# An Optimization Approach to Scheduling Make and Break Operations

Prepared for BART by

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## Executive Summary

In this report, we discuss a model designed to inform our client, Bay Area Rapid Transit (BART), in planning make and break operations for its "Fleet of the Future" train cars. Currently, BART employs making and breaking to adjust train lengths throughout a service day and to minimize train car operating hour accrual, while maintaining an acceptable level of service to passengers. Over the next 6-8 years, BART will gradually replace its aging legacy fleet of A, B and C cars with the "Fleet of the Future," which will comprise of 1,200 D (control) and E (non-control) cars.

Our objective was to determine the optimal schedule of make and break operations for each yard or tail track, given a fleet of D:E cars in a 2:3 ratio. We accomplished this by designing a mixed integer linear program that aims to minimize operating, maintenance and making and breaking costs for BART while ensuring anticipated passenger demand is met. Existing BART data and data gathered through yard visits were used as input for the model.

We found that minimal making and breaking should be performed once BART has reached a steady state fleet composed of only new train cars. However, our results also indicate that BART should operate a mix of 5-car and 10-car consists to reduce energy consumption and car operating hour accrual. Based on these findings we recommend that BART acquire a fleet with a 2:5 ratio of D to E cars, which will enable it to operate 60% (648 out of 1,081) of the cars configured as 5-car consists/10-car breakable consists and 40% (433 out of 1,081) as 10-car unbreakable consists. This compromise will allow BART to maintain the flexibility to make and break, while reducing purchasing costs for the remainder of their new cars.

# Introduction

### Making and Breaking

Making and breaking is the practice of altering train lengths throughout an operational day. “Making” is the operation of combining two consists to make one longer consist and “breaking” is the opposite. This gives transit systems the flexibility to run train sets of different lengths to meet passenger demand, while also minimizing operating costs.

Through conversations with BART operations staff and research on transit system practices, we derived the main advantages and disadvantages of making and breaking. It allows for reduced train car operating hour accrual and hence less regular maintenance, reduced power consumption and a higher spare ratio of train cars. However, it incurs increased wear-and-tear on certain components (e.g. couplers) and labor costs for the yard operators.

Currently, BART’s main motivation for breaking trains is to prolong the lifespan of its aging legacy fleet (A, B, C cars). On numerous lines, BART will typically run longer (8-10 cars) trains during the AM peak, break to shorter (4-6 cars) trains for the midday period, and then make longer trains for the PM peak.

### BART Background and the Fleet of the Future

Bay Area Rapid Transit (BART) is the main public train system of the Bay Area and provides about 125 million passenger trips annually, with about 430,000 every weekday. BART operates on an annual budget of approximately $900 million and is one of the least subsidized public transit systems in the country (60% of its revenue comes from operating revenue). BART first opened in 1972, making it nearly 50 years old. Small projects and retrofits are constantly being carried out to keep the aging system working as smoothly as possible. One of the major upgrades currently underway is the introduction of an entire new fleet of train cars (the ‘Fleet of the Future’), synchronous with the stepwise retirement of legacy train cars. Although the first new cars are already in service, it will be nearly a decade until the legacy fleet can be completely retired.

**Current Operations**

As shown in Figure 1, the BART system consists of six main lines (one of which only runs between SFO Airport and Millbrae and has limited service) as well as the eBART extension (operates between Pittsburg/Bay Point and Antioch) and the OAK airport connector. We exclude eBART, the OAK connector, and the SFO-Millbrae line from our analysis because makes and breaks are not performed on these routes. BART’s six main lines do not operate independently of each other. In sections of the system where multiple lines overlap, tracks and stations are shared between lines. Due to this common infrastructure, train cars can operate on any of the six main lines. However, during a single day, trains typically operate on one line (e.g. trains on the Richmond-Warm Springs line spend the entire day running back and forth between Richmond and Warm Springs).

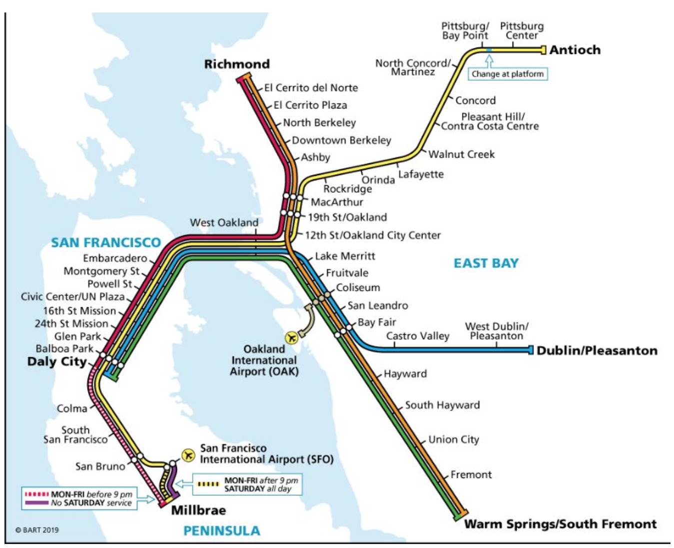



Figure 1: The 2019 BART system map

BART service can be partitioned into three major schedule categories: Weekdays, Saturdays, and Sundays/Holidays. On Saturdays, trains operate with larger headways (time between successive trains) than on weekdays. On Sundays and holidays, BART offers more limited service, with only four lines in operation. We focused on weekday make/break operations because these are by far the most frequent and present the greatest challenge for make/break scheduling. Table 1 provides an overview of the pattern of consist lengths and associated makes and breaks on the five main lines.

| **Line** | **Make/Break Operations** |
|---|---|
| Warm Springs-Daly City | None (10-car consists all day) |
| Richmond-Warm Springs | 6/8 → 4 → 6/8 OR 6/8 all day |
| Bay Point-SFO | None (10-car consists all day) |
| Richmond-Millbrae | 8/9/10 → 4/5 → 8/9/10 |
| Dublin-Daly City | 9/10 → 4/5 → 9/10 |

Table 1: Breakdown of BART's current weekday make and break operations by line

## Problem Statement

As BART transitions to a Communications Based Train Control (CBTC) system and introduces the new fleet (D/control cars and E/non-control cars), it will expand its fleet and reduce headways from 15 to 12 minutes. The CBTC system will allow for reduced headways through improved reliability and accuracy of train location tracking compared to the current fixed-block automatic train control (ATC) system. By 2026, BART plans to have 1,081 train cars in service. BART plans to order as few D cars as possible as they are costlier that E cars and have to be fitted as a CBTC operational control car. As such, they would like to purchase D:E cars to obtain a 2:5 D:E ratio if possible; otherwise, they would purchase them in a 2:3 ratio if deemed necessary for the purpose of making and breaking.

Our task was to create, for the anticipated train schedule, a make and break plan that minimizes BART's operational and maintenance costs. Subsequently, we would determine the ratio of D to E cars that would be required to support this make and break schedule. To accomplish this, we designed and implemented a mixed integer linear program to determine a make/break schedule that would be the most economical for BART.

Our model is based on the following assumptions about the BART system and its operations:

- Consists will contain only 5 or 10 cars.
- The 1,081 train cars will all be either D or E cars.
- The system layout is the same as it currently is (i.e. no Berryessa extension and no yard openings/closures).
- There will be a 2:3 ratio of D to E cars
- Fleet consists of 5-car modules that can move independently, and two such modules can be coupled and decoupled (DEEEDDEEED → DEEED + DEEED).
- Power and maintenance costs are both linear functions of the distance a train car travels.
- Makes and breaks only occur at yards or tail tracks at the end of a route (i.e. a train traveling from Warm Springs to Richmond will not stop at the Hayward yard to be shortened or lengthened).
- There will always be enough yard/tail track space for a make/break to be carried out.
- Inventory fulfillment of train-cars are carried out at each yard/tail track. Rather than breaking a 10-car consist arriving to the yard to send out a 5-car consist, the 10-car consist goes to inventory while a 5-car consist is sent out from inventory, if available. This avoids unnecessary making and breaking costs.

## Conceptual Framework

### System Representation

To represent the BART system in our model, we defined directed lines that correspond to the five main lines. We exclude the SFO-Millbrae line, eBART, and the OAK connector because make/break operations do not occur on these segments. The directed lines are listed in Table 2.

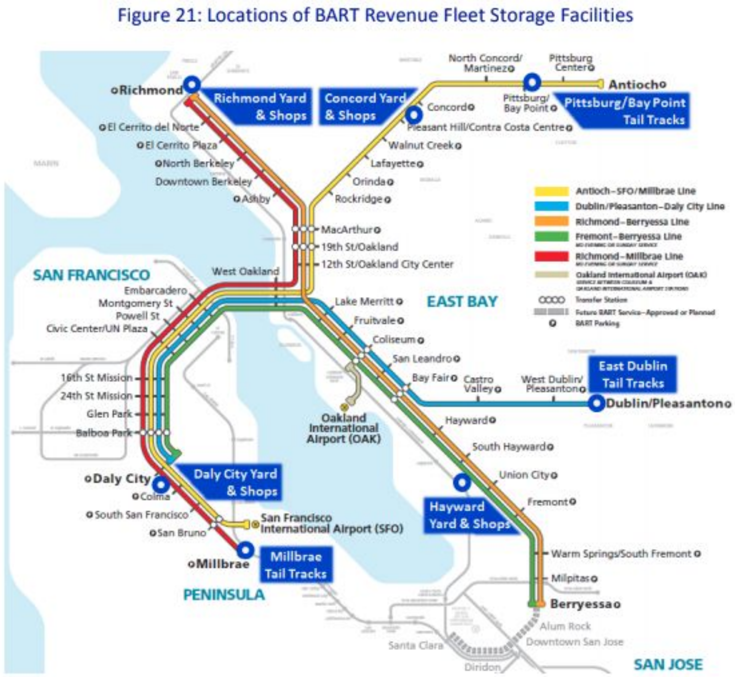



Figure 2: BART system map with yards and tail tracks

| Directed Line Label (A) | Corresponding Route |
|---|---|
| 1 | Richmond-Millbrae |
| 2 | Millbrae-Richmond |
| 3 | Richmond-Warm Springs |
| 4 | Warm Springs-Richmond |
| 5 | Daly City-East Dublin |
| 6 | East Dublin-Daly City |
| 7 | Pittsburg/Bay Point-SFO |
| 8 | SFO-Pittsburg/Bay Point |
| 9 | Daly City-Warm Springs |
| 10 | Warm Springs-Daly City |

Table 2: Directed Lines

We also define the “train state” (the TS decision variables) for every train on our design day schedule. Every train is either in a 10-car consist state or a 5-car consist state. Each scheduled train departure on each directed line has a departure index (1,2,3…). Therefore, an example of one element of our model output (translated from mathematical notation) is the following: “departure 1 on directed line 1 is a 5-car consist.”

## Solution Procedure

We needed to perform several preprocessing tasks before solving the problem.

**Forecasted Weekday Schedule**

Our first pre-processing step was to create an initialization schedule. Since our model returns recommended consist lengths (5 or 10 cars) for each departure in a day, it requires a train schedule for the desired day as input. The SCRAM report BART provided us with has information on the departure time and consist lengths for all of the trains on the six main lines. We started by referencing this document to determine appropriate departures times. We then modified the schedule to reflect changes BART plans to make by 2026 (according to the Fleet Management Plan). These changes are summarized in Tables 3 and 4.

| | |
|---|---|
| Peak period | AM: 0700 - 1000<br>PM: 1600 - 1900 |
| Peak hour (busiest) | AM: 0800 - 0900<br>PM: 1700 - 1800 |
| Base headways (min) | 12 |
| Evening (after 1900) headways (min) | 15 |
| First train dispatched | 0400 |
| Last train dispatched | Orange, Yellow, Blue: 0000<br>Red: 1830<br>Green: 2030 |

Table 3: Characteristics of the 2026 schedule

| **Lines** | Red | Green | Blue | Yellow |
|---|---|---|---|---|
| East Bay → San Francisco | | | | |
| 0700-0800 | 1 | 1 | 1 | 3 |
| 0800-0900 | 1 | 1 | 1 | 7 |
| 0900-1000 | 1 | 1 | 1 | 3 |
| San Francisco → East Bay | | | | |
| 1600-1700 | 1 | 1 | 1 | 3 |
| 1700-1800 | 1 | 1 | 1 | 7 |
| 1800-1900 | 1 | 1 | 1 | 3 |

Table 4: Forecasted Rush Trains for 2026 schedule

**Ridership Demand by Time of Day**

The second step involved estimating passenger demand throughout the day. We used origin-destination data to generate the demand curves shown below in Figure 3, which display clear AM and PM peaks. We incorporated a 30% growth factor that BART employs to account for the anticipated increase in passenger demand by 2026. This analysis allowed us to determine time intervals in which running 5-car trains would be infeasible due to high levels of passenger demand. Using this knowledge allowed us to simplify the model by fixing some of the decision variables as 10-car consists. This data was also used in our passenger demand constraint to ensure that enough train cars are provided in a given time period to meet demand.

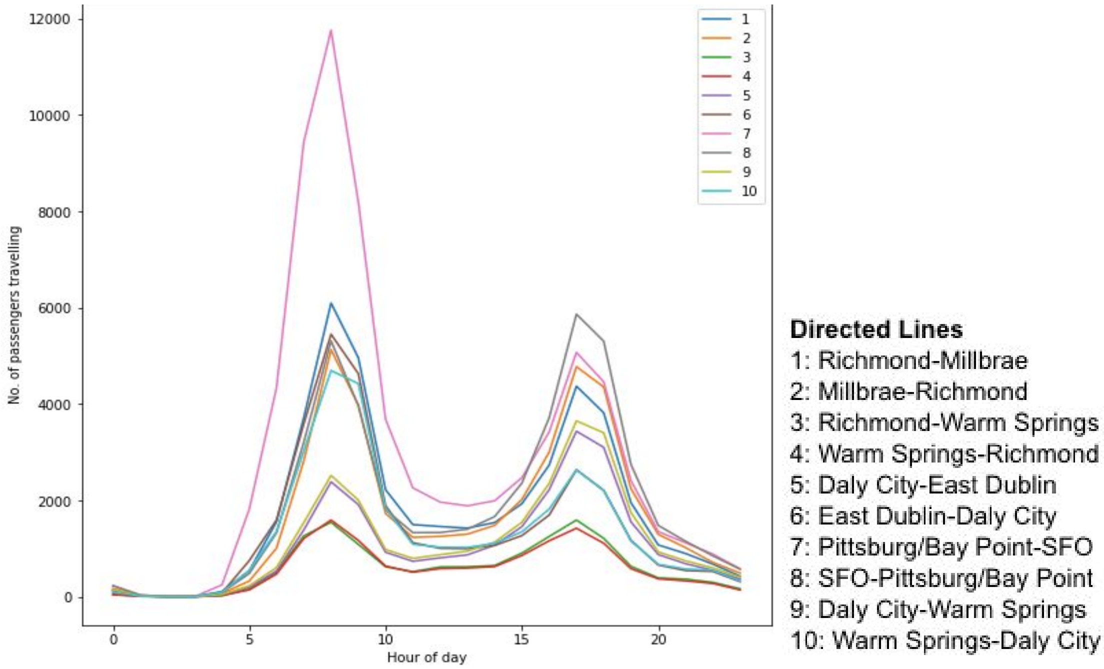



Figure 3: Directed line passenger demand by time of day

**Relations/Database Management**

Finally, we had to establish relationships between the following datasets for the model formulation:

- Passenger Demand Intervals
- Directed Line-Departure Indexes
- Yard-Shifts
- Yard-Event Indexes

By mapping passenger demand intervals to the relevant directed line departures, the model is able to determine if departures within that interval would suffice given the forecasted demand for the Passenger Demand constraint.

By mapping yard shifts onto the yard events, the model ensures that the yard team on shift is able to handle the corresponding number of makes and breaks scheduled to occur for the Yard Operator Make/Break Capacity constraint.

By mapping yard events to directed line departures, arrivals and departures from yards can be tracked for the Yard/Tail track Inventory Balance constraint.

## Model Formulation

**Sets**

| **Sets** | **Explanation** | **Values** |
|---|---|---|
| A | Directed Line a | As in Table 2 |
| C(a) | Departure Index c for Directed Line a | 1 - Last departure along directed line a |
| D | Yard/tail track d | Richmond, Daly City, Warm Springs, Millbrae, East Dublin, Pittsburg/Bay Point, SFO |
| S | Shift s | 10 two hour shifts from 240 (4 AM) to 1440 (12 AM) |
| T | Train Length t | 5<br>10 |
| J(d) | Departure Index at Yard d | 1 - Last arrival/departure from yard |
| Z | Interval z | 20 one-hour intervals from 240 (4 AM) to 1440 (12 AM) |

Table 5: Sets

**Parameters**

The following are treated as known parameters in our model and should be provided as input before running the model. These values were obtained through BART or estimated based on available data.

| Parameter | Description |
| --- | --- |
| $C$ | Electricity and maintenance cost of running a 5-car consist per car-mile<br>(composed of industrial rate of power that BART pays and regular and preventive breakdown maintenance costs) |
| $D_a$ | Car-mile per directed line |
| $C_y$ | Cost per Yard Team Shift |
| $C_{M/B}$ | Cost of a make or a break |
| $P_{az}$ | Peak number of passengers travelling along directed line a during time interval z |
| $CC_{5\text{-cartrain}}$ | Passenger carrying capacity of a 5-car consist |
| $F_{ac}$ | Time-adjusted multiplier for carrying capacity of a train corresponding to departure index c of travel segment a. Specifically, this is the overlap between the hourly interval and duration of time a train is on a directed line. For instance, a consist travelling from Richmond to Millbrae from 0845 to 1000 has a multiplier of 0.25 for the interval 0800-0900 and 1 for the interval 0900-1000 |
| $Y_{dj}$ | (For yard event) 1 if Arrival, -1 if Departure |

Table 6: Parameters

**Decision/Auxiliary Variables**

| Variable | Type | Description |
| --- | --- | --- |
| $TS_{ac}$ | Indicator (short for Train State) | 0 → 5-car consist<br>1 → 10-car consist |

| | | |
|---|---|---|
| $M_{dj}$ | Indicator | Indicates whether a make occurs at yard d at event index j |
| $B_{dj}$ | Indicator | Indicates whether a break occurs at yard d at event index j |
| $L_{ds}$ | Integer | Level of staffing at yard d on shift s |

Table 7: Decision Variables

Our definition of a shift is a relaxation of a yard operator's typical full 8-hour shift. In this model, a shift is defined as one 2-hour period in which a yard operator solely does making and breaking. Realistically, a yard operator's shift would involve more jobs than making and breaking and they would work a full workday.

| **Auxiliary Variable** | **Description** |
|---|---|
| $I_{dtj}$ | Inventory of t-car consists at (just after) event index j at yard d |

Table 8: Auxiliary Variables

**Objective Function**

The objective function seeks to minimize the cost of power consumption and operation, labor costs and a make/break cost (accounts for associated wear/tear on train components). Below, we present each term in the objective function.

Electricity and regular maintenance

$$C \cdot \sum_{a \in A, c \in C(a)} [(1 + TS_{ac}) \cdot D_a]$$

The first component of our objective captures electricity and regular maintenance costs. The term in the parentheses, $1+TS_{ac}$, represents the number of 5-car consists on directed line a for departure index c. For each, we multiply this value by $D_a$, the car-mile per directed line a, to get the car-miles travelled. Summing over all train departures in the system gives the total car miles travelled. Multiplying by C, the electricity and maintenance cost per car-mile, gives the total cost of electricity and regular maintenance.

Yard operator labor cost

$$C_y \cdot \sum_{s\in S} \sum_{d\in D} L_{ds}$$

The second part of our objective captures the labor costs associated with making and breaking. We record the level of shift (number of yard teams) required to support the stipulated number of makes and breaks and in a shift. Summing across all yards and shifts gives us the total number of yard team-shifts required. Multiplying by the cost of a yard team shift gives the total cost of labor to perform making and breaking operations.

Making and breaking wear

$$C_{M/B} \cdot \sum_{d\in D} \sum_{j\in J(d)} (M_{dj} + B_{dj})$$

The final piece of the objective captures a wear and tear cost associated with making and breaking. We sum across all yards and yard event indexes to find the total number of makes and breaks. Multiplying that by the cost of a make/break gives us the total wear and tear as a direct result of making and breaking.

**Constraints**

Our problem is subject to the following constraints:

Anticipated Passenger Demand

$$P_{az} \leq CC_{5cartrain} \cdot \sum_{c(a)\in z}[(1 + TS_{ac}) \cdot F_{ac}], \forall a \in A, \forall z \in Z$$

This ensures that the adjusted carrying capacity of all train sets operating along a directed line is able to meet the anticipated hourly ridership demand obtained in the preprocessing step. Each train set carrying capacity is adjusted to account for the overlap between the duration a train set is traversing a directed line and the hourly interval bounds.

Yard/Tail Track Inventory Balance

$$I_{d5j} = I_{d5j-1} + Y_{dj} \cdot T_{ac} + M_{dj} - B_{dj}$$
$$I_{d10j} = I_{d10j-1} + Y_{dj} \cdot (1 - T_{ac}) - 2 \cdot M_{dj} + 2 \cdot B_{dj},$$
$$\forall d \in D, \forall j \in J(d), \forall a, c \in d, j$$

$$I_{dtj} \geqslant 0, \forall d \in D, \forall j \in J(d), \forall t \in T$$

This tracks the number of 5-car and 10-car consists at each possible make/break location in the system, by accounting for all departures, arrivals, makes and breaks at the yard at every yard event index. By ensuring non-negativity of inventory, it ensures that a train car of a certain consist length must exist in that yard/tail track if it is stipulated to depart.

End of Day Reset

$$I_{dt0} = I_{dtj}, \forall d \in D, j = max(j \in J(d)), \forall t \in T$$

The inventory of 5 and 10 car consists at each yard must be the same at the start and the end of the day. This allows the schedule to be repeatable over consecutive weekdays.

Yard Capacity

$$\sum_{t \in T} I_{dtj} \leqslant G_d, \forall d \in D, j \in J(d)$$

This ensures that the number of 5 and 10 car consists at a yard at a given yard event index does not exceed the capacity of that yard.

Disallow infeasible makes and breaks

$$M_{dj} = B_{dj} = 0, \forall d \in (WarmSprings, SFO), \forall j \in J(d)$$

This prevents makes and breaks at end-of-line yard/tail tracks that lack the necessary make/break infrastructure and personnel.

Yard Operator Make/Break Capacity

$$\sum_{j \in s}(M_{dj} + B_{dj}) \leq M \cdot L_{ds}, \forall d \in D, \forall s \in S, \forall j \in J(d)$$

Enforces an upper limit on the number of makes and breaks that a single yard team can perform during one shift (2-hour time period) of the model. This is to be translated from the 2-hours shifts to actual 8-hour shift durations of the yard workers.

## Results and Recommendations

### Results

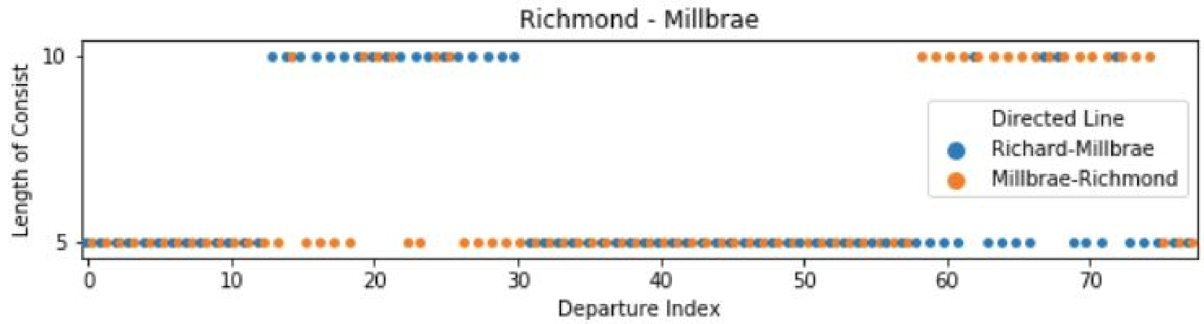
We found that making and breaking should be performed far fewer times per day when BART has transitioned to the new fleet. However, we also observed that running a mix of 5-car and 10-car consists will be optimal, as displayed in Figures 4-8, which indicate whether each departure should be a 5-car or

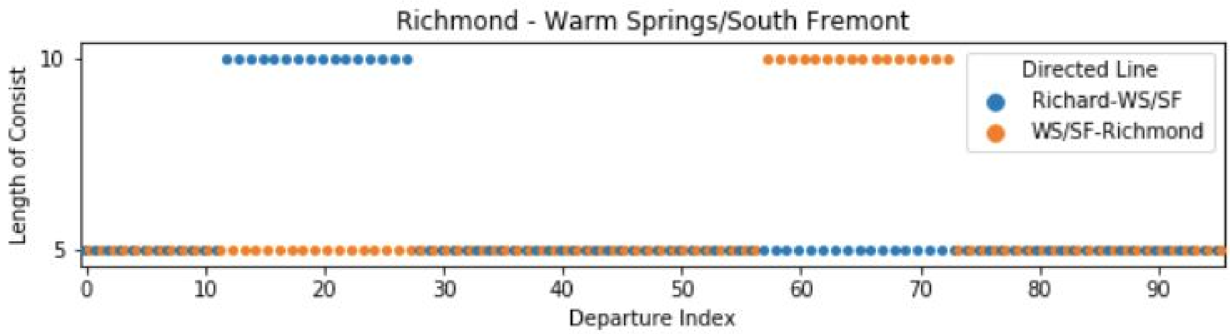
10-car train. This result reflects the challenge of reducing energy consumption and maintenance costs associated with operating hour accrual while meeting the hard constraint of satisfying passenger demand.

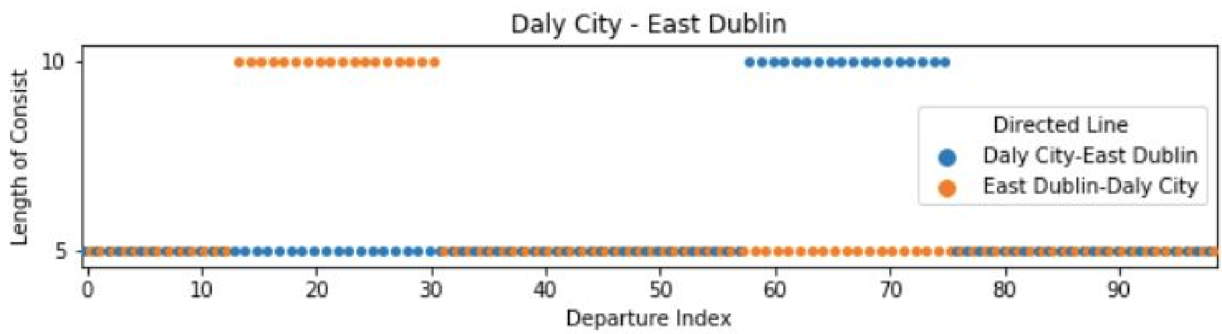
The indicated 5-car consists during morning and evening commute hours, typically interspersed among 10-car consists, are adequate for meeting passenger demand during the peak-hour since the Fleet of the Future will have reduced headways (15 to 12 minutes) due to the new CBTC system. Also, BART’s schedule for 2026 calls for more trains to cross the bay during rush hour (23 to 30 trains per hour).

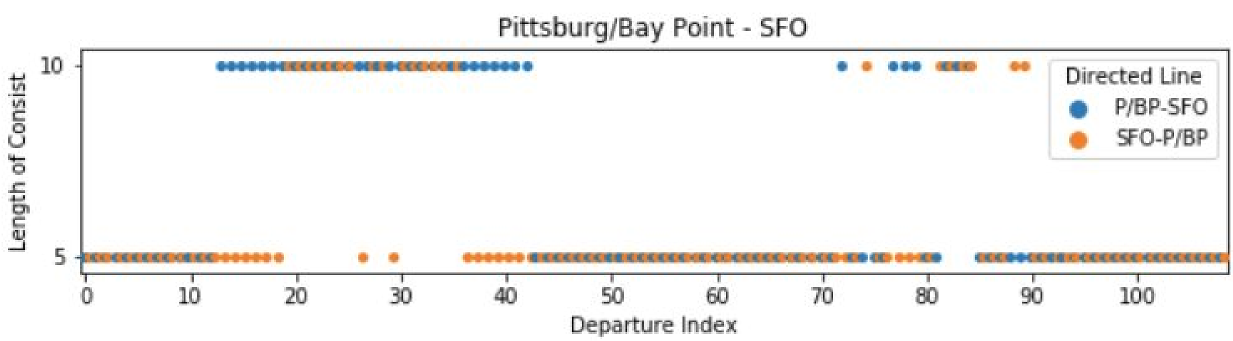
For the Richmond-Millbrae lines and Pittsburg/Bay Point-SFO lines, there is a significant number of 10-car consists going from the East Bay to Downtown San Francisco in the AM peak hours, while in the PM peak most of the trains traveling from Downtown San Francisco back to the East Bay are also 10 car-consists. This is shown in these two graphs by the large number of 10-car consists of blue color (East Bay to San Francisco trips) for the 10-30 departure index range (AM peak), and the high amount of 10-car consists represented by orange dots (San Francisco to East Bay trips) for the 60-90 departure index range (PM peak).

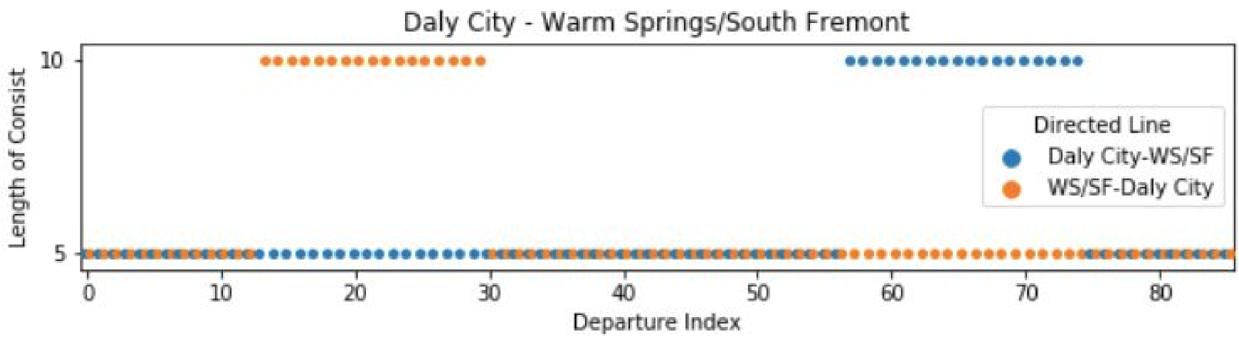
A bi-directional peak does exist for these lines, meaning that there are many 10-car consists heading to the East Bay from San Francisco for both the AM and PM peaks, as well as many 10-car consists heading to San Francisco from the East Bay for both the AM and PM peaks. This indicates that the Richmond-Millbrae and Pittsburg/Bay Point to SFO lines are quite busy, during AM and PM commute times, regardless of the direction of the trains.


Richmond - Millbrae
Length of Consist
Departure Index
Directed Line
Richard-Millbrae
Millbrae-Richmond


Richmond - Warm Springs/South Fremont
Length of Consist
Departure Index
Directed Line
Richard-WS/SF
WS/SF-Richmond


Daly City - East Dublin
Length of Consist
Departure Index
Directed Line
Daly City-East Dublin
East Dublin-Daly City


Pittsburg/Bay Point - SFO
Length of Consist
Departure Index
Directed Line
P/BP-SFO
SFO-P/BP




Figures 4-8: Plots of our model's output for the 10 directed lines. The dots depict recommended consist length for each departure on the input train schedule.

**Cost and Sensitivity Analysis**

Based on the consist lengths of departures indicated by our model, our baseline strategy corresponds to a mix of 60% (or more) 5-car consists and 40% (or less) 10-car unbreakable consists. We compared that composition with an "all 10-car" strategy, which is the operation of 10-car unbreakable consists throughout the entire day that BART considers pursuing.

Overall, the majority of the costs are operating costs from electricity and maintenance cost proportional to car miles, and not the yard operator salaries nor making and breaking. The 10-car scenario yielded an objective function cost that is 60% higher than the optimal objective function cost from the baseline scenario. Table 9 displays a comparison of these two solutions. When comparing these values against the BART's daily operating costs (around \$360,000 to \$1.45 million after scaling current values by 1.3 to account for increased passenger load in 2026), the amounts given to us by the model are reasonable.

