based on a knowledge of why unequal headways occur. Once effective strategies are developed, then in principle their cost can be balanced against the benefits, as derived from this paper, to find the optimum level of control.

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Proposed Approach to Determine Optimal Number, Size, and Location of Bus Garage Additions

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A proposed technique for determining the location, size, and number of new bus-garage additions is described. First, different cost components (nonrevenue transportation cost, operating cost, and construction cost) related to new garages (location, size, and number) are identified, and it is shown how most of the current techniques fail to consider the full ramifications of all of these cost elements. Second, an optimization model is presented that includes the full range of cost components that deserve consideration in decisions related to the number, location, and size of new garages. A case study is also presented in which the implications of the full range of cost components are tested on an actual fixed-facility problem. The case study uses the proposed technique in its most fundamental state. The analysis shows that some of the less visible but recurring nonrevenue cost components may significantly affect the total annual garage cost. On the other hand, the more prominent, one-time construction cost may be of marginal importance in the annual cost of the garages distributed over the life of the facility.

Determining the location, size, and number of new bus garages is a problem commonly faced by expanding transit agencies. However, little independent research has been devoted to developing a standard and accurate technique to determine the least-cost number, size, and location of garage facility expansions. The importance of the use of a standard and accurate technique for such purposes is twofold:

1. The addition of a new garage (or garages) represents a long-term commitment to a costly portion of the transit system. The following costs are quite important with respect to other system costs and can vary considerably in magnitude according to the prospective garage number, location, and size alternatives: (a) the costs of nonrevenue travel to and from work assignments, (b) the cost of operating the garage, and (c) the costs of new construction.
2. Locating and sizing a new bus garage is often one of the more controversial aspects of transit planning. Bus garages often occupy prime industrial sites but, because bus operators are public agencies, they do not enhance the local tax base. Furthermore, the movement of buses into and out of a garage often has a disrupting effect on traffic flow on adjacent arterials. For these reasons and others, proposals for new bus garages often meet with strong local opposition. Thus, it seems only prudent that the decision maker should have accurate information relative to the total cost ramifications to justify his or her choice of the location and size of a proposed garage or the number, location, and size of proposed garages.

This paper reviews methods that transit authorities have used to locate and size garage additions. The analysis techniques are described so that the reader can contrast existing techniques with the proposed technique. Next, a proposed technique is presented, along with a case study, to portray the possible cost saving resulting from its use. Finally, directions for future development of the proposed technique are outlined.

PROBLEM STATEMENT

The basic goal of all transit agencies is to provide transit service in the most equitable and cost-effective manner. The development of criteria defining the number, size, and location of fixed facilities constitutes a key element in the realization of this goal. A mislocated or improperly sized facility can, over a few years, account for millions of dollars in wasted funds. Conversely, the dollars saved by optimally locating and sizing these facilities can be more effectively used in other areas of system operations.

All of the characteristics of a garage scheme should be examined with regard to the entire transit system before the minimum-cost garage configuration is identified. Because it is possible to identify a broad array of combinations of the number, size, and location of proposed facilities, in conjunction with varied existing facilities, the determination of the least-cost combination becomes a complex problem. However, the amount of money that is inefficiently spent (accumulated over the life of a garage network) as a result of the nonoptimal number, location, and size of such facilities makes it necessary to find solutions to this complex problem.

A cost-minimization technique must do two things: (a) estimate the costs related to the number, size, and location of garages for all feasible options and (b) determine the cost-minimizing total garage network. Estimating the costs related to a garaging scheme is not a trivial task, and a review of existing methods will show that none of the existing techniques comprehensively estimate all related costs. There are three transit-system costs that depend on the number, size, and location of bus garages: (a) nonrevenue transportation costs, (b) garage operating costs, and (c) garage construction costs.

Nonrevenue transportation costs are composed of three elements: deadheading, relief, and spread-time costs.

