Abridgment

Innovative Scheduling for the Bay Area Rapid Transit System

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This paper explains the scheduling constraints imposed by both the computer automated block system (CABS) logic and the track geometry of the Bay Area Rapid Transit (BART) system in the Oakland area, which is called the wye because the track configuration is like a Y. The alternative schedules that were developed within these constraints to ameliorate the excess passenger demand on the Concord-Daly City route are also presented.

The BART system consists of the following five lines or system segments:

1. C Line—trackage and stations between Concord and Rockridge,
2. R Line—trackage and stations between Richmond and Ashby,
3. A Line—trackage and stations between Fremont and Lake Merritt,
4. M Line—trackage and stations between Daly City and Oakland West, and
5. K Line—trackage and stations between MacArthur and Twelfth Street in Oakland.

These lines are shown in Figure 1. During normal operations, trains are turned back at the Concord, Richmond, Fremont, and Daly City stations. Service is provided on the Concord-Daly City, Fremont-Daly City, and Richmond-Fremont routes. Trains on these routes merge and demerge at the Oakland wye, which is the trackage bounded by Lake Merritt, Oakland West, and Twelfth Street stations. This trackage is also shown in Figure 1.

CABS operates as an independent backup system to provide computer-enforced train separation beyond that provided by the primary train-control system. A following train is held at a station until a leading train has cleared the station.

WYE SCHEDULING CONSTRAINTS

There are limitations on the train patterns that can be scheduled to be in the wye simultaneously (i.e., nonconflicting trains), and there are constraints on the time required before the next nonconflicting set of trains can be scheduled into the wye (i.e., scheduled headway in the wye). The limitations are determined by the wye track geometry and the CABS logic. Consequently, the wye imposes restrictions on how many train patterns can be scheduled into the wye and when they can be scheduled.

Train Movement

The following acronyms are used to indicate the trains that correspond to the Concord-Daly City, Fremont-Daly City, and Richmond-Fremont routes.

Train	Route	Train	Route
DC	Daly City to Concord	FR	Fremont to Richmond
CD	Concord to Daly City	FD	Fremont to Daly City
RF	Richmond to Fremont	DF	Daly City to Fremont

As shown in Figure 1, some lines have more than one route overlaid on the lines. The following are the trains that run along the designated lines.

Line	Train	Line	Train
C	CD (DC)	M	DC (CD)
R	RF (FR)		DF (FD)
A	FR (RF)	K	RF (FR)
	FD (DF)		CD (DC)

The trains in parentheses are the corresponding trains that run in the opposite direction along the route.

The five nonconflicting patterns for train movement (A, B, C, D, and E) that can be allowed in the wye at the same time are shown in Figure 2. The nonconflicting patterns not shown are those for single train movements in the wye. To check the validity of a given pattern, one can simply refer to the schematic diagram of the wye in Figure 2 to see whether there are any merge conflicts between any pair of trains in a particular pattern. (A matrix for train conflict can be used to summarize the information in Figure 2.)

Headway

The CABS logic imposes a constraint on the time interval between one train pattern in the wye and the next train pattern entering the wye. This time interval is the headway between trains in the wye. The headway constraint in the wye is the longest time interval during which a train can block the wye. For example, the longest time interval is that associated with the run from Oakland West to Lake Merritt. This time interval is the sum of the run time, plus CABS logic clear-out time, and the difference in dwell times between Lake Merritt and Oakland West. This time interval or the minimum theoretical headway is approximately 4 min. This theoretical headway is achievable only if perfect control is exercised to maintain time-slot synchronization. The actual headway (approximately 6 min) is larger than the theoretical headway (approximately 4 min) because of variabilities in station dwells, interstation run times, and train headways as the trains enter the wye. As the scheduled headway going into the wye decreases, the congestion in the wye (as measured by train delays) increases. This increase can be interpreted as a queueing delay, which will increase if the arrival rate increases and the service rate remains invariant.

SIMPLIFIED BART SCHEDULE

Many essential elements of a schedule can be represented by a time line on which the times of nonconflicting train patterns that enter the wye can be indicated. The time indicated in Figure 3 is relative time for meets at the wye; point 0 on the time line can be any actual time. To get the dispatch times from Concord, Richmond, Fremont, or Daly City to meet at the times indicated in the wye, one simply works backward in time by adding up the programmed dwells and run times from the wye

to the appropriate dispatch station.

