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Measuring Cost Variability in Provision of Transit Service

Brian D. Taylor, Mark Garrett, and Hiroyuki Iseki

**The cost of producing public-transit service is not uniform but varies by
trip type (e.g., local or express), trip length, time of travel, and direction
of travel, among other factors. However, the models employed by public-
transit operators to estimate costs typically do not account for this vari-
ation. The exclusion of cost variability in most transit-cost-allocation
models has long been noted in the literature, particularly with respect
to time-of-day variations in costs. This analysis addresses many of the
limitations of cost-allocation models typically used in practice by devel-
oping a set of models that account for marginal variations in vehicle-
passenger capacity, capital costs, and time-of-day costs. FY 1994 capital
and operating data are used for the Los Angeles Metropolitan Trans-
portation Authority (MTA). This analysis is unique in that it combines
a number of previously and separately proposed improvements to cost-
allocation models. In comparison with the model currently used by the
Los Angeles MTA, it was found that the models developed for this analy-
sis estimate (*a*) higher peak costs and off-peak costs, (*b*) significant cost
variation by mode, and (*c*) lower costs for incremental additions in
service. The focus is on the limitations of the rudimentary cost-allocation
models employed by most transit operators and not on the Los Angeles
MTA per se. This analysis found that an array of factors addressed
separately in the literature can be incorporated simultaneously and
practically into a usable cost-allocation model to provide transit sys-
tems with far better information about the highly variable costs of
producing service.**

Many transportation managers in the private sector might be sur-
prised to learn that their public-sector counterparts often have lim-
ited information on the costs of providing public-transit service.
Airlines and private shipping companies often develop highly
sophisticated models to estimate how the cost of carrying passen-
gers or freight varies by season, day of the week, time of day,
direction, and mode. In contrast, public-transit managers often
have only rudimentary information linking budgetary inputs to
service outputs. One might argue that, as publicly subsidized ser-
vices, transit systems need not be as concerned with such fine-
grained, cost-estimation detail as profit-driven, private businesses.
But the broad, social-policy objectives of public transit do not
obviate the need for good cost information to guide managers,
transit-policy boards, and funding agencies. For example, most
policy boards adopt fare structures without a clear understanding
of how the cost of service varies from passenger to passenger or
trip to trip. Similarly, in making decisions on adding or deleting
peak-period or off-peak service, transit managers and boards often
may have limited or incomplete information about the cost or savings
from such changes.

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Quite obviously, trips on public transit are not uniform; among
other factors, they vary by trip type, trip length, time of travel, and
direction of travel. Likewise, the services deployed by transit oper-
ators to serve these trips—paratransit vans, buses, rail operating as
demand response, local service, or express service—vary signifi-
cantly. The cost of operating these modes and services obviously
varies, sometimes dramatically. Yet the techniques employed by
most public-transit operators to estimate these costs do not account
for this variability. In addition, they are not structured to distinguish
the estimation of overall costs from those at the margin.

A number of scholars over the years have raised concerns over the
limitations of transit-cost-estimation techniques used in practice.
These techniques use a variety of methods to relate the production
of transit service to costs. The most common approach uses models
that allocate budgetary line items to various measures of service out-
put, and most moderately sized and large transit systems use cost-
allocation models of one form or another (*1*). Such models can, for
example, aid management in tracking cost efficiency over time or in
estimating the costs or savings of changes in service (*2*). In a more
limited fashion, the models are used by policy makers and funding
agencies to make informed choices over the deployment of services
and allocation of funding (*3*). Over the years, a number of researchers
have suggested modifications to improve the models to account for
the variability of transit costs, particularly with respect to time-of-
day differences in costs. However, transit operators generally have
been slow to adopt such improvements into practice (*4*).

This gap between research on transit-cost-allocation models and
their application in practice is addressed by developing a set of
related models that account for marginal variations in capital costs,
vehicle capacity, and time-of-day costs. Capital and operating data
from the Los Angeles Metropolitan Transportation Authority (MTA)
were used. This analysis is unique in that it combines a number of
previously and separately suggested modifications to cost-allocation
models.

The results of the models developed for this analysis are com-
pared with those of the current Los Angeles MTA model, which is
typical of those used by U.S. transit operators. In this comparison,
the total systemwide costs of bus and rail are estimated separately.
The estimated variations in costs among individual bus lines then
are compared. Finally, the estimated costs of incremental additions
of bus service are compared in a sample of five lines. These com-
parisons clearly reveal substantial deviations in estimated modal and
time-of-day costs between the models developed for this analysis
and the standard Los Angeles MTA model. This analysis also shows
that models developed here to account for variations in capital costs,
vehicle-passenger capacity, and time-of-day costs can be imple-
mented practically using data normally available to transit operators.
This produces a more fine-grained analysis to better inform decision
making.

