Site Selection and Sizing of an LRV Storage Yard

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The San Francisco Municipal Railway (MUNI) is in the process of expanding its light-rail vehicle (LRV) system, to include track extensions and a new storage and maintenance facility. Methodology used by Manna Consultants to evaluate the operating cost savings (deadheading and driver relief costs) associated with alternative storage yard configurations and locations is described. A mathematical model was programmed on Lotus 1-2-3 to allow rapid analysis of alternative scenarios that were developed through conferences between Manna, MUNI, and the San Francisco Public Utilities Commission. The study determined that the new yard should be designed to accommodate LRVs only, and not a mixture of LRVs and historic streetcars, as had been proposed. For the current fleet, the new yard was found to reduce annual deadheading and relief costs by $1,000,000 per year. Although significant, this saving alone would not justify construction of a new storage yard. Justification comes from the need to store an expanded fleet that cannot be accommodated by the existing yards.

The City of San Francisco is planning an expansion of its light-rail vehicle (LRV) system, to include track extensions and an additional storage and maintenance facility. At present, the city's Municipal Railway System (MUNI) operates five LRV lines over 21 mi of track, carrying an average of 130,000 passengers per weekday. The route structure is radial, with lines heading west out of the downtown in a common subway, then splitting to run separately along the surface on the western side of the city.

All LRVs are now stored and maintained at the Metro Center and Geneva yards, which are located adjacent to each other at the western terminus of the J, K, and M lines as shown in Figure 1. The yards have a nominal capacity of 135 vehicles combined, but are currently operated above capacity to accommodate the LRV fleet of 130 vehicles along with a fleet of 30 historic streetcars (which are only used during special streetcar festivals).

Manna Consultants was engaged by the San Francisco Public Utilities Commission (SFPUC) to design and evaluate a new storage and maintenance facility—Metro East—to be located on the eastern side of the city, in the vicinity of the downtown. Metro East would be near the terminus of a track extension planned to serve locations south of the downtown, including the Southern Pacific Railway commuter terminal and a major new real estate development. The purpose of Metro East is two-fold:

1. To provide space to store and maintain an expanded fleet, including vehicles needed to cover
   —The LRV track extension,
   —Headway improvements on existing lines, and
   —A new full-time historic surface streetcar line along Market Street.
2. To reduce operating costs associated with positioning vehicles and drivers on lines that are distant from the existing yards.

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A flexible model was developed to evaluate the operating cost savings taking into account yard size, configuration, and location. A crucial decision was whether the new yard should both accommodate the historic streetcars and the LRVs, or whether it should be dedicated to the LRVs. Because a mixed facility would require additional investment, it would have to be justified by operating cost savings. A second issue was whether the new yard could provide substantial cost savings on the existing L and N lines, which do not terminate near the existing Metro Center and Geneva yards.

The methodology was adapted from prior work on selecting bus garage sites (*1–5*). In many respects, the issues are the same for buses and LRVs. For both, facilities should be situated close to the points where vehicles begin and end their blocks (the series of runs performed by a vehicle during a day). To evaluate any combination of sites, each block is assigned to the site that minimizes operating costs, given restrictions on storage capacity. The total operating cost, along with site-specific costs, is then a basis for comparing alternative plans.

The added complication with LRVs is that it is difficult to identify the precise starting and ending points of blocks. At MUNI, as with many other LRV systems, vehicles are considered to be in revenue service from the moment they leave the yard until the moment they return. One might argue, then, that all blocks begin and end at the existing yards. But this perspective is unduly biased against new locations: the optimal place for any new yard would have to be the same location as the existing yard, because this policy would minimize the distance to start and end points. Clearly, some point other than the existing yard should be selected for starting and ending blocks. But where?

DELINEATION OF FIXED AND VARIABLE COSTS

The approach was to divide operating costs into two categories, those that were fixed with respect to yard locations, and those that varied with respect to yard locations. The analysis sought to evaluate only the variable costs.