The current BART schedule alternates between pattern A (trains CD, FR, and DF are in the wye simultaneously) and pattern B (trains DC, RF, and FD are in the wye simultaneously). To determine the headway of trains on a line (e.g., the C Line), one must first determine the trains that run on that line and then measure the time between trains on the time line. (Headways on a line are longer than headways in the wye, since trains from several lines merge in the wye.) For example, trains on the C Line are CD (or DC); thus the headway between CD trains and the C Line is 12 min. Trains on the M Line are CD and FD (or DC and DF); thus the headway between CD and FD trains on the M Line is 6 min (Figure 3).

ALTERNATIVE SCHEDULES

There is a greater demand for service on the Concord-Daly City route than on the Fremont-Daly City and Richmond-Fremont routes. CD trains typically run with load factors of three (i.e., three times as many passengers as seats). The alternative schedules that could provide more service to the Concord-Daly City

Figure 1. The BART system.

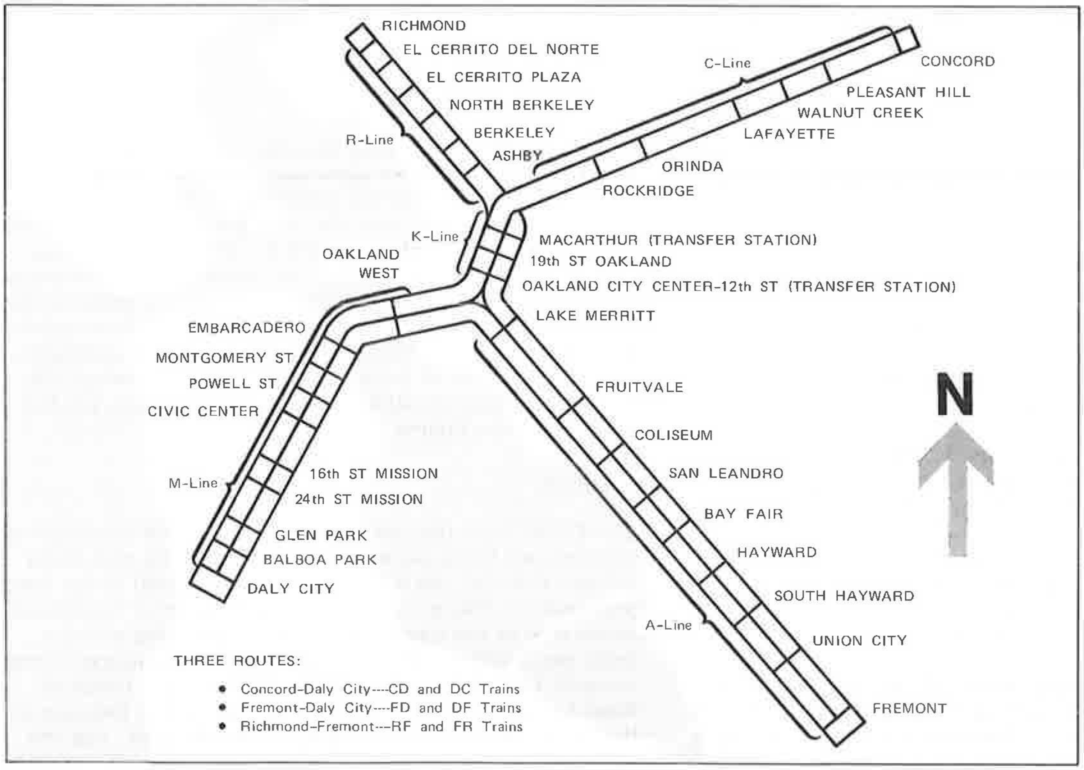


Figure 2. Diagram of wye and main nonconflicting train patterns.

