# **Optimization of** Making-and-Breaking **Scheduling**

Nicholas Lorio, Lee Dao Ming, Jason Tang, Ajay Janakiram
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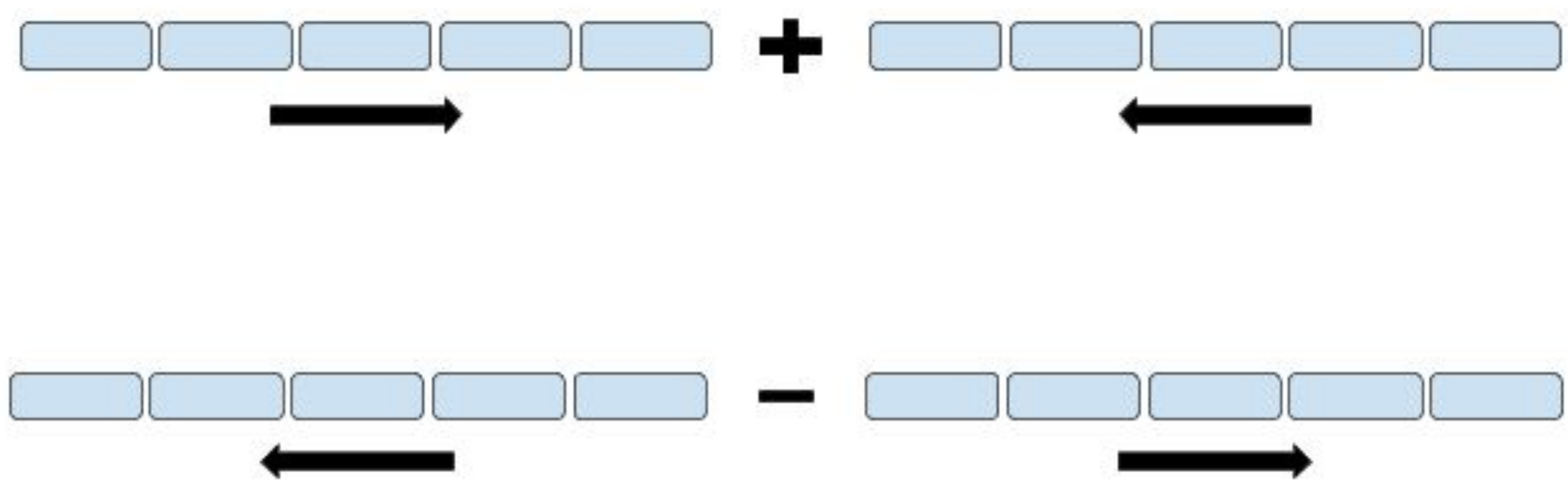
# What is Making and Breaking?

Long Consist → Short Consist → Long Consist



# Outline

1. Background
2. Problem Scope & Motivations
3. Pre-processing
4. Model
5. Results
6. Analysis
7. Recommendations/next steps