1. Deadhead costs--The cost of the labor and vehicle mileage to bring buses from the garage to their in-revenue service points (pull-outs) and the cost of returning to the garage from the out-of-revenue service points (pull-ins) are the deadhead costs. A nonoptimal location of storage facilities may result in a significant amount of wasted funds in deadhead cost.
2. Relief cost--During the duration of a bus assignment (a block), a driver relief may be required. A relief may incur an additional transportation cost to the block for the garage under consideration. The relief cost assessed against the block is added to the deadhead transportation cost of a block.
3. Spread-time penalty--Spread-time penalty is the labor cost of having a driver scheduled for an 8-h split shift that does not begin and end within the period set in an agreement with the driver's union. A spread-time penalty is incurred when a driver works on a split shift that overlaps the specified period.

Spread-time-penalty savings are most evident when a suburban garage site is contrasted with an urban core site. This is because on suburban commuter routes the outer site has the advantage of being closer to morning in-revenue service points (pull-outs) and evening out-of-revenue service points (pull-ins). Because outer sites are closer to commuter route ends, a split shift can be served from the suburban facility and effectively used to cover both peaks with less elapsed time from beginning to end to the split shift, thereby decreasing the incidence of spread-time penalties.

The operating costs of a garage are the daily costs of servicing the buses, maintaining the facility, and allocating manpower and buses to blocks. The average operating cost per vehicle should show definite economies of scale that must be weighed against the diseconomies of scale of nonrevenue transportation costs (1).

Garage construction costs are the expenses of buying the land and of erecting and equipping the building. These costs depend on the size and number of the garages constructed. There are economies of scale in construction costs that must be weighed against the diseconomies of scale of nonrevenue transportation costs (1).

CURRENTLY USED TECHNIQUES

In reviewing existing methods used to size and locate garage additions, four basic techniques were identified: (a) the center-of-gravity method, (b) the rectilinear-distance method, (c) the scalar distance proxy method, and (d) the actual time and distance cost method. All of the identified techniques locate garages with respect only to minimizing deadheading. None consider garage number, size, and location costs other than with respect to nonrevenue transportation costs. The techniques reviewed and their associated drawbacks are discussed below.

Center-of-Gravity Method

The most common technique used to locate bus-garage additions is the center-of-gravity (CG) method. The CG method requires the user to identify all pull-in and pull-out points on a Cartesian coordinate system. Then the CG is found by determining the average point with respect to all pull-in and pull-out points in the vertical and the horizontal directions independently. The coordinate of the vertical and horizontal averages is assumed to be the location (the center of gravity) that will minimize deadhead travel distances (2). The CG method used to find the location of one garage within a system is expressed mathematically as follows:

$$x^* = \sum_{i=1} W_i a_i \Big/ \sum_{i=1}^{m} W_i \quad (1)$$

and

$$y^* = \sum_{i=1} W_i a_i \Big/ \sum_{i=1}^{m} W_i \quad (2)$$

where

a,b = coordinates of the pull-out and pull-in points,
W = number of bus movements to or from each pull-out or pull-in point,
x*,y* = coordinate of the center of gravity, and
i = a pull-out or pull-in point (1,2,...,m).

A multiple garage location problem can be solved by using the CG method and dividing the transit service area into a number of sectors within each of which a proposed garage is located. The CG of each sector is the proposed site of a garage under that sector scheme. The total vertical and horizontal deadhead distances are calculated from the Cartesian coordinate system and summed. Then another sector scheme is developed. The total vertical and horizontal distances from different iterations of sector schemes are compared, and the scheme with the least total deadhead distance is selected.

In summary, the CG method is fairly simple to apply and has received widespread application (2). However, some of its assumptions appear conceptually inaccurate. To illustrate the assumptions that do not appear conceptually correct, an allied problem is formulated:

$$\text{Minimize } F(x,y) = \sum_{i=1}^{m} W_i [(x-a_i)^2 + (y-b_i)^2] \quad (3)$$

$$\{[\partial F(x^*,y^*)/\partial x^*], [\partial F(x^*,y^*)/\partial y^*]\} = (0,0) \quad (4)$$

The partial derivatives of Equation 3 with respect to x and y, when set equal to zero, yield Equations 1 and 2, the solution to the CG problem. Thus, it is implied in the CG method that the resulting proposed garage location minimizes the weighted, squared Euclidean distance (straight-line distance) from the CG to all pull-out/pull-in points.