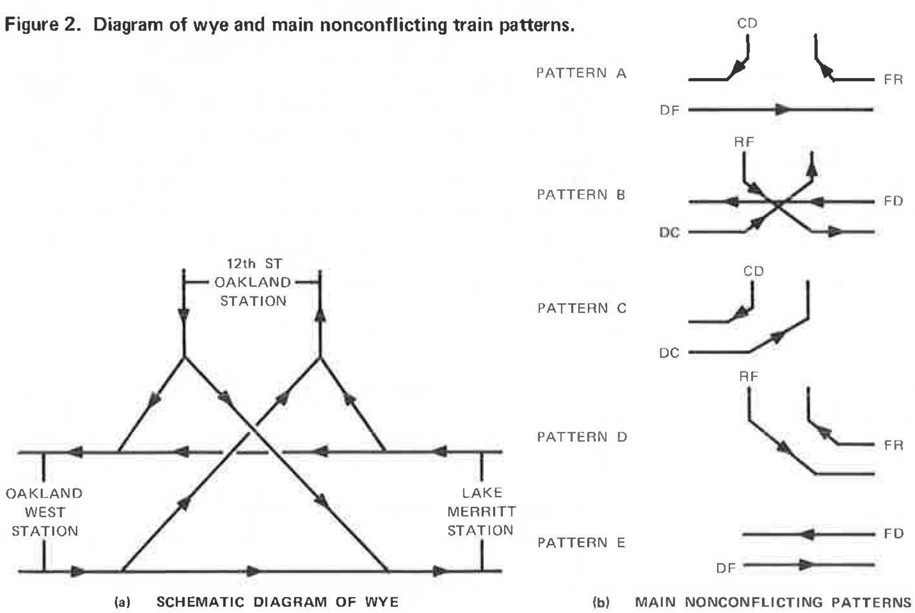


Figure 3. AB schedule with 6-min headway.

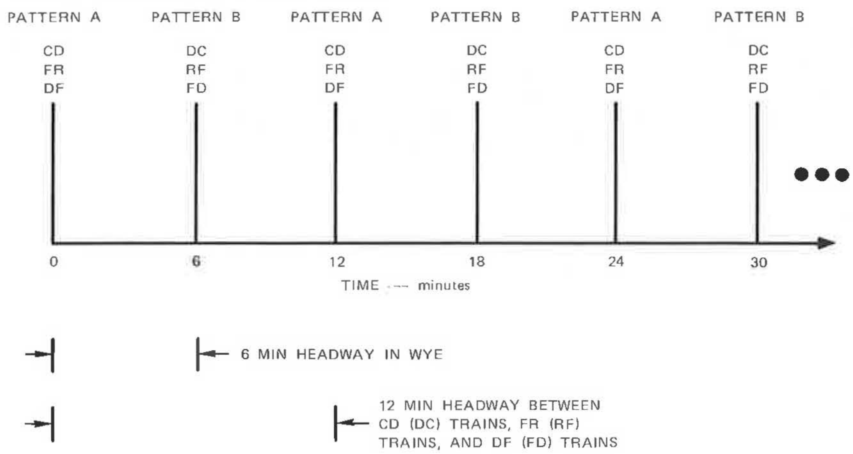
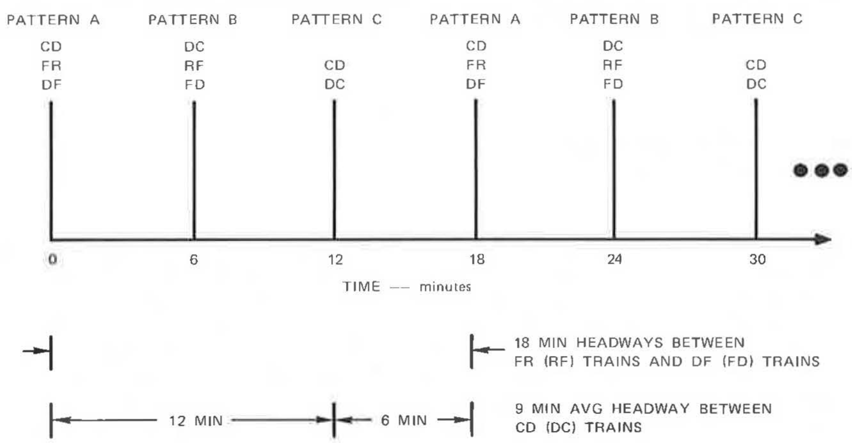


Figure 4. ABC schedule with 6-min headway.



route without significantly reducing the service to the other two routes are discussed below.

The current schedule for BART alternates between the nonconflicting train patterns A and B. Given a specific uniform headway in the wye (6 min), the AB schedule is the most efficient way of getting the greatest number of trains through the wye at a given time. As shown in Figure 3, each pattern (A followed by B) contains three trains, and these are the maximum number of trains that can be in the wye at the same time. If our goal is to schedule the optimal mix of trains for carrying passengers rather than scheduling the greatest number of trains through the wye, then we can improve on the AB schedule.

ABC Schedule

Figure 4 shows an ABC schedule with a 6-min headway for increased service on the Concord-Daly City route. Although this service is favorable for the Concord-Daly City route (i.e., average headway of 9 min), the 18-min headways for the Richmond-Fremont and Fremont-Daly City routes are unattractive.

In terms of moving the maximum number of trains through the wye, the ABC schedule is less efficient than the AB schedule; pattern C contains only two trains instead of the maximum three trains. However, during pattern C, the wye is less congested. This lack of congestion allows for a periodic recovery phase every third pattern and therefore should contribute to a reduction of the headway in the wye beyond the currently scheduled 6-min headway. This reduced headway should not significantly increase the congestion in the wye. Thus, the system has a chance to catch up every third pattern.