Delineating the fixed from the variable costs was a matter of considerable discussion between MUNI, SFPUC, and

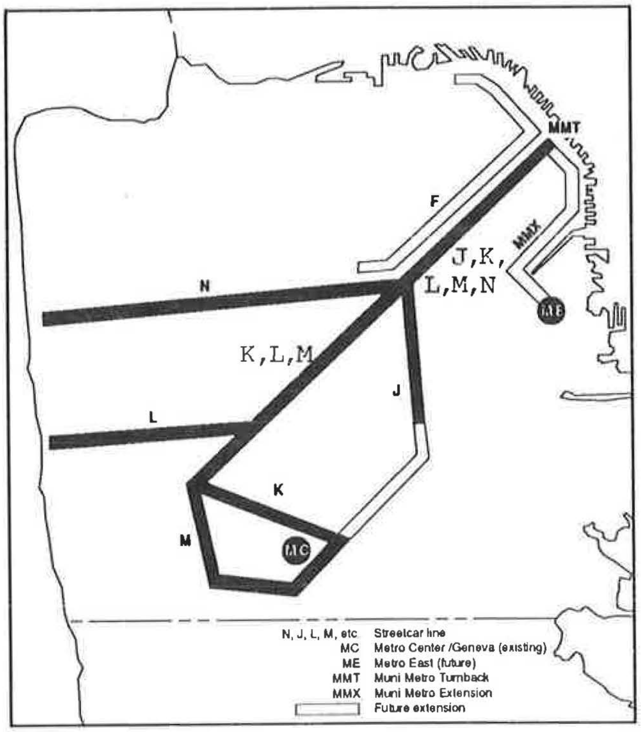

FIGURE 1 Map of MUNI Metro LRV System, showing added MMX Line. Inner terminal is MUNI Metro Turnaround (MMT), or Embarcadero.

Manna. In the meetings, a variety of reasonable perspectives was expressed. The following is something of a middle ground, agreeable to all.

Blocks were first divided into two categories: (a) base service, and (b) supplemental service. Blocks in the first category serve both the a.m. and p.m. peaks, as well as the midday period, usually with one or more driver relief. Blocks in the second category serve only the a.m. or only the p.m. peak (there are roughly equal numbers of both), and do not require a driver relief. All blocks on Saturday and Sunday fell in the base category, whereas Monday to Friday had a mixture of base and supplemental blocks.

For the a.m., blocks were designated to begin either at an outer terminal (the line terminus away from the downtown) or the inner terminal (the terminus in the downtown). The number of blocks beginning at the inner terminal was set to equal the number of vehicles needed to provide a minimum outbound headway of 20 min at the start of the day. Because the running time from inner to outer terminal was roughly 40 min on each line, and because vehicles operate in two-car trains, this meant four blocks were designated to begin at the inner terminal on most lines. After the first 40 min, outbound runs could be covered by trains arriving from the outer terminal. All remaining blocks were designated to begin at the outer terminal, to provide shorter headways for inbound service during the morning peak.

In the evening, the process is reversed for base service, the ending points being identical to the a.m. starting points. For supplemental service during the a.m. peak, all blocks were assumed to end at the inner terminal. Because the purpose of the supplemental service is to provide inbound capacity, vehicles would cease to be productive once they completed their last run to the inner terminal. Supplemental service for the p.m. peak is the mirror image of that for the a.m. peak. Blocks begin at the inner terminal at the start of the rush, and end at the outer terminal.

From the standpoint of minimizing deadheading, it is advantageous for blocks to begin and end at the same location. Therefore, it was decided that, where possible, the blocks beginning at the inner terminal should be supplemental vehicles. (The exception was the M line, which does not provide supplemental service.) This policy allowed supplemental vehicles to be stored at Metro East, enter service at the inner terminal, and leave service at the inner terminal.

The proposed track extension (MMX in Figure 1) was treated in the same way as existing lines, with its inner terminal located downtown and its outer terminal located away from downtown (in this case south instead of west). There was some discussion as to whether or not the extension should be treated independently, for it would in fact be operated as an extension of the existing N line. It was concluded that the extension should be treated independently. The predominant travel on the extended N line would be toward the downtown, but it would come from two distinct directions—from the east on the existing line and from the south on the extension. Therefore, vehicles would have to begin service from distinct outer terminals.

COST TYPES

Two types of variable costs were included in the analysis: (a) deadheading costs, and (b) driver relief costs. Deadheading costs were evaluated for each block by calculating the travel time from each yard site (including the current site) to each of the block's terminals (starting and ending), and multiplying by an hourly cost (accounting both for vehicle and driver costs).