OVERVIEW OF COST-ALLOCATION MODELS

Transit-cost-allocation models are based on the concept that the cost of supplying service is a function of the service produced, measured in terms of vehicle hours or seat miles of service. Transit costs include both operating costs and capital costs, though most cost-allocation models include only operating costs. These costs can be differentiated into variable, semifixed, and fixed costs (*2, 5–7*):

- Variable costs—costs directly linked with vehicle operations (e.g., driver wages and fringe benefits) and nondriver variable costs (e.g., fuel and vehicle maintenance);
- Semifixed costs—costs not directly linked to service changes but influenced by the level or pattern of service (e.g., rolling stock, revenue collection, and marketing); and
- Fixed costs—costs insensitive to marginal changes in service levels (e.g., shop-building maintenance, administrative costs, buildings and equipment, and other long-term fixed costs).

Vehicle hours and vehicle miles are two of the most common outputs used to measure unit costs. Most models use some combination of vehicle hours of operation and vehicle miles to account for costs such as labor, fuel, tires, and maintenance. For example, labor costs such as driver wages and fringe benefits, which constitute a large portion of operating costs, are typically assigned to vehicle hours. Costs of fuel, maintenance, and repairs are usually assigned to vehicle miles of operation. In addition, the peak number of vehicles in service may be included in the model to account for overhead items. These include administrative expenses, plant maintenance, and storage costs that generally do not vary either by vehicle hours or vehicle miles but are assumed to be more closely related to fleet size (*8*). Additional variables such as the number of revenue passengers or peak-period vehicle *pull-outs* (vehicles leaving the yard to begin revenue service) also can be added to the model (*8, 9*).

Combining the classification of direct-operation, direct-overhead, and indirect-overhead costs with the variables typically used in cost-allocation models produces a total of nine potential combinations, as shown in Figure 1. Some combinations, such as peak vehicles and variable costs, typically will not have expense items assigned to them, whereas others such as vehicle hours and fixed-overhead costs may or may not have an expense assigned to them, depending on the particular costs estimated by the model.

To calibrate a model, systemwide expenses are estimated and assigned to one or more of the specified outputs that are considered most closely related to those costs. After each individual expense item is assigned, a coefficient representing the unit-cost rate for each variable unit-of-service output is determined by summing the expenses in each category and dividing by the respective level-of-service output. To determine the cost of a service change, these cost rates are simply multiplied by the expected net change in each respective output quantity and then summed. The method is easy to

understand and can be calibrated and applied using data normally collected by transit operators. The basic function can be expressed as follows (*10*):

$$C = \sum_{i=1}^{n} U_i * X_i \qquad (1)$$

where

C = estimated costs,
i = particular measurable service characteristic that represents the scale of operations,
n = number of service characteristics included in model,
U_i = unit cost of characteristic i, and
X_i = quantity or value of characteristic i in analysis.

These models commonly take two forms. *Partially allocated models* generally include only variable costs and some semifixed costs and are used to estimate the costs of marginal or incremental service changes (*1, 11*). *Fully allocated models* include variable and most or all fixed costs (though in practice they commonly exclude capital costs), and they are used mainly to compare performance between modes or systems. The sum of the individual route costs produced by a fully allocated model thus equals the total-system cost (*12*). The test of a good model—either partially allocated or fully allocated—is that it accurately links changes in service to changes in cost.

Unfortunately, the cost-allocation models used in practice are often a hybrid of partially and fully allocated models. By including some semifixed and fixed costs, such models tend to overestimate the costs or savings associated with small changes in service (*7, 9, 13, 14*). On the other hand, by excluding most capital costs (land, vehicles, buildings, etc.), they significantly underestimate the full cost of transit service because, in the long run, all expense items can be considered variable and are appropriately included in the model. A robust cost-allocation model thus segregates expenses into variable, semifixed, and fixed costs, and it considers only those costs that vary with service outputs over the scope and scale of the analysis. Cherwony et al. (*12*) have termed this dynamic approach to cost-allocation modeling *fixed-variable analysis*.