5/10 C Line Schedule

The 5/10 C Line schedule is basically an ABC schedule that operates at 5-min (instead of 6-min) headways during the morning and afternoon peak periods; pattern C is removed during off-peak hours. If the headways are 5 min (instead of 6 min), then headways average 7.5 min on the Concord-Daly City route and 15 min on the Fremont-Richmond and Daly City-Fremont routes during peak periods (Figure 4). For early morning service, pattern C is removed but its time position is unfilled. This gives 15-min headways on all routes. At approximately 6:30 a.m., the first pattern C trains are dispatched from Concord. These pattern C dispatches will continue during the morning peak and will result in a 5-min headway for trains in the wye during that peak. The pattern C trains will be removed in the afternoon between the peak periods to give 15-min headways. This cycle is repeated at approximately 4 p.m. for the afternoon peak.

SIMULATION COMPARISONS

A computer simulation of the CABS logic for the BART system was used to compare the 6-min headway AB and

ABC schedules during the peak period. This comparison was used to evaluate the hypothesis that a recovery phase in the wye occurs every third pattern in the ABC schedule, and this recovery phase allows the congestion to dissipate. Our results indicate that there are substantially fewer delays with the ABC schedule than with the AB schedule. The AB schedule was then compared with the 5/10 C Line schedule during the peak period. Our results indicate that both schedules have roughly the same amount of delay, even though the 5/10 C Line schedule has a 5-min rather than a 6-min headway in the wye.

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Abridgment

Procedure for Optimizing Rapid Transit Car Design

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To design a transit car, one must consider the constraints of the system such as tunnel width, clearances on horizontal and vertical curves, station spacings, signal systems, maximum speed, passenger demand and capacity requirements, and the ability of new equipment to mate with old equipment. It is difficult to select or design a car that meets these constraints; however, it is more difficult to choose a design that provides the most economical solution.

For example, as the length of a transit car increases, there is also an increase in weight, power consumption, maintenance, and capital costs. If cars were designed individually, then it would be obvious that shorter cars minimize the total cost. However, the constraint of passenger demand or the capacity that must be provided dictates that more cars will be needed to provide for capacity if cars are shorter in length. In many cases, this trade-off favors the longer car length because the need for fewer cars outweighs the added costs associated with each car.

PROCEDURE

This paper discusses a methodology that can be used to either develop an approximate initial car design or to analyze an existing design by varying the number of design elements to determine their effects. A computer program was developed to implement the methodology. The program can be used as either a design tool or a planning tool. The program is designed to perform an economic analysis that provides the minimum total annual costs. These costs include the sum of capital costs, operating labor costs, power costs, and vehicle maintenance costs. Thus, all design elements of the car are related not only to the initial cost of the car itself but also to the total costs. Therefore, a car can be designed that will provide the lowest total costs over the 30 or 35-year life of the car to the operating authority.

A set of equations was developed to describe the interactions between car design elements and cost. These equations and the constraints imposed by operating and service characteristics form a closed set of relations so that a minimum cost solution may be found. For example, equations were developed that relate the passenger capacity of the car to its length and width. Likewise, equations were also developed to describe the effect of increasing length on weight, power consumption, capital costs, and maintenance costs. An increase in passenger capacity was related to the need for more air conditioning and heating, which results in an increase in capital, power, and maintenance costs. An increase in the weight of a car relates to an increase in power, which results in an increase in the cost and weight of motors. Additionally, the lengths of the cars were related to the number of car-kilometers traveled per year per car and to the total number of cars needed to operate the system, which are also functions of demand, route distance, and headways. Average speed, which is a function of maximum speed, station spacing, acceleration and deceleration, and dwell times, was related to the number of cars and the number of crews (amount of operating wages) needed to operate the system.

Thus, an entire set of equations was developed that produces the total costs incurred by a system for the purchase, operation (power and on-board labor), and maintenance of vehicles and is based on meeting a specified demand and supplying a specified level of service. This set of equations is capable of being optimized to provide the car design associated with minimum total cost per year.

A set of approximately 250 equations was developed from data and from physical and known relations to form the interaction between car design and cost. To facilitate the development of these equations, we divided them into specific groups and subgroups, according to the following analysis.

The total costs were minimized by equalizing all costs. Therefore, all costs are in annual dollars. Thus, for capital or initial costs, the annual cost that is based on a particular interest rate and service life of the car was determined by using an appropriate capital recovery factor. For power consumption, the annual cost was deter-