The CG method has received widespread application in the transit industry, primarily because of its simplicity. There are, however, a number of serious drawbacks to these techniques:

1. The CG method implies that the resulting proposed garage location minimizes the weighted squared Euclidean distance (straight-line distance) from the CG to all pull-out/pull-in points. Since it is not possible to travel through urban areas in a straight line, the use of Euclidean distance is clearly too simplistic.
2. The size and number of garages are determined independently of the analysis.
3. Because the objective of the method is to find the location for a garage addition that minimizes the weighted, squared Euclidean distance and not cost, it is impossible to treat other costs in the analysis (i.e., construction and operating cost).
4. Even if the CG method yields a location that will minimize deadheading, it does not account for the relief costs and spread-time penalties included in nonrevenue transportation costs.

Rectilinear-Distance Method

The rectilinear-distance method assumes that buses pull out and pull in along a Manhattan (Cartesian) grid system and that travel cost (as a function of distance) is the same throughout the grid (3). Thus, the location that will minimize the rectilinear distance between a garage and pull-out/pull-in points will minimize deadheading costs. The method, in its simplest form, can be expressed as follows:

$$\text{Minimize } F(x,y) = \sum_{i=1}^{m} W_i(|x - a_i| + |y - b_i|) \quad (5)$$

Equation 5 can be restated as two separate optimizing problems:

$$\text{Minimize } F_1(x) = \sum_{i=1}^{m} W_i|x - a_i| \quad (6)$$

and

$$F_2(y) = \sum_{i=1}^{m} W_i|y - b_i| \quad (7)$$

One of the interesting properties of the solution to the rectilinear-distance problem is that the optimum vertical and horizontal coordinate location of the new facility is a median location (4). Because this property has a pictorial interpretation, the problem can be solved graphically. At least one transit operator was found to have located garages by solving the rectilinear-distance problem graphically (5). However, the rectilinear-distance problem is normally solved by picking a point (perhaps the CG) and stepping around the selected point until Equation 5 approaches its least value.

Some of the faults in the assumptions implicit in the rectilinear-distance method are the following:

1. The method is based on the computation of rectilinear distances. Although urban streets are often based on a grid system, the arterials that carry the bulk of traffic are radials and circumferentials.
2. The cost of deadheading is assumed to be proportional to rectilinear distance and equal in cost per unit of distance everywhere. Since travel costs vary depending on the kind of roadway, this assumption appears to be simplistic.
3. The rectilinear-distance method locates facilities with respect to deadhead travel only, a fault this method has in common with the CG method.

Scalar Distance Proxy Method

In the scalar distance proxy method, a scalar value is used for deadheading travel costs to candidate garage locations from pull-out/pull-in points instead of a coordinate system. Usually, a proxy for actual travel costs such as air-line distance or estimated travel time is used (6,7). This method sums the total of the proxy deadhead travel costs to candidate garage locations. The location with the smallest total cost is the best candidate.

This approach does not have the capability to distinguish between locations for originating bus assignments in a multifacility problem. Thus, this method can only treat a single-garage-location problem and assumes that the user knows which bus assignment will start from the additional facility. However, the method has the positive attribute of only examining sites that are identified for investigation rather than using all points in space for candidate sites, as is done with the CG and rectilinear-distance methods.

The only objective of the method is to minimize deadheading costs, and it does not examine other cost considerations. Thus, this technique is nearsighted in its treatment of garage size and location in relation to costs.

Actual Time and Distance Cost Method

The actual time and distance cost method allocates bus assignments to garages based on total deadheading and relief costs (8). Actual travel time and distance costs are obtained by using maps to measure the distances and estimate travel times. The bus assignments are relegated to the garage in a garaging scheme that possesses the least total relief and deadhead cost. Once all bus assignments are relegated to a garage, the number of vehicles assigned to a garage is checked to ensure that garage capacities are not exceeded. If a garage is assigned more vehicles than its capacity will allow, bus assignments are relegated to other garages based on the least difference in cost increase due to being relegated to a garage of second least cost. Once the capacities of all garages are satisfied, the total relief and deadheading costs of all bus assignments relegated to all garages are summed. Other garage schemes (different locations and numbers of garages) are subjected to the same process, and the least-total-cost garaging scheme is selected.

This technique has the advantage of using actual travel time and distance costs, but the method seems quite laborious when applied to a large network. In addition, because the method's only objective is to minimize deadheading costs and it does not examine other cost considerations, this technique is also nearsighted in its treatment of costs.