Exclusion of Capital Costs from Fixed-Cost Calculations

The cost-allocation models used in practice typically do not account for the cost of capital (vehicles, equipment, etc.). A few previous studies have noted this omission and have included capital costs to compare productivity between different bus systems (*15*) or between different modes (*11*). One explanation for the exclusion of capital expenses in most cost-allocation models is that transit operations in the United States usually are funded primarily through

	Variable Costs	Semi-fixed Costs	Fixed Costs
Vehicle hours	Strong	Strong	Moderate
Vehicle miles	Strong	Moderate	Weak
Peak vehicles	Weak	Strong	Strong

FIGURE 1   Relationships between cost inputs and service outputs [after Taylor (*6*)].

fare-box revenues and local subsidies, whereas capital costs are more often funded by state and, especially, federal subsidies that are more likely to be considered off-budget by transit operators. From the perspective of the taxpayer, of course, such distinctions are not especially meaningful. Given the current policy emphasis on multimodal transit service, including capital costs is especially important because the combination of capital and operating costs can vary substantially across alternative modes. In addition, the omission of capital costs also can be a problem when the costs of publicly operated and privately contracted transit services are compared (*16*).

Modal Variations in Passenger Capacity

In comparing system performance among different modes, operators do not normally consider differences in vehicle-passenger capacity among various transit modes (*11*). In other words, a vehicle hour of transit service is not directly comparable among paratransit, bus, and rail. Failure to account for vehicle capacity can bias modal comparisons against higher-vehicle-capacity modes like rail.

Problem of Peaking

As early as the 1920s, the growth of automobile ownership and usage began to erode the use of transit for off-peak travel. Today the automobile dominates metropolitan travel, and transit plays a subordinate role in all but the centers of the oldest, largest American cities. In particular, transit agencies have lost most weekend, evening, and counterdirection traffic, resulting in an increasing temporal and directional concentration of transit demand (*17, 18*). Studies clearly have shown that it costs significantly more per unit of output to provide service in the peak periods than in the off-peak (*7, 8, 19–21*). In practice, however, transit-policy-board members rarely consider the costs of peaking on transit service.

Public transit is a highly labor-intensive industry. Costs related to labor represent the largest proportion of operating costs. The cost of labor, though, can vary significantly throughout the day. Labor contracts often limit or prohibit part-time labor and limit split and spread-time shifts, resulting in underutilization of the workforce and thereby lowering labor efficiency (*17, 18, 22*). Although many of these excess-wage expenditures occur during off-peak periods, a reasonable argument can be made for attributing them to the peak because they would not be incurred but for peak service levels (*15*).

Moreover, during peak periods, many vehicles carry passengers predominantly or exclusively in one direction, resulting in less efficient utilization of equipment. High peak-hour service demands increase fleet costs associated with purchasing and maintaining additional vehicles needed only for peak service (*22, 23*). In addition, peak-period-only service runs proportionally increase the costs of deadheading vehicles to and from storage yards. Because fixed costs are generally scaled to peak-level service, average unit-cost models that are temporally insensitive may not capture actual cost differences in which different routes have similar peak vehicle requirements but different off-peak requirements (*24*).

In a survey of 30 transit agencies, Cohen et al. (*4*) found that none used cost-allocation models that distinguished between the cost of providing service by time of day or day of week. Also, the survey revealed that transit officials recognize deficiencies in their cost-allocation procedures but that operators continue to use simple cost-estimation methods, even though more sophisticated techniques are available.

Other Limitations

Regardless of the number of added refinements, however, there are limitations inherent to all cost-allocation models. For example, there is little agreement in the literature about which output measures best reflect changes in cost (*11, 13, 25*). Some cost items might be related to more than one measure (*7*). The various output measures used, such as vehicle hours and vehicle miles, are not independent but in fact are highly correlated (*7, 9*). Finally, because these models are usually based on systemwide costs, they do not fully account for cost variations on individual routes (*8*).

