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Rail Transit

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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.

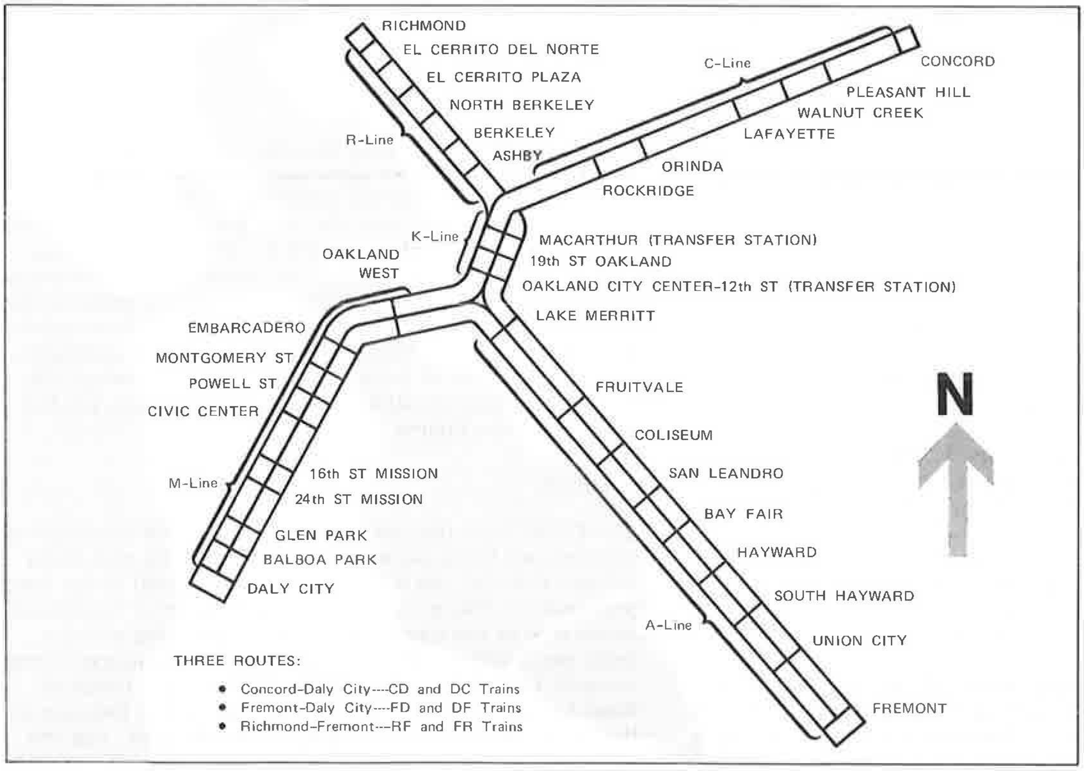
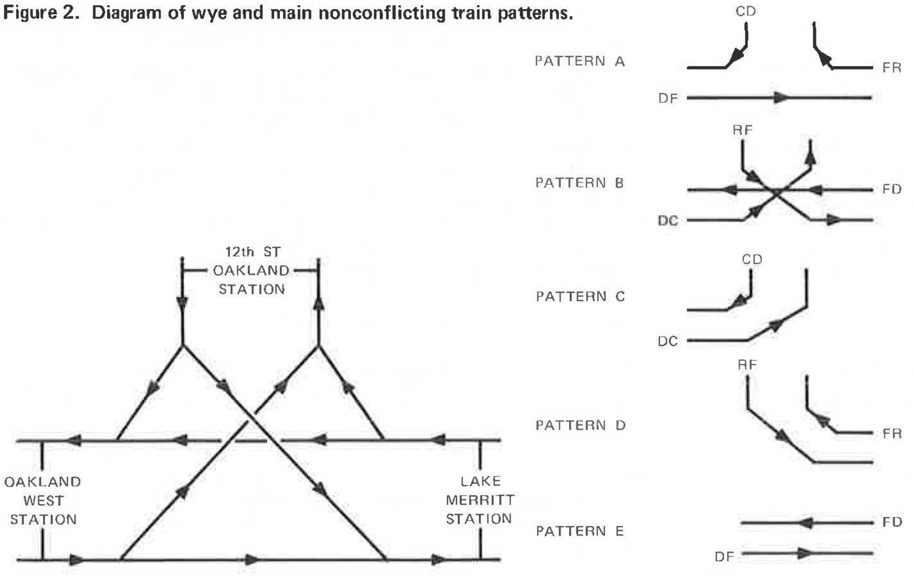


Figure 2. Diagram of wye and main nonconflicting train patterns.



(a) SCHEMATIC DIAGRAM OF WYE (b) MAIN NONCONFLICTING PATTERNS

Figure 3. AB schedule with 6-min headway.

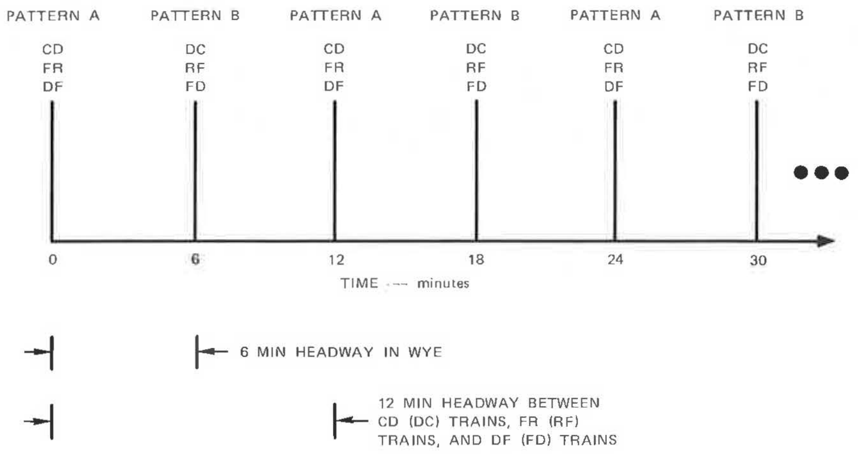
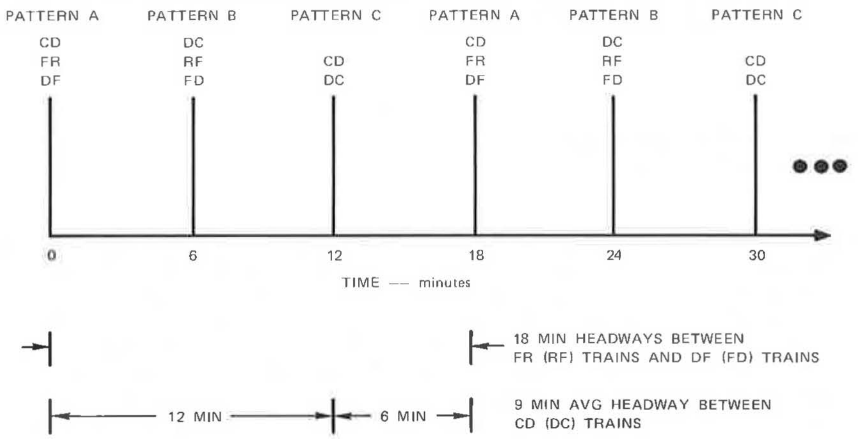


Figure 4. ABC schedule with 6-min headway.



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.

ACKNOWLEDGMENT

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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 determined by megajoule per car per year multiplied by the cost of a megajoule. For maintenance, the annual cost is the cost of parts and labor, and, for operating labor, it is the annual cost of labor. Since these calculations are for one car only, they are in error because car length, speed, and other characteristics affect the total number of cars and person-hours of labor needed to provide the required service. All of the annual costs must be calculated for the total number of cars (and trains) needed in the system. A set of physical equations that relate the elements of car design to the total number of cars needed and total car-kilometers traveled is described below. (Maintenance and power are dependent on total car-kilometers run in the system per year.)

Therefore, the objective function, which is the total cost to be minimized, is the sum of annual power cost for all car-kilometers operated, annual maintenance cost for all cars, annual operating (on-board) labor based on total train-hours of operation per year, and annual costs for all cars so that the required service can be provided.

EQUATION GROUPS

The first group of equations describes the cost relations between each car component and the subassembly. These costs vary with the size, weight, and requirements of the components. For example, as car capacity increases, there will also be an increase in the air-conditioning capacity and the cost of the air-conditioning units. The costs of all components and subassemblies are summed to yield total car cost. The calculation for annual cost of purchasing the required number of cars is based on the cost per car, number of cars, and capital recovery factor for a specified service life and interest rate.

The second group of equations concerns power consumption in which consumption is divided into traction power and auxiliary power such as that used for air conditioning or lighting. The methodology is designed in such a way that power regeneration and energy storage systems may be included by modifying and inserting various equations. Within the subgroup of traction power consumption is car weight, which is one of the prime importance variables. Total car weight is the sum of the weight of all components, including body and frame plus the weight of passengers. The individual weight equations describe the relation between component weight and car design. For example, as the air-conditioning requirements increase, the weight of the air-conditioning equipment will also increase. The total power consumption, auxiliary plus traction, is summed for all car-kilometers traveled per year, and the calculation for cost of power consumption is based on a specified cost per megajoule.

The third group of equations concerns maintenance in which the equations relate the type of component, car design, frequency of maintenance, and cost of labor and cost of parts to total maintenance costs. The annual maintenance cost of each car item is summed for all car items, which yields a total annual maintenance cost per car. This cost is summed for all cars in the system and is based on the actual, total car-kilometers run in the system per year.

The fourth group of equations concerns operating labor in which cost of train crews is related to number of train-hours of service (average velocity, route distance, headway), car design, and total operating labor costs. Descriptions of automatic train operation and automation equipment and their related equations form a subgroup of this category. The operating costs are summed for all train-hours run in the system per year.

The fifth group of equations relates certain elements of car design such as length, acceleration, and maximum velocity to the number of cars needed to operate the system, the number of total car-kilometers run in the system, and the kilometers per car aggregated during the year. The physical equations relate the number of passengers per car, number of cars per train, and number of trains per hour needed to meet demand to the car design parameters. This last group of equations is divided into three subgroups that can be added to or substituted for the previous equations so that the program may consider rubber-tired cars, motor-trailer car combinations, or articulated cars.

DEVELOPMENT OF EQUATIONS

The equations come from several sources, and approximately half are derived directly from physical relations such as cars per train to headway, passenger demand, and car capacity, or the relation that describes car-kilometers per year per car. The other half comes directly from the various data sources. All of the data concerning car specifications and performance for 64 rapid transit cars were analyzed by using multiple regression techniques. These techniques produced linear regression equations that describe the relation between a dependent variable and several independent variables. In many cases, this method produces simple equations that adequately describe known but extremely complicated relations. For example, the calculation of traction power consumption is complicated. However, based on the traction power consumption of 64 vehicles, a linear regression equation (with a multiple correlation coefficient of 0.92) that involves power, velocity, acceleration, deceleration, and weight of vehicle as independent variables was used to evaluate the power consumption (dependent variable). The same procedure produces a linear equation for determining the power per motor needed to meet given performances. Thus, this set of simple linear equations was developed to be used for cost minimization.

For many of the component weight, initial cost, and maintenance equations, the regression techniques proved successful because they produced linear equations for the relations. However, some equations appear to be nonlinear. In some cases, the relations were linear but the equations were in nonlinear form since the variables used in the equations are constant. In a handful of cases, the equations were truly nonlinear. For these cases, the computer was used to linearize the equations by generating several thousand values of the dependent variable and then running through all values and combinations of the independent variables within the range of interest. Least squares curves were applied to produce a linear equation that is based on the data points generated. For many equations this technique provided excellent results. (For the following equations, SI units are not given for the variables inasmuch as the operation of the model requires that the units be in U.S. customary.) The equation for car capacity is

$$\mathrm{CAPCAR} = [(L)(W)(k)]/[P(A) + (1 - P)B] \qquad (1)$$

where

L = car length,
W = car width,
k = usable floor area factor,
P = percentage of seats (total car capacity),
A = square feet per seat, and
B = square feet per standee.

However, the linear equation for car capacity is

$$\mathrm{CAPCAR} = 3.19(\mathrm{L}) - 27.7(\mathrm{A}) - 111.4(\mathrm{P}) - 31.0(\mathrm{B}) + 20.15(\mathrm{W}) - 5.5(\mathrm{NCAB}) + 18.2 \qquad (r = 0.98) \tag{2}$$

The difference between the values calculated by the two forms of the equation is less than 1.0 percent.

Only three equations were not easily transformed into linear form. For one equation, the problem was solved by holding one of the variables (headway) constant for each computer run. For the other two equations, three- and four-part linear equations were developed.

MODEL EQUATIONS

The regression analysis on the data base for 64 cars with a correlation coefficient of 0.92 produced the following equation for kilowatt-hours of traction power consumption (KWHTRC).

$$\mathrm{KWHTRC} = 0.000\,08(\mathrm{CAR\ WT}) + 0.004\,25\,(\mathrm{HP}) + 0.16(\mathrm{MAX\ VEL}) - 0.678(\mathrm{DEC}) + 0.284\,(\mathrm{NMOT}) + 0.304\,(\mathrm{ACC}) - 8.802 \tag{3}$$

where

KWHTRC = kilowatt-hours of traction power consumption per car-mile;
CARWT = car weight in pounds, including full load of passengers;
HP = horsepower per car;
MAX VEL = maximum velocity in miles per hour;
DEC = deceleration rate in miles per hour per second;
NMOT = number of motors per car; and
ACC = average initial acceleration rate in miles per hour per second.

Power consumption is also calculated for auxiliary equipment such as interior lights, ventilation and air conditioning, interior heating, air compressor, and motor generator or converter.

A series of equations are used to determine the weights of all the individual components of the car. These equations are functions of the other car design parameters, and the sum is the total car weight. The weight of passengers is

$$\mathrm{PASSWT} = (150\ \mathrm{lb})(\mathrm{CAPCAR}) \tag{4}$$

where car capacity (CAPCAR) is determined by a separate equation that relates to car dimensions, seating arrangement, and area per seat and standee. The weight of the car body is a function of car dimensions, type of construction, and materials, and all of these can be selected and entered into the program.

A general equation was set up to sum the costs of operations such as routine and major maintenance and overhaul and replacement. The cost of a particular operation is the number of person-hours multiplied by the wage per person-hour and the cost of parts. This value, multiplied by the number of times per year the operation is performed, yields the total maintenance cost per year for that operation and car item. That value is then multiplied by the number of identical items per car to provide cost per car. The same procedure is used for all three operations (routine and major maintenance and overhaul and replacement). Thus, the total is based on actual car-kilometers and is multiplied by total car-kilometers run in the system per year (CMPYPS). This figure yields the systemwide annual cost of all maintenance on a particular car item. These values, for each maintenance item, are summed and give the grand total of all car maintenance costs per year.