# BART Background

Main public train system of the Bay Area

Opened in 1972

Provides 125 million trips annually

# Current BART System

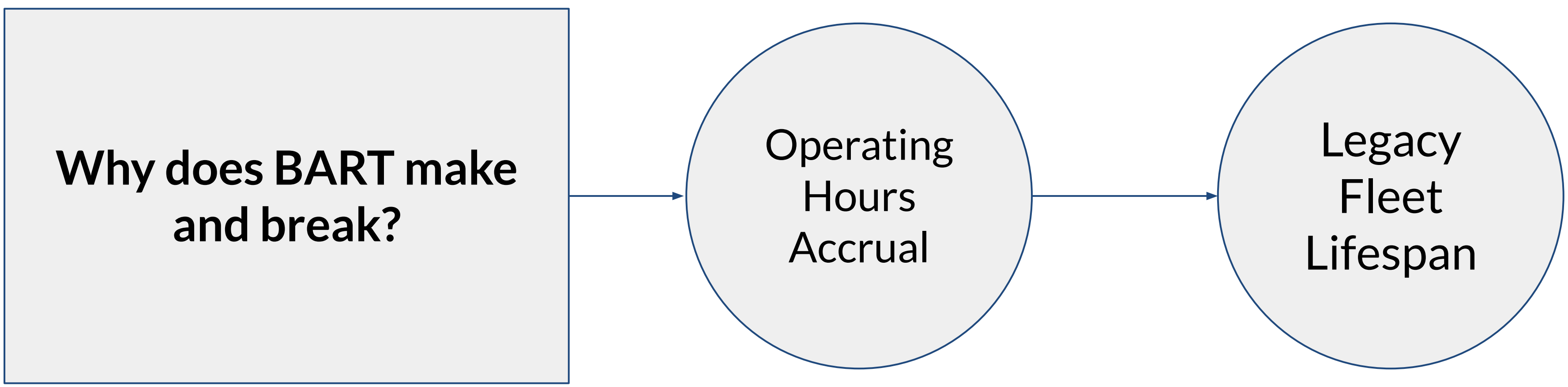
# Fleet of the Future


Introduced over next decade

1081 new cars by 2026

‘D’ (control) and ‘E’ (non-control) cars

# Motivation for Making and Breaking



# Problem Statement / Motivation

1) Determine the optimal make/break schedule for 2026 weekday BART operations.
2) Find the necessary ratio of D to E cars that can support this schedule so that BART can determine an appropriate purchasing plan for the rest of their new cars.


# Pros and Cons of Making/Breaking

| Pros | Cons |
|---|---|
| Reduction in train car operating hour accrual | Increased wear on certain train car components such as couplers |
| Reduction in power consumption | Increased labor costs |
| More spares available throughout the day | |

# Model Assumptions

1. Fleet of 1080 cars
   a. Ratio of D:E cars is 2:3
   b. 5-car (DEEED) consists as a basic unit
   c. 10 car or 5 car consists only


2. Only 5-10 & 10-5 car make-and-break

3. Conventional weekday

4. All current yards and tail tracks remain open
   a. Utilize current capacity of yard and tail tracks

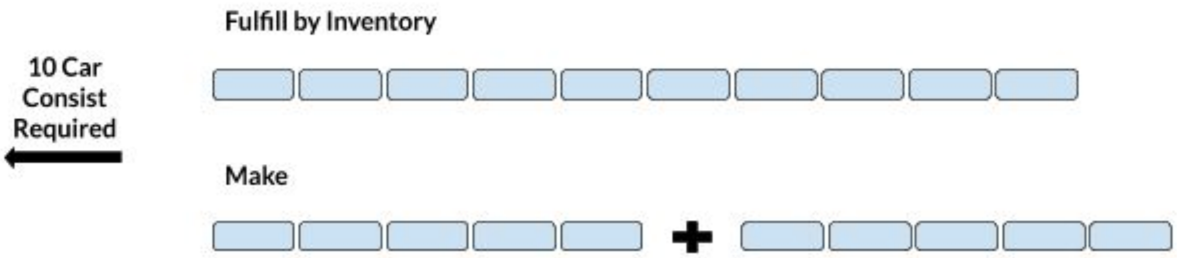
# Model Assumptions

5. Forecasted passenger demand by time of day resembles current demand.

6. Trains start the day and finish the day at end-of-line yards/tail tracks

7. Relies on current BART railway network

8. Inventory fulfillment policy



# System Representation in Steady State

Figure 21: Locations of BART Revenue Fleet Storage Facilities


## Directed Lines

- 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

# Parameter derivation

Assumptions: A, B proxies the D, E cars

Data obtained through draft of Fleet Management Plan, BART Ridership reports/dataset, emails exchanged with Operations Planning department.

Ridership demand obtained through latest (Jan/Feb 2019 monthly ridership data). Assumed equal sharing of passenger loads across a station serviced by 2 lines

# Parameter derivation

**Cost of electricity/ car-mile: $0.3539/car-mile**

- A,B (proxies D,E respectively) : 3.3708 kwh/car-mile
- Industrial rate of power: $0.105/kwh

*'According to the most recent Maintenance Plan, each of the 8 PM visits takes an average of* ***15.5 labor hours.'*** *The Overhaul plan estimate is about* ***410 labor hours per overhaul*** *for the entire vehicle, with 128 of those owing to the Coupler. Overhauls are once every 7 years.*

**Cost of regular maintenance:**

(Labour hrs/yr) x (Salary $/labor hour / Car-miles/yr)

- Car-miles/yr: 122275 (A) 137605 (B)
- Labor hrs/yr: 15.5*365 + 410/7 = 5716
- Maintenance worker salary/hr = 33
- Cost/car-mile: 1.543 (A Car) 1.371 (B Car)

# Parameter derivation

**Cost of yard team/shift:**

- 2 hour shift, 3 person team, $33/hr: $198/team-shift

**Max no. of makes and breaks/shift**

- 8 min aux cycle, 2 hr shift: 15 makes and breaks

*Couplers receive about 2.17 hours of labor per PM visit.*
*218 of the 410 labor hours/overhaul of vehicle is owed to coupler*