COMPREHENSIVE COST-ALLOCATION MODEL

Data collected by the Los Angeles MTA for the 1994 fiscal year are used. Contrary to the popular perception of Los Angeles as the most automobile-dominated metropolitan area in the United States, the Los Angeles MTA is the second-largest public-transit system in the country in unlinked passenger trips. The Los Angeles MTA operates 131 bus and 3 rail lines serving 391 million passengers annually. Although the Los Angeles MTA cost-allocation model has been modified and improved over the years, it is typical of most models used in practice in that it does not account for variations in capital costs, vehicle-passenger capacity, or time of day. The Los Angeles MTA model relates operating costs to vehicle hours, vehicle miles, peak vehicles, and the number of passenger boardings (*10*), as follows:

$$OC_j = \left(U_{VH} * VH_j + U_{VM} * VM_j + U_{PV} * PV_j + U_{TP} * TP_j \right)$$
$$* (1 + F) \tag{2}$$

where

OC = estimated operating costs,
j = unit of analysis in question (system, line, etc.),
U = unit cost per service output,
VH = scheduled vehicle hours,
VM = scheduled vehicle miles,
PV = p.m.-peak vehicles,
TP = total passengers, and
F = fixed-overhead cost factor.

This model allocates costs for labor to scheduled vehicle hours (e.g., fuel, maintenance, and repair equipment to scheduled vehicle miles), fixed nonmaintenance labor and administration costs to peak vehicles, and overhead costs (e.g., customer service and ticket sales) to passenger boardings. Also, the model includes a constant multiplier to allocate indirect expenditures (e.g., data collection, planning, and management) to each line based on their share of overall operating costs. The formula is calibrated for each fiscal year based on total annual operating costs.

Accounting for Variability of Service and Costs

Several studies have proposed modifications to account for the effects of peaking. These temporal-variation models typically provide separate cost estimates for two periods—the peak period and the off-peak or base period. Most suggested approaches to allocating variable costs apply different unit-cost factors to the peak and off-peak periods. Studies of semifixed operating and capital-cost allocation generally allocate a higher percentage (or all) of these
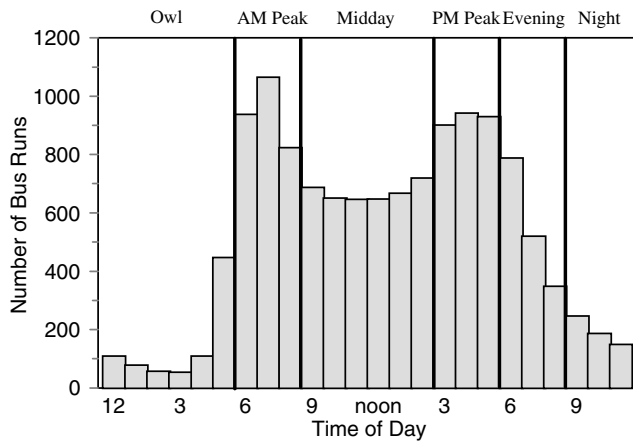
FIGURE 2   Time-of-day variations in service levels for Los Angeles MTA.

costs to the peaks. In this research, both operating and capital costs are combined, and service is disaggregated into multiple time periods to better reflect the changes in transit demand and service throughout the day.

Figure 2 shows the number of Los Angeles MTA service runs occurring in a typical 24-h period. Based on this service profile, the service day can be divided into six periods—owl (12:00 to 6:00 a.m.), a.m. peak (6:00 to 9:00 a.m.), midday (9:00 a.m. to 3:00 p.m.), p.m. peak (3:00 to 6:00 p.m.), evening (6:00 to 9:00 p.m.), and night (9:00 p.m. to 12:00 a.m.). To determine operating costs during these six service periods, appropriate values were substituted for vehicle hours, miles, and passenger boardings, as shown in Figure 3, which diagrammatically illustrates the variation in service and costs during a 16-h portion of a typical weekday. Whereas the initial service-

cost calculations were made for all six periods (to more accurately capture the temporal variability of service), for simplicity the total costs for three periods were aggregated—*base* (night plus owl), *shoulder* (midday plus evening), and *peak* (a.m. peak plus p.m. peak). In comparison with the two-period peak-base models proposed by others, the time periods used in this analysis better reflect the service profiles of most U.S. transit operators.

Adjustment of Operating Costs Associated with Vehicle Hours

A review of the literature suggests that the unit costs of service should be adjusted to reflect variations in labor productivity and vehicle usage throughout the day. Three methods have been proposed by others to allocate variable costs by time of day. The statistical approach regresses operating-cost data from different run types at different times of day to estimate peak and off-peak costs (*26*). A second, the resource-based approach, modifies output-quantity estimates by time of day and day of week based on changes in the number of pay hours and vehicles required by various service runs (*12*). A third method, the cost adjustment approach, and the one applied here calculates separate coefficients for costs associated with different service outputs for each time period. In allocating costs to the different time periods, costs that vary by service level at different times of day are distinguished from those costs that are generally invariant with respect to time.