The following is an example of an individual maintenance equation for trucks.

$$\mathrm{MAJOR}\ (\mathrm{miles}) = -0.21\,(\mathrm{TKWT}) - 500(\mathrm{MAX\ VEL}) + 110\,000 \tag{5}$$

Thus, the maintenance of trucks is related to kilometers, velocity, and truck weight.

PREPROGRAM

The preprogram is a series of 60 questions that ask the user to select the values of all of the constants and input parameters that were previously described. For convenience, the questions are divided into groups. One group concerns the system (route length, station spacing, capacity, headways, station length, acceleration and deceleration rates, and maximum car length), and another group concerns the vehicle technology and tracking system (steel-on-steel or rubber tire, car body materials, type of braking such as disc or tread, controls such as conventional or choppers, and married pairs of single unit cars). A third group consists of amenities such as air conditioning, type of seat construction, carpeting, lighting levels, and window area. The fourth group is a miscellaneous category that includes wage scales for maintenance, service life and interest rate for capital recovery, average winter temperature for heating requirements, and cost to purchase electricity.

After the questions are answered, the preprogram adjusts the main program and is run to produce a car design that minimizes total annual costs. Or, a car design can be fed into the computer by entering the real values or output values, i.e., the car design output includes exterior and interior dimensions and the weights, costs, power consumptions and maintenance costs of all of the components and subassemblies of the car. If these values are entered as input, the program can be used to compare an existing design with the optimal design produced by the computer. Or, any one or combination of variables can be changed in value to determine the sensitivity of the overall design to these variables. An example of this procedure for a car design is as follows.

Since the output for a car design is approximately 350 values, this example shows only the values pertinent to sensitivity and cost analyses. These analyses are beneficial because they produce some initial results and conclusions about car design and cost sensitivity and give the reader some insight into the many possibilities for using the program.

Previously discussed constants and input parameters are used in the following example to determine an approximate car design for a high-demand and high-density operation (1 km = 0.6 mile; 1 $\mathrm{m/s^2}$ = 3.3 $\mathrm{ft/s^2}$; and 1 m = 3.3 ft).

Input	Dimension or Description	Input	Dimension or Description
DEMAND	60 000 people/h	ACC	1.1 $\mathrm{m/s^2}$
HW	1.5 min	DEC	1.1 $\mathrm{m/s^2}$
CAPTRN	1500 people/train	STA SPAC	0.8 km
DIST	64.4 km/round trip	WIDTH	3.2 m
AVGVEL	32.2 km/h		
DWELL	30 s		

The highest and lowest limits of length chosen for this car design are 25.9 and 12.2 m (85 and 40 ft) respectively. The design options include air conditioning, stainless steel exterior, and a married pair operation. The results indicate that the most economical solution would

Table 1. Annual cost of cars by length.

Car		Annual Cost ($)				
Length (m)	Number	Power[a]	Capital	Maintenance	Operating	Total
12.2	259	3 600 000	3 400 000	600 000	1 200 000	8 800 000
18.3	192	6 300 000	2 700 000	1 900 000	1 200 000	11 100 000
22.9	142	7 000 000	2 400 000	2 900 000	1 200 000	13 500 000
25.9	108	8 300 000	2 300 000	3 600 000	1 200 000	15 400 000

Note: 1 m = 3.3 ft.

[a] As the total number of cars decreases, the cost of power will also decrease; however, these decreases are not at the same rate. As the length and mass of the car increase, the power consumption also increases.

be a 25.9-m (85-ft) car length. Thus, the important car features would be as follows (1 m = 3.3 ft; 1 kg = 2.2 lb; 1 kW = 1.4 hp; 1 m/s^2 = 3.3 ft/s^2; and 1 MJ = 0.3 kW·h).

Feature	Dimension or Description
LENGTH	25.9 m
WIDTH	3.2 m
CAR WT	60.8 Mg/empty car
CAPACITY	280 passengers/84-seat car
PM	97 kW/motor
MAX VEL	80.5 km/h
AVGVEL	32.2 km/h
STA SPAC	0.8 km
DWELL	30 s
ACC	1.1 m/s^2
DEC	1.1 m/s^2
CAR COST	$224 000/car in 1972 dollars
POWER CONSUMPTION	
TRACT	27.3 MJ/car·km
AUX	5.4 MJ/car·km
Total	32.7 MJ/car·km

In addition to the above, a total of 644 cars is needed to operate this route. This total accounts for 22 percent of the cars being out of service for maintenance at any time. During rush hour, trains having six cars each would be used (6 cars × 280 people/car = 1680 people/train).

The total annual costs for this solution are as follows (1 MJ = 0.3 kW·h and 1 km = 0.6 mile).

Item	Annual Amount ($)
Capital cost for 644 cars, 35 years and 7 percent	11 000 000
Power cost, 0.6 cent/MJ and 53 100 000 car·km	6 600 000
Operating cost, 2 crewmen/train and $8/h; including fringe benefits	3 200 000
Maintenance cost for 644 cars and 53 100 000 car·km; $6/h, including fringe benefits	1 300 000
Total	22 100 000

In many cases, the length of a car is predetermined. The upper limit may be determined by tunnel clearances, or an operating authority may desire to order new cars that match existing cars for mating purposes. In this case, it is interesting to examine the difference in total costs between the optimum length and the desired length.

For a system in which 12.2 m (40 ft) was determined as the best solution, the values of 18.3, 22.9, and 25.9 m (60, 75, and 85 ft) were fixed respectively. The resulting annual costs are given in Table 1.

SUMMARY

There are many possibilities for using this methodology. Sensitivity analyses have shown that the program operates realistically, that is, a slight change in the maintenance life of a wheel bearing will not affect car length or any other major design feature. Cost comparisons may be made for cars of different lengths, various interest rates on capital investment, and various system parameters such as headway, demand, and system length. The program may be updated for new data and new costs to account for inflation, changing technology, and other factors.

ACKNOWLEDGMENT

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Abridgment

At-Grade Crossings of Light Rail Transit

David Morag, De Leuw, Cather and Company

The growing interest in the performance characteristics of light rail transit (LRT) is primarily related to taking advantage of a wide variety of rights-of-way and employing a broad range of station configurations. Newly proposed light rail transit systems may be on an exclusive right-of-way (ROW), within existing streets, or on a semiexclusive ROW, which means that the transit line is on an exclusive ROW but has an at-grade, protected crossing at intersections with streets. The impact of semiexclusive lines on motor-vehicle traffic is analyzed in this paper.

A major concern for transportation planners in considering semiexclusive LRT lines is the potential impact these lines have on traffic at grade crossings where there is high-frequency and priority LRT operation. The purpose of this paper is to provide a methodology for analyzing and estimating the effect of semiexclusive LRT line on motor-vehicle traffic. The estimates of traffic volumes through at-grade crossings per lane per hour presented in this paper may be compared with actual traffic counts on city streets to provide a basis for comprehending the following major concerns of the planner:

1. The expected level of impact on traffic,
2. The restrictions required on the crossing approaches,
3. The improvements required in terms of added lanes, and
4. The minimum grade separation requirements.

BASIC OPERATIONAL DEFINITIONS

The wide variety of existing characteristics of light rail vehicles (LRVs) and the proposed operational philosophies for LRT that could affect this analysis require that this paper be restricted to discussing the following set of operational definitions that are common to many of the newly proposed LRT systems.

1. The operational characteristics of the standard LRV are used exclusively in numerical computations.
2. The average characteristics of motor vehicles are used.
3. The LRV is capable of crossing protection by preemption and of traversing the crossing at the average operating speed. (Preemption is actuated from a distance that is sufficient for safely stopping the LRV in the event of crossing protection failure.)
4. The crossing protection method assumed for this analysis is the conventional railroad gates (2).

In general, this analysis assumes that, for the achievement of adequate schedule speeds, an LRT system must be able to minimize the number of stops and acceleration-deceleration maneuvers per trip.

METHODOLOGY

Crossing Time Limitations

The number of motor vehicles per hour per lane at an at-grade crossing is limited by the total time per hour during which the crossing protection system is not actuated (open gates). In concept, this total time is equal to the total green signal time in conventional traffic signals. However, in the case in which the street crossing is preempted by the LRV and in which train arrivals are totally synchronized, the cycle time is equal to the headway of the operating train. For this case, the total green signal time for motor-vehicle crossings is equal to the headway of the LRV minus the time for the LRV to preempt, advance to, and clear the crossing and the time for the gates to reopen.

For totally synchronized LRV arrivals, the total crossing time per cycle available for motor vehicles [$G^*(\psi)$] is defined in Equation 1. The variables are defined in Table 1.

$$G^*(\psi) = h - [(b-1)(KV/2d)] - [(\psi L + nW + C)/V] - [(\alpha + \gamma R)/S] - (S/2a) - (T + t + \phi) \qquad (1)$$

For the general case in which bidirectional LRV operation is maintained on a dual-track facility, the total green signal time for motor-vehicle crossing will depend on the probability of synchronized LRV arrivals at the crossing. If it is assumed that there are three levels of options (totally synchronized, totally unsynchronized, and half synchronized) and the probability theory is used, then the expression for total crossing time per cycle available for motor vehicles [$G(\psi)$] is obtained as shown in Equation 2.

$$G(\psi) = G^*(\psi)^2/h \qquad (2)$$

Therefore, the ratio of motor-vehicle crossing time to total cycle time (G/C) is

$$G/C = G(\psi)/h \qquad (3)$$

The ratio G/C that is defined in Equation 4 assumes that the LRVs traverse the intersection at their operating line speed (V).

Locating LRT stops just before and after street crossings is common in the designs of many LRT systems. The crossing of an LRV that accelerates from a stop or decelerates to a stop on the far side of the crossing affects the crossing time available for motor vehicles in different ways. LRVs that accelerate from stops have the least impact, since LRVs are available at the crossing side and proceed once the protection system is actuated. The impact on crossing time for synchronized LRV arrivals [$g^*(\psi)$] is

$$g^*(\psi) = h - [(2/d_0)(\psi L + nW + C)]^{0.5} - (S/2a) - [(\alpha + \gamma R)/S] - (t + \phi) \qquad (4)$$

To account for the probability of synchronized train acceleration from stops at both approaches, the ratio of motor-vehicle time to total cycle time (g/C) is used.

$$g/C = g(\psi)/h \qquad (5)$$

The G/C and g/C ratios are used to compute traffic volumes.

Vehicle Flow Calculations

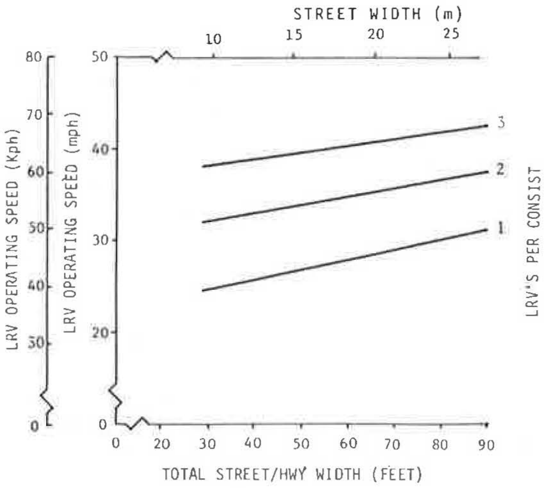
The calculations of vehicle flow through at-grade crossings are based on G/C, g/C, and a value for base flow per lane per hour (1). The base flow value used in this paper refers to an LRT system that operates in a location on the fringe of a metropolitan area that has a population of 1 million. Traffic operation during peak hour is at level of service D. The average flow includes trucks and buses (8 percent), and parking and turn movements on the crossing approaches are prohibited. The

Table 1. Typical parameter values.

Symbol	Variable	Value
K	Design safety factor of LRT for headway protection	1.35
T	Reaction time of LRV attendant and controls, s	2.5
t	Average reaction time of motor-vehicle driver, s	1.0
V	Operating line speed of LRV, km/h	8 to 48.3
S	Average speed of motor vehicle, km/h	40.3
R	Width of single LRT track and clearance, m	7.16
W	Width of single lane, m	
	Two-lane street	3.2
	Three-lane street	3.35
	Four-lane arterial street	3.5
	Six-lane divided highway	3.66
C	Width of curbs, medians, and clearances, m	
	Two to three-lane street curbs and clearances	2.44
	Four-lane arterial street and median	3.66
	Six-lane divided highway and median	5.49
γ	Number of LRT tracks at crossing	2
n	Number of traffic lanes of street or highway	2, 3, 4, 6
d	Deceleration rate of Boeing LRV, m/s^2	2.65
d_0	Acceleration rate of Boeing LRV, m/s^2	1.37
a	Average deceleration rate of motor vehicle, m/s^2	4.57
ϕ	Reaction and verification time of Webco gates, s	9
L	Length of single Boeing LRV, m	21.64
α	Average length of motor vehicle, m	6.1
b	Number of blocks in control design for LRT headway protection	2
ψ	Number of cars in LRT consist	—
h	Operating headway of LRV	—

Note: 1 km/h = 0.62 mph; 1 m = 3.28 ft; and 1 m/s^2 = 3.28 ft/s^2

Figure 1. Optimum LRV operating speed at an at-grade crossing to minimize impact on traffic.



maximum motor-vehicle flow (F) per peak hour per lane through at-grade crossings occurs at G/C = 1.0. This flow was determined to be

$$F = 740(0.85)(1.2)(1.3)(0.97)(1.14)(1.25) = 1356 \qquad (6)$$

Optimum LRV Operating Speed

The expression derived in the previous section for motor-vehicle flow per hour per lane indicates that, for any given set of constant parameters that define the characteristics of street lane, track, and motor vehicle, there is an LRV operating speed (V) that will maximize the number of motor vehicles through the crossings. The optimum operating speed (V_{opt}) is obtained by taking the time derivative (dv/dt) and equating it to zero.

$$V_{opt} = \{[2d(\psi L + nW + C)]/[(b - 1)K]\}^{0.5} \qquad (7)$$

LANE CAPACITY ESTIMATES

The variables used to calculate the estimated flow per

Figure 2. Motor-vehicle flow per hour per lane by LRV consist size and operating speed.