Relief costs were calculated by multiplying driver travel time to and from relief points (line running time plus ½ headway, as specified in MUNI's labor contracts) by hourly compensation. Relief costs are incurred when a driver's run begins and ends at different locations. For base service, these costs occur on vehicles that do not return to their storage yard during the course of the day (currently, the L and N lines; see Figure 1), because driver exchanges cannot occur at the vehicle's home base. For these lines, relief costs are incurred exactly twice per day, when the first driver of the day returns from the relief point to the storage yard, and when the last driver of the day travels from the storage yard to the relief point. The relief was assumed to occur at the point on the line that is closest to where the vehicle is stored.

For supplemental blocks, relief costs are only incurred when a vehicle is stored overnight at Metro Center/Geneva, on the western side of the city, and stored during the middle of the day at Metro East, in the vicinity of the downtown. (It would never be desirable to do the reverse—Metro East overnight, Metro Center/Geneva midday—because the predominant direction of travel is toward Metro East in the morning, and away from Metro East in the evening.) At the expense of somewhat higher driver compensation, this policy would reduce deadheading costs at the end of the a.m. peak, and at the start of the p.m. peak. Relief cost was calculated on the basis of the travel time between the yards, multiplied by driver compensation.

A third relevant cost, which was not included, was compensation for split shifts. MUNI believed that their compensation scheme was too complicated to incorporate in a planning model, that part-time drivers would cover many of the supplemental routes, and that travel relief costs would reflect much of the split-shift costs.

These costs comprise the variable portion of the system costs. All remaining costs, such as the cost of operating the blocks themselves, were assumed to be fixed, and were not included in the calculations. An attractive feature of this approach was that it was not necessary to make any assumptions as to the number of runs or the length of time in each block. This cost would be independent of the yard location.

EVALUATION APPROACH

To summarize, for any possible site for Metro East a plan had to be devised for storing vehicles. For base service, a vehicle (represented by a block) could either be stored at Metro East or at Metro Center/Geneva. For supplemental service, a vehicle could be stored at Metro East or at Metro Center/Geneva, or it could be stored at Metro Center/Geneva overnight and at Metro East at midday. The choice was based on variable costs, taking into account both deadheading and relief costs, and also taking into account yard capacities.

For each site considered, a matrix representing the costs of assigning each block to each yard was generated in Lotus 1-2-3. The Lotus 1-2-3 model provided flexibility to quickly compare alternative sites. A single entry represented the travel time from the new yard to the downtown terminus of all lines. By changing this single entry (i.e., by moving the yard either closer or further from the terminus), a new cost matrix would be automatically generated. A new cost matrix could also be generated if the driver compensation or vehicle operating cost changed, also through adjustment of single entries.

The Lotus 1-2-3 model was set up to assign vehicles to yards and generate cost estimates, for the following scenarios:

Scenario	*Description*
Unrestricted	Expanded fleet, without restriction on storage capacity.
Scenario 1	Expanded fleet, with storage capacity for 90 LRVs at Metro East, 90 LRVs at Metro Center, and 45 historics at Geneva.
Scenario 2	Expanded fleet, with storage capacity for 45 LRVs and 45 historics at Metro East, 90 LRVs at Metro Center, and 45 at Geneva.

The number of active vehicles to be assigned is provided in Table 1. It was assumed that for every four LRVs assigned to a yard, one additional space would be allocated for a reserve vehicle. Therefore, a yard capacity of 90 LRVs would translate into an active fleet of 72 vehicles and a reserve fleet of 18. For the historic cars, two reserve vehicles were needed for each active vehicle. This unusually large ratio was because of higher maintenance requirements, and the need to store special vehicles (including open-air cars) that would only be used occasionally. Therefore, a yard capacity of 45 historic cars translated into an active fleet of 15 vehicles and a reserve fleet of 30 vehicles. In total, 159 active vehicles and 66 reserve vehicles had to be assigned to 225 spaces.

Calculating the unrestricted cost was simply a matter of choosing the least cost location for each block, and summing the costs. This resulted in the minimum possible operating cost, but demanded that more vehicles be stored at Metro East than it could accommodate. For the two restricted scenarios, some of the LRVs had to be reassigned from Metro East to Metro Center/Geneva. This reassignment was accomplished by selecting the blocks for which the cost difference between the two locations was smallest (in cases where several new locations are being considered, this could be accomplished by solving a transportation problem through linear programming). Under Scenario 2, some of the historic cars also had to be reassigned from the existing yard to Metro East.