Accounting for Labor Utilization

To account for time-of-day differences in labor utilization, the vehicle-hours factor is multiplied by a labor-utilization factor derived for each period and representing the relative share of the ratio of pay
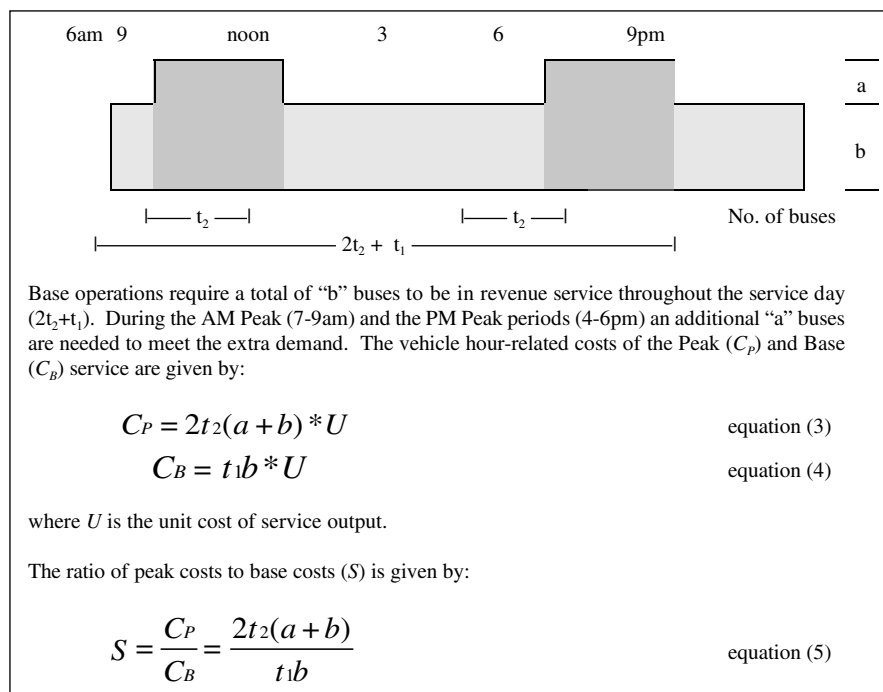

Base operations require a total of "b" buses to be in revenue service throughout the service day $(2t_2+t_1)$. During the AM Peak (7-9am) and the PM Peak periods (4-6pm) an additional "a" buses are needed to meet the extra demand. The vehicle hour-related costs of the Peak (C_P) and Base (C_B) service are given by:

$$C_P = 2t_2(a+b)*U \qquad \text{equation (3)}$$

$$C_B = t_1b*U \qquad \text{equation (4)}$$

where U is the unit cost of service output.

The ratio of peak costs to base costs (S) is given by:

$$S = \frac{C_P}{C_B} = \frac{2t_2(a+b)}{t_1b} \qquad \text{equation (5)}$$

FIGURE 3   Average cost approach to allocating costs by service levels [after Cervero (*15*)].

hours to scheduled vehicle hours. The basic form of the model is given by Yu (*27*):

$$LUF_i = \left(\frac{PH_i}{VH_i}\right)\frac{\sum_i VH_i}{\sum_i PH_i} \tag{6}$$

where

LUF_i = labor-utilization factor for period i,
PH_i = pay hours for period i, and
VH_i = vehicle hours for period i.

Cherwony and Mundle (*19, 28*) developed a peak-base model based on this approach to compute separate vehicle-hour unit-cost estimates for the peak and base periods. Vehicle-hour coefficients are adjusted to account for the relatively higher proportion of pay hours during peak operations based on the relative productivity of labor (*n*), which is a ratio of pay hours to vehicle hours in the peak and off-peak, and the service index (*s*), which compares vehicle hours by time of day (Equations 7 and 8 can be derived directly from Equation 6):

$$U_{PVH} = LUF_P * U_{VH} = \frac{n(1+s)}{(1+ns)} * U_{VH} \tag{7}$$

$$U_{BVH} = LUF_B * U_{VH} = \frac{(1+s)}{(1+ns)} * U_{VH} \tag{8}$$

where

$0 < LUF_B < 1 < LUF_P$,
U_{PVH} = vehicle-hour unit-cost estimate for peak,
U_{BVH} = vehicle-hour unit-cost estimate for base,
n = relative labor productivity [$= (PH_P/VH_P)/(PH_B/VH_B)$],
s = vehicle-hour coefficient [$= (VH_P/VH_B)$],
$PH_{P \text{ or } B}$ = pay hours for peak or base period, and
$VH_{P \text{ or } B}$ = vehicle hours for peak or base period.

