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

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Abridgment

Procedure for Optimizing Rapid Transit Car Design

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

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

PROCEDURE

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

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

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

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

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

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

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

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

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).

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

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

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

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.

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

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 m/s^2 = 3.3 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 m/s^2
HW	1.5 min	DEC	1.1 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.

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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 vol-