PROPOSED TECHNIQUE

A proposed technique to estimate transit system costs in relation to the number, size, and location of garages is presented below with illustrative examples. Later, the use of the proposed technique in a simplified form is demonstrated through a case study.

Nonrevenue Transportation Costs

Garage capital costs can be determined by estimating the construction costs of garages of varying sizes. Garage operating costs can be determined by estimating labor costs, supervisory employee costs, maintenance costs, and materials costs of garages of varying sizes. However, determining the nonrevenue transportation costs of multiple garages is quite complex. The means by which the components of nonrevenue transportation cost are accounted for is discussed below.

Before nonrevenue transportation costs are estimated, work rules regarding driver relief and spread times must be specified. The work rules are, to some degree, similar for all transit operators, but specific rules depend on the local union contract. The rules used in this description are those of the Minneapolis-St. Paul Metropolitan Transit Commission (MTC) that were in effect during 1976. However, the methodology may be restructured to fit the work rules of other operators.

Relief Costs

During specific work assignments (blocks), a driver relief may be required. Relief can sometimes be provided through the transit network. This requires that the driver be able to make connections from the garage to the relief point with only a 10- to 15-min bus ride and no transfers. If relief cannot be accomplished through the transit network, the relieving driver drives another bus to a point of interception with the block that requires relief. The drivers exchange vehicles, and the relieved driver returns to the garage.

Spread-Time Penalties

The MTC labor agreement specifies that, any time a driver works a split shift that overlaps a 10.5-h period, the overlapping time will be paid at 1.5 times the normal rate. In 1976, the average system wage rate, including an average quantity of spread-time penalties, was 19¢/min. If there was a spread-time penalty on a specific block, the average wage rate during the period of the penalty was 25¢/min. Spread-time penalty is paid at only 6¢/min above the average because fringe benefits, union dues, and other ancillary items are not paid at the accelerated rate when a spread-time penalty is incurred.

Cost Estimation Technique

To estimate the cost of various facilities, one must determine the nonrevenue transportation costs for operating all blocks out of all garages. In this way, the cost of any capacity of garages in any possible scheme can be assessed with respect to its transportation costs. A simplified two-garage example is presented here to demonstrate the use of the technique.

The solid line in Figure 1 is the path of route 1, and the dashed lines are the deadheading paths to the two garages, A and B. This example considers only the first three blocks on the route, which have the following pull-out and pull-in assignments:

Block	Pull-Out Point	Pull-In Point	Relief	Time Period
1	E	C	0	Morning
2	D	C	0	Morning
3	E	C	3	All day

In developing the cost estimates, only the total costs of the times and distances along the minimum paths between the garages and the pull-outs and pull-ins, respectively, are of concern. Thus, instead of dealing with miles or minutes of distance, the costing operation deals with dollars of distance, along the minimum-cost paths.

For example, the following costs were generated for the deadheading legs:

Garage to Point	Cost ($)
A to C	4
A to D	8
A to E	16
B to C	17
B to D	10
B to E	2

These costs were fabricated for this example, but they are indicative of actual estimated costs based on the MTC 1976 labor cost of 19¢/min and bus operating cost of 66¢/mile.

The nonrevenue transportation costs of blocks 1, 2, and 3 of route 1 are given in Table 1. The costs of blocks 1 and 2 are the sums of their deadheading-cost paths; however, the cost of block 3 is a little more difficult to calculate. Block 3 has three reliefs and, because a relief can be provided through the transit network from garage A, relief from garage A incurs no cost. There is no transit link between garage B and route 1. If block 3 were to come from garage B, relief would have to be provided by making three round trips to point E at a cost of $2/one-way trip or $12 for all three round trips. Therefore, a cost of $12 is assigned to block 3 coming from garage B, which makes it less costly to assign the block to garage A.

Spread Time

Any possible spread-time-penalty saving is usually attributable to servicing commuter runs from a suburban location. To determine the sensitivity of location to spread-time penalties, all commuter runs are assumed to bear such penalties. The totals for nonrevenue transportation costs are recalculated, and a comparison can be made to determine how important potential spread-time penalties are in relation to other costs.

Figure 1. Garage layout: route 1.