Studies by Kemp et al. (*7*), Cervero (*8, 15*), Charles River Associates (*20*), and Parody et al. (*21*) used this method to modify vehicle-hour unit costs between the base and peak periods. Charles River Associates and Parody et al. used a constant value, 1.20, as an estimate of relative labor productivity for bus systems based on a survey of prior studies (the sample values ranged from 1.09 to 1.337). Cervero also apportioned operating expenses between peak and off-peak time periods on the basis of a sample of individual bus lines for the precursor agency of the Los Angeles MTA. Pay hours were assigned to the base or the peak using *attribution rules* developed with agency staff based on a determination of whether the pay hours were caused by demands in the peak, in the base, or both. These time-period adjustments resulted in a 30.2 percent difference in relative labor productivity (*n*) and a 28.3 percent difference in vehicle-hour coefficients (*s*) between the peak and base period for the system (there were 39.3 percent more pay hours than vehicle hours in the peak and 7 percent more in the base) (*15*). Because labor costs account for more than half of total operating costs, these differences in vehicle-hour unit costs are not trivial. Given variations in available operating data from system to system, a number of other methods to account for time-of-day differences in labor utilization have been proposed over the years (*4, 29, 30*).

Using a method similar to the peak-base model discussed earlier, the vehicle-hour coefficients in the Los Angeles MTA model were adjusted to reflect the variation in peak and off-peak labor costs. Data were not available on the ratio of pay hours to vehicle hours by time of day for the study period, so Cervero's (*15*) average labor-productivity factor and data on the peak-to-base ratio of vehicle hours for each bus line (*s*) were used to calculate peak and off-peak (base plus shoulder) unit costs for each line using Equations 6 and 7. For the off-peak, the sum of vehicle hours in the midday, evening, night, and owl periods was used. For the peak period, vehicle hours in the a.m. and p.m. peak periods were used.

Accounting for Vehicle Utilization

Nearly all transit vehicles deadhead to and from storage facilities or maintenance yards at the start and conclusion of revenue service. For vehicles operated in peak-period-only service, the ratio of out-of-service vehicle miles to in-service vehicle miles is greater than for vehicles in revenue service for longer periods. In other words, vehicle utilization is in general lower during peak periods than during off-peak periods. To account for this time-of-day variation in vehicle utilization, costs were allocated on the basis of total (or scheduled) vehicle miles, but in-service vehicle miles and hours were used to develop the unit-cost measures. Doing so, in effect, applied a vehicle-utilization factor comparable with the labor-utilization factor described earlier.

Including Fixed and Semifixed Costs

For fixed costs that do not vary by unit-of-service output, a different method is needed to allocate costs to each time period. Charles River Associates (*20*) and Parody et al. (*21*) reviewed studies that examined capital-cost allocation to the peak and off-peak periods, classifying the prior studies into two groups—(*a*) those in which all capital costs were assigned to the peak on the assumption that these resources would not be needed but for the peak-period demand (*6, 19, 30–32*), and (*b*) those in which capital costs were apportioned by the relative usage between the peak and the off-peak on the assumption that operators would supply some level of service even without peak service (*8, 15, 20, 33–36*). Acknowledging this split in the literature, Charles River Associates (*37*) used a peak to off-peak factor of 85 percent for subway and commuter-rail capital expenses and 80 percent for bus capital expenses. Similarly, Cervero (*15*) used a ratio of 85/15 between the peak and base, respectively, to attribute some of the depreciation of buses to off-peak usage and allocated noncapital overhead costs, as shown in Figure 4.

In a more refined application of the principles shown in Figure 4, the Bradford Bus Study (*34*) allocated overhead costs—including vehicle-facility costs, nonmaintenance and administrative labor costs, and other overhead costs—according to the number of vehicles in service for the whole system during each time period. This method assumes that all buses in service during the period with the smallest number of in-service vehicles will be used in any other periods that have higher vehicle requirements. From the number of incremental vehicles and vehicle operating hours, the fixed costs to provide service over the whole system can be calculated for each period. These costs then can be further disaggregated to individual lines (within each time period) by the relative number of buses for each line (*34*).