TABLE 1 ACTIVE VEHICLES BY LINE

Active Vehicles by Line	CURRENT				PROPOSED(1)			
	Peak(2)	Midday	Sat	Sun	Peak	Midday	Sat(3)	Sun(3)
F	0	0	0	0	15	9	6	5
J	12	7	4	4	19	11	6	6
K	18	9	7	6	20	10	8	7
L	23	9	9	7	33	13	13	10
M	20	20	8	7	22	22	9	8
N	29	18	12	9	34	21	14	11
MMX(4)	0	0	0	0	16	10	6	5
TOTAL	102	63	40	33	159	96	62	52

(1) Based on Metro Turnaround study. J line adjusted upward by 3 to cover extension. L line adjusted downward by 5, to resolve discrepancy with current service, and to attain total LRV fleet of 144, or 80% of total LRV fleet size of 180.
(2) Current peak is average of a.m. and p.m. service
(3) Assumes same as % drop on Sat and Sun as current
(4) MMX: Muni Metro extension to Metro East

Both actions result in a cost increase over the unrestricted solution.

Table 2 presents a sample output from Lotus 1-2-3 for one of the yard locations considered. In the data section of the spreadsheet, the travel time from Metro East to the inner terminal, the operating cost per vehicle-hour, the driver compensation per hour, and the number of runs that begin at the inner terminal (Embarcadero) are specified by the user. Total costs are calculated internally and summarized in the results section.

In the cost analysis section of the spreadsheet, costs are calculated on a line-by-line basis. First, costs are calculated for base service from the outer terminal, then for peak service, and finally for base service beginning at the inner terminal (Embarcadero). For each type of block, costs are calculated for each storage option: Metro Center/Geneva or Metro East for base service and inner terminal service, and Metro Center/Geneva or Metro East or Metro Center/Geneva night plus Metro East day for peak service. The minimum cost solution is selected, subject to restrictions on yard capacity. The detailed costs are summed to obtain the summary costs already mentioned. Not shown are additional data on the number of vehicles by line and yard capacity.

RESULTS

From the standpoint of operating costs alone, Metro East was found to be a better place than Metro Center/Geneva for storing the following types of vehicles:

- All service beginning or ending at the inner terminal (Embarcadero),
- Midday only storage of all supplemental service,

TABLE 2 SAMPLE OUTPUT FROM LOTUS 1-2-3 SPREADSHEET EVALUATING EXPANDED FLEET

SUMMARY	EXPANDED	
DATA	TT to ME	12 min
	Oper Cost	70 $/hr
	TT Cost	23 $/hr
	# Emb Start	4
RESULTS	Unrestricted	57283 $/week
	Scenario I	61504 $/week
	Scenario II	67058 $/week

COST ANALYSIS

TOTAL COST -- BASE SERVICE ($/wk)

	MC/Gen	ME	Min
F	4372	4803	4372
J	0	6964	0
K	0	6728	0
L	8035	8976	8035
M	0	11685	0
N	17702	13949	13949
MMX	7606	0	0
TOTAL	37714	53105	26355

DH COST -- BASE SERVICE ($/wk)

	MC/Gen	ME	Min
F	3136	4125	3136
J	0	6195	0
K	0	5985	0
L	6440	7933	6440
M	0	10395	0
N	14803	13949	13949
MMX	6251	0	0
TOTAL	30630	48582	23525

TT ALLOWANCE -- BASE SERVICE ($/wk)

	MC/Gen	ME
F	1236	678
J	0	769
K	0	743
L	1595	1043
M	0	1290
N	2900	0
MMX	1355	0
TOTAL	7085	4523

TOTAL COST -- PEAK SERVICE ($/wk)

	MC/Gen	ME	MC-ME	MIN
F	3220	2147	2569	2147
J	1680	2660	1449	1449
K	2520	3990	2174	2174
L	13160	10173	12237	10173
M	0	0	0	0
N	9240	6405	8721	6405
MMX	3873	560	3643	560
TOTAL	37714	53105	30794	22908

DH COST -- PEAK SERVICE ($/wk)

	MC/Gen	ME	MC-ME	MIN
F	3220	2147	1680	1680
J	1680	2660	560	560
K	2520	3990	840	840
L	13160	10173	8680	8680
M	0	0	0	0
N	9240	6405	6720	6405
MMX	3873	560	2753	560
TOTAL	33693	48582	23525	18725