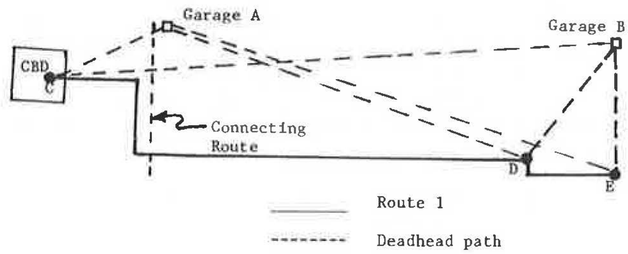

Table 1. Total nonrevenue transportation costs.

Garage	Block	Cost ($) Pull-Out	Pull-In	Relief	Total
A	1	16	4	0	20
	2	8	4	0	12
	3	16	4	0	20
B	1	2	17	0	19
	2	10	17	0	27
	3	2	17	12	31

Figure 2. Garage layout: route 13.

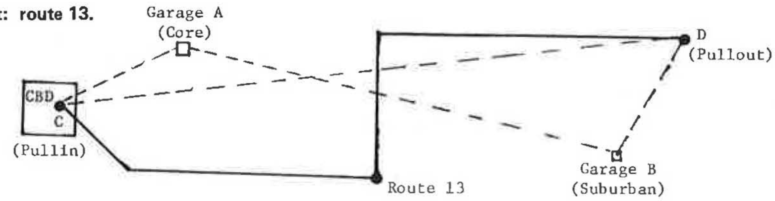

Table 2. Nonrevenue transportation costs with and without spread-time penalties.

Garage	Spread-Time Condition	Cost ($) Pull-Out	Pull-In	Relief	Total
A	With	21	4	0	25
	Without	18	4	0	22
B	With	10	14	0	24
	Without	9	14	0	23

An example (similar to the previous example but for a different route) is shown in Figure 2 to illustrate the checking of the sensitivity of costs to spread-time penalties. Spread-time penalties are assumed only on morning pull-outs and evening pull-ins; if one uses the MTC labor costs as an example, this increases labor costs from 19¢/min to 25¢/min on potential penalty legs. The deadheading costs corresponding to these two labor costs for the example shown in Figure 2 are given below:

Garage to Point	Deadheading Cost ($) At 19¢/min Labor Cost	At 25¢/min Labor Cost
A to C	4	5
A to D	18	21
B to C	14	16
B to D	9	10

Only one (morning) block of route 13 without a relief is necessary to illustrate how spread time is accounted for. Table 2 gives two nonrevenue transportation cost totals, one using straight-time labor costs and the other using spread-time labor penalties on the pull-out leg.

Based on straight time, the least-cost garage for the block in the example would be garage A, the core city site. If the block does bear a spread-time penalty, it should be assigned to the garage of least cost, garage B at the suburban site. It should be noted that, for every morning commuter block of this nature, there is a mirror-image evening commuter block that should also be assigned to the suburban site.

If the analyst is unsure whether this particular block will bear a spread-time penalty, to be conservative it can be assumed that the block will bear a spread-time penalty. Thus, the least-cost origin for the example is assumed to be the suburban site. However, when the total nonrevenue transportation cost is summed, the spread-time penalty should not be included. In the average MTC labor-cost figure, an average quantity of spread-time penalties was included and it should not be counted again. Therefore, spread-time penalties are only brought into the analysis to help in determining the least-cost block assignment to a garage.

The example shown here is the exception rather than the rule. Deadheading costs are the sum of travel-distance (66¢/mile) and time costs. The additional 6¢/min for spread-time penalties will generally have an insignificant effect on total nonrevenue transportation costs and on the final assignments of blocks to garages.

Distance and Time Cost

For all metropolitan planning areas, there exists a computerized highway network that is coded with average velocities and lengths of highway links. The mileage cost (66¢/mile) and the labor cost (19¢/mile) are applied to the highway network, and the Federal Highway Administration and Urban Mass Transportation Administration (UMTA) network programs will determine the minimum-cost paths and accumulate the costs from every network centroid to every other centroid. Centroids can be moved or created so that they are approximately located at every pull-in and pull-out point and at every possible garage location. In this way, one can determine the costs of traveling from every pull-in and pull-out point along the minimum-cost path to every existing or prospective garage point. The advantage of this methodology is that the transportation costs are not proxy measures but rather are the actual measured costs from every point of interest to every other point of interest. By using the distance and time costs derived from the computerized highway network, one can estimate the total actual nonrevenue transportation costs to serve all blocks from all garages.