The Bradford Bus Study method was used to allocate fixed operating, vehicle capital, and nonvehicle capital costs to individual lines by time period. For the allocation of vehicle capital costs, Figure 5 shows
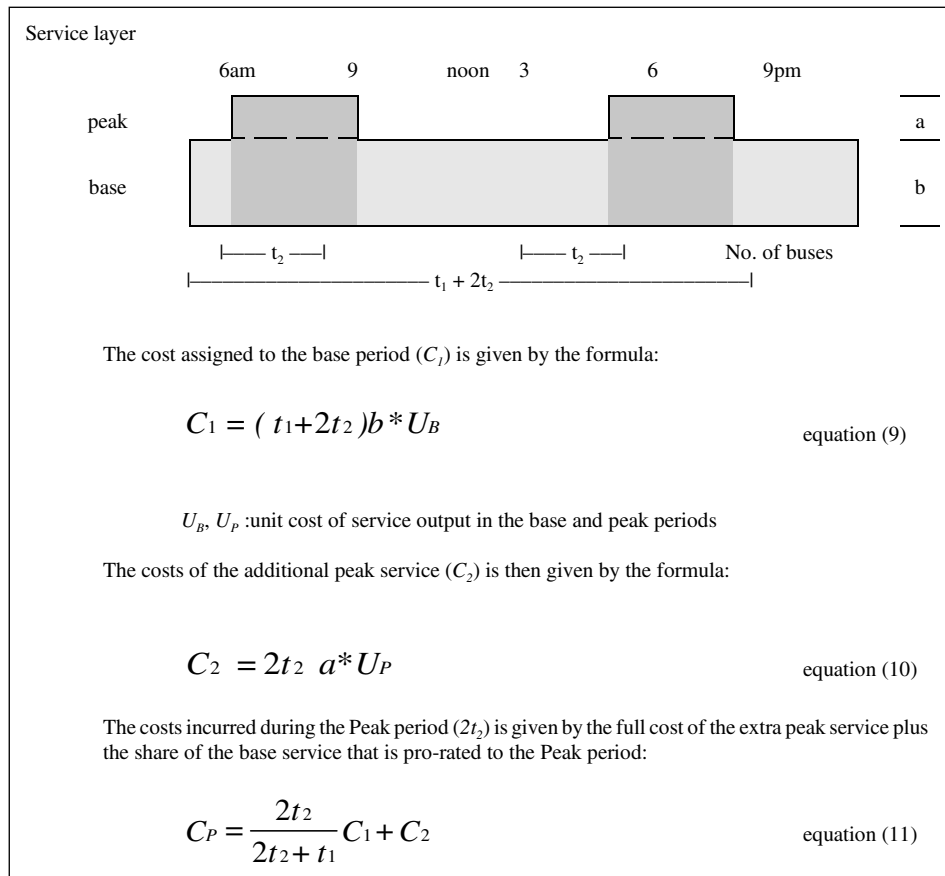
Service layer

The cost assigned to the base period (C_1) is given by the formula:

$$C_1 = (t_1 + 2t_2)b * U_B \qquad \text{equation (9)}$$

U_B, U_P :unit cost of service output in the base and peak periods

The costs of the additional peak service (C_2) is then given by the formula:

$$C_2 = 2t_2 \ a * U_P \qquad \text{equation (10)}$$

The costs incurred during the Peak period ($2t_2$) is given by the full cost of the extra peak service plus the share of the base service that is pro-rated to the Peak period:

$$C_P = \frac{2t_2}{2t_2 + t_1} C_1 + C_2 \qquad \text{equation (11)}$$

FIGURE 4   Marginal cost approach to allocating costs by service levels [after Cervero (*15*) and Levinson (*29*)].

a representation of the number of buses in service during each service period during a typical weekday and the apportionment of the total vehicle capital costs for the whole system to each time period for each service layer. The total number of buses required for each period is indicated in the column at the left. Owl service required 58 buses, night service required an additional 207 buses, evening service required another 638 buses, and so forth. Buses in the first service layer (I) operate 24 h/day. Thus, if a line has owl service, those buses

are assumed to be available for use the rest of the day, and therefore the capital costs of those vehicles are spread over all time periods. The share of capital costs needed to provide 1 h of service for the whole system in this layer can be obtained by dividing the daily capital cost of a bus ($94.14) by the number of required buses (58) divided by 24 h. Capital costs were annualized using generally accepted accounting principles. Space limitations do not permit a full description of these calculations, although the details are available from the authors.