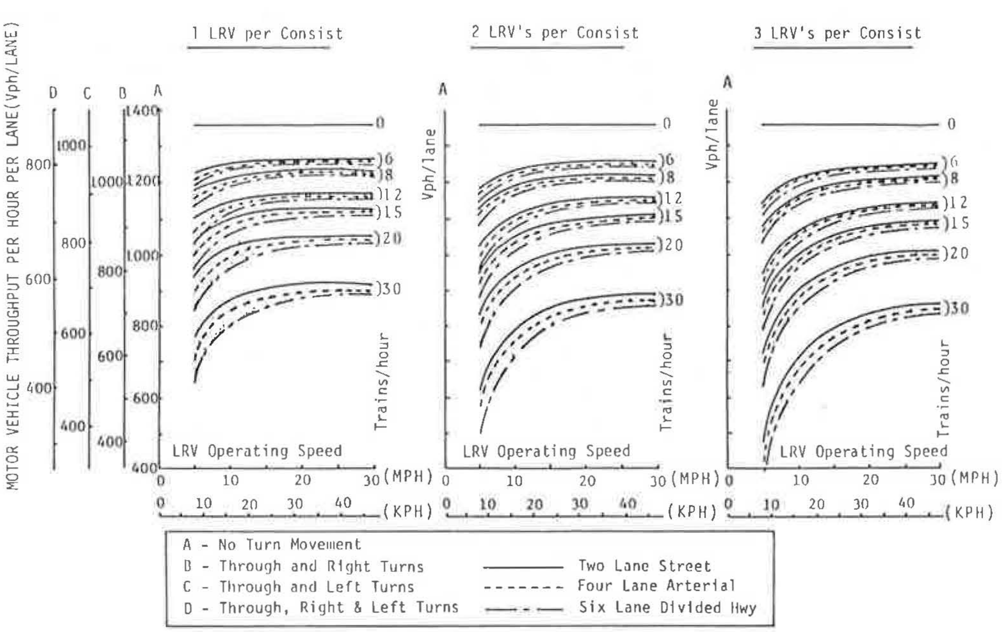
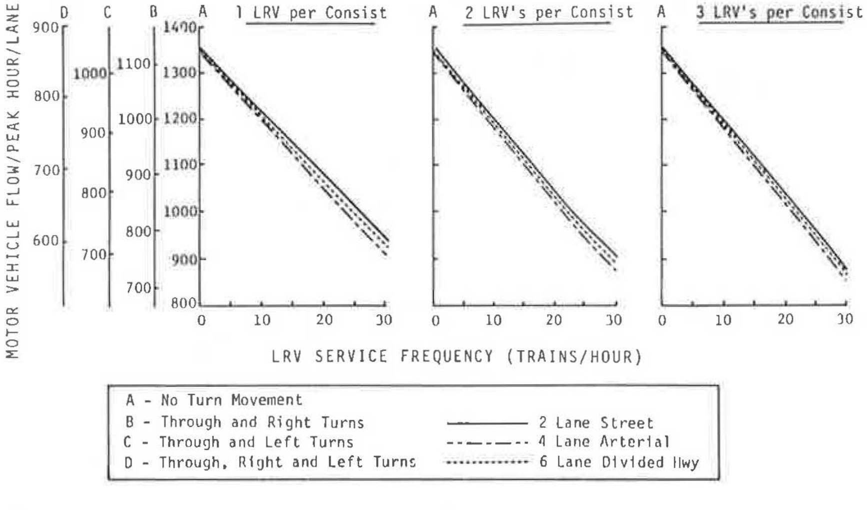


Figure 3. Motor-vehicle flow per hour per lane by LRV consist size and service frequency.



peak hour per lane through at-grade crossings on semiexclusive LRT line-street intersections are given in Table 1 and are typical for the average motor vehicle, LRT tracks, and street lanes. This analysis is based on the Boeing articulated LRV. Optimum LRV operating speed for minimum traffic impact is obtained by substituting the values given in Table 1 into Equation 7. The optimum LRV operating speed is shown in Figure 1.

Case 1 Flow Estimates

Case 1 applies to the LRV that traverses intersections at its average operating speed. By substituting the values given in Table 1 into Equation 6 and by using G/C as defined in Equation 4, the vehicle flows (vehicles per peak hour per lane) through an at-grade crossing for a two-lane street, a four-lane arterial, and a six-lane divided highway were computed. A summary of the flow estimates and a comparison of the sensitivity of traffic flow per peak hour per lane to LRV consist size and operating speed are shown in Figure 2. The traffic flow per hour per lane with fewer movement restrictions (B, C, and D scales) is also shown in Figure 2.

Case 2 Flow Estimates

The flow estimates for case 2 deal with the special case described in Equation 5 in which the LRV consist accelerates through an at-grade crossing from a transit stop that is located at the intersection approaches. By substituting the values given in Table 1 into Equation 6 and by using g/C as defined in Equation 5, the estimated volumes of motor-vehicle flow per peak hour per lane through an at-grade crossing for a two-lane street, a four-lane arterial, and a six-lane divided highway for various LRT service frequencies and consist sizes were computed. A comparison of flows by both throughput and sensitivity to street width, consist size, and service frequency is shown in Figure 3. The flow estimates for case 2 are independent of LRV speed, since continuous acceleration through the crossing is assumed. Once the train clears the crossing, the peak speeds achieved by the crossing LRVs were found to be well within the operational limits.

SUMMARY AND CONCLUSIONS

The methodology and lane capacity estimate developed in this paper are designed to aid the transportation planner in the analysis of traffic impact due to the implementation of semiexclusive LRT lines. This type of analysis may provide the planner with the tool by which the grade separation requirement could be minimized or staged to some future year for the cases in which the motor-vehicle flow that was estimated at the time of the analysis would exceed the crossing capacity, the additional ROW for crossing improvement was unavailable or too costly, or totally grade-separated intersection must be considered.

The results of this analysis indicate that the deployment of LRT semiexclusive lines in fringe areas is a feasible alternative to transit lines that are totally grade-separated, fixed guideways. This analysis also indicates that, for LRT systems planned for multicar consist operation at high service frequencies, locating transit stops at grade-crossing approaches is desirable to reduce traffic impact.

However, this analysis considered only independent at-grade crossing situations, and additional considerations would be required to analyze the impact of at-grade crossings on adjacent intersections with signals. These intersections may require synchronization with the preempted crossing protection system.

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Abridgment

Impact of Transit Line Extension on Residential Land Use

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Land users can be defined as those members of society who continually weigh the characteristics of land sites to determine the suitability of each site for a particular social or economic need. If the characteristics are suitable, then one or more land users might exert pressure for changing or redeveloping a given site. To evaluate the impacts of new transportation systems on land development, transportation and land use planners must be able to identify the important physical, institutional, and transportation characteristics that are responsible for the change (2). One physical characteristic is the suitability of urban land for residential, recreational, industrial, or governmental uses. One transportation characteristic is the accessibility of a given site to employment, shopping, and recreation opportunities. A particular combination of physical and transportation characteristics will generate interest and action by certain land users to develop a given site. To control land development, society has used zoning ordinances as the primary political mechanism to regulate the type, quality, and magnitude of development. The purpose of this paper is to investigate the effectiveness of zoning regulations in controlling residential land development in a community that is served by a new extension line of a high-speed rail rapid transit system.

IMPACT OF TRANSIT LINE EXTENSION

The city of Quincy is a suburb of approximately 90 000 people and is located on the southern boundary of the city of Boston (1). Before 1971, the majority of residents commuted to the central business district (CBD) of Boston by automobile in about 25 min. Since the public bus service was primarily structured to serve Quincy Center, which is the CBD of Quincy, the public transportation service to downtown Boston was poor. By transferring from bus to rail rapid transit at either Fields Corner or Ashmont stations, a Quincy commuter could commute to the CBD of Boston by public transit. The average commuting time was 50 min or more. The rail transit line before 1971 is shown by the solid line in Figure 1.

In 1971, the South Shore Line of the rail rapid transit system was extended to Quincy Center, and intermediate stops were added at Wollaston and North Quincy stations. This line is shown by the broken line in Figure 1. In addition to the extension line, the bus lines were rerouted to serve as a collector system for the new transit line extension so that access from most Quincy neighborhoods to a transit station was 15 min or less. The commuting time via the new line from Quincy Center to the Boston CBD is approximately 22 min.

Since 1963, there has been an upward trend in the construction of residential dwelling units. Closer examination shows that the construction of residential dwelling units has generally been greater in areas where there is better access to transit stations. Since the opening of the new transit line, the number of dwelling units constructed per year in the area of Quincy Center has more than doubled. In 1971, the city of Quincy issued new zoning regulations. The primary purpose of these regulations was to maintain the low-density characteristic of neighborhoods in Quincy and to stimulate new development in the areas that are close to the new transit stations. A mathematical model was developed to explain the effectiveness of this measure.

Figure 1. Rail rapid transit service from Quincy to the Boston CBD.

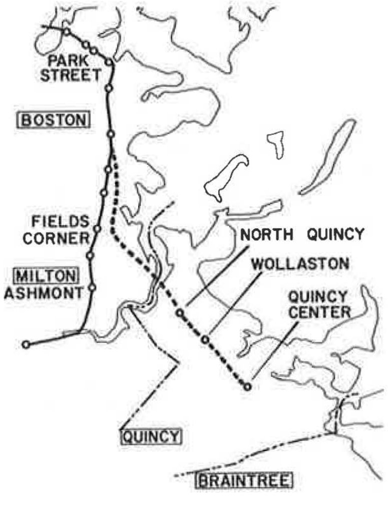
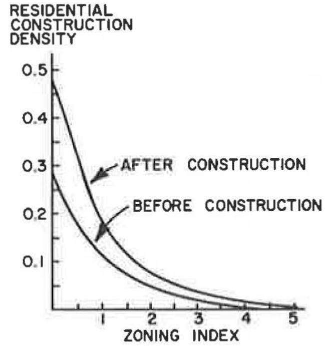


Figure 2. Density models for before and after residential construction.



MODEL DEVELOPMENT

The primary objective for establishing a mathematical model was to determine the significant variables that explained the development that took place in Quincy. Models can also be used to evaluate transportation and governmental policies for similar regions. Since the selection of model variables has an important bearing on the adequacy of the model as a planning tool, then the model should account for and be sensitive to all changes in the physical, institutional, and transportation characteristics of the area. However, many of these characteristics are not quantifiable measures. For example, the attitudes of the people and their political representatives toward land development are not quantifiable. As a result, some important information is not introduced into the model or is introduced by use of surrogate variables. Typically, travel time or speed is used to measure transportation service. Service characteristics such as comfort and convenience are not easily measured; therefore, they do not appear in most transportation planning models. Thus, travel time or speed is the best measurable quantity available, and it is used to measure the transportation service overall. In the transit impact study of Quincy, travel time as well as surrogate measures such as the zoning policy and public transportation service variables were used in the model.

For the model to account for events or impacts over time and by area, data were collected for the period 1963 to 1973 and stratified by traffic analysis zone. The boundaries of these zones were originally established in a transportation study of the Boston metropolitan area in early 1960 (1). The data were stratified into one of three time periods: 1963 through 1966, 1967 through 1970, or 1971 through 1973. These periods corresponded to the preconstruction, construction, and operating phases of the extension of the South Shore Line. The stratification of data in this fashion was dictated by the fact that the transportation service characteristics will remain the same over time. Thus, the only measurable differences that occur are during the periods before and after the opening of the line to the public. A similar situation exists for the zoning index. The 1943 zoning ordinance remained relatively unchanged until 1971 when it was replaced with a new set of regulations. Thus, the selection of model variables and the model structure were influenced by the availability and form of data.

Data on location and type (single and two family) of residential dwelling unit construction from 1963 through 1973 were gathered for the city of Quincy. Each new dwelling unit was placed in one of 13 traffic analysis zones. Since the analysis zones are unequal in size, a land density measure was used. The number of new residential dwelling units that were constructed in zone i per square hectometer per time period (acre per time period) (D_i) was used to measure the change in development over time.

A zoning index (Z_i) was introduced to reflect the character of current and future land development that is and will be permitted in zone i. The zoning index is the ratio of land area zoned for low-density residential development to land area zoned for medium and high-density residential development. The zoning index is a continuous variable that can have values between zero and infinity. A value of zero indicates an area is zoned for medium and high-density uses only. In contrast, the value of infinity indicates that a zone can be used for low-density residential uses only. The zoning indexes for Quincy ranged from a low of 0.06 (or 5.5 percent of the land area zoned for low-density development) at Quincy Center to a high of 4.6 (or 82 percent of the land area zoned for low-density development) at a traffic zone that is east of Wollaston Station and borders on Quincy Bay. Typically, for neighborhoods that were primarily of single and two-family dwelling units, the zoning regulations were more restrictive. The traffic zone for Hough's Neck and Germantown, the peninsula that extends into Quincy Bay near the Braintree border, had the greatest zoning change. Before rezoning, 56 percent of the land was zoned for low-density development, and, after rezoning, 82 percent of the land was zoned for low-density development.

The impact of transportation on each analysis zone was measured by the transportation service variables. Travel time by automobile, bus, and rail rapid transit was considered as well as measures of public transport inconvenience. Accessibility to stations was measured in terms of travel time needed to commute between the zone centroid and nearest transit station and the number of vehicles used to commute between the zone centroid and the Boston CBD. These variables measured the inconvenience of public transport. For example, before 1971, a commuter from Quincy Center had to transfer among three public transit vehicles. Currently, the commuter has direct transit rail passage to the Boston CBD.

In 1967, the commuters and land users did not experience a change in public mass transportation that could be measured in terms of travel time savings, but they did know that an improved service would eventually be offered. A Y-variable was introduced into the model to reflect the influence that the state of construction had on the transit line. This variable reflects the lack of direct transit service to the Boston CBD for the period 1963 through 1966 ($Y = 0$), and it reflects the anticipated and actual service for the period 1967 through 1973 ($Y = 1$).

RESULTS

Multiple linear regression analyses were performed on various linear and log-linear transformations for the variables discussed above. The results indicate that the log-linear model gives the best results. The Z_i zoning index and the Y-variable are statistically significant at the 10 percent level. The transportation service variables were not found to be statistically significant. The mathematical form for the log-linear model is

$$D_i = 0.292(0.393)^{Z_i}(1.71)^Y \quad (1)$$

This model has a 36 d.f. and a coefficient of determination equal to 0.63. The model shows that, after construction began on the transit line extension, there was an increase in dwelling unit construction. As a result of the improvement in the public transportation service that was offered to the entire study region, one would expect this increase in dwelling unit construction. Before construction of the transit line, Y equals zero; therefore, Equation 1 is reduced to

$$D_i = 0.292(0.393)^{Z_i} \quad (2)$$

After the construction of the transit line is initiated, Y equals one; therefore, the model simplifies to

$$D_i = 0.499(0.393)^{Z_i} \quad (3)$$

The curves of Equations 2 and 3 are shown in Figure 2, and they illustrate the effects that the construction of the extension line and implementation of a zoning ordinance had on the residential development in Quincy.