Figure 9 displays the sensitivity analysis we performed on our three objective function costs. We observed the effect a change in each of these costs had on the optimal solution and found that car operating (electricity and regular maintenance) cost is the only one that has a significant impact. Therefore, BART should prioritize obtaining an accurate estimate for this cost.

| **Cost($/day)** | **Baseline** | **All 10-car** |
|---|---|---|
| Operating cost (Electricity & wear-and-tear) | 455,536 | 729,843 |
| Yard operator salaries | 396 | 0 |
| Make-and-break | 659 | 0 |
| **Total** | 456,592 | 729,843 |

Table 9: Cost breakdowns for optimal vs all 10-car operating strategy

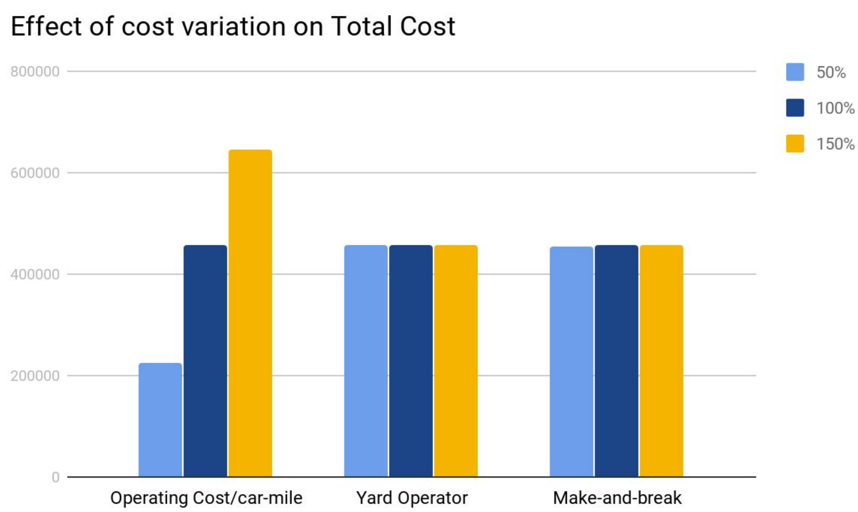



Figure 9: Sensitivity analysis on objective function costs

**NPV Analysis**

This NPV analysis will help BART develop an optimal purchasing strategy for their 2026 fleet consisting of D and E cars. We found the cost of a D car to be $2 million, and the cost of an E car to be $1.7 million. Table 10 outlines the total cost of the 2026 fleet for BART if they follow either the baseline strategy or all

10-car strategy, both of which were described in the Cost and Sensitivity Analysis section. The All 10-car strategy has a cheaper overall fleet cost than the baseline strategy.

| | **Baseline Strategy Requirements (40% 2:8, 60% 2:3)** | **All 10 Car Consist Requirements** |
|---|---|---|
| | 346 D Cars | 216 D Cars |
| | 734 E Cars | 864 E Cars |
| **Total Cost of Fleet** | 1.94 billion | 1.9 billion |

Table 10: Total Cost of Fleet by Strategy

To calculate the NPV of cost for both strategies, we first assumed that each day in the year has the same cost as a conventional week day. Given that there are 365 days in a year, the baseline strategy has a yearly consist operational cost of around \$166 million annually, from 2026-2046. Under these same conditions, the all 10-car strategy has a yearly consist operational cost of around \$266 million annually, from 2026-2046. These annual operational costs are calculated from the total costs for each strategy in Table 9. If we assume an interest rate of 4%, and a 2019 initial investment that corresponds to the total cost of the fleet for each strategy (Table 10), the formula for NPV of cost is as follows:

$$(\text{2019 Initial Investment}) + \left(\sum_{y=0}^{20} \frac{\text{Yearly Operational Cost}}{(1.04)^y}\right) \div (1.04)^7$$

This yields an overall baseline strategy NPV cost of \$3.78 billion. The All 10-car strategy has a higher NPV cost of \$4.58 billion. This translates to a saving of \$800 million today.

**Recommendation**

After comparing the baseline solution to the all 10-car consist solution, we recommend that BART use the **baseline solution** recommended by our model and obtain a 2026 fleet with 310 D cars and 771 E cars. This will reduce BART's purchasing costs by allowing their next train car order to consist of only E cars (which are cheaper than D cars). The 2:5 ratio of D to E cars will allow BART to operate 60% (648 of the 1,081) of its fleet as 5-car consists (either in 10-car breakable consists or as individual 5-car units) and 40% (433 of the 1,081) as unbreakable 10-car consists. This mixed operation will yield lower operating expenses than an all 10-car operating plan by reducing energy consumption and car operating hour accrual.

**Next steps**

We have focused our analysis on a typical weekday schedule, with the steady state 2026 fleet (1081 cars of only types D and E) and also made numerous assumptions to simplify our model. Naturally, there are many ways to extend the analysis to more closely reflect actual operations.

The first is to adjust the model to incorporate a fleet with A, B, C, D, and E cars. Solving the optimization problem with a different proportions of cars in the fleet could help BART determine making and breaking over the next decade as they slowly retire legacy cars and transition to the Fleet of the Future cars. However, this would require significant changes to our model, in which we would have to account for 5 different types of cars instead of just the D and E cars. BART may also want to account for a spare ratio during peak hours or account for malfunctioning cars. This could be handled by additional constraints on inventory requirements.

It would also be desirable to improve our parameter estimates both through gathering more data and formulating more accurate ways to calculate unknown quantities. This would entail more site visits to other yards and tail tracks beyond those we visited, to gain a better understanding of how their operations may differ.

Finally, BART may also want to determine the best make/break schedules for many more scenarios. As a first step, we focused on accurately modeling a simple situation (i.e., standard weekday schedules in which the inventory of consists at each yard is the same at the end of the day as at the beginning etc.). However, there are many variations that still need to be solved. Examples of these variations include: weekend schedules, special days (public holidays,days with major sporting events, etc).

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- San Francisco Bay Area Rapid Transit District Contract Book. (2012). Technical Specifications.
- Estimates for Costs of D and E cars sourced from:
  - Ross, and Matier. “It's Been a Bumpy Ride as New BART Cars Spend Time in the Shop for Repairs.” *SFChronicle.com*, San Francisco Chronicle, 16 July 2018, www.sfchronicle.com/bayarea/matier-ross/article/It-s-been-a-bumpy-ride-as-new-BART-cars-spend-13074356.php.