FIGURE 5   Marginal cost approach to allocating vehicle capital costs for Los Angeles MTA.

Similarly, buses added for use in the shoulder period also are available for service during the peak period, and their capital costs are spread over the shoulder and peak periods. Buses assigned exclusively to the highest peak period (a.m. peak) operate only 3 h. The capital cost for 1 h of service exclusively during the a.m. peak period equals the daily capital cost of one bus times the number of buses in the top service layer (VI), 6, divided by 3 h of service. These hourly figures were multiplied by the number of hours in each service period to obtain the values shown in Figure 5. Costs for each service period are the sum of the figures in each of the columns. Similar assignments were made for the operating overhead costs assigned to peak vehicles. To account for the fact that some of these costs should be attributed to weekend service, the weekday totals were adjusted by a factor representing the relative shares of week-day and weekend service for each period. These values then were distributed to each individual line in proportion to the number of required vehicles on each line during that time period.

In contrast to the semifixed character of vehicle capital and oper-ating overhead costs, however, nonvehicle capital costs are likely unrelated to the peak nature of transit service. Thus, assigning such costs using the Bradford method would inappropriately increase costs assigned to the peak period. Therefore, nonvehicle capital costs were simply allocated to each time period based on the proportion of total in-service vehicle hours in each time period.

Allocation of Light-Rail Operating and Vehicle Capital Costs

Operating and capital costs of the Los Angeles MTA's light-rail transit (LRT) service were allocated in a similar fashion to that described for bus service. Because of data limitations, however, costs were allocated to each period using a three-variable cost-allocation model (vehicle hours, vehicle miles, and peak vehicles) instead of the four-variable model used for buses. In addition, data limitations also prevented the application of a labor-utilization factor to peak-period LRT costs.

Resulting Models

Using the modifications described in the preceding sections, three variants of the comprehensive cost-allocation model were devel-oped—a fully allocated model and two partially allocated models, defined as follows:

Fully allocated model:

$$FAC_{i,j} = OC_{i,j} + CC_{i,j}$$
$$= \left(LUF_{i,j} * U_{VH} * VH_{i,j} + U_{VM} * VM_{i,j} + PVC_{i,j} + U_{TP} * TP_{i,j}\right)$$
$$* (1 + F) + VCC_{i,j} + OCC * \left(IVH_{i,j}/IVH_{\text{day,system}}\right) \quad (12)$$

$$\left(LUF_{i,j} = 1, F = U_{TP} = 0 \text{ for LRT}\right)$$

Partially allocated model I:

$$PAC_{i,j} = OC_{i,j} + VCC_{i,j}$$
$$= \left(LUF_{i,j} * U_{VH} * VH_{i,j} + U_{VM} * VM_{i,j} + PVC_{i,j} + U_{TP} * TP_{i,j}\right)$$
$$* (1 + F) + VCC_{i,j} \quad (13)$$

Partially allocated model II:

$$PAC_{i,j} = OC_{i,j} + VCC_{i,j}$$
$$= \left(LUF_{i,j} * U_{VH} * VH_{i,j} + U_{VM} * VM_{i,j}\right) + VCC_{i,j} \quad (14)$$

where

  FAC = costs estimated by fully allocated model,
  PAC = costs estimated by partially allocated model,
     i = time of day (base, shoulder, and peak) or daily,
     j = unit of analysis in question (system, line, etc.),
   CC = estimated capital costs (vehicles, buildings, equipment, land, etc.),
  PVC = peak-vehicle cost estimated by modified model,
  VCC = vehicle capital costs,
  OCC = other capital costs,
  IVH = in-service vehicle hours,
   OC = estimated operating costs,
     U = unit cost per service output,
   VH = scheduled vehicle hours,
   VM = scheduled vehicle miles,
   PV = p.m.-peak vehicles,
   TP = total passengers, and
     F = fixed-overhead-cost factor.

FINDINGS

After a new cost-allocation model to account for variations in capi-tal costs, vehicle-passenger capacity, and time-of-day costs was developed, operating data compiled by the Los Angeles MTA were used to compare these three variations of this new model with the model currently used by the Los Angeles MTA. The fully allocated model was used to examine systemwide costs and to compare costs between the bus and LRT modes. The partially allocated models I and II were used to compare costs between bus lines within the Los Angeles MTA system and to estimate the cost of small service increases on five sample lines. The results of these comparisons reveal significant time-of-day variations in costs and even greater dif-ferences in costs between modes. Neