12
M	113.8	6.0	6.0	1.5	10.0	15.0	19.0	28.5
N	127.8	6.0	6.0	1.5	10.0	15.0	22.0	33
				Total:	40	60	81.00	121.5

FBTC Peak

Line	Round trip time	Scheduled Headway	Modified Headway	# Cars per train	Train/hr subway	Cars/hr subway	Operating Trains	Operating Cars
J	90.9	5.0	4.4	1.5	13.6	20.5	21.0	31.5
K/T	184.7	12.0	10.6	1.5	5.7	8.5	18.0	27
L	91.6	6.0	5.3	1.5	11.4	17.0	18.0	27
M	113.8	12.0	10.6	1.5	5.7	8.5	11.0	16.5
N	127.8	5.0	4.4	1.5	13.6	20.5	30.0	45
				Total:	50	75	98.00	147.0

CBTC Non-Peak

Line	Round trip time	Scheduled Headway	Modified Headway	# Cars per train	Train/hr subway	Cars/hr subway	Operating Trains	Operating Cars
J	88.4	10.0	10.0	1.5	6.0	9.0	9.0	13.5
K/T	182.2	10.0	10.0	1.5	6.0	9.0	19.0	28.5
L	89.1	10.0	10.0	1.5	6.0	9.0	9.0	13.5
M	111.3	10.0	10.0	1.5	6.0	9.0	12.0	18
N	125.3	10.0	10.0	1.5	6.0	9.0	13.0	19.5
				Total:	30.0	45	62.00	93.0

CBTC Peak

Line	Round trip time	Scheduled Headway	Modified Headway	# Cars per train	Train/hr subway	Cars/hr subway	Operating Trains	Operating Cars
J	88.4	9.1	9.1	1.5	6.6	9.9	10.0	15
K/T	182.2	9.0	9.0	1.5	6.7	10.0	21.0	31.5
L	89.1	8.1	8.1	1.5	7.4	11.1	12.0	18
M	111.3	9.5	9.5	1.5	6.3	9.5	12.0	18
N	125.3	7.5	7.5	1.5	8.0	12.0	17.0	25.5
				Total:	35.0	52.5	72.00	108.0

Table B-9 Primary CBA, Number Of Operating Trains, Calculations

Note that the number of operating trains are different for the FBTC and CBTC Alternatives. The Primary CBA is based on historical records. Number of operating trains is a function of the scheduled headway, expected throughput, and round trip time. Scheduled headways are used as the basis with which to generate modified headways, which are calculated to meet throughput goals (trains per hour in the subway). Trains per hour for the FBTC tables are shown as uncoupled. Divide by two for number of coupled trains. Roundtrip times are based on the scheduled roundtrip time (for year 2010) plus an additional 25% for layover/recovery.

Yr	Capital cost	Train control maintenance costs	Operations costs		
			CCO	Portal supervisors	Vehicle
1	$ 104,250,000	$ 500,000	$ 600,000	$ -	$ 76,678,680
2	$ -	$ 515,000	$ 618,000	$ -	$ 78,979,040
3	$ -	$ 530,450	$ 636,540	$ -	$ 81,348,412
4	$ -	$ 546,364	$ 655,636	$ -	$ 83,788,864
5	$ -	$ 562,754	$ 675,305	$ -	$ 86,302,530
6	$ -	$ 579,637	$ 695,564	$ -	$ 88,891,606
7	$ -	$ 597,026	$ 716,431	$ -	$ 91,558,354
8	$ -	$ 614,937	$ 737,924	$ -	$ 94,305,105
9	$ -	$ 633,385	$ 760,062	$ -	$ 97,134,258
10	$ -	$ 652,387	$ 782,864	$ -	$ 100,048,285
11	$ -	$ 671,958	$ 806,350	$ -	$ 103,049,734
12	$ -	$ 692,117	$ 830,540	$ -	$ 106,141,226
13	$ -	$ 712,880	$ 855,457	$ -	$ 109,325,463
14	$ -	$ 734,267	$ 881,120	$ -	$ 112,605,227
15	$ -	$ 756,295	$ 907,554	$ -	$ 115,983,383
16	$ -	$ 778,984	$ 934,780	$ -	$ 119,462,885
17	$ -	$ 802,353	$ 962,824	$ -	$ 123,046,772
18	$ -	$ 826,424	$ 991,709	$ -	$ 126,738,175
19	$ -	$ 851,217	$ 1,021,460	$ -	$ 130,540,320
20	$ -	$ 876,753	$ 1,052,104	$ -	$ 134,456,530
21	$ -	$ 903,056	$ 1,083,667	$ -	$ 138,490,225
22	$ -	$ 930,147	$ 1,116,177	$ -	$ 142,644,932
23	$ -	$ 958,052	$ 1,149,662	$ -	$ 146,924,280
24	$ -	$ 986,793	$ 1,184,152	$ -	$ 151,332,009
25	$ -	$ 1,016,397	$ 1,219,676	$ -	$ 155,871,969
26	$ -	$ 1,046,889	$ 1,256,267	$ -	$ 160,548,128
27	$ -	$ 1,078,296	$ 1,293,955	$ -	$ 165,364,572
28	$ -	$ 1,110,645	$ 1,332,773	$ -	$ 170,325,509
29	$ -	$ 1,143,964	$ 1,372,757	$ -	$ 175,435,274
30	$ -	$ 1,178,283	$ 1,413,939	$ -	$ 180,698,332
NPV:	$ 104,250,000	$ 11,510,000	$ 13,810,000	$ -	$ 1,764,780,000

Table B-10 Secondary CBA, Costs For CBTC Alternative, Years 1-30

This table summarizes the yearly costs for the CBTC alternative, Secondary CBA. Additional capital expenditures for signal refurbishment or additional LRVs are not included. Vehicle operations costs derive from the number of operating trains. Vehicle operations costs include both driver labor hours and traction power costs (kWh). Wages are burdened x3 and increase 3% yearly. One CBTC central control operator and one LRV dispatcher at central control are represented under the CCO column. No coupling supervisors are required.

Year	Capital cost difference	Maintenance cost difference	Operations cost difference		
			CCO	Portal supervisors	Vehicle
1	$12,140,000	$ 305,000	$ (300,000)	$ 900,000	$ (405,600)
2	$ -	$ 314,150	$ (309,000)	$ 927,000	$ (417,768)
3	$ -	$ 323,575	$ (318,270)	$ 954,810	$ (430,301)
4	$ -	$ 333,282	$ (327,818)	$ 983,454	$ (443,210)
5	$ -	$ 343,280	$ (337,653)	$ 1,012,958	$ (456,506)
6	$ -	$ 353,579	$ (347,782)	$ 1,043,347	$ (470,202)
7	$ -	$ 364,186	$ (358,216)	$ 1,074,647	$ (484,308)
8	$ -	$ 375,112	$ (368,962)	$ 1,106,886	$ (498,837)
9	$ -	$ 386,365	$ (380,031)	$ 1,140,093	$ (513,802)
10	$ -	$ 397,956	$ (391,432)	$ 1,174,296	$ (529,216)
11	$ -	$ 409,894	$ (403,175)	$ 1,209,525	$ (545,092)
12	$ -	$ 422,191	$ (415,270)	$ 1,245,810	$ (561,445)
13	$ -	$ 434,857	$ (427,728)	$ 1,283,185	$ (578,289)
14	$ -	$ 447,903	$ (440,560)	$ 1,321,680	$ (595,637)
15	$ -	$ 461,340	$ (453,777)	$ 1,361,331	$ (613,506)
16	$ -	$ 475,180	$ (467,390)	$ 1,402,171	$ (631,912)
17	$ -	$ 489,435	$ (481,412)	$ 1,444,236	$ (650,869)
18	$ -	$ 504,119	$ (495,854)	$ 1,487,563	$ (670,395)
19	$ -	$ 519,242	$ (510,730)	$ 1,532,190	$ (690,507)
20	$ -	$ 534,819	$ (526,052)	$ 1,578,155	$ (711,222)
21	$ -	$ 550,864	$ (541,833)	$ 1,625,500	$ (732,559)
22	$ -	$ 567,390	$ (558,088)	$ 1,674,265	$ (754,535)
23	$ -	$ 584,412	$ (574,831)	$ 1,724,493	$ (777,172)
24	$ -	$ 601,944	$ (592,076)	$ 1,776,228	$ (800,487)
25	$ -	$ 620,002	$ (609,838)	$ 1,829,515	$ (824,501)
26	$ -	$ 638,602	$ (628,133)	$ 1,884,400	$ (849,236)
27	$ -	$ 657,760	$ (646,977)	$ 1,940,932	$ (874,713)
28	$ -	$ 677,493	$ (666,387)	$ 1,999,160	$ (900,955)
29	$ -	$ 697,818	$ (686,378)	$ 2,059,135	$ (927,983)
30	$ -	$ 718,752	$ (706,970)	$ 2,120,909	$ (955,823)
NPV:	$12,140,000	$ 7,020,000	$(6,900,000)	$ 20,710,000	$ (9,330,000)

Table B-11 Secondary CBA, Differences In Costs Between FBTC And CBTC Alternatives, Years 1-30

Positive numbers represents benefit (savings) of CBTC over FBTC. In the Secondary CBA, the number of operating trains is constant before and after cutover to CBTC.

Year	Trip time benefit	Wait time benefit
1	$ 4,253,156	$ 7,964,747
2	$ 4,380,751	$ 8,203,690
3	$ 4,512,173	$ 8,449,800
4	$ 4,647,538	$ 8,703,294
5	$ 4,786,965	$ 8,964,393
6	$ 4,930,573	$ 9,233,325
7	$ 5,078,491	$ 9,510,325
8	$ 5,230,845	$ 9,795,635
9	$ 5,387,771	$ 10,089,504
10	$ 5,549,404	$ 10,392,189
11	$ 5,715,886	$ 10,703,954
12	$ 5,887,363	$ 11,025,073
13	$ 6,063,983	$ 11,355,825
14	$ 6,245,903	$ 11,696,500
15	$ 6,433,280	$ 12,047,395
16	$ 6,626,278	$ 12,408,817
17	$ 6,825,067	$ 12,781,081
18	$ 7,029,819	$ 13,164,514
19	$ 7,240,713	$ 13,559,449
20	$ 7,457,935	$ 13,966,233
21	$ 7,681,673	$ 14,385,220
22	$ 7,912,123	$ 14,816,776
23	$ 8,149,487	$ 15,261,279
24	$ 8,393,971	$ 15,719,118
25	$ 8,645,790	$ 16,190,691
26	$ 8,905,164	$ 16,676,412
27	$ 9,172,319	$ 17,176,704
28	$ 9,447,489	$ 17,692,006
29	$ 9,730,913	$ 18,222,766
30	$ 10,022,841	$ 18,769,449
NPV:	$ 97,890,000	$ 183,310,000

Table B-12 Secondary CBA, Wait And Trip Time Benefits

Positive numbers represents benefit (savings) of CBTC over FBTC. See Table B-15 for summary of wait and trip time benefits for year 1. Wait and trip times are based on the prevailing wage which increases 3% a year. Increased operating flexibility to due implementation of CBTC and elimination of coupling means that wait times are shorter for all passengers.

Passenger trip characteristics	Weekday Ridership	Non-peak periods			Peak periods			All
		Headway	Ridership	Wait time	Peak headway	Ridership	Wait time	Avg. weekday wait time
Embarc. to Van Ness only	19,100	1.50 min	9,550	0.75 min	1.20 min	9,550	0.60 min	0.68 min
Van Ness to West Portal only	19,100	2.50 min	9,550	1.25 min	2.00 min	9,550	1.00 min	1.13 min
J,K,L,M,N through portal	89,132	7.50 min	44,566	3.75 min	6.00 min	44,566	3.00 min	3.38 min
							Average wait time:	2.63 min

Table B-13 Secondary CBA, Weekday Average Wait Time

Passenger trip characteristics	Weekend ridership	Headway	Wait time
Embarc. to Van Ness only	8,911	1.50 min	0.75 min
VN to West Portal only	8,911	2.50 min	1.25 min
J,K,L,M,N through portal	41,583	7.50 min	3.75 min
		Average wait time:	2.93 min

Table B-14 Secondary CBA, Weekend Average Wait Time

Total hours of coupling time averted:	366,651 hrs
Benefit of coupling time averted:	$4,253,156
FBTC weekday wait time:	3.13 min
FBTC weekend wait time:	3.58 min
FBTC average wait time:	3.20 min
CBTC weekday wait time:	2.63 min
CBTC weekend wait time:	2.93 min
CBTC average wait time:	2.68 min
Difference in wait time:	0.52 min
Yearly ridership:	39,284,076
Total difference in wait time :	343,308 hrs
Benefit of wait time change this year:	$7,964,747

Table B-15 Secondary CBA, Summary Of Wait And Trip Time Benefits, Year 1

FBTC Non-Peak

Line	Round trip time	Scheduled Headway	Modified Headway	# Cars per train	Train/hr subway	Cars/hr subway	Operating Trains	Operating Cars
J	90.9	6.0	6.0	1.5	10.0	15.0	16.0	24
K/T	184.7	12.0	12.0	1.5	5.0	7.5	16.0	24
L	91.6	12.0	12.0	1.5	5.0	7.5	8.0	12
M	113.8	6.0	6.0	1.5	10.0	15.0	19.0	28.5
N	127.8	6.0	6.0	1.5	10.0	15.0	22.0	33
				Total:	40	60	81.00	121.5

FBTC Peak

Line	Round trip time	Scheduled Headway	Modified Headway	# Cars per train	Train/hr subway	Cars/hr subway	Operating Trains	Operating Cars
J	90.9	5.0	4.4	1.5	13.6	20.5	21.0	31.5
K/T	184.7	12.0	10.6	1.5	5.7	8.5	18.0	27
L	91.6	6.0	5.3	1.5	11.4	17.0	18.0	27
M	113.8	12.0	10.6	1.5	5.7	8.5	11.0	16.5
N	127.8	5.0	4.4	1.5	13.6	20.5	30.0	45
				Total:	50	75	98.00	147.0

CBTC Non-Peak

Line	Round trip time	Scheduled Headway	Modified Headway	# Cars per train	Train/hr subway	Cars/hr subway	Operating Trains	Operating Cars
J	88.4	10.0	7.5	1.5	8.0	12.0	12.0	18
K/T	182.2	10.0	7.5	1.5	8.0	12.0	25.0	37.5
L	89.1	10.0	7.5	1.5	8.0	12.0	12.0	18
M	111.3	10.0	7.5	1.5	8.0	12.0	15.0	22.5
N	125.3	10.0	7.5	1.5	8.0	12.0	17.0	25.5
				Total:	40.0	60	81.00	121.5

CBTC Peak

Line	Round trip time	Scheduled Headway	Modified Headway	# Cars per train	Train/hr subway	Cars/hr subway	Operating Trains	Operating Cars
J	88.4	9.1	6.4	1.5	9.4	14.1	14.0	21
K/T	182.2	9.0	6.3	1.5	9.5	14.3	29.0	43.5
L	89.1	8.1	5.7	1.5	10.6	15.9	16.0	24
M	111.3	9.5	6.6	1.5	9.0	13.5	17.0	25.5
N	125.3	7.5	5.2	1.5	11.4	17.2	24.0	36
				Total:	50.0	75	100.00	150.0

Table B-16 Secondary CBA, Calculations Of Number Of Operating Trains

Note that the number of operating trains is the same for both the FBTC and CBTC Alternatives. Number of operating trains is a function of the scheduled headway, expected throughput, and round trip time. Scheduled headways are used as the basis with which to generate modified headways, which are calculated to meet throughput goals (trains per hour in the subway). Trains per hour for the FBTC tables are shown as uncoupled. Divide by two for number of coupled trains. Roundtrip times are based on the scheduled roundtrip time plus an additional 25% for layover/recovery.

Appendix C - Incident Data and Calculations

An extensive examination of incident data was undertaken in order to determine whether any change in train malfunctions or accidents could be attributed to the implementation of CBTC. Muni provided incident data from 6/30/1996 to 1/1/2003 with approximately 43,000 incidents in total. These incidents were analyzed via text search and numerical techniques as described below.

Raw data

Each row of data corresponds to one incident. For each incident, the following information is provided:

1. Incident ID (tag) number
2. Date and time the incident began
3. Device used to Communicate the incident (Radio or Telephone)
4. The incident reporter
5. Dispatcher ID number
6. Operator ID number
7. RUN number of the train
8. Train line where the incident occurred
9. Vehicle ID number involved in the incident (note: Boeing vehicles are 1200-1399, and Breda vehicles are 1400-1599)
10. Location of where the incident occurred
11. Text description of the incident (note: There are no preformatted incident codes so this field is a text description per the discretion of the operator)
12. Inbound (IB) or Outbound (OB)
13. Vehicle disabled start time
14. Vehicle disabled end time
15. Line disabled start time
16. Line disabled end time
17. Vehicle number if vehicle is replaced, else blank
18. ME, PR, CA, WO, KI, FL, or PO - DIVISION - should be Metro for this data
19. T, S, or blank - Car Trade or Sent In (to yard)
20. Text description of actions taken.
21. Duration of vehicle downtime
22. Duration of line downtime
23. Two digit # - ID of person who entered the data.
24. Data processing

This study paid particular attention to the following metrics:

1. Date and time the incident began
2. Vehicle ID number involved in the incident (note: Boeing vehicles are 1200-1399, and Breda vehicles are 1400-1599).
3. Location of where the incident occurred.
4. Text description of the incident (note: There are no preformatted incident codes so this field is a text description per the discretion of the operator).

The length of downtime was not considered. The text description of each incident was evaluated with search criteria to determine if the incident was within the CBTC study area (i.e. the Muni Metro subway) and if the incident was reported as a fixed-block signaling event or CBTC event:

The following determined a CBTC incident: “ATCS” or “AUTO” or “LOOP” or “MODE”. Certain other conditions were included to refine the data such as the removal of incidents with “AUTO” and “CRASH”, “ACCIDENT”, or “COLLISION” which indicate automobile-LRV collision. The following determined a fixed-block signaling incident: “CAB” or “SIGNAL”.

The total number of incidents were counted and correlated to time periods and vehicle manufacturer. Although the analysis can attribute incidents to the train control system (either fixed-block or communications-based), detailed descriptions of the types of incidents, their severity, or financial impact are not available. Therefore, the CBA does not distinguish any cost difference between the two alternatives based on these incidents.

Appendix D - Sample Criteria Weighting

Criteria weightings for the selection of alternatives are identified using the criteria weighting matrix. This matrix allows each criterion to be compared to other criteria for relative importance. This methodology allows for a more rigorous establishment of relative criteria weightings. The comparison process is limited to two elements at a time. If one criteria is preferred over another, a numerical score of one to four is given to the preferred criteria depending on the level of preference. If criteria are preferred equally, they are both given a score of 1. The sum of each criterion's scores is tabulated into a raw weighting.

	A. Safety	**B.** Reliability	**C.** Capacity	**D.** Initial Cost	**E.** Disruption	**F.** Operational Cost	**G.** Maintenance Cost	**H.** System Diagnostics	**I.** Proprietary
A. Safety									
B. Reliability	A/B-1								
C. Capacity									
D. Initial Cost									
E. Disruption									
F. Operational					E-2				
G. Maintenance									
H. System						F-3			
I. Proprietary	A-4								

Table D-1 Criteria Weighting Matrix

In each box, preferences between each of the two criteria under comparison are entered. The letter of the preferred criteria is entered, along with the degree of preference. '4' indicates major preference (ex. *A-4*), '3' indicates medium preference (ex. *F-3*), '2' indicates minor preference (ex. *E*-2), and '1' indicates no preference to either criteria or that they are equally important (ex. *A/B-1*).

For example, for the box in the top left corner, if a safe system is preferred much more than a reliable system, 'A-4' is placed in the box to indicate that there is a 'major preference' of safety over reliability. It is, however, much more likely to rate safety and reliability both as highly valued but also equally preferred. Individual value aside, relative to each other, they are equally preferred. So 'A/B-1' would be written to indicate that there is no preference for one over the other. On the other hand, having a safe system is much more important than concerns about whether a technology is proprietary. In corresponding box comparing those criteria, you would write 'A-4.'

The number accompanying each occurrence of a letter is summed for each criteria. For items rated as ‘no preference,’ a ‘1’ is added to each criteria represented. The totals become the criteria weights for the qualitative comparative analysis.

	A. Safety	**B.** Reliability	**C.** Capacity	**D.** Initial Cost	**E.** Disruption	**F.** Operational Cost	**G.** Maintenance Cost	**H.** System Diagnostics	**I.** Proprietary
Total:									

Table D-2 Totals From Criteria Weighting Matrix, Raw Weightings

Appendix E - Train Control Maintenance Costs

Assumptions for O&M costs:

1. FBTC maintenance tasks limited to fixed-block signaling and track circuit equipment.
2. Muni has all necessary staff and resources with which to maintain signal system in a state of good repair.
3. Muni signal maintenance staff maintain signaling equipment for systemwide LRV and trolley-buses. That is, there are no signal staff dedicated to CBTC exclusively.
4. Maintenance tasks based on APTA Recommended Practices, CBTC Maintenance Manuals, and interviews with Muni staff.
5. Time required for maintenance tasks is based on internal assumptions (DC voltage reading takes five minutes, an oscilloscope reading takes 10 minutes etc.).
6. In general, all wayside maintenance requires two people.
7. 50% time added to all maintenance tasks for contingency (travel time etc.)
8. Approx. 1000 vital relays before CBTC, 250 vital relays after.
9. Track circuit and fixed-block signaling maintenance ended with start of CBTC.
10. 150 vehicles in service.
11. A printed circuit board in a vehicle or station controller requires repair every five years.
12. A FBTC wayside fixed-block signaling transmitter/receiver required repair every five years.
13. FBTC carborne fixed-block signaling equipment required repair every five years.

FBTC Wayside Maintenance							
Task	# equip in service	Interval (mos.)	Times per year	Hours per task	Task hrs+50%	Personnel per task	Annual labor-hrs
PREVENTATIVE							
Calibrate wayside vital relays	1000	36	0.33	1.0	1.5	1	500
Field test wayside vital relays	1000	6	2.00	0.3	0.5	2	2000
Test track circuits	100	6	2.00	3.0	4.5	2	1800
Maintain CCO equipment	1	1	12.00	8.0	12.0	1	144
Total wayside preventative maintenance hours:							4444
Task	# equip in service	Interval (mos.)	Times per year	Hours per task	Task hrs+50%	Personnel per task	Annual labor-hrs
CORRECTIVE							
Repair vital relay	1000	240	0.05	8.0	12.0	1	600
Repair track circuit Tx/Rx	200	60	0.20	8.0	12.0	1	480
Total wayside corrective maintenance hours:							1080
Total for all FBTC wayside:							5500
Maint. hrs. per mi/yr:							950
FBTC Carborne Maintenance							
Task	# equip in service	Interval (mos.)	Times per year	Hours per task	Task hrs+50%	Personnel per task	Annual labor-hrs
PREVENTATIVE							
Cab signaling equip. inspection/test		12	1.00	4.0	6.0	1	816
Yard cab signaling departure test		12	1.00	2.0	3.0	2	816
Total carborne preventative maintenance hours:							1632
Task	# equip in service	Interval (mos.)	Times per year	Hours per task	Task hrs+50%	Personnel per task	Annual labor-hrs
CORRECTIVE							
Repair cab-signaling antenna	136	24	0.50	2.0	3.0	1	204
Repair vehicle cab-signaling equipment		60	0.20	8.0	12.0	1	326
Total carborne corrective maintenance hours:							530
Total for all FBTC carborne:							2150
Maint. hrs. per vehicle/yr:							16

Table E-1 FBTC Train Control Maintenance Effort, Wayside And Carborne.

CBTC Wayside Maintenance								
Task	Subtask	# equip in svc	Interval (mos.)	Times per year	Hours per task	Task hrs+50%	Personnel/task	Annual labor-hrs
PREVENTATIVE								
Test inductive loop								
	Loop sig check	25	6	2.0	3.5	5.3	2	525
	Loop current adj.	25	12	1.0	0.5	0.8	2	38
	Loop cable insp.	na	12	1.0	3.5	5.3	2	11
	Loop cable test	25	12	1.0	2.0	3.0	2	150
	RFB cable test	16	12	1.0	1.0	1.5	2	48
Calibrate station controller vital relays		240	36	0.3	1.0	1.5	1	120
Field test station controller vital relays		240	6	2.0	0.3	0.5	1	240
Test station controller		8	12	1.0	2.5	3.8	2	60
Test axle counter		100	12	1.0	1.0	1.5	2	300
Test portal intrusion		18	3	4.0	0.5	0.8	2	108
Test station emergency stop button		14	3	4.0	0.5	0.8	1	42
Maintain CCO equipment		1	1	12.0	8.0	12.0	1	144
Broken Rail Detection		na	6	2.0	2.0	3.0	1	6
Total wayside preventative maintenance hours:								1791
Task	Subtask	# equip in svc	Interval (mos.)	Times per year	Hours per task	Task hrs+50%	Personnel/task	Annual labor-hrs
CORRECTIVE								
Splice inductive loop		25	24	0.5	4.0	6.0	2	150
Repair station controller vital relay		240	240	0.1	1.0	1.5	1	18
Repair station controller PC board		8	60	0.2	16.0	24.0	1	38
Total wayside corrective maintenance hours:								206
Total for all CBTC wayside:								2000
Maint. hrs. per mi/yr:								350