**Making and breaking:**

- 0.5 x coupler maintenance cost as proxy
- Only concerns D cars
- <u>Salary cost, Coupler maintenance hours, No. of makes and breaks</u> → Cost of making and breaking ~ $36.63/make-and-break. *Rough estimate*

# Parameter derivation

**Forecasted passenger demand:**

- SRTP & CIP Report 2019

| | FY19 | FY20 | FY21 | FY22 | FY23 | FY24 | FY25 | FY26 | FY27 | FY28 |
|---|---|---|---|---|---|---|---|---|---|---|
| Average Weekday | 413,000 | 433,700 | 443,900 | 458,400 | 473,900 | 483,500 | 490,500 | 500,100 | 535,800 | 548,000 |
| Total Annual (M) | 119.7 | 126.4 | 129.4 | 133.6 | 138.1 | 140.9 | 143.0 | 145.8 | 156.2 | 159.7 |
| Annual Change | - | 5.0% | 2.4% | 3.3% | 3.4% | 2.0% | 1.4% | 2.0% | 7.1% | 2.3% |

**Yard-to-yard distances:**

- Distance matrix provided

See raw derivation

# Preprocessing Steps

1. Realistic Steady State Weekday Schedule
2. Ridership Demand by Time of Day
3. Relations/Database Management

# Forecasted Weekday Schedule

100s - Warm Springs/Daly City

| Cars: | A | B | C | D | E |
|---|---|---|---|---|---|
| AM | 0 | 62 | 28 | 4 | 6 |
| PM | 0 | 62 | 28 | 4 | 6 |

| | S-M | M-S | S-M | M-S | S-M | M-S | S-M | M-S | S-M | M-S | S-M | M-S | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A70 | | | | | | | | | | | | |
| CBBBCCBBBC | 101 | 101 | 101 | 101 | 101 | 101 | 101 | 101 | 101 | 101 | 101 | 101 | H |
| Dispatch Time | 05:01 | 06:13 | 07:30 | 08:43 | 10:00 | 11:13 | 12:30 | 13:43 | 15:00 | 16:13 | 17:30 | 18:43 | |
| Patrons | | | | | | | | | | | | | |
| Size | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | |
| PPC | | | | | | | | | | | | | |

- Departure Times Per Directed Line
  - Fixed
- Headways
  - 15 min → 12 min
- Travel times
  - Inclusive end of line station to yard
- Operating hours

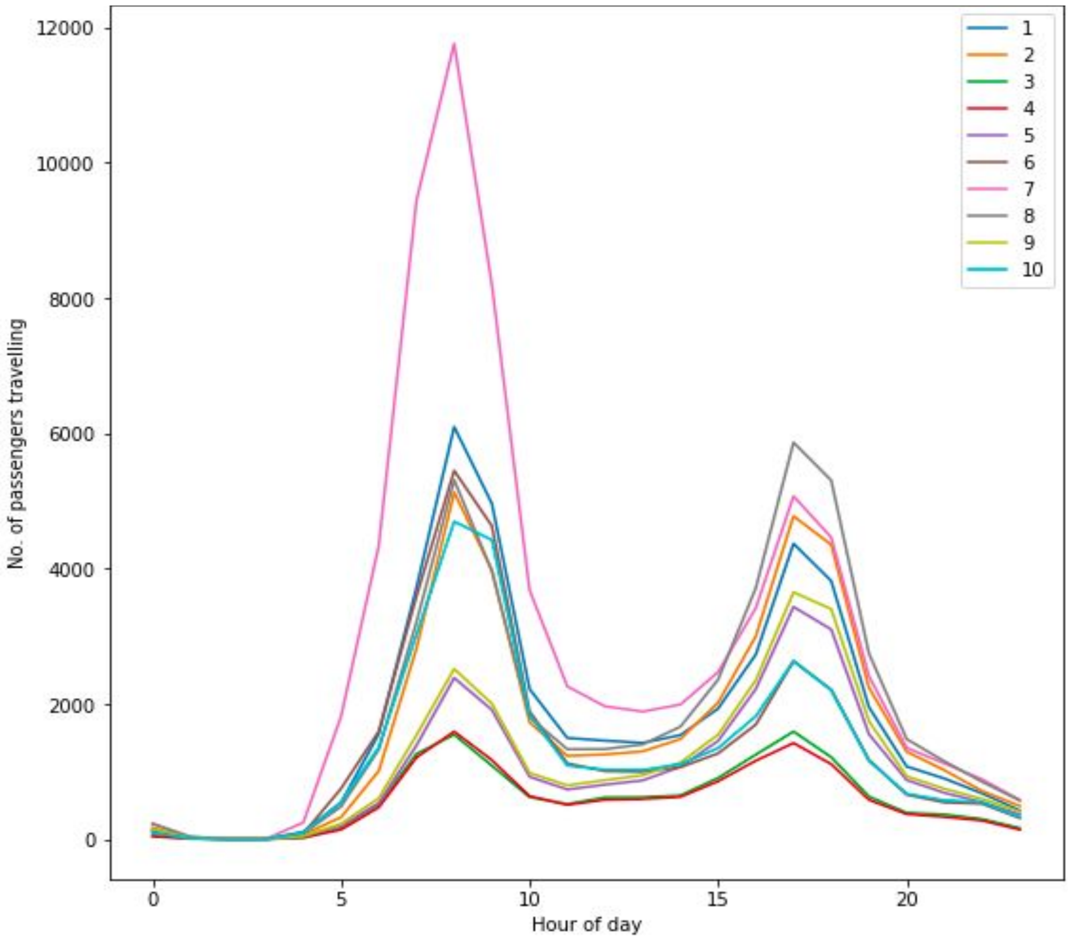
# Schedule Assumptions

- **Peak period:** 20 base Transbay trains/hr (GYRB)
- All trains begin/end at end of line yards/tt

| **Rush trains** | Green | Yellow | Red | Blue |
|---|---|---|---|---|
| 1st hour | 1 | 3 | 1 | 1 |
| Peak hour | 1 | 7 | 1 | 1 |
| 3rd hour | 1 | 3 | 1 | 1 |

| | |
|---|---|
| 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 (shut down after 2000)<br>Green: 2030 (shut down after 2200) |

# Ridership Demand by Time of Day




**Data:** Hourly Origin-Destination counts

Aggregated by directed lines

**AM & PM Peaks**

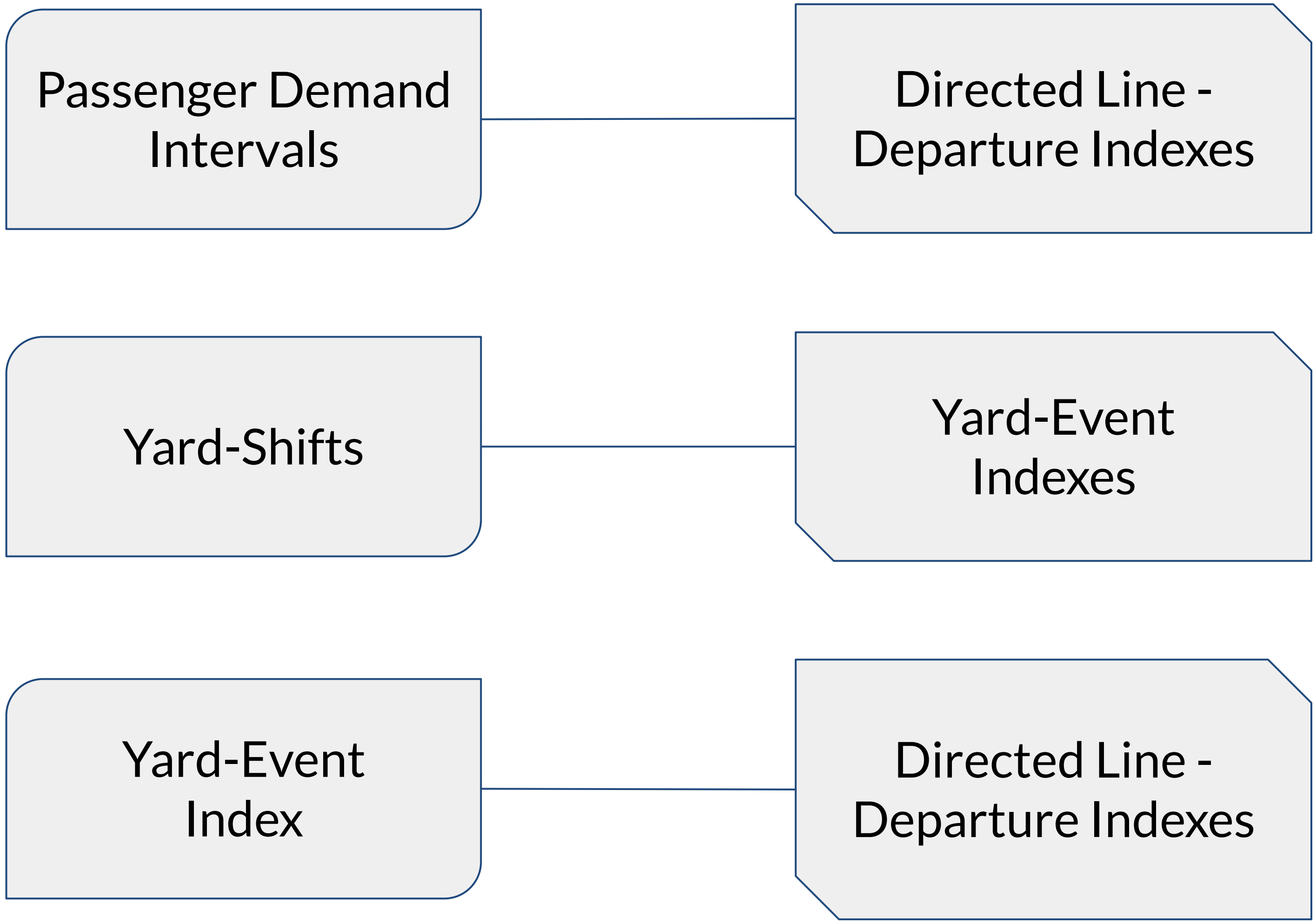
- East Bay → SF
- SF → East Bay

**PreProcessing** for peaks

- making/breaking not logical

Departures to be considered for making / breaking ?

# Relations


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

# How We Approached the Problem

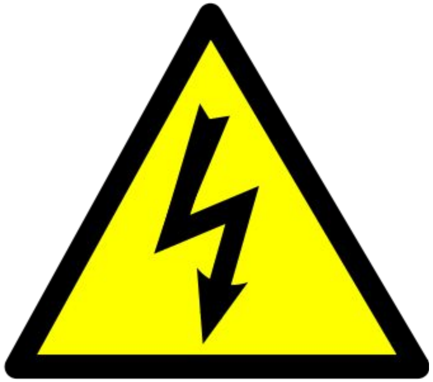
1. **PreProcessing** in Pandas
2. **Formulated the model** as a Mixed Integer Linear Program
3. **Solved** using Gurobi Solver in Python

# Decision variables

| Variable | Type | Description |
|---|---|---|
| $TS_{ac}$ | Indicator | $0 \rightarrow$ 5-car consist<br>$1 \rightarrow$ 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 |

Also Auxiliary Inventory Balance Decision Variable

# Objective Function



VS

# Electricity and Regular Maintenance

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

C = Electricity and maintenance cost of running a 5-car consist per car-mile

$(1 + TS_{ac})$ = 1 if 5-car, 2 if 10-car consist

$D_a$ = Car-mile per directed line

# Yard operators

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

$C_y$ = Cost per yard team shift

$L_{ds}$ = Level (No. of) of yard teams on shift

# Makes-and-Breaks

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

$C_{M/B}$ = Cost of make-and-break

$M_{dj}$, $B_{dj}$ = Make/Break at (just before) yard event

# Passenger demand flow

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

| | |
|---|---|
| $P_{az}$ | No. of people travelling along each direct line during an interval |
| $CC_{5\text{-cartrain}}$ | Carrying capacity of a 5-car train |
| $F_{ac}$ | Capacity multiplier based on interval overlap |
| $1 + TS_{ac}$ | 5 or 10-car |

# Yard Inventory Balance

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

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

| | |
|---|---|
| $I_{dtj}$ | No. of 5/10 car consist in yard at an event index |
| $Y_{dj}$ | (For yard event) 1 if Arrival, -1 if Departure |