The introduction of the transit line extension caused an overall expansion in residential dwelling unit construction, as shown by Equations 2 and 3. However, the greatest portion of this overall growth occurred in zones that permitted this kind of development in the past. Zones containing the new transit stations or a high level of commercial activity had the least restrictive policy for high-density land use and showed the greatest increase in residential construction activity. In contrast, zones that border on Quincy Bay experienced a lesser increase in construction activity. This was due to the restrictive land use policy. These results are shown in Figure 2. The indexes for zones with a high degree of construction activity and a low degree of construction activity range from 0.1 to 0.2 and 2.0 to 4.6 respectively.

Thus far, the discussion has focused on the initiation of construction of the new line. A discussion of the effect of controlling the magnitude of residential dwelling unit construction by changing the zoning regulation policy is investigated below. The concept of demand elasticity (3) was used to evaluate the sensitivity to zoning policy change. Zoning elasticity is defined as the ratio of the percentage of change in construction of new residential dwelling units to the percentage of change in zoning regulations. The zoning elasticity based on the above mathematical model is

$$e_Z = -0.934Z_i \quad (4)$$

Since the zoning elasticity is a function of the zoning regulations before the zoning change, then the analysis zones that were previously restricted to low-density uses become more sensitive to the zoning changes than those zones that were permitted medium and high-density development. A hypothetical example illustrates this effect and will also illustrate the use of the mathematical model.

Two traffic analysis zones (zones 1 and 2) were assumed to have equal land areas of 40.47 hm^2 (100 acres) each. Zone 1, the business and commercial zone, has 4.05 hm^2 (10 acres) of land zoned for low-density development. In contrast, zone 2 has 32.38 hm^2 (80 acres) zoned for low-density development or for single and two-family dwelling units. It was assumed that a new, less restrictive zoning policy for low-density development was imposed on each zone. Thus, the area of low-density development land from each traffic analysis zone that was reclassified as medium and high-density development land was 4.05 hm^2 (10 acres). By use of the definition of zoning index, the zoning index for zone 1 before and after rezoning equals 0.11 and 0.0 respectively. The percentage of change in residential dwelling unit construction per square hectometer (acre) per time period (D_i) is forecast by using the zoning elasticity equation (Equation 4). Thus, from Equation 1, the zoning elasticity is estimated to be equal to -0.103. Since there is a 100 percent change in the zoning index, the percentage of increase in residential dwelling unit construction is forecast to be equal to 10.3. A similar calculation for zone 2 results in an increase of 156 percent. A comparison of the percentages of change in residential dwelling unit construction shows that a neighborhood that is zoned for single and two-family dwelling units will experience more rapid change than an area that is zoned for medium and high-density development.

CONCLUSIONS

The mathematical model for the city of Quincy illustrates the following:

1. Residential land development will be stimulated by the construction of the new extension line of the rapid transit system;
2. Land developers will begin construction of new housing units when construction of the new transit line is initiated and will not wait until the line is open for service;
3. Zoning regulation is a significant mechanism for controlling the location and type of land development;
4. Neighborhoods that are primarily zoned for single and two-family dwelling units are particularly vulnerable to rapid change in neighborhood character, if a zoning regulation permits construction of medium and high-density units; and
5. Since transit service variables are not statistically significant variables, they have no quantifiable impact on land development.

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Abridgment

Evaluation of Alternative Station Spacings for Rapid Transit Lines

Howard Permut, Chicago Regional Transportation Authority

The planning and design of both new rapid transit systems and extensions to existing systems are currently being undertaken in numerous cities. A basic part of this process is defining and evaluating the routes for the transit line. Usually, the stations associated with a proposed new line are located in an ad hoc manner that is based on surrounding land use, engineering and environmental factors, and a general concept of proper spacing. Once located, the stations are considered part of the line and are not evaluated independently of the line (3, 4, 6, 7).

This paper presents a case study in which two alternatives for station spacing for noncentral business district (non-CBD) sections of rapid transit lines are evaluated in terms of capital and operating costs, demand, and user benefits. The case study involves the use of either a long or a short station spacing for a proposed rapid transit line in Chicago.

PROPOSED NORTH LAKEFRONT LINE AND TWO ALTERNATIVE STATION SPACINGS

A high priority in the 1995 Transportation System Plan (2) for the Chicago area is a new rapid transit line that would parallel the lakefront on the north side. The proposed line is 8.8 km (5.5 miles) long and would connect with an existing rapid transit line on its north end and a proposed subway at its southern terminus.

The North Lakefront corridor is a densely populated area with a large number of individuals who have high incomes and work in the CBD. The area is well served by the Chicago Transportation Authority (CTA) bus network with five express and six local bus routes that provide access to the CBD. The western fringe of the area is served by two rapid transit lines. The high quality of CTA service and the large number of CBD workers have resulted in high-intensity use of the transit system in this area. For the majority of trips made in this area, either the express or local bus services are used.

The two alternatives for station spacings were chosen because they represented realistic strategies for station locations on the line. The first strategy (short alternative) involves 10 stations that are approximately 0.8 km (0.5 mile) apart; the second strategy (long alternative) involves 5 stations that are approximately 1.6 km (1 mile) apart. The exact station locations are determined by complementary land use and engineering factors.

TRADE-OFFS

The basic trade-offs between the two alternatives are shown in cost and demand and user savings. Compared with the long alternative, the short alternative costs more to construct and operate, increases the user's in-vehicle time, but decreases the user's access times to stations. The impact on line-haul and access time indicates that the alternatives attract unequal numbers of riders as well as provide for differing user savings. Thus, while the cost of one alternative is clearly lower, the relative magnitude of both the ridership and user savings associated with each alternative is not easily determined.

The North Lakefront corridor is the testing area for the two alternatives because it is densely populated. It was also assumed that the short alternative would be more appropriate because the long alternative provides a higher quality of service in lower density areas. Thus, if the short alternative is not superior to the long alternative in this area, then the short alternative would not be appropriate for any other area that was densely populated.

Costs

A detailed evaluation was undertaken to provide a quantitative examination of the trade-offs between the two alternatives. This evaluation included an analysis of the costs, the ridership, and the user savings associated with the long and short alternatives. The costs of the two alternatives were divided into total capital and annual operating costs and are in 1975 dollars. The capital cost includes all expenses and contingencies incurred in constructing the right-of-way and the stations. Vehicle or support facility costs were not included in these costs.

The annual operating cost includes all expenses incurred in operating both the vehicles and the stations. Operating costs similar to those of a comparable high-volume CTA Line were used.

Demand and User Savings

Since the number of riders attracted to a facility is a monotonically increasing function of the user savings provided by the facility, the demand and user savings are related. However, due to the trade-offs between access and line-haul times, it was not inherently clear which alternative would provide the greatest savings and would also attract the largest ridership.

Demand and user savings were estimated only for daily trips between the North Lakefront corridor and the CBD and were classified by previous mode of travel. New trips by any mode of travel were not included in this analysis. Both demand and user savings were calculated as functions of the total factored user utilities, which include both travel times and costs. Total factored utilities (5, 9) are expressed in units of in-vehicle minutes and are equal to the sum of travel time (1 min of out-of-vehicle time equals 2 min of in-vehicle time) and travel cost (1 min of in-vehicle time equals 4 cents). Based on historical precedent, it was assumed that the Lake Shore Express service no longer operated.

Diverted Trips

The number of previous transit users attracted to each alternative was estimated by using a disaggregate, minimum-path assignment process. For each existing transit user, the factored utility of the prior route (bus or rail) was compared to that of the proposed alternative. The user was then assigned to the route that had the minimum disutility. If the current service was the Lake Shore Express, then the best remaining local bus service and the proposed alternative were compared.

This procedure was followed for all individual peak-period trips that were taken from the 1970 Home Interview Survey (1). The total number of individual sample trips attracted to the line was then adjusted by a series of factors that accounted for sampling size, return trips, and off-peak trips between the North Lakefront corridor and the CBD.

The number of automobile users diverted was estimated by using an existing model in a marginal manner (9). This involved determining the change in the factored utility of the transit mode resulting from the institution of the proposed alternative and calculating the corresponding number of automobile users who would divert to the transit mode because of this change. It was assumed that all of these automobile-diverted trips would use the proposed alternative.

For both transit and automobile-diverted trips, the user savings are expressed in in-vehicle minutes and include both times and costs. For each case, the estimations were made in conjunction with demand and under the same assumptions. For transit-diverted trips, user savings are calculated for the individual trips and factored in the same manner as transit demand to provide daily hours saved. For automobile-diverted trips, the number of daily hours saved is defined in terms of the consumer surplus function, estimated for each traffic zone, and then totaled. For each zone, the savings for previous automobile users are equal to the number of automobile-diverted trips multiplied by one-half the average savings of the automobile users.

QUANTITATIVE COMPARISON OF ALTERNATIVES

A comparison of the two alternatives is given in Table 1. The long alternative is superior to the short alternative in terms of three criteria:

1. It is less expensive to construct (31 percent) and operate (10 percent),
2. It attracts more riders (3 percent), and
3. It offers greater user savings (16 percent).

These results can be further interpreted by noting that (a) the short alternative would probably attract a greater percentage of local, intra-Lakefront corridor trips than would the long alternative; and (b) in terms of demand and user savings, the long alternative would probably increase once the Lakefront Line is joined on its northern end with either of the two existing lines. The probability of the latter is due to the fact that the long alternative would provide a superior level of service at the stations of the existing line. Thus, the long alternative would attract a greater demand, and this would result in greater user savings at these stations.

SENSITIVITY ANALYSIS

The sensitivity of the analytical results, to both the utility measurement and the discontinuation of express bus service, was analyzed. Both demand and user savings were calculated by using the procedures previously mentioned; however, travel decisions were based on unfactored utilities (1 min of in-vehicle time equals 1 min of out-of-vehicle time and 1 min of in-vehicle time equals 4 cents). It was also assumed that the Lake Shore Express service was discontinued.

Table 2 gives the results of these analyses under different sets of assumptions. With respect to the com-

Table 1. Quantitative comparison of alternatives.

Criterion	Alternatives		Difference	Percentage of Improvement With Long Alternative
	Long	Short		
Cost, 1975 $				
Total capital[a]	161 000 000	232 000 000	71 000 000	31
Annual operating[b]	7 160 000	7 935 000	775 000	10
Demand, daily one-way trips				
Bus diverted	19 944	19 390	554	3
Rail diverted	8 547	8 547	0	0
Automobile diverted	1 656	1 336	320	24
Total	30 147	29 273	874	3
User savings, daily in-vehicle hours				
Bus diverted	1 487	1 071	416	39
Rail diverted	1 675	1 669	6	0
Automobile diverted	64	48	16	33
Total	3 226	2 788	428	16

[a] Calculated by assuming construction costs of $10 375 000/right-of-way km ($16 600 000/right-of-way mile) and $15 600 000/station (8).

[b] Calculated by assuming operating costs of $0.85/vehicle-km ($1.36/vehicle-mile) and $155 000/station year (8).

Table 2. Sensitivity analysis of alternatives under various assumptions.

Criterion	Factored Utilities[a]				Unfactored Utilities[b]			
	No Bus Service		Bus Service		No Bus Service		Bus Service	
	Long	Short	Long	Short	Long	Short	Long	Short
Demand, daily one-way trips								
Bus diverted	19 944	19 390	17 174	14 404	27 700	31 578	26 592	29 362
Rail diverted	8 547	8 547	8 547	8 547	6 919	6 919	6 919	6 919
Automobile diverted	1 656	1 336	1 774	1 610	1 566	1 064	1 578	1 226
Total	30 147	29 273	27 495	24 561	36 185	39 561	35 089	37 507
User savings, daily in-vehicle hours								
Bus diverted	1 487	1 071	1 773	1 579	2 622	2 004	2 649	2 226
Rail diverted	1 675	1 669	1 675	1 669	611	522	611	522
Automobile diverted	64	48	73	59	54	29	55	32
Total	3 226	2 788	3 521	3 307	3 287	2 555	3 315	2 780

[a] The value of out-of-vehicle time equals twice the value of in-vehicle time.

[b] The value of out-of-vehicle time equals the value of in-vehicle time.

parison between the long and short alternatives, the most important results are (a) in terms of relative magnitude for the alternatives, only demand (not user savings) is sensitive to the analytical assumptions and (b) only the method of utility measurement (not the existence versus nonexistence assumptions of the Lake Shore Express service) has an impact.

Thus, the comparison between the alternatives is sensitive to only one of the analytical assumptions. In terms of theoretical validity, the assumption for travel decisions based on factored utilities is more precise than that based on unfactored utilities (5). Although the impact of the method of utility measurement should be noted, it is the first analysis that is better than the second analysis. Thus, the long alternative is again superior to the short alternative.

CONCLUSION

This report analyzed two alternatives for station location on a rapid transit line. The evaluation shows that, in terms of cost and demand and user savings, the long alternative is superior to the short alternative for the non-CBD section of a rapid transit line in Chicago.

The transferability of these results to other areas in Chicago as well as to other cities in general must be used with caution. Before determining station locations, factors such as local trip-making characteristics, detailed land uses, and competing bus, rapid transit, and commuter rail services must be examined. However, the evaluation approach used in this paper can be applied to comparing alternative strategies for station locations as well as to individual station locations in various circumstances. The use of such a systematic method should significantly improve the planning and designing of rapid transit systems.

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Discussion

Vukan R. Vuchic, Department of Engineering, University of Pennsylvania

Permut has authored several interesting reports on various aspects of transit planning; however, I want to dispute both the methodology used in and results derived from Permut's work presented here.

It has been shown in literature (10, 11, 12, 13) that spacing of stations on the line should vary depending on the density of population along the line and on the number of passengers traveling through the area. It is too simplistic to take two sets of uniform spacings and compare them based on the assumption that one of them must be optimal.

The basic trade-off in determining station spacings is between the operating speed of the line and the area it covers. The higher the operating speed is, the more the line will attract long trips, but fewer people along the corridor will be attracted to it. It is this trade-off that must be considered in searching for the optimum.

The author makes an assumption that the number of passengers who use the line will be constant regardless of the station spacings. But Permut assumes that the long spacings will attract more passengers from the outlying areas because the travel time is shorter by 4 to 5 min. Thus, the author arrives at the conclusion that 1.6-km (1-mile) spacings would attract more passengers than 0.8-km (0.5-mile) spacings! This is not only unrealistic for the conditions in the corridor studied, but it also leads to a basic deficiency of the model: One side of the trade-off that affects the station spacings is eliminated. Thus, by definition, the optimization problem has one extreme as the solution: All elements become better as the station spacings increase. The conceptual error in the model can be proved very clearly: If one takes 3.2-km (2-mile) spacings rather than 1.6-km (1-mile) spacings, i.e., reduce the number of stations by one-half, the model would show that this further reduction of the number of stations is optimal. Proceeding in the same manner, one would come to the obviously absurd result that the line has only one station (i.e., the outer terminal) and that all the passengers from the corridor would walk to that terminal!

Approaching this problem from the empirical side leads to the same type of comments. Most rapid transit systems have station spacings that average about 0.8 km (0.5 mile). In high-density areas, the spacings are only 0.5 to 0.6 km (0.3 to 0.4 mile); only on regional lines that depend mostly on park-and-ride do the average spacings approach 1.5 to 1.6 km (0.9 to 1.0 mile). There is simply no way that 1.6-km (1-mile) spacings would be optimal in a dense corridor such as the one analyzed in this case. The number of passengers who would not be attracted to such a line because of this long spacing would not be negligible; it would be extremely high. Another item that should be considered is the possibility of using a skip-stop operation. This operation would allow a greater number of stations without reducing the operating speed, at least during the periods of high-frequency service or the peak hours.

In conclusion, the analysis of two sets of approximately uniform station spacings is an overly simplistic approach. Moreover, the model used in this study is incorrect because it omits the impact of a greater number of stations on passenger attraction from the corridor served and thus incorrectly finds that longer spacings are always better than shorter spacings. It should also be mentioned that, if errors are made in determining the number of stations, it is better to err on the high side since a station can be closed for some periods of the day more easily than it can be constructed on a line that is in operation. Permut's analysis errs on the low side of stations, and this error could lead to a situation that would require an extremely expensive correction after the line has been constructed. Several of our recently built rapid transit systems suffer from such errors in their initial planning, and the planners find that the building of additional stations is extremely difficult. Let us learn from previous errors.

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Author's Closure

In response to Vuchic's comments, I would like to review the purpose of the paper, the problem that the analysis addressed, the methodology used, and the empirical aspect of the station spacing problem.

The work presented a case study in which two possible station placement strategies for a proposed rapid transit line in a high-density corridor were evaluated. In either case, the location of stations was not a direct function of a predetermined uniform spacing, but it was based on specific land use and engineering factors that were taken in conjunction with a general concept of station spacing.

The evaluation of the two alternative spacings included both service capabilities and cost (annual operating and total capital). With respect to service, the basic trade-off is between in-vehicle and out-of-vehicle time (or operating speed and line coverage as stated by Vuchic), and the service portion of the analysis directly addressed this point.

The analysis methodology did not assume that the number of passengers using the line would be constant for the two alternative spacings. The demand on each line was estimated for two different market groups (current transit and automobile users) by using a specific model for each market. The resultant number of riders attracted to the two lines varied because of the service characteristics of the line.

Furthermore, it is incorrect to assume that the overall evaluation process was of a linear nature, i.e., if 1.6-km (1-mile) spacing is superior to a 0.8-km (0.5-mile) one, then a 3.2-km (2-mile) spacing would be better than 1.6-km (1-mile) spacing and so on. Thus, the extreme solution was not a line with only one terminal station. This study identified only two points on the evaluation curve, and it is incorrect to extrapolate beyond this area by concluding that the longer the spacing is the better the line will be. In fact, it is extremely doubtful that, unless population densities at the terminal are inconceivably large and the densities along the line are correspondingly small, the demand and user savings associated with a line with a single terminal station would be greater than that of a line with 1.6-km (1-mile) or 0.8-km (0.5-mile) spacing.

From an empirical standpoint, the average station spacing on the rapid transit systems in cities such as Chicago, Boston, Cleveland, Washington, and Atlanta (including closely spaced downtown stations) is greater than 1.6 km (0.5 mile). Furthermore, in Chicago, the closely spaced stations on the Congress Rapid Transit Line constructed in the late 1950s were recently closed because of low ridership levels. Since the capital cost of constructing a subway station is in the vicinity of $15 000 000 to $20 000 000 and the annual operating cost of the station is approximately $200 000, it is questionable whether the number of stations on rapid transit lines should be overdesigned to minimize the possibility of adding stations in the future.

In summary, Vuchic has not shown that the evaluation methodology is deficient in any fashion. Furthermore, there is no indication that the analytical results are compromised. Finally, the basic conclusion of the paper is not to determine the optimal station spacing, but rather to systematically and empirically evaluate different station spacings on proposed rapid transit lines.

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Abridgment

Design of Elevated Guideway Structures for Light Rail Transit

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Currently, all levels of government in North America realize the need for making transit a real alternative to the personal use of the automobile in major urban centers. The innovative use of the diesel bus has proven effective in a number of cities, but there remain corridors with sufficient demand to justify a fixed-guideway system. The rail mode is the only system that uses widely proven technology, and it is most efficient when operating in an exclusive right-of-way. In many cases, full right-of-way does not exist in these corridors; therefore, it must be created. With new subway construction costing around $32.5 million/km ($50 million/mile) and the acquisition of surface property a time-consuming and unpopular process, it appears that the objections to the elevated guideway must be reviewed if the service and operating cost benefits of a fully (or largely) exclusive right-of-way are to be obtained at a reasonable capital cost.

The earlier generations of transit vehicles were noisy, and the unsightly three-quarter century old elevated guideway structures such as those of New York and Chicago amplified this noise. Thus, elevated guideways have a reputation as an undesirable urban neighbor. The modern transit vehicle is significantly quieter than its predecessors, and a growing understanding of the wheel-rail mechanisms that generate noise and of noise barrier design gives promise of noise reductions to come. Furthermore, modern structural design techniques in both steel and concrete can produce serviceable and elegant structures that might enhance the streetscape of commercial and industrial areas in cities of North America.

This paper outlines a rationale for designing an elevated guideway for urban rail transit, and applies this rationale to a design of a double-track guideway for a proposed light rail transit (LRT) line.

DESIGN RATIONALE

The rationale for designing elevated guideway structures for LRT presented here organizes the thinking of the designer and his or her approach to the design problem. It superimposes the overall objective of the project on the guideway design effort and insists that all factors that affect the design, including those factors beyond the control of the designer, are recognized and understood. These factors are organized into three groups: (a) performance requirements that specify guideway function; (b) constraints that limit the choices available to the designer; and (c) design considerations that tell the designer how to choose among options, all of which satisfy the performance requirements and constraints. The priorities of factors in these groups may change with time. For instance, low cost may be a design consideration in the early stages of a project, but when capital budgets are allocated it becomes either a performance requirement or a constraint.

Performance Requirements

Performance requirements specify the function of the guideway and are quantifiable. An elevated guideway for LRT must provide safe and reliable support and guidance for trains and support for other system components in a secure right-of-way that facilitates the operator's inspection and maintenance tasks.

The structure must withstand all stresses and strains imposed on it through its lifetime under serviceability and ultimate limit states. If derailment or crash occurs, trains must be contained within the guideway, must be restrained from crossing onto other tracks, and must not cause irreparable damage to the primary structure. Support piers in areas of public vehicular access must be protected against vehicle impact, or the guideway superstructure must remain standing if any single pier is demolished. The guideway must be secure against unauthorized access, and it must be protected against accumulation of debris such as snow and ice. The guideway must have a walkway to provide access for inspection and maintenance personnel and for controlled evacuation of passengers in an emergency. It must provide secure support and attachment for other system components such as rails, power distribution equipment, and signals. The elevated guideway must be acceptable in the neighborhoods through which it passes. Airborne and groundborne noises and vibration due to train operation must conform to standards set for the various land uses adjacent to the line.

Constraints to Design

Constraints limit the choices of the designer in meeting the performance requirements for the structure and may cause special, more costly features to be imposed on the design. Typically, constraints arise from the route corridor available, e.g., topographic and existing structural features and station locations may require special curvatures or restrict pier placement, and vehicles and other system components may require geometric compatibility.

Constraints may be real or arbitrary. Real constraints are based on engineering difficulty and cost of choosing a particular option. Arbitrary constraints arise from irrational preferences, inadequate study, or political activity and must be recognized and closely questioned.

Design Considerations

Design considerations provide the designer with the logic to choose between design alternatives that satisfy all performance requirements and constraints. The major design considerations are cost and aesthetics.

A low-cost design process requires a clear understanding of the purpose of the guideway and a detailed knowledge of the cost and availability of materials and construction techniques. The two most important means of ensuring low cost are thorough planning and insistence on standard design. Good planning ensures that adequate property is available for access and construction sites, utility and road relocations are minimized, and other municipal projects are coordinated with transit construction to share costs. Standard design requires that readily available materials, well-known construction techniques, and simple and repetitive details are used in the structure. Special structures such as crossovers and stations integral with the guideway structure should be minimized. The design should have enough flexibility so that it can be built with a minimum of change over a range of span lengths. Specifications, tender documents, drawings, and contracts should be complete and unambiguous so that bidders can make reliable estimates that include low contingency allowances. Design alternatives should be provided such that they can be used to increase competition in bidding.

In the planning stages of a project, guideway architecture probably has little to do with the acceptability of the guideway in a particular location. However, a slender and elegant structure that is carefully integrated with the location might find increasing acceptance with time, especially if it provides efficient transit service.

DESIGN STUDY

This rationale is applied to designing a section of an elevated guideway for a specific LRT line. Initially, this line will use a shared right-of-way and will be operated by unidirectional light rail vehicles (LRVs) with doors on one side and street level loading. Later, an exclusive right-of-way will be developed that will be operated by new bidirectional vehicles with doors on both sides and platform loading. This design study develops a suitable guideway configuration and examines in some detail a typical four-span structure.

Vehicle Specifications

The LRV is 15.5 m (51 ft) long, 2.6 m (8.5 ft) wide, and 3.4 m (11 ft) high. It draws propulsive power from an overhead wire 4.3 m (14 ft) above the top of the rail. The vehicle has two bogies, and each bogie has two axles. A lateral clearance of 15.3 cm (6 in) is required on each side of the vehicle to accommodate its dynamic envelope. The vehicle has a mass at crush load of 34.93 Mg (77 kips) that gives a loading of 87.32 Mg (19.25 kips)/axle. Vehicles may operate as trains of two or four units.

Guideway Cross Section

Figure 1 shows the performance requirements, vehicle dimensions, and design considerations of a double-track guideway. The primary structural member of this guideway is the central spine girder. From each side of the girder a deck supporting the track system is cantilevered, and at each end of the decks are the outside barrier walls. The spine girder and barrier walls confine vehicles in the event of derailment or crash, act as barriers for airborne noise, and provide support for signal and power cables. Compared with the same guideway without barrier walls, when the barriers are given a good absorptive treatment, they are estimated to provide a noise attenuation of about 8 dBA for an observer at ground level away from the guideway.

The top of the spine girder is a walkway, which utilizes otherwise unusable space for maintenance personnel. Compared to the alternative of two exterior walkways, use of this location reduces overall guideway width and hence cost. The walkway is made level with the vehicle floor to facilitate emergency evacuation from the vehicles and to perform as an effective noise barrier. The LRV that will operate on the line initially requires an emergency exit panel to be added for compatibility with the guideway cross section. Rungs are provided for access to the deck from the walkway, and a handrail may be installed along the centerline of the spine girder for the safety of personnel. Poles mounted on the spine girder carry the overhead electric supply wire and guideway lighting. Adequate space is available on the deck for conversion to a third-rail power supply. The barrier wall is visually integrated with the guideway because it hides the spine girder and part of the vehicle.

Superelevation can be applied to this cross section by twisting the spine girder. This retains relationships between track, spine girder, and barrier wall so that the clearances required for curvature are minimized. Two free-standing platform structures that share a control area at grade beneath the guideway provide a station that is independent of the guideway structure.

The guideway cross section may appear to be a snow trap. However, if frequent train operations prove inadequate to disperse snow accumulations, then an occasional pass by a snowplow that is attached to a train or a blower with an elephant trunk that throws snow over the barrier wall should keep the guideway sufficiently free of snow for operation. This snow clearance must be coordinated with the authorities responsible for street snow clearance to protect the passersby and to avoid undue buildups below.

Figure 1. General layout of double-track guideway.

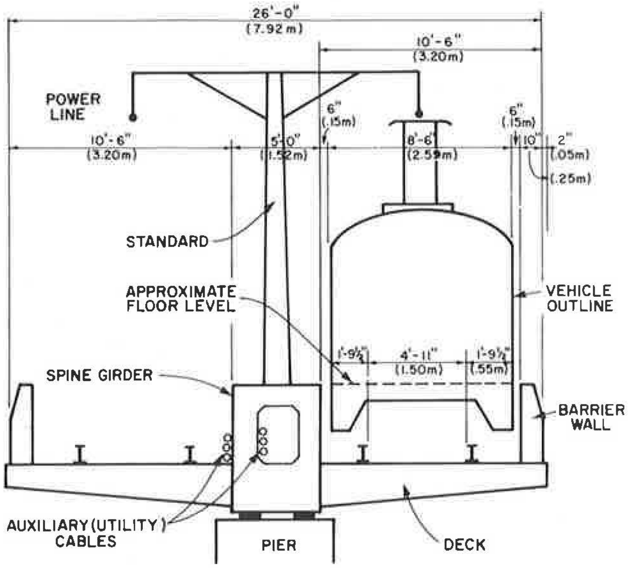
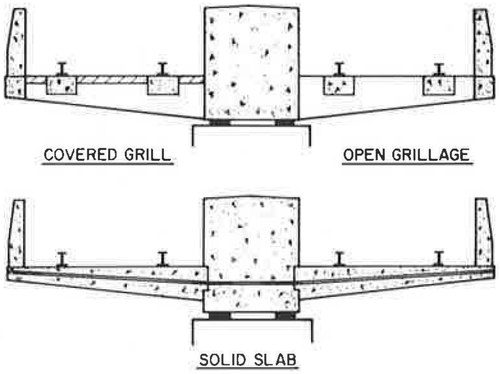


Figure 2. Deck options for a guideway structure.



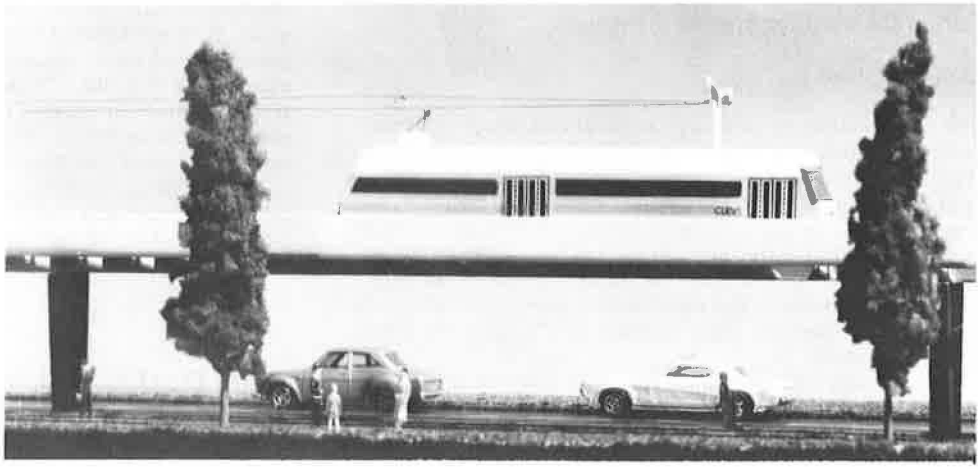
Structural Design

The guideway structure consists of the spine girder, a deck that transfers loads laterally into the spine girder, and a barrier wall. Preliminary designs were made for a constant depth spine girder with four continuous spans of 24.4, 30.5, 30.5, and 24.4 m (80, 100, 100, and 80 ft). Figure 2 shows the three deck options that were considered: a solid tapered slab, an open grillage, and a grillage with a 10.2-cm (4-in) cover slab.

For span lengths of around 30.5 m (100 ft), an economical and structurally adequate spine girder with a prismatic section of prestressed concrete has a depth-to-span ratio of 1:17. For greater spans, the spine girder may be haunched over the piers at the same depth-to-span ratio with depth at midspan about 70 percent of that over the piers. Both the prismatic and haunched options give a guideway an appearance that is generally pleasing, as shown in Figure 3. A spine girder depth of 1.8 m (6 ft) was adequate for resisting all combinations of flexural, shear, and torsional loads in both service and ultimate limit states. Maximum flexural and shear stresses are produced by fully loading both tracks simultaneously, whereas maximum torsion stresses are produced by fully loading only one track. The design criteria followed the American Concrete Institute's recommendations (ACI-443). These recommendations provide for an impact factor of 30 percent of live load for dynamic effects, a rolling factor (between the rails) of 10 percent for torsional analysis, a longitudinal force factor of 10 percent for operational braking, a centrifugal force factor of 20 percent on curved tracks, and a derailment force factor of 40 percent that acts normal to the barrier wall over a distance of 3.1 m (10 ft).

The girder is solid in the negative moment regions and anchorage zones and hollow with a 22.9-cm (9-in) wall thickness for the rest of its length. Prestressing is provided by multistrand or multiwire tendons that have low relaxation characteristics. Concrete and steel requirements are similar to those for normal highway bridges. At some increase in weight, the solid deck provides greater ultimate shear and torsional stiffness strength than the grid. For structural purposes, use of the grid option necessitates a slight increase in beam depth. The dimensions for this beam for the chosen span lengths fit very well with the geometric requirements of the vehicle (Figure 1), but variations in the

Figure 3. Scale model of a guideway structure.



spine girder cross section are possible. The open or partially closed grid may prove attractive in areas where heavy snowfall is experienced, provided that noise is not a problem. The open grid requires a wire mesh attachment for the safety of track personnel.

The structure is quite stiff with a maximum live load plus impact deflection less than $\frac{1}{1600}$ of any span, and it has a first mode natural frequency of about 4 Hz. Continuity of the structure and continuous welded rails guarantee an excellent ride, which may be maintained if the rails can be shimmed relative to the deck.

The piers are of standard reinforced concrete design and support the spine girder on neoprene bearing pads that allow expansion. The girder-pier support system resists overturning of the guideway under the most adverse loading conditions on both straight and curved tracks without special anchorage details.

Construction Options

There are a large number of construction options for this guideway structure because the spine girder, deck, and barrier walls can be made structurally independent of one another.

The spine girder may be cast in place or precast and posttensioned after erection. The deck may be cast in place or precast in short segments and added to the girder by using a transverse posttensioning to reduce construction time and cost. Separate crews may be used for girder and deck erection. The segmental construction technique may be applied at sites where there is limited access or along streets where traffic disruption is to be minimized. The girder and deck are integrally precast in segments that are 3.05 to 6.1 m (10 to 20 ft) long and are erected by cantilevering from both sides of the piers without falsework. Continuity is provided by posttensioning the segments longitudinally as they are erected and also after closure. For any of these construction options, the barrier wall may either be cast in place or precast and bolted to the deck.

Cost

Several construction options have been costed in detail, and each option is estimated within ±10 percent of $1969/m ($600/ft) in 1975 Canadian dollars. This estimate includes foundations on spread footings, piers, and a double-track guideway structure, which is built under ideal conditions. The estimate excludes tracks, power, signals, and installation costs. Physical complications on a specific route might raise this cost substantially; however, the span length flexibility and construction options available within this guideway concept provide the best opportunity for coping with these difficulties without the need for special structures.

CONCLUSIONS

The significance of guideway considerations in vehicle design is most apparent in the initial cost and operational strategy of the system. The guideway absorbs an appreciable portion of the capital cost of a transit system. Hence, compromises in guideway configuration to accommodate an existing vehicle design might be adversely reflected in the overall cost of present as well as future systems. The operational aspects in terms of safety, convenience, and service might also be seriously hampered.

A rationale has been presented for the design of elevated guideway structures for LRT. This rationale is neither a specification nor a code, but it should form the basis for either. It identifies performance requirements that must be met for the structure, constraints that limit the designer's range of choice in meeting the performance requirements, and design considerations that provide the basis for making design choices.

By using this rationale, a guideway concept has been developed for a proposed LRT line. This concept features a central spine girder that acts both as the primary structural member and an access walkway and from which decks are cantilevered to carry the tracks. Barrier walls are mounted on the outside of the decks for vehicle containment and noise abatement. The basic guideway concept has considerable structural and construction flexibility so that the variant or variants that best suit a particular route may be chosen to gain maximum benefit from mass production. The guideway is estimated to cost $1969/m ($600/ft) for foundations, columns, and double-track structure. Since the structural depth is hidden by the barrier wall, the guideway is a slender and elegant structure.

ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of R. A. Dorton, Structural Office Manager of the Ministry of Transportation, who guided development of the concept, and C. Sadler, who did much of the detailed structural analysis.

Discussion

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The proposed design of an elevated structure for light rail transit is apparently both economical and aesthetically pleasing. It requires a very small total width. However, it appears that two potentially serious problems have not received sufficient attention.

The first problem is snow removal. Although the rail vehicles are least susceptible to impedance by snow, a heavy snowfall can, in this case, require physical removal rather than only running the vehicles at certain intervals. An open grill bottom could not be used because it allows dripping of oil and minor particles on the area below the structure. For this reason, grills are illegal on elevated structures in many countries. A possible solution may be to have a vehicle with a blower that would throw the dispersed snow from the aerial structure.

The second problem is that the proposed design makes it impossible to have access to the vehicles from the side below their bodies. Since many minor mechanical or electrical failures in vehicles can be repaired from this side, it is always essential that access to the trucks, control, and other equipment be available along each side of the vehicle. This requirement is absolute, and it must be given careful consideration in determining the distance between the vehicle profile and concrete fence on each side of the track.

These two problems should be carefully studied and adequate solutions found before any further testing and implementation of this design are undertaken.

Authors' Closure

The serious problem of snow removal was briefly discussed in the paper, and it is recognized as an area of doubt until actual operational experience is obtained. Since our paper was written, further information (1) has come to our attention. This information indicates that snow removal can be achieved for elevated guideways by a satisfactory mechanical means. The open grill would not be contemplated in cases in which dripping of oil or other debris might be hazardous; its primary use might be in cases in which the guideway is inaccessible to the public and airborne noise is not a problem.

The second problem clearly illustrates the need for recognition of guideway constraints in vehicle design as well as the more usual converse. A subway vehicle operating in tunnel provides essentially no opportunity for access to vehicle components. Thus, in the event of failure, the other vehicles of the train provide a self-rescue capability. There are only two cases for the Toronto Transit Commission subway in which there is a need for access underneath the vehicle: if the operator needs to free a tripped emergency brake and to free a suicide victim from the vehicle undercarriage. The LRT line for which this guideway is designed would operate multicar trains; therefore, the need for operator intervention is reduced since it is preferred policy for a faulty vehicle to be towed out of service rather than for the operator to attempt to repair it. If there are some functions the operator must reset after a fault, it should be a straightforward matter to modify the vehicles with reset mechanisms that are accessible from the walkway, if not from the vehicle interior. In this study, it is preferred to modify the vehicles rather than the guideway on the line because it is expected that the initial existing LRV operating on the line will ultimately be replaced by a vehicle designed for exclusive right-of-way operation. Thus, the guideway concept is designed to reflect ultimate rather than immediate needs.

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Model for Cost-Effective Maintenance of Rail Transit Vehicles in Urban Mass Transit Systems

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A new computer-based model to assist rail transit management in determining maintenance schedules for rail transit vehicles is presented. The model evaluates the aggregate cost and service implications of conducting prescheduled inspections and preventive maintenance activities for the various components of a transit vehicle. The model also consolidates information on size of vehicle fleet, cost of maintenance and repair of vehicle parts, relations between maintenance frequency and subsystem failures, and historical patterns of the different types of in-service breakdowns. On this basis, the model determines relations among preventive maintenance alternatives, average number of transit cars available for peak service, expected number of in-service car failures, and the total cost of maintenance and repair. The model was originally developed for use by the Massachusetts Bay Transportation Authority in Boston. Preliminary findings in the initial application of the model to generate and evaluate alternative maintenance schedules for the authority's Red Line suggest that use of the model could result in noticeable, though probably not dramatic, savings for this particular line. The authority intends to refine the data used in these analyses and to extend the use of this model to its other lines. The model is a conversational FORTRAN program. It can be adopted for use in any rail transit system that has the required data on vehicle maintenance and repair activities.

Transit vehicles, like most complex pieces of equipment, are prone to unforeseeable failure. Although preventive maintenance programs may keep the frequency and nature of nonscheduled repairs within acceptable bounds, the notion of acceptability is subjective from the rail transit management's point of view. In-service breakdowns will disrupt the scheduled flow of cars along the line and directly inconvenience or even endanger the passengers. Up to a point, a transit system manager will naturally desire to keep the cars in working order through a regular program of preventive maintenance. Maintenance, however, is a non-revenue-producing activity and must be kept within reasonable bounds. If service reliability is satisfactory and accidents are rare, then transit managers are unlikely to expand their preventive maintenance programs. The costs and impacts of vehicle inspection and repair activities must be identified before a sense of the economic trade-offs between preventive and remedial work can be gained.

To aid transit managers in appreciating these trade-offs and to help them in evaluating alternative vehicle maintenance schedules, we have developed the Maintenance Analysis and Scheduling System for Transit Management (MASSTRAM), which is a computer-based model. MASSTRAM analyzes the cost and service implications of alternative preventive maintenance strategies for various subsystems of the vehicle and displays tabular and graphical data that identify various trade-offs between costs and service loss. MASSTRAM is programmed in FORTRAN and is designed for conversational interaction with the user.

This paper describes the vehicle maintenance problem and the basic concepts and capabilities of MASSTRAM. Preliminary findings are presented for the initial application of the model by the Massachusetts Bay Transportation Authority (MBTA) to a rapid transit line in the Boston area. The application efforts described include plans for the implementation of a controlled experiment in which the effect of alternative preventive maintenance intervals is estimated. The paper concludes with some observations on the possible implementation of MASSTRAM elsewhere.

VEHICLE MAINTENANCE PROBLEM

The essential contribution of a preventive maintenance program is the support it provides for the delivery of high-quality transit service. At one level, the dependencies of transit service on vehicle maintenance are largely intuitive. Transit service is measured in a variety of ways such as convenience, speed, safety, and comfort. Convenience and speed depend in part on the establishment of reasonably short headways (the time interval between consecutive trains on the same line). The feasibility of meeting headways clearly depends on the size of the fleet, the percentage of the fleet that is in running condition, the physical layout of the line, and the operating speed of the vehicles. Perhaps another less obvious condition is the type and frequency of in-service breakdowns that also affect the achievement of target headways, since these breakdowns disrupt the planned flow of vehicles. By influencing the effective size of fleet and controlling the likely breakdown rate, the vehicle maintenance policy partially determines the convenience and speed of the transit service. Passenger safety and comfort, both important measures of transit service, are also affected by maintenance policy.

The requirements for preventive maintenance are determined by many factors such as the design of the transit vehicle, the physical layout and condition of the line, and the age of the fleet. One other crucial factor that deserves special mention is the number of spare vehicles. At any time, one may calculate how many spare vehicles exist by subtracting the number of vehicles needed for use in peak-period service from the total number available for use. By this definition, the number of spare vehicles will vary daily because some vehicles are brought in for inspections or repairs and others that were in the repair shop are returned to the pool of available cars. Thus, spare vehicles reduce the impact of failures by providing a backup supply.

If the number of vehicles in the total fleet barely exceeds the established peak-hour requirement, it is likely that the number of spares will always be low and the pressure to keep all vehicles in good working condition constant. Multiple breakdowns in a single day can eliminate the stock of spare vehicles for the next peak period, thus making it impossible to meet the desired headways. In such a situation, a carefully designed, comprehensive, preventive maintenance program is crucial since routine inspections, timely minor repairs, and adjustments are needed to guard against frequent major breakdowns. Paradoxically, when the repair needs of the fleet are small, it is difficult to implement intensive and frequent preventive maintenance. Thus, this procedure requires that a number of different cars be taken out of service each day for routine inspections, thereby reducing the number of spare vehicles available for service that day. However, it is possible to schedule preventive maintenance activities during the night shift, as is done in Philadelphia. Short of purchasing more vehicles to supplement the existing fleet, this reduction in spare vehicles can only be countered by an increase in the planned headways, an increase that is large enough to provide for an adequate number of spare vehicles that could be properly maintained and used as a cushion against emergencies. Thus, when a few spare vehicles are available, the strategic decision regarding the optimal frequency of preventive maintenance may center on a trade-off between achieving the planned headway or experiencing an increased variability in headway to account for unplanned, in-service breakdowns. (Current practice in the transit industry seems to stress a marketing strategy for meeting publicized headways.) Thus, it seems unlikely that a decision would be made to increase the existing headways on a regular basis for accommodating the more extensive or frequent preventive maintenance of vehicles. It is more likely that this trade-off would be explicitly determined and acted on in cases such as designing and scheduling new transit systems or new fleets of vehicles on existing lines.

In contrast, a different kind of situation may arise when a large number of spare vehicles are available. For example, the costs for the preventive maintenance program might be cut, if vehicles that break down can be replaced from a large number of spare vehicles. However, this strategy is short term, and the fleet will gradually deplete because deferred maintenance results in serious vehicle failures that necessitate major overhauls before these vehicles can be returned to active duty. Eventually, the original surplus will no longer exist and the resultant failures will have incurred other costs because of service disruptions and adverse passenger reactions. Despite these long-term dangers, transit managers are often faced with severe budgetary pressures and they often view the cutback of preventive maintenance activities as an easy short-term saving.

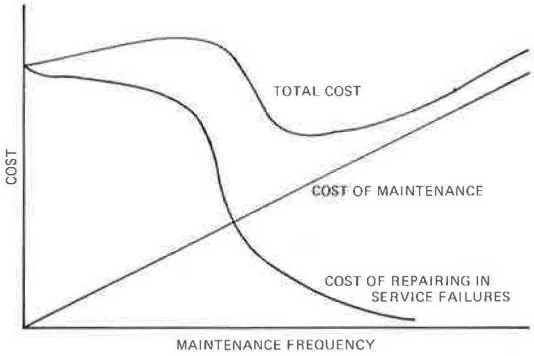
Each transit system needs to define a vehicle maintenance program with capacities and capabilities that best meet its own special performance requirements. Viewed from this system perspective, a vehicle maintenance program is undoubtedly a crucial component of a viable transit service policy. But how much maintenance is appropriate? And, at what frequencies should maintenance be performed? These are the questions that demand a careful cost-benefit analysis. MASSTRAM, a conversational FORTRAN program, has been designed and developed to aid transit managers in performing this task.

COST-EFFECTIVE CONSIDERATIONS

Preventive maintenance involves the repair of items or the restoration of certain components to their initial operating condition (e.g., lubricating, wheel trueing, filling brake cylinders and hoses with appropriate liquids and gases, cleaning out motors with compressed air). For any particular fleet of transit cars, a preventive maintenance program attempts to find a cost-effective balance between two opposing forces. Not enough preventive maintenance leads to costly service-disrupting vehicle failures, and too much preventive maintenance incurs unnecessary expenses and unjustifiably reduces the number of in-service cars. More specifically, the two types of costs that must be balanced are (a) the cost of scheduled inspections for regular adjustments, repairs, and replacement of components that might not last until the next scheduled inspection; and (b) the cost of repairing and replacing a component that failed while the train was operating and carrying passengers. Thus, the overall goal of any analytic effort to establish or review a preventive vehicle maintenance policy is to aid management in identifying the desirable balance among these opposing forces.

The curve shown in Figure 1 for cost of repairing in-service failures indicates that, the more frequent preventive maintenance is, the greater the reduction in failure rates and repair costs associated with such failures will be. This will be the case for vehicle components that fail because of wear and tear (e.g., brake shoes) or age (e.g., rubber hoses). Since a transit car

Figure 1. Cost functions for maintenance and repair.



has many components with these characteristics, a more active preventive maintenance program will generally result in fewer expected failures over a period of time. Naturally, in any particular situation there are uncontrollable factors such as a major snowstorm that can lead to component failures despite the existing level of preventive maintenance.

Another dimension of the maintenance-failure relation is service reliability. Certain serious breakdowns will render a vehicle unusable; thus the passengers will have to be discharged and the transit line will be delayed until the crippled vehicle is cleared away. The ultimate costs of such incidents are hard to determine since crucial considerations such as loss of patronage and public confidence are not easily converted to dollars and cents. Nevertheless, some indication of the trade-off between hard dollars spent on maintenance and repair and soft dollars attributed to in-service failures should be made available to transit management.

MASSTRAM was developed to satisfy this need in two stages. First, as shown in Figure 1, total tangible costs are minimized by establishing an economic balance between the costs of scheduled inspections and the costs of repairing and replacing components that fail while the train is operating and carrying passengers. The maintenance schedule leading to this cost minimum is evaluated in terms of in-service failures or the expected number of cars available for peak service.

Second, with these trade-off estimates, management can proceed to select the most desirable alternative that is based on an implicit valuation of service considerations. Thus, MASSTRAM assists management in selecting a maintenance schedule that will be cost-effective over the course of the existing planning horizon. Since MASSTRAM is designed to reflect aggregate performance over a period of time, it does not attempt to predict the probability of different patterns of occurrences within a single planning period.

DEVELOPMENT OF MASSTRAM

MASSTRAM is a flexible planning tool that can be readily applied by transit managers to the type of complex assessment just described. Therefore, in the development of this model, it was especially important to include certain generalized capabilities that would allow different users to tailor the model to their own needs. Several important considerations were represented that included levels of maintenance, level of aggregation for planning horizon, and rail vehicle representation.

Levels of Maintenance

There are three benchmark levels of maintenance for a fleet of transit cars: (a) daily inspection, (b) regular periodic maintenance at 6400 to 19 200-km (4000 to 12 000-mile) intervals, and (c) overhauls at 320 000-km (200 000-mile) intervals. The daily inspection usually amounts to no more than a quick visual check of certain key components before a transit train is brought into service. In contrast, overhauls can vary in terms of scope and intensity that range from putting on a new coat of paint to completely disassembling a transit car or replacing and repairing a number of major components. Thus, a vehicle may undergo only one or two major overhauls during its useful economic life, whereas regular periodic maintenance is done several times a year.

The regular periodic maintenance typically involves an average of 20 to 25 person-h of work/transit car. It is roughly analogous to the periodic tune-ups and inspections that a conscientious automobile owner performs to ensure that his or her car is running safely and properly. In many transit systems, the regular periodic maintenance is actually a program of different maintenance tasks to be carried out at different intervals. For example, the Green Line streetcars of the MBTA in Boston are given an A-inspection every 6400 km (4000 miles) and a more thorough and comprehensive B-inspection every 12 800 km (8000 miles). The maintenance shops for the Bay Area Rapid Transit (BART) in San Francisco schedule a more comprehensive maintenance activity every third inspection interval, rather than trying to do the same work at each of the monthly checkups. The maintenance shop for the Port Authority Transit Corporation (PATCO) in Philadelphia schedules increasingly comprehensive maintenance at 4800, 19 200, 57 600, 115 200, and 384 000-km (3000, 12 000, 36 000, 72 000, and 240 000-mile) intervals. The Red Line of the MBTA used an A-inspection every 6400 km (4000 miles) and a B-inspection every 12 800 km (8000 miles) until 1971. At that time, a new inspection and maintenance procedure was instituted to be performed every 8000 km (5000 miles).

MASSTRAM is primarily designed for evaluating long-term policies that are relative to regular periodic maintenance. It is not designed to generate daily maintenance schedules, give details regarding the specific cars to be inspected on a given day, or designate specific work crew assignments. Though MASSTRAM is not currently designed to include the vehicle overhaul activity, it can easily be extended to evaluating the overhaul schedules in situations in which the same set of maintenance facilities are used for both periodic maintenance and overhauls. For example, the PATCO system in Philadelphia has one maintenance facility at the end of the line. For such a transit system, an overhaul can be treated as an extensive maintenance operation. This situation is in contrast to a system such as BART that has three maintenance facilities; two facilities concentrate on periodic maintenance and a third facility does both periodic maintenance and major overhauls. It is possible to use MASSTRAM for analyzing the overhaul schedules in this situation; however, this procedure is more complicated. At MBTA, overhaul and periodic maintenance are performed in geographically distinct locations, and the heavy maintenance shop caters not only to rapid transit cars but also to streetcars and buses. In this type of situation, MASSTRAM is primarily applicable to establishing policies for regular periodic maintenance (e.g., generation and evaluation of the intervals at which the different components of the cars in the fleet should be maintained).

Level of Aggregation for Planning Horizon

Budgetary cycles of 1 year are standard for most transit authorities. Since budget preparation and control are one important area of application for MASSTRAM, its standard planning horizon is also 1 year. However, the planning horizon can be changed to any length desired. For example, in negotiating a labor contract, management can use MASSTRAM to evaluate the impact of new hourly rates on maintenance costs and to determine whether the new rates would make a shift in the maintenance schedule desirable. In such a situation, a planning horizon equal to the contract period may be more meaningful than the standard 1-year horizon. Similarly, in planning for a completely new fleet of vehicles, a planning horizon equal to the warranty period of the most important components might be desirable.

Rail Vehicle Representation

As a strategic planning model, MASSTRAM does not explicitly recognize particular rail transit cars. Instead, it functions in terms of an average transit car. (Equivalently, MASSTRAM can use an entire fleet of vehicles as its basic unit of analysis, since, in concept, the characteristics of the total fleet and associated maintenance criteria can be represented by the characteristics of the average car in the fleet multiplied by the number of vehicles in the fleet.) However, vehicle maintenance policy alternatives are not identified in terms of an entire train; individual cars; or the several major systems of a rail vehicle such as the control system, truck, or car body. Indeed, a key contribution of a model such as MASSTRAM is to identify the tradeoff possibilities among alternative maintenance options for the many different subsystems of the vehicle. (MASSTRAM incorporates decision rules for constructing cost-effective maintenance cycles.) The extent to which a transit car should be represented by systems and the extent to which these systems should be separated into subsystems are important technical decisions that have managerial ramifications. When the particular set of subsystems to be included in MASSTRAM are specified, unnecessary detail must be traded off against oversimplified aggregations.

In the initial application of MASSTRAM to the Red Line of the MBTA, a transit car is represented as a collection of 26 subsystems. These subsystems are as follows.

System and Code	Subsystem
Control	
co01	Motor generator
co02	Compressor
co03	Compressor motor
co04	Compressor switch
co05	Heat and fan
co06	d-bar cable and button banks
co07	Cineston
co08	Relays and switches
co09	Grids and connections
Trucks	
tr01	Truck frame
tr02	Wheels
tr03	Contact shoes
tr04	Emergency trips
tr05	Hand brake and cable
tr06	Drawbar
tr07	Brake shoes
tr08	Suspension
tr09	Operating unit
Air brakes	
ab01	Cineston and d-man control
ab02	Batteries
Motors	
mo01	Traction motors
mo02	Brushes
Car body	
cb01	General condition
cb02	Window glass
cb03	Destination signs
cb04	Door, light, and crew signal equipment

By using this set of categories, the level of detail through which different systems are represented intentionally varies. What one abstractly represents as a subsystem in MASSTRAM may physically correspond to a very specific item (e.g., the compressor switch) or to a large group of individual items (e.g., relays and switches). The grouping of items into subsystems is primarily guided by physical proximity, functional similarity, and similarity with respect to the type of tasks performed during an inspection.

APPLICATION OF MASSTRAM

MASSTRAM can aid management in setting cost-effective maintenance schedules by (a) evaluating any specified schedule, (b) determining an optimum schedule subject to conditions imposed by the management, and (c) providing curves that show the trade-off between maintenance costs and number of failures.

As an introduction to MASSTRAM, a sample set of model output is presented below. Although realistic, these outputs are only illustrative. A comparison between the standard schedule in which all subsystems are maintained at 8000 km (5000 miles) and a modified schedule in which some subsystems are maintained at 6400 and 12 800-km (4000 and 8000-mile) intervals is given below.

Item	Standard	Modified
Estimated hours for maintenance		
Straight	17 110	17 110
Overtime	6 844	4 572
Total	23 954	21 682
Inspection	5 967	5 112
Emergency	17 987	16 570
Vehicle status		
Vehicles in service per day	105	109
Vehicle-hours out of service	197 771	181 538
Vehicle failures	3 444	3 185
Maintenance costs, $		
Regular	222 000	222 000
Overtime	102 000	68 000
Total	324 000	290 000

The modified schedule is the least costly schedule under the condition that the schedule contains, at the most, two different maintenance intervals. In this comparison, the modified case shows an expected annual net saving of 2272 h (about 10 percent) for maintenance labor. The modified case requires fewer hours per year for scheduled inspections (855 or 14 percent) and fewer hours for emergency repairs (1917 or 8 percent). In this illustrative comparison, the expected net annual savings of $34 000 (about 10 percent) is due entirely to a reduction of overtime costs. The costs for parts that were ignored in these sample runs would tend to make maintenance more frequent. The modified maintenance schedule not only costs less but should also result in better service since fewer (259 or 8 percent) in-service vehicle failures are expected during the year and the annual vehicle-hours lost are reduced by 16 233 h. On the average, this results in having four more vehicles available for service on this line.

Table 1 gives the detailed subsystem evaluations for the modified schedule. Subsystem evaluations are listed in terms of the expected person-hours required for regular inspections (i.e., preventive maintenance) and emergency repairs, the estimated number of failures per year, and the associated annual vehicle-hours out of service. Note that the subsystems are maintained at 6400 and 12 800-km (4000 and 8000-mile) intervals.