Table E-2 CBTC Train Control Maintenance Effort, Wayside

CBTC Carborne Maintenance							
Task	# equip in svc	Interval (mos)	Times per year	Hours per task	Task hrs+50 %	Person nel/task	Annual labr-hrs
PREVENTATIVE							
Carborne ATCS equipment test/inspection	151	12	1.0	2.5	3.75	1	566
Vehicle ATCS yard departure test	151	12	1.0	2	3	2	906
Total carborne preventative maintenance hours:							1472
Task	# equip in service	Interval (mos)	Times per year	Hours per task	Task hrs+50 %	Person nel/task	Annual labr-hrs
CORRECTIVE							
Repair vehicle ATCS PC board	151	60	0.2	2	3	1	91
"No-trouble-found" problems	na	na	52.0	15.0	na	1	780
Total carborne corrective maintenance hours:							871
Task	# equip in service	Interval (mos)	Times per year	Hours per task	Task hrs+50 %	Person nel/task	Annual labr-hrs
OVERHAUL							
Overhaul ATC relay	151	24	0.5	2	3	1	227
Overhaul tachometer	151	60	0.2	4	6	1	181
Total carborne overhaul hours:							408
Total for all CBTC carborne:							2750
Maint. hrs. per vehicle/yr:							18

Table E-3 CBTC Train Control Maintenance Effort, Carborne

Appendix F - Capital Costs

The tables below summarize the capital costs for the train control systems for both the FBTC and CBTC Alternatives.

Item	Cost
Alcatel contract:	$66.3 M
Consult. contract (safety):	$5.7 M
Consult. contract (enginr.):	$16.3 M
Muni support budget:	$13. M
Tax:	$3. M
Total:	$104.3 M

Table F-1 Capital Costs For The CBTC Alternative

Assumes installation of the CBTC throughout the Muni Metro, including the MMT. CBTC is laid in parallel to the existing conventional cab-signaling system in the Embarcadero - West Portal portion. All LRVs have new CBTC signaling equipment installed. Much of the wayside fixed block train control equipment remains in place although no vehicles are currently equipped to receive speed codes. The fixed-block track circuits can still detect block occupancy and this information is displayed on a mimic board in the central control room. Costs for maintaining the wayside fixed-block train control are not included with CBTC costs. Costs are taken from project planning and progress reports.[46]

Item	Units	Unit Cost	Cost	Overhead	Cost incl. overhead
Wayside FBTC Overhaul	30,160ft.	$1,653/ft.	$49.9 M	$31.4 M	$81.3 M
Wayside FBTC MMT Overhaul	2,000ft.	$1,653/ft.	$3.3 M	$2.1 M	$5.4 M
Carborne FBTC Overhaul	151 vehicles	$66,114/veh	$10. M	$6.3 M	$16.3 M
Central Control Overhaul	1	$8,264,238	$8.3 M	$5.2 M	$13.5 M
				Total:	$116.4 M

Table F-2 Capital Costs For The FBTC Alternative

Assumes overhaul of entire FBTC system, both wayside and carborne.

Appendix G - Service Level Data and Calculations

Service level information was provided by in spreadsheet form by Muni for LRV activity for the years 1998 through 2008. The data provided train and vehicle counts per hour for all weekdays. The data provided only the counts of trains or vehicles passing the Montgomery Station in the westbound direction. Analysis of this data provided the historical “throughput” in trains and vehicles per hour through the Muni Metro subway.

Endnotes

[1] A. Perles. “The People's Railway: The History of the Municipal Railway of San Francisco.” Glendale, CA. Interurban, 1981. Print.

[2] “Muni Metro by the Numbers.” San Francisco Examiner. 26 Sept 26 1998

[3] Dan Rosen and Leonard Olson “San Francisco Muni Metro: Operating Issues and Strategies.” Transportation Research Board Special Report. Issue 195 (1982). 141-144. Print.

[4] Subway and tunnel track are shown dashed. Several passenger stations are indicated for reference. K line and T line are operated as one contiguous line.

[5] Patricia DeVlieg. “S.F. Muni’s CBTC System: A Brave New World.” APTA Rail Transit Conference. St. Louis. 14 June 2000. slide 23.

[6] T.J. Sullivan. “Management Briefing Contract MR-1034R Advanced Train Control System.” 17 Mar 1992. 110,154. Print.