# Other constraints

Same start and end yard state

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

Yard capacity

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

Disallow makes-and-breaks where inappropriate

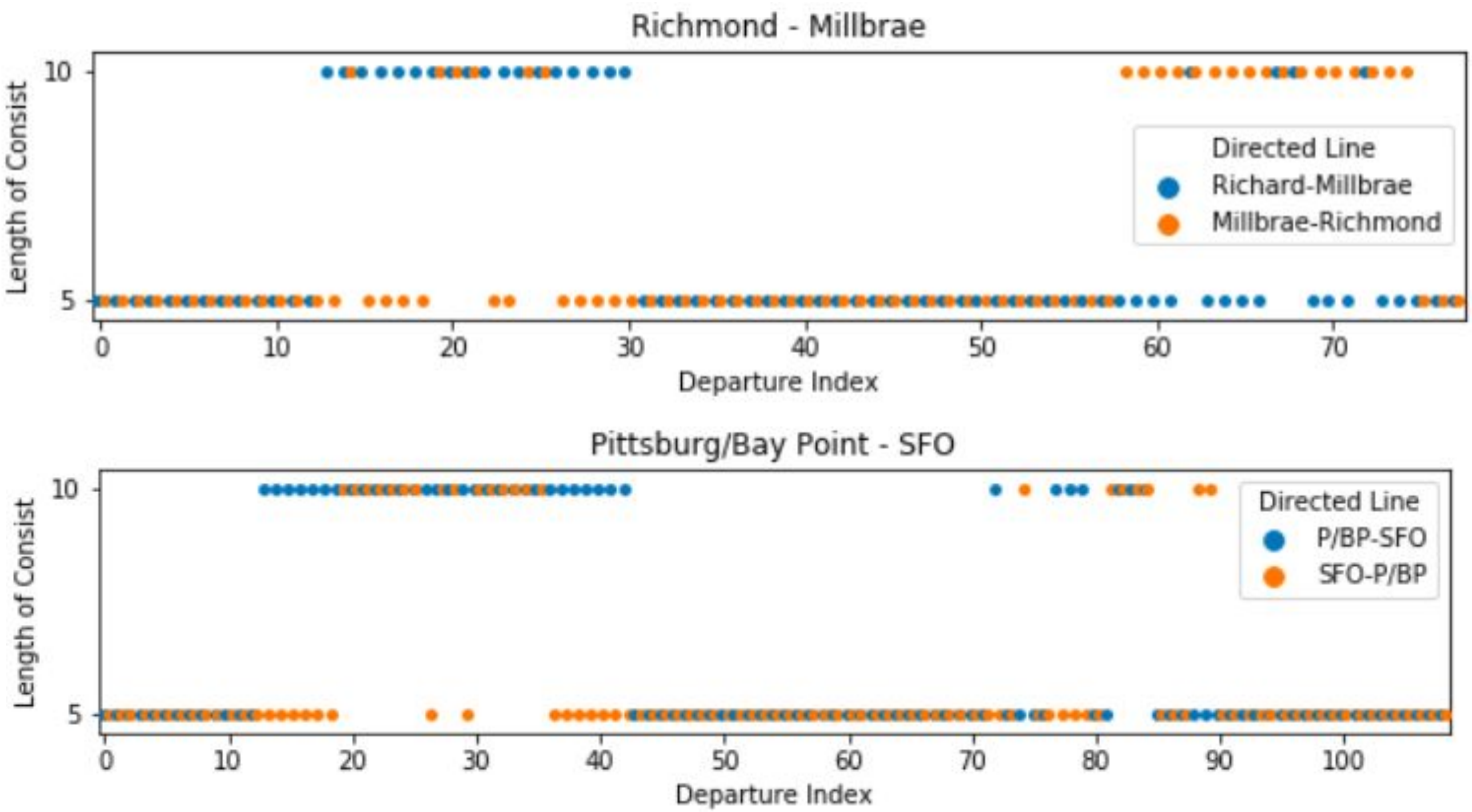
$$M_{dj} = B_{dj} = 0, \forall d \in (WarmSprings, SFO), \forall j \in J(d)$$

Capacity for makes-and-breaks

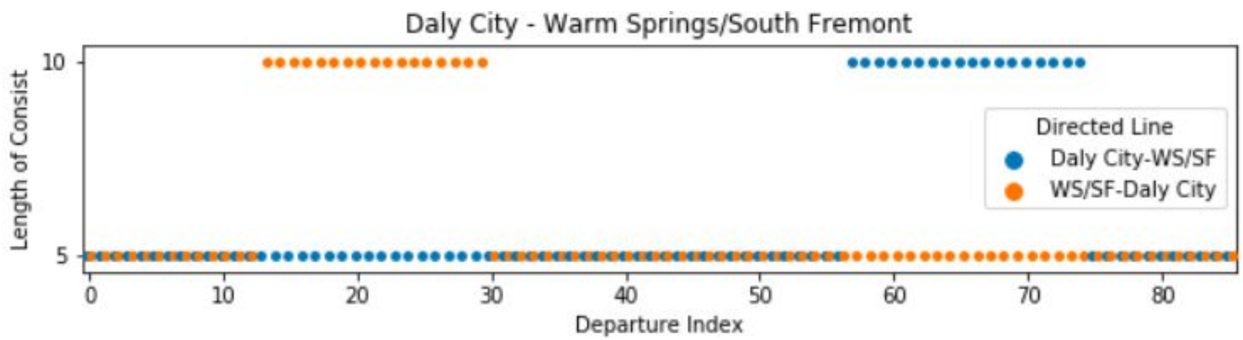
$$\sum_{j \in s} M_{dj} + B_{dj} \leqslant M \cdot L_{ds}, \forall d \in D, \forall s \in S, \forall j \in J(s)$$

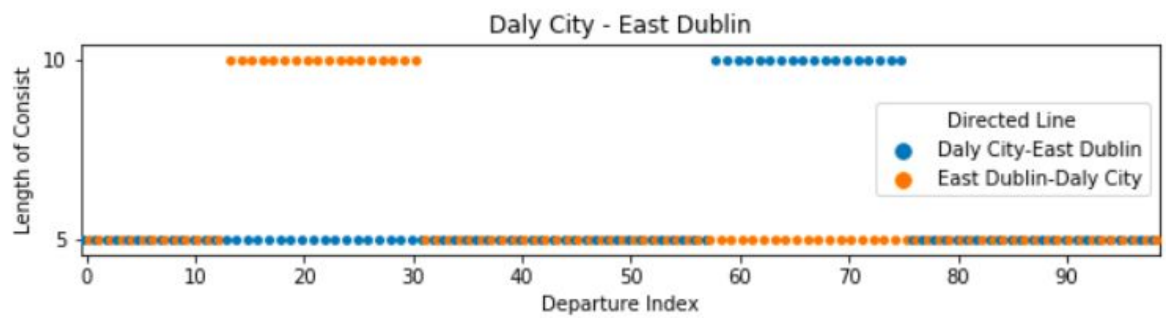
Max. no of m&b that can be
performed by a team on shift

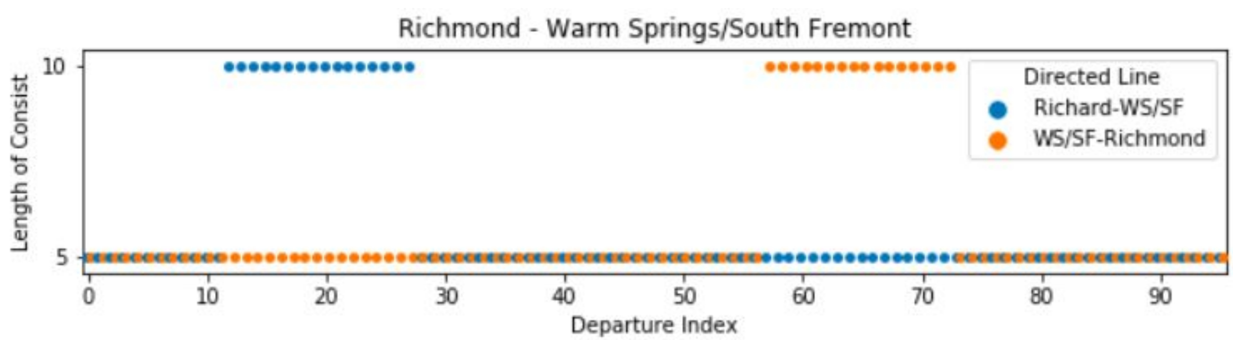
# Results


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

# Results


Daly City - Warm Springs/South Fremont
Length of Consist
10
5
0
10
20
30
40
50
60
70
80
Departure Index
Directed Line
Daly City-WS/SF
WS/SF-Daly City


Daly City - East Dublin
Length of Consist
10
5
0
10
20
30
40
50
60
70
80
90
Departure Index
Directed Line
Daly City-East Dublin
East Dublin-Daly City


Richmond - Warm Springs/South Fremont
Length of Consist
10
5
0
10
20
30
40
50
60
70
80
90
Departure Index
Directed Line
Richard-WS/SF
WS/SF-Richmond

# Result: Total Costs

| Cost($) | 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 |

# Analysis

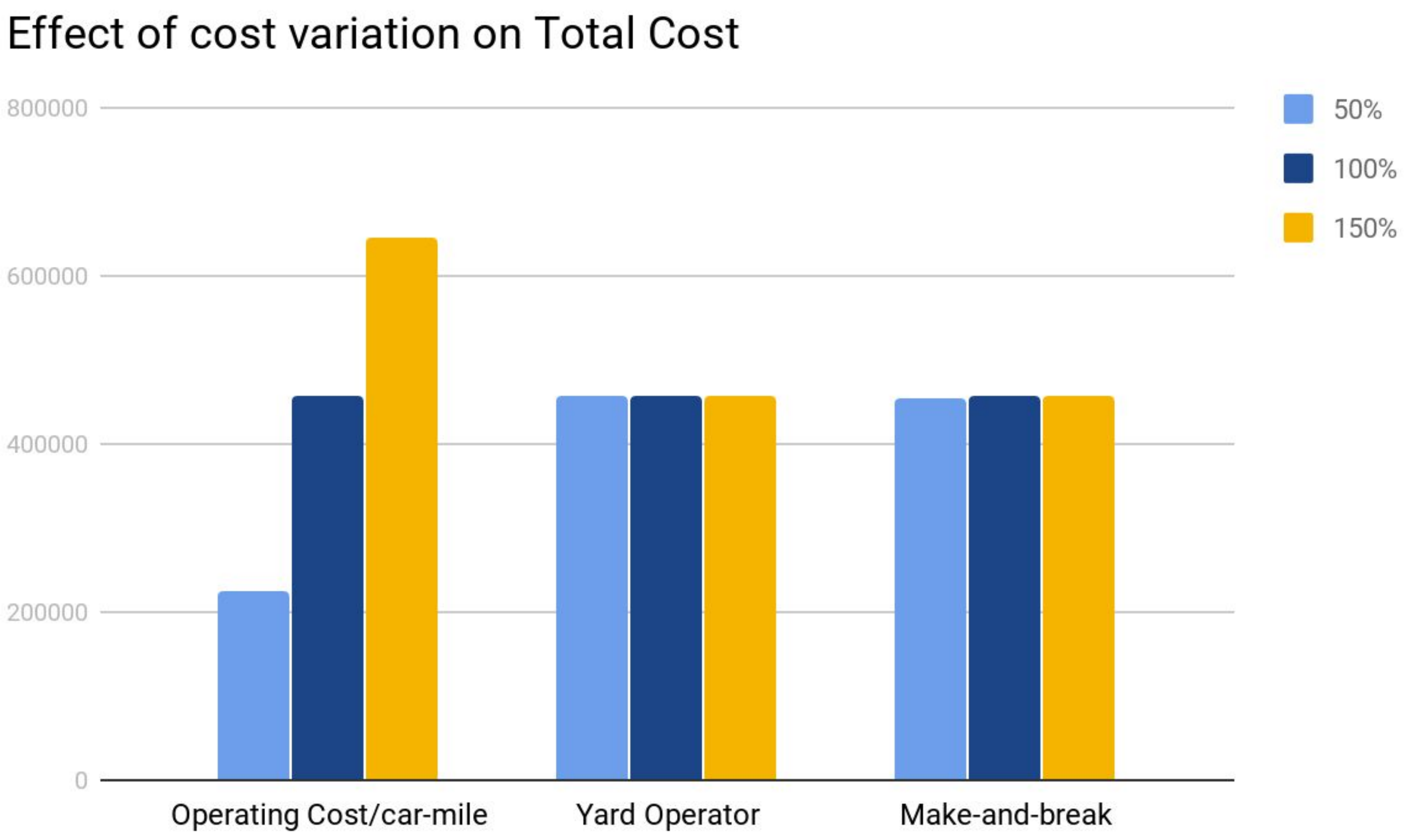
- Operating costs dominates

- Inventory fulfillment:
    - Jump in availability (~750 to 1081 cars), spare ratio
    - Excess inventory of either train set consist length

- ‘Green’: Run 5-cars whenever possible

- Robust:
    - Consist length constrained by passenger demand
    - Not sensitive to small changes in other constraints

# Sensitivity Analysis



# Scenario Breakdown

**Baseline: Feasible to purchase a lower ratio of D:E cars than 2:3**

a. Create 2026 fleet with 2:5 ratio of D:E cars
b. Greater Flexibility → 2:3 car ratio

D ~ 2 million / car

E ~ 1.7 million/car

| | **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 |

# Scenario Breakdown

**NPV of cost for both scenarios**

- Initial Investment Cost in 2019
- Yearly Consist Operational Cost over the next 20 years [2026 - 2046]
  - **Baseline:** ~166 million annually
  - **All 10 Car:** ~266 million annually
- Assume an interest rate of 4%

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

| **Baseline NPV** | **All 10 Car NPV** |
|---|---|
| 3.78 billion | 4.85 billion |

# Recommendations for BART

**Proceed with baseline purchasing strategy**

- Lowest NPV cost
- Run a mix of breakable and unbreakable consists
  - 60% 5 car consist
  - 40% unbreakable 10 car consist

# Potential Next Steps

Transitional/Mixed Fleet prior to Steady State

Account for Spare Ratio Requirement

Consider Malfunctioning Cars

Analyze other (non-weekday) schedules

# Thank you

# To do slide

2. Sensitivity analysis
   - LB, UB of parameter values
   - Effect on objective function costs

- Comparison of Baseline and Green scenario
  - Piechart to show cost breakdown (None since e+w&t dominates)
- Sensitivity analysis for parameter values
  - Establish lower bound, upper bounds
  - Effect on objective function
  - For constraint?

# Current Make and Break Operations

| 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 |