TT ALLOWANCE -- PEAK SERVICE ($/wk)

	MC/Gen	ME	MC-ME
F	0	0	889
J	0	0	889
K	0	0	1334
L	0	0	3557
M	0	0	0
N	0	0	2001
MMX	0	0	889
TOTAL	0	0	9560

TOTAL COST -- EMB SERVICE ($/wk)

	MC/Gen	ME	MIN
F	2582	724	724
J	3997	1448	1448
K	3997	1448	1448
L	4126	1448	1448
M	2317	888	888
N	4157	1375	1375
MMX	2078	687	687
TOTAL	23256	8019	8019

DH COST -- EMB SERVICE ($/wk)

	MC/Gen	ME	MIN
F	2487	672	672
J	3967	1344	1344
K	3967	1344	1344
L	3967	1344	1344
M	2287	784	784
N	3967	1344	1344
MMX	1983	672	672
TOTAL	22624	48582	23525

TT ALLOWANCE -- EMB SERVICE ($/wk)

	MC/Gen	ME
F	95	52
J	31	104
K	31	104
L	159	104
M	31	104
N	190	31
MMX	95	15
TOTAL	632	515

- All service on the new Metro Extension and the N line, and
- Supplemental service on the F and L lines (both overnight and midday).

These vehicles (110 in total) constituted the unrestricted solution, which exceeded the planned Metro East capacity by 20 vehicles. Comparing Scenario 1 to Scenario 2, it was concluded that it would not be worthwhile to accommodate the historic cars at Metro East, because of the small number of historic cars that should be assigned there. Subtracting these, 102 LRVs were left for Metro East, or just 13 percent more than the planned capacity. Of these 102 vehicles, 12 were reassigned to Metro Center/Geneva, to meet the target yard size of 90 vehicles. This solution is shown in Figures 2 and 3. In Figure 3, for each line, blocks are classified by inner versus outer terminal, and base versus supplemental (MC = Metro Center/Geneva, ME = Metro East, MC/ME = Metro Center/Geneva night and Metro East day). Fortunately, it was found that a redesign of Metro East would provide sufficient space for 12 more cars. Therefore, the current plan provides for a full 102-vehicle capacity. The projected variable cost for this plan amounts to $60,000 per week, which is $7,000 per week less than Scenario 2.

The analysis was designed to compare the relative merits of alternative locations and configurations, not to measure the cost effectiveness of building a new yard. Nevertheless, for the current fleet size, the savings in deadheading and relief costs were found to be $1,000,000 per year. Clearly these savings alone could not justify the project. The primary motivation for Metro East is that the existing storage yards are too small to accommodate an expanded fleet and that it would be more expensive to expand the existing yards than to build a new yard at an alternative location.

To a great extent, the study confirmed the expectations. Metro East would be a good place to store vehicles that begin and end their runs away from the existing yards. The N line, the new Metro Extension, and all runs beginning at the inner terminal were obvious candidates. A less obvious choice was the supplemental L service, whose outer terminal is closer to Metro Center/Geneva, but whose inner terminal is closer to Metro East. Through analysis, it was found that by storing the vehicles at Metro East, both midday and overnight, MUNI could eliminate the driver relief cost of $3,600 per week, and that this saving would more than compensate for a slight increase in deadheading costs of $1,500 per week.

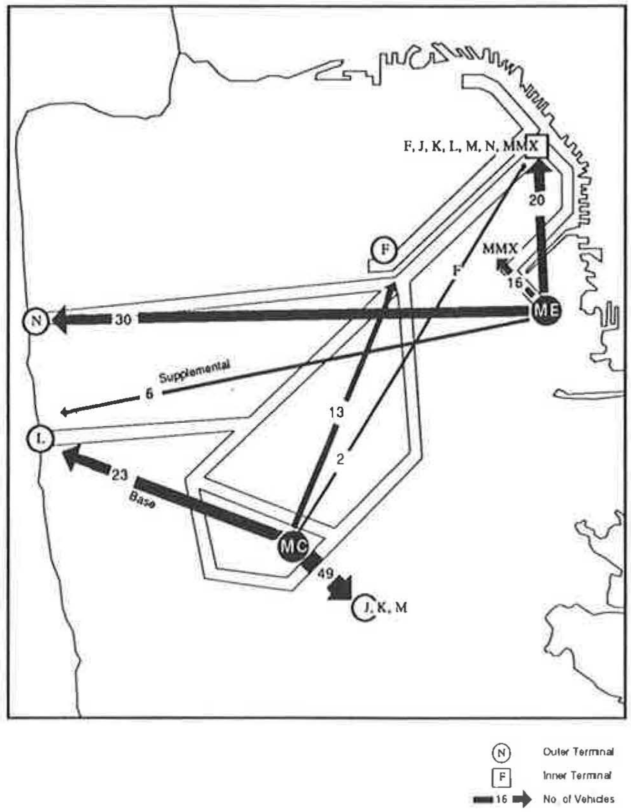

FIGURE 2 Assignment of active vehicles to yards for weekdays; 72 active vehicles are stored at Metro East and 87 active vehicles are stored at Metro Center/Geneva.

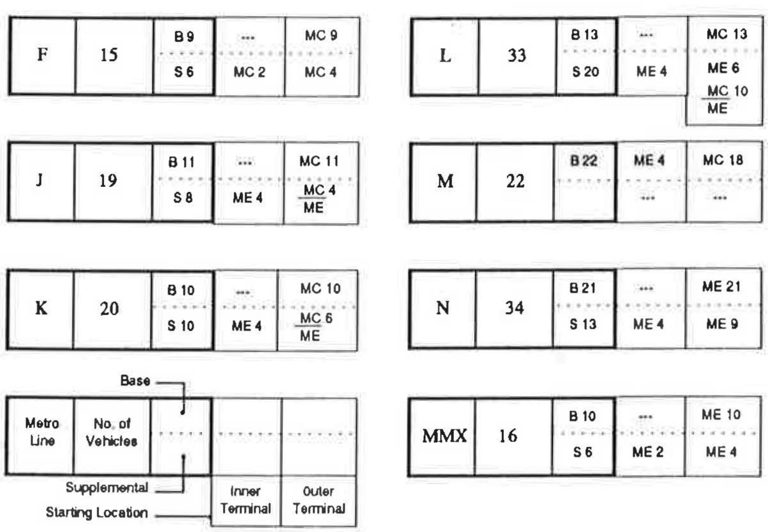

FIGURE 3 Assignment of blocks to yards for weekdays.

Most of the L line vehicles should continue to be stored at Metro Center/Geneva, because the outer terminal of the L line is closer to Metro Center/Geneva than to Metro East. Also, cost savings from storing the N line vehicles at Metro East are not enormous (under $10,000 per week), despite the fact that the N line operates far from Metro Center/Geneva. The reason is that the outer terminal of the N line is only slightly closer to Metro East (49 min) than it is to Metro Center/Geneva (52 min). Combined, these facts indicate that Metro East is a far from optimal location from the standpoint of deadheading/relief costs for existing lines. A preferred location would be on the western side of San Francisco, near the outer terminals of the L and N lines. However, there are few feasible sites there, or for that matter, anywhere else in San Francisco. Within the South of Market Area, on the other hand, there are several options. The analysis allowed comparing the operating costs for these alternatives as an input to the site selection process.

A weakness in the analysis is that all costs are assumed to vary proportionately with the number of deadheading hours and the number of driver travel hours. In reality, work rules might prevent a savings of an hour here or an hour there from being translated into real cost reductions. Unless the number of drivers (and, perhaps, vehicles) is reduced, costs may remain more or less the same. Unfortunately, the number of drivers is dictated more by the number of vehicles needed to cover the peak-period demand than by deadheading that occurs before or after the peak periods. Nevertheless, even if direct cost savings do not materialize, service improvements will. Therefore, the cost evaluation is a suitable way to compare alternatives.

Finally, returning to the issue that vehicles are actually in revenue service whenever they are outside the yard, reducing deadheading must also reduce some types of service. For instance, our proposal reduces service in the morning, heading from the existing yards to the outer terminals of the L and N lines (by 6 and 30 runs, respectively). However, few people benefit from this service, which is why the cost of these runs is allocated to deadheading. At the same time, the proposal increases outbound service from the downtown in the early morning (i.e., deadheading to outer terminals of L and N lines). This service will likely benefit few people, which is why it is also put in the deadheading category.

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