# Appendix

### A.1: Gurobi/Python Code and Outputs

Sent as attachments with report in email.

### A.2: Preprocessing Files

Sent as attachments with report in email.

### A.3: Distance in Miles Between BART Stations and Yards

| | | | | | | |
|---|---|---|---|---|---|---|
| K | OW | **Oakland Wye** | K10 | 12th St. Oakland City Center | 0.35 | |
| | K10 | 12th St. Oakland City Center | K20 | 19th St. Oakland | 0.71 | |
| | K20 | 19th St. Oakland | K30 | MacArthur (Oakland) | 1.52 | **2.58** |
| C | K30 | MacArthur (Oakland) | C10 | Rockridge (Oakland) | 1.57 | |
| | C10 | Rockridge (Oakland) | C20 | Orinda | 4.39 | |
| | C20 | Orinda | C30 | Lafayette | 3.75 | |
| | C30 | Lafayette | C40 | Walnut Creek | 3.47 | |
| | C40 | Walnut Creek | C50 | Pleasant Hill/Contra Costa Centre | 1.71 | |
| | C50 | Pleasant Hill/Contra Costa Centre | C60 | Concord | 4.06 | |
| | C60 | Concord | C70 | North Concord/Martinez | 2.23 | |
| | C70 | North Concord/Martinez | C80 | Pittsburg/Bay Point | 4.98 | **26.16** |
| E | C80 | Pittsburg/Bay Point | E20 | Pittsburg Center | | |
| | E20 | Pittsburg Center | E30 | Antioch | | |
| R | K30 | MacArthur (Oakland) | R10 | Ashby (Berkeley) | 1.74 | |
| | R10 | Ashby (Berkeley) | R20 | Downtown Berkeley | 1.20 | |
| | R20 | Downtown Berkeley | R30 | North Berkeley | 1.05 | |
| | R30 | North Berkeley | R40 | El Cerrito Plaza | 2.20 | |
| | R40 | El Cerrito Plaza | R50 | El Cerrito del Norte | 1.84 | |
| | R50 | El Cerrito del Norte | R60 | Richmond | 2.31 | **10.34** |

| | | | | | | |
|---|---|---|---|---|---|---|
| | OW | **Oakland Wye** | M10 | West Oakland | 1.48 | |
| | M10 | West Oakland | M16 | Embarcadero (SF) | 5.85 | |
| | M16 | Embarcadero (SF) | M20 | Montgomery St. (SF) | 0.36 | |
| | M20 | Montgomery St. (SF) | M30 | Powell St. (SF) | 0.44 | |
| **M** | M30 | Powell St. (SF) | M40 | Civic Center/UN Plaza (SF) | 0.51 | |
| | M40 | Civic Center/UN Plaza (SF) | M50 | 16th St. Mission (SF) | 1.11 | |
| | M50 | 16th St. Mission (SF) | M60 | 24th St. Mission (SF) | 0.89 | |
| | M60 | 24th St. Mission (SF) | M70 | Glen Park (SF) | 1.65 | |
| | M70 | Glen Park (SF) | M80 | Balboa Park (SF) | 1.15 | |
| | M80 | Balboa Park (SF) | M90 | Daly City | 1.80 | **15.24** |
| | M90 | Daly City | W10 | Colma | 1.55 | |
| **W** | W10 | Colma | W20 | South San Francisco | 1.94 | |
| | W20 | South San Francisco | W30 | San Bruno | 2.43 | |
| | W30 | San Bruno | W40 | Millbrae | 2.91 | **8.83** |
| **Y** | W30 | | | | | |

| Line | Starting Node | | Ending Node | | Distance (miles) | Line Length |
|---|---|---|---|---|---|---|
| | OW | **Oakland Wye** | A10 | Lake Merritt (Oakland) | 0.58 | |
| | A10 | Lake Merritt (Oakland) | A20 | Fruitvale (Oakland) | 2.75 | |
| | A20 | Fruitvale (Oakland) | A30 | Coliseum (Oakland) | 2.10 | |
| | A30 | Coliseum (Oakland) | A40 | San Leandro | 2.96 | |
| **A** | A40 | San Leandro | A50 | Bay Fair (San Leandro) | 2.55 | |
| | A50 | Bay Fair (San Leandro) | A60 | Hayward | 2.87 | |
| | A60 | Hayward | A70 | South Hayward | 2.94 | |
| | A70 | South Hayward | A80 | Union City | 3.75 | |
| | A80 | Union City | A90 | Fremont | 3.22 | **23.72** |
| | A90 | Fremont | S10 | Irvington | 2.44 | |
| | S10 | Irvington | S20 | Warm Springs (Fremont) | 2.19 | **4.63** |
| | S20 | Warm Springs (Fremont) | S40 | Milpitas | 6.87 | |
| **S** | S40 | Milpitas | S50 | Berryessa (San Jose) | 2.79 | **9.66** |
| | S50 | Berryessa (San Jose) | | Alum Rock/28th Street | 1.75 | |
| | | Alum Rock/28th Street | | Downtown San Jose | 1.54 | |
| | | Downtown San Jose | | San Jose Diridon | 1.12 | |
| | | San Jose Diridon | | Santa Clara | 2.19 | **6.60** |
| | A50 | Bay Fair (San Leandro) | L10 | Castro Valley | 3.00 | |
| **L** | L10 | West Dublin/Pleasanton | L20 | West Dublin/Pleasanton | 8.58 | |
| | L20 | Dublin/Pleasanton | L30 | Dublin/Pleasanton | 1.33 | **12.91** |