[7] T.J. Sullivan 110

[8] T.J. Sullivan 130

[9] T.J. Sullivan 110

[10] T.J. Sullivan 106, 146

[11] “Evaluation of The Costs and Benefits of and Alternatives To Procurement of an Advanced Train Control System Under Contract No. MR1034R.” 16 Mar 1993. Print.

[12] T.J. Sullivan 108,112

[13] T.J. Sullivan 9

[14] Chuck Finnie. “Consultants working hard to tune up Muni Metro.” San Francisco Examiner. 26 Jan 1999.

[15] T.J. Sullivan, 19. Does not include costs for outside project management consultants.

[16] Kathleen Sullivan. “Muni knew about trolley lemons in '70s.” San Francisco Examiner. 14 Sept 1998.

[17] Elaine Cartwright. “Integration of a New Generation of Light Rail Vehicles into the SF Muni.” APTA Rail Transit Conference. 10 June 1995. 16.

[18] 77 or 78 depending on source. “Muni Metro by the Numbers.” San Francisco Examiner. 26 Sept 26 1998.

[19] Dan Rosen 145

[20] These headways produce 25 train per hour throughput in the subway.

[21] T.J. Sullivan 101

[22] Patricia DeVlieg, slide 23. Data for 7-8 AM not available and not included in this chart.

[23] Minutes of Meeting of 33rd Muni Safety Advisory Board (Muni-591). 20 Nov 1998.

[24] T.J. Sullivan 41

[25] P. DeVlieg. Comments to draft version of this report. 7 July 2010.

[26] T.J. Sullivan 71

[27] Minutes of Meeting of 34th Muni Safety Advisory Board (Muni-577). 18 Sept 1998.

[28] Rescue Muni Forums. 10 Dec 1997 to 10 Mar 1999. Accessed Jan 2010. <http://www.lumiere.net/home/forums/archives/rescuemuni/>

[29] Minutes of Meeting of 34th Muni Safety Advisory Board (Muni-577). 18 Sept 1998.

[30] Minutes of Meeting of 34th Muni Safety Advisory Board (Muni-577). 18 Sept 1998.

[31] Minutes of Meeting of 33rd Muni Safety Advisory Board (Muni-591). 20 Nov 1998.

[32] "Muni Capital Projects Monthly Report No. 23." FTA Project Management Oversight Program. 14 Dec 2000.

[33] Martin, Charles. "San Francisco Muni ATCS Project Safety V&V Process." Proceedings of the 7th International Conference on Automated People Movers. Copenhagen. 5 May 1999. Most of section 6.2.4 is excerpted from this source with permission from the author.

[34] At the upper limit of the technology. "Muni Completes ATO Upgrade." International Railway Journal. 1 June 2001

[35] "Evaluation" 50

[36] "Evaluation" 65

[37] ECONWest and Parsons Brinckerhoff Quade & Douglas "TCRP Report 78 - Estimating the benefits and costs of public transit projects: A guidebook for practitioners" Washington, DC: Transit Cooperative Research Program. 2002. 11-9

[38] Although peak hours are defined by Muni as weekdays 5-9 AM and 3-7 PM, analysis revealed that the highest tunnel throughput generally occurred during the 7-10 AM and 4-7 PM periods.

[39] "Transit Effectiveness Project." SFMTA. Accessed August 2010. <http://www.sfmta.com/cms/mtep/tepover.htm>. Source of ridership patterns is the Muni Transit Effectiveness Project, a 2006 study that gathered ridership data from throughout the Muni bus and rail service area.

[40] See Table B-8 for a summary of trip and wait time benefits for the Primary CBA.

[41] Slightly above upper limit for technology.

[42] See Table B-15 for a summary of trip and wait time benefits for the Secondary CBA.

[43] William C. Vantuono. “Look, Ma-No Hands! Tearing Up the Tracks Under ATO on New York City’s Canarsie Line.” Railway Age. April 2007.

[44] “FOCUS: Subway transformation.” Thales Group. Accessed January 2011. <http://www.thalesgroup.com/Markets/Security/Newsletters/Ground_Transportation/2010_Issue_4_-_December/Newsletter_Content/FOCUS__Subway_transformation/>

[45] 48 trains per hour represents the upper limit of sustained operations in the Muni Metro subway. "Muni Completes ATO Upgrade." International Railway Journal. 1 June 2001.

[46] Evaluation” 50 and Patricia DeVlieg, slide 20

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