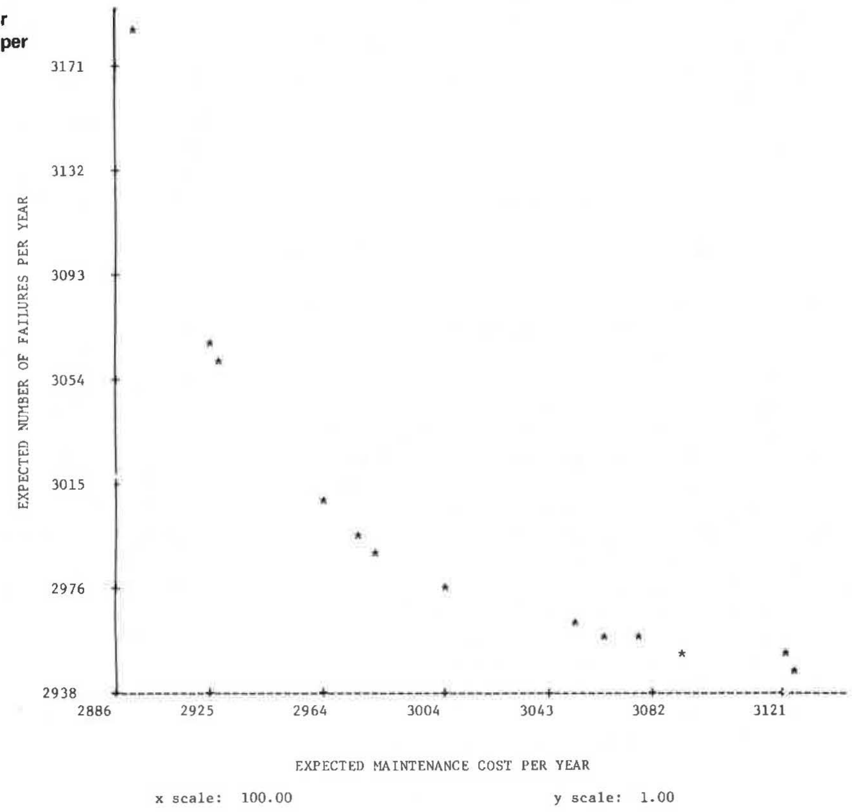
If Table 1 were compared with a table for the standard program of 8000-km (5000-mile) intervals, it would show the expected net changes required for preventive maintenance and nonscheduled repairs. For each subsystem that has been shifted to a 6400-km (4000-mile) inspection interval, the number of failures will decrease since the preventive maintenance effort is increased. The opposite occurs for those subsystems that have been

Table 1. Sample output of MASSTRAM for subsystem evaluation.

Code	Subsystem	Maintenance Interval (km)	Expected Person-Hours Required for Maintenance: Regular	Emergency	Total	Out-of-Service Vehicle-Hours per Year	Vehicle Failures per Year
ab01	Cineston and d-man control	12 800	83	73	157	122	5
ab02	Batteries	12 800	75	160	235	1 523	23
cb01	General condition	6 400	442	680	1122	9 443	227
cb02	Window glass	6 400	233	678	911	2 594	75
cb03	Designation signs	6 400	83	9	93	97	9
cb04	Door, light, and crew signal equipment	6 400	525	2475	3000	27 831	619
co01	Motor generator	12 800	71	53	124	2 520	42
co02	Compressor	12 800	71	206	276	4 263	137
co03	Compressor motor	6 400	0	0	0	0	0
co04	Governor switch	12 800	63	33	95	1 105	33
co05	Heat and fan	6 400	125	1936	2061	3 228	242
co06	d-bar cable and button banks	12 800	112	137	250	1 246	91
co07	Cineston	12 800	79	201	280	2 361	101
co08	Relays and switches	12 800	500	1803	2303	20 193	451
co09	Grids and connections	12 800	75	561	636	3 930	70
mo01	Inspect trac motors	6 400	508	2202	2710	11 512	183
mo02	Motor brushes	6 400	0	0	0	0	0
tr01	Truck frame	6 400	600	1931	2531	14 093	161
tr02	Wheels	12 800	292	572	864	2 551	36
tr03	Contact shoes	6 400	250	2039	2289	23 652	255
tr04	Emergency trips	12 800	150	189	339	1 777	47
tr05	Hand brake and cable	12 800	83	81	164	1 268	40
tr06	Drawbar	12 800	100	6	106	139	4
tr07	Brake shoes	12 800	125	20	145	1 038	20
tr08	Suspension	12 800	192	309	501	5 691	206
tr09	Operating unit	12 800	275	215	490	4 412	108

Note: 1 km = 0.6 mile.

Figure 2. Plot of expected number of failures per year as a function of expected maintenance cost per year.



shifted to a 12 800-km (8000-mile) interval. However, the total annual cost related to any particular subsystem may either increase or decrease depending on the net aggregate change between the preventive and failure-responding efforts. On balance, considering all of the vehicle subsystems together, this modified schedule represents a less intensive preventive maintenance program than the standard 8000-km (5000-mile) inspection program.

MASSTRAM can be used to examine a broad range of trade-offs between increased preventive maintenance and decreased in-service vehicle failures. A set of efficient schedules can easily be determined for which the expected number of failures is reduced with a minimum increase in the associated total cost. A set of results for schedules of 6400 or 12 800-km (4000 or 8000-mile) intervals for vehicle subsystem inspection is given below.

Expected Maintenance Cost per Year ($)	Expected Failures per Year	Expected Maintenance Cost per Year ($)	Expected Failures per Year
289 768	3185	299 799	2985
292 271	3069	303 416	2969
292 637	3062	305 236	2962
296 130	3016	306 024	2960
296 995	3005	307 835	2956
297 899	2997	310 929	2951
298 736	2991	311 841	2950

For each line of the table, MASSTRAM will have determined a complete maintenance schedule such as that shown in Table 1. Figure 2 shows a plot of the frequency for this cost-failure trade-off that can also be generated by MASSTRAM. The cost increases shown in the plot and the table arise when some of the subsystems are rescheduled from 12 800 to 6400-km (8000 to 4000-mile) intervals. The specific sequence of these changes is designed to be the most cost-effective way of achieving a particular reduction in the total number of failures. Thus, management must select the maintenance schedule that will best serve the opposing cost and service objectives of the transit system during the current planning horizon.

Data Requirements

The input data required by MASSTRAM are given below.

1. General operating statistics include (a) total kilometers for all vehicles on the line during a specified time period, (b) total number of serviceable vehicles, (c) number of required vehicles for peak service, and (d) average time for moving an in-service vehicle to the repair shop.
2. Maintenance and repair crew characteristics include (a) average annual working hours for each type of repairman (straight time and overtime), (b) number of available workers and average hourly wage rate for each type of repairman, and (c) overtime pay rate.
3. Maintenance and repair-related activities and events organized by subsystem include (a) number of workers in each category required for maintenance or repair of each subsystem together with the average elapsed time per worker for performing a particular task, (b) direct material cost attributable to maintenance or repair activities, (c) average number of hours for holding a transit car when a subsystem must be repaired because of in-service failure, (d) maintenance interval in number of kilometers between the scheduled inspection of each vehicle subsystem, (e) failure rate (per 16 000 km) that is related to the maintenance interval being used, and (f) probability of a subsystem failing and a vehicle needing repair.

The availability of machine readable input data is a fundamental assumption in the design and construction of MASSTRAM. The effective use of MASSTRAM requires an automated data collection and processing system such as the Maintenance Planning System (MPS) that is currently used in the BART system or the Computerized Maintenance Record System (CMRS) that is soon to be installed for the Red Line of the MBTA. Such preexisting data bases would not be organized to feed MASSTRAM directly with data. Instead, summarized data from these systems would be used.

The current MASSTRAM data base for the Red Line was assembled by using a combination of interviews and previously conducted special purpose studies and sampling the manually kept historical records. Interviews with the car house foremen yielded subjective estimates for much of the required data. In this manner, relations between maintenance intervals and failure frequencies for the different vehicle subsystems were obtained. These estimates were then converted to quantitative form for use by MASSTRAM.

The only true means of verifying the maintenance interval-failure rate relations is to collect actual performance data while the maintenance intervals are being varied. This can be accomplished experimentally by intentionally changing the maintenance interval for selected subsystems on a number of rail vehicles. Experimenting with a shorter maintenance interval involves some additional cost but no added risk. At longer intervals, the subsystem should be closely monitored so that if a failure appears imminent it can be tallied as a failure and repaired at once. In this way, longer maintenance intervals can be tested without increasing in-service failures during the course of the experiment. This experimental procedure is being adopted at the Red Line by the MBTA to provide systematic data for refining the failure rate relations and to encourage a movement toward a more cost-effective maintenance program.

Managerial Prerequisites

Satisfying the input data requirements is only one of the prerequisites for a successful implementation of MASSTRAM. There are three other key organizational requirements: direct operations management involvement, a predictable work environment, and a rational budget-making process. Each of these aspects is briefly discussed below.

Once a maintenance schedule is established, it must be carefully implemented and monitored. Successful use of the model requires not only that cost-effective maintenance schedules be determined, but also that they be achieved. If the maintenance schedules are not achieved, the problem may well be in the area of management and control rather than in the realm of strategic planning for which our model has been developed. If technological or labor-related practices tend to be unstable, generating an unpredictable work environment, then implementation and control actions by management can become especially difficult.

Furthermore, it is important to realize that this evaluation model, like others applied elsewhere, can do no more than aid management in making rational and informed decisions. It is ultimately up to management to interpret the output of the model in light of available options and costs. In the case of rail rapid transit systems, managers of vehicle maintenance must be committed to the installation of a complete planning

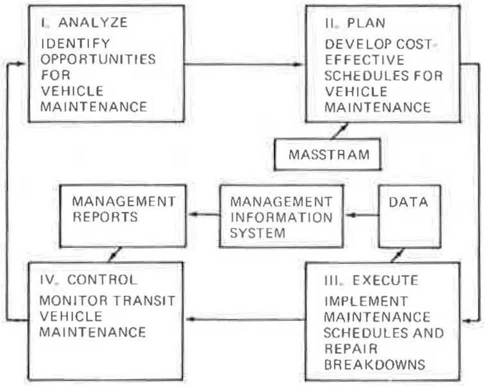


Figure 3. Contribution of MASSTRAM to improve transit system management.

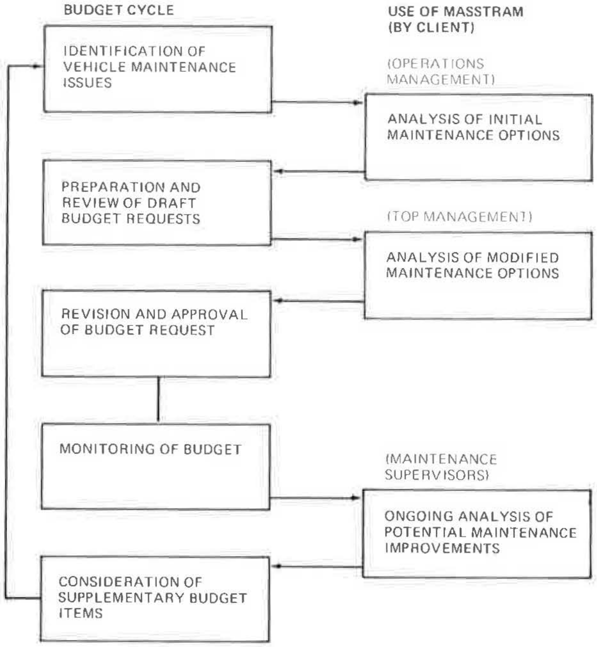


Figure 4. Use of MASSTRAM throughout budgetary cycle.

and programming approach to decision making. The major features of such a managerial approach, as shown in Figure 3, involve a continuing cycle of program planning, execution, control, and analysis.

Within such a planning and control process, MASSTRAM can aid management in the following types of activities:

1. The development of alternative guidelines for vehicle maintenance scheduling within a fixed budget or manpower allotment,
2. The determination of budgeting/manpower implications of changes to the maintenance schedule or intensity,
3. The projection of budgeting/manpower implications of trends in vehicle breakdown (as related to maintenance schedules),
4. The assessment of how potential provisions of new labor contracts could affect cost-effective vehicle maintenance schedules,
5. The assessment of maintenance program expansion necessary to achieve enhanced transit service objectives, and
6. The development of cost-effective maintenance schedules in planning for significant changes in the existing fleet of vehicles.

Even with extensive management involvement, it is possible for MASSTRAM to be less effective than desired because of misconceptions concerning the work environment and capacities of the system. The model makes no explicit judgments regarding the ability of a maintenance shop to conduct the various needed types of vehicle inspections and repairs. In other words, the model is neutral on issues such as the relative skills of existing repairmen or the potential for improved productivity. The model user supplies data that realistically reflect operational aspects of vehicle maintenance; the model calculates the aggregate performance implications resulting from the specified data and associated assumptions. Despite this neutrality, computer-based program evaluation models implicitly assume that the operational activity being modeled is represented within realistic bounds. MASSTRAM will accept any level of the repairman's productivity specified by the manager or planner. It is crucial that there be some productivity level that can confidently be employed for this purpose.

For example, if past levels of the repairman's productivity are used as a basis for determining inputs of the model, there should be a high degree of confidence that productivity levels are likely to remain constant over the current planning horizon. If, however, the model is being run under an assumption of improved productivity levels, then there should be persuasive evidence that such levels are indeed achievable. Variations on this theme would account for and include operational assumptions such as the average skill level of the work force, the reliability of the rail vehicle components, the availability of spare parts, and the extent of cooperation and communication between members of the transportation departments and the maintenance shop departments. Different lines of a single transit system, e.g., the MBTA, could exhibit different maintenance requirements.

A third prerequisite for the successful implementation of MASSTRAM is that transit management as a whole engages in a fairly rational budget-making process. Figure 4 shows how the model can be used within a budgetary cycle. A reliable model, a conducive operational system, and a committed line management are helpful, but, if budget choices do not reflect managerial decisions, such decisions and the tools that support them will not have a considerable impact. In the case of rail vehicle maintenance programs, our model can evaluate the incentives and costs associated with changes in the timing of preventive maintenance. Increased inspections and overhauls may indeed be cost-effective in the long run, but such incentives can only be achieved if annual (and perhaps supplemental) budget reviews offer the opportunity for considering a wide range of managerial choices. For example, if budgetary guidelines deny the possibility of any planned use of overtime work in the maintenance shops, then much of the potential value of analytic model-based findings in this area is lost. Often, when an organization's budgetary guidelines are rigid, it operates either in a business as usual mode, or in difficult times, through reactive cutbacks of men, machines, and service. Models might be of some use at that time, but will be of less use than when the development of a new program strategy is being encouraged.

CONCLUSION

Vehicle maintenance is an essential part of a rail rapid transit system. Many people care about the maintenance of the vehicles. The operators, the car house repairmen, foremen and supervisors, and local agency management work together inside the transit organization to make improved maintenance a planning goal and an everyday reality. Federal officials who sponsor the design, development, and capital improvement of rail transit systems look to transit managers to achieve the service levels that were planned; there is the hope that the elements of transit improvement programs such as the construction of modern car houses and the purchase of new rail vehicles will be well supported by effective operating programs such as preventive maintenance. Other people care about the system simply because they ride it and depend on it. In the spirit of responding to these concerns and hopes, MASSTRAM was developed for use by rail transit management to aid managers of rail vehicle maintenance in their ongoing planning, programming, and budgeting activities.

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