Optimization

The objective of the optimization is to use estimates of garage capital and operating costs and nonrevenue transportation cost to select a garage scheme (including existing and proposed facilities) that minimizes the total cost. This is known as a location-allocation problem. The optimization must search through the feasible combinations of decision variables and select the combination that minimizes the system cost variables. There are three decision variables: (a) the size of each garage, (b) the location of each garage, and (c) the number of garages in the system. The optimization must minimize the following three system variables: (a) construction costs for all new facilities, (b) nonrevenue transportation costs, and (c) operating costs for the facilities.

The optimization problem is to

$$\text{Minimize total cost} = \sum_{j=1}^{m} \sum_{i=1}^{k} T_{ij}(n_{ij}) + \sum_{i=1}^{k} O_i(n_i) + \sum_{i=1}^{k} C_i(n_i) \qquad (8)$$

subject to

$$\sum_{i=1}^{k} n_i = N,$$

$$\sum_{i=1}^{m} n_{ij} = n_i, \text{ and}$$

$$n_i \geq 0,$$

where

m = total number of blocks assigned to garage i;

k = total number of garages;
j = pull-out/pull-in paired points of each block going to garage i;
T_{ij} = total matrix of nonrevenue transportation costs from pull-out/pull-in paired points j to garage i;
n_i = number of blocks allocated to garage i, $i = 1,...,k$;
$O_i(n_i)$ = operating costs of garage i as a function of its size n_i (the number of blocks is converted to the quantity of buses needed to serve n_i blocks);
$C_i(n_i)$ = construction cost of garage i as a function of its size n_i (the number of blocks is converted to the quantity of buses needed to serve n_i blocks); and
N = total number of blocks assigned to all garages.

CASE STUDY

A case-study example has been developed by using the assumption that the number, size, and location of garages that minimize nonrevenue transportation costs also minimize total cost related to the number, size, and location of garages in the garaging scheme. It is recognized that this simplistic assumption disregards the effects of operating and

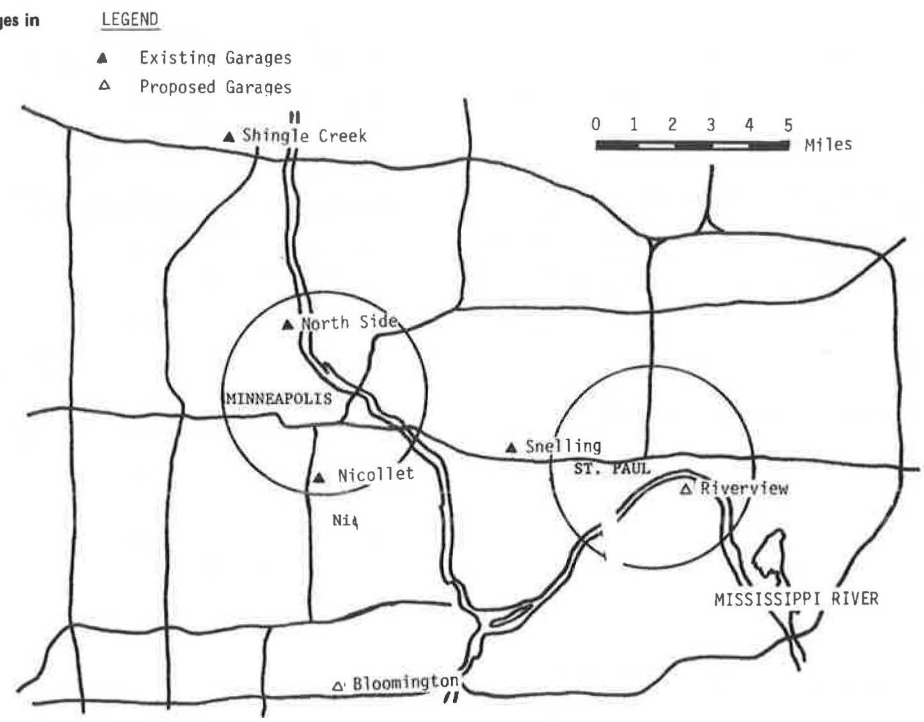

Figure 3. Location of bus garages in Minneapolis-St. Paul area.

Table 3. Garage-related annual MTC system costs for alternative scenarios.

Garage	Peak Demand (no. of vehicles)	Capacity (no. of vehicles)	Cost ($) Construction	Operating	Transportation
Existing MTC System					
Snelling	229	250	-	1 045 933	1 480 740
Nicollet	243	270	-	1 103 834	1 626 900
North Side	261	300	-	1 190 653	1 260 630
Shingle Creek	146	150	-	801 509	1 160 870
Total	879			4 141 929	5 529 140
Planned MTC System					
Bloomington[a]	165	200	283 824	899 245	1 472 620
Nicollet	243	270	-	1 103 834	1 421 580
Shingle Creek[b]	242	300	213 955	1 103 834	1 824 680
Snelling	229	250	-	1 045 955	1 480 740
Total	879		497 779	4 152 868	6 199 620
Recommended System					
Nicollet	243	270	-	1 103 834	1 626 900
North Side	261	300	-	1 190 653	1 243 230
Shingle Creek	116	150	-	703 774	986 870
Snelling	113	150	-	703 744	355 830
Riverview[a]	146		283 824	703 774	672 800
Total	879		283 824	4 405 809	4 885 630

Note: Amounts in 1976 dollars.
[a]New. [b]Expanded.

Table 4. Garage-related system costs for MTC projected 1985 transit network.

Garage	Peak Demand (no. of vehicles)	Capacity (no. of vehicles)	Cost ($) Construction	Operating	Transportation
Planned MTC System (as of 1976)					
Bloomington[a]	270	300	372 716	1 190 653	2 855 920
Nicollet	243	270	-	1 103 834	1 531 490
Shingle Creek	242	270	213 955	1 103 834	2 027 970
Snelling	144	175	-	801 509	604 650
Riverview[a]	202	225	304 766	972 600	1 233 080
Total	1101		891 437	5 172 430	8 253 110
Recommended System					
Northside	261	300	-	1 190 653	1 350 750
Bloomington[a]	122	150	283 824	703 774	1 075 320
Nicollet	243	270	-	1 103 834	1 456 090
Shingle Creek	129	150	-	703 774	1 052 110
Snelling	144	175	0	801 509	609 950
Riverview[a]	202	225	304 766	972 600	1 233 080
Total	1101		588 590	5 476 144	6 777 300

Note: Amounts in 1976 dollars.

[a]New.

capital costs on the size, location, and number decision. However, this case study is meant to show the importance of having accurate information on costs related to garage number, size, and location.

Based on the above assumption, blocks are assigned to the garage that has the least nonrevenue transportation cost. Once all blocks are assigned a garage, the size of the garage necessary to serve all assigned blocks is determined. Then the three system cost components for each facility can be totaled and the total cost of the scheme determined. The same process is repeated for garage schemes with varied numbers of garages and at different locations. The results of various iterations of the process are compared, and the minimum-total-cost garage scheme is selected.

This demonstration is intended to show some of the possible payoffs of using the proposed technique (9). This application is quite limited in that it only examines the few sites the transit operator has subjectively selected and is in no way an exhaustive search of all possible sizes and locations of fixed facilities. This by no means serves as a plan for the operator's fixed-facility improvements and is only a demonstration.

The MTC operated three older bus garages--North Side, Snelling, and Nicollet--and a new facility at Shingle Creek (see Figure 3). The MTC had developed a facility expansion program that can be summarized as follows:

1. Increasing the capacity at Shingle Creek to 300 vehicles,
2. Building a 200-vehicle facility in Bloomington that would be increased to 300-vehicle capacity in the future,
3. Phasing out the North Side site, and
4. Building a garage in St. Paul at Riverview in the future.

The first step in the demonstration was to estimate the nonrevenue transportation costs of serving all bus assignments from all existing garages (Snelling, North Side, Shingle Creek, and Nicollet) and all proposed garage sites (Riverview and Bloomington). Nonrevenue transportation costs were calculated in the manner specified earlier. Estimates of operating and construction costs for garages of various sizes were taken from a 1975 MTC study (1). Different cost elements are presented in Table 3 for three alternative scenarios: (a) the existing MTC fixed facilities, (b) MTC's planned facilities, and (c) the recommended facility locations and sizes that resulted from this demonstration. Table 3 indicates that, based on the 1976 system, the MTC plan would cost approximately $1.18 million/year more than the existing garage system and $1.27 million/year more than the recommended system.

Table 4 gives costs of the proposed 1985 system under two scenarios: (a) MTC's planned facilities and (b) the recommended facility sizes and locations that resulted from this demonstration. A review of Table 4 shows that, based on the proposed 1985 transit network, the MTC plan would cost $1.48 million/year more than the recommended system.

In the analysis, a check of possible assignments of blocks to garages was made with respect to spread-time penalties. All blocks that could possibly have a spread-time penalty were assumed to bear one. As a result of this exercise, a total of 4 blocks out of well over 1500 were reassigned to a suburban location. Thus, in this case, spread time did not have a significant impact on the analysis.

This demonstration is limited to a few options and assumes that a garage number, size, and location scheme that minimizes nonrevenue transportation cost minimizes total costs. However, it is intended to show the significance of the costs that can be saved by using a simplified version of the proposed optimization.

CONCLUSIONS

The determination of the number, size, and location of bus-garage additions is a problem that must be treated with care, and the resulting choice should have an accurate and technically sound basis. Most of the currently used techniques do not use a comprehensive costs basis and, at the very least, they are founded on conceptually inaccurate assumptions. The survey of currently used methods presented in this paper clearly indicates that new methods need to be sought out.

This paper presents a method to be used to seek out a minimum-cost garage number, size, and location scheme from an exhaustive array of feasible combinations. As part of an UMTA-sponsored study at Wayne State University, we are currently in the process of developing a more comprehensive method for solving the garage location problem. The importance of the development of such a technique is portrayed in the MTC case study through the application of a simplified version of the technique. Further, the analysis shows that some of the less visible but recurring cost components (deadheading and relief costs) may significantly affect the total annual costs of a proposed garaging system. On the other hand, new construction costs, which may seem highly important during the earlier planning stage, may have marginal ramifications for total system costs when spread over the life of the project.

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Abridgment

Practical Methodology for Determining Dynamic Changes in Bus Travel Time

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Research undertaken to develop and examine two methods of treating bus travel time—(a) measurement and (b) processing and analysis for planning needs—is reported. These methods are intended mainly for the scheduler responsible for scheduling buses to trips so as to take into account any dynamic changes in bus travel time. The motivation for the research comes from the existing system at Egged (the Israel National Bus Carrier), which uses a single mean value for bus travel time (for a given bus line) for all days of the year. The method chosen for data collection on bus travel time is based on the use of the tachograph, which is currently an integral part of bus equipment. The tachograph allows for a current report on departure and arrival times of trips through the turn of a special knob by the driver. In comparison with other information systems being tested today, the tachograph is simple and inexpensive to use. The accumulated data on bus travel time are transferred by use of a statistical method to calculate means and standard deviations for three cross sections: daily, weekly, and seasonal. The criteria for the statistical method are that it be simple, flexible, systematic, and practical so that the outcome will be compatible with the objective of planning work schedules for buses.

Egged (the Israel National Bus Carrier) operates a widespread geographic network of about 4000 lines. These lines are urban, suburban, regional, and intercity, with a vehicle fleet size of more than 5000 buses covering an average of 54 000 daily trips. The planning process for such a vast number of daily trips is clearly a complex and challenging undertaking.

One of the more crucial input elements in the planning process is bus travel time (BTT). This element depends on trip time (hour, day, week, season), number of passengers, and the habits of each individual driver. This paper describes a method implemented for Egged on how to measure and consider BTT, particularly from a practical viewpoint. Before demonstrating this method, however, let us represent the general planning process of a large-scale bus company and indicate how travel time affects this process.

The planning process is composed of five major components: (a) planning bus stops, (b) planning bus routes, (c) setting timetables, (d) scheduling buses to trips, and (e) assigning drivers. Since interrelations exist among the five components, it is desirable to analyze them simultaneously. If so, BTT would influence the whole planning process. However, the complexity of the system induces separate treatment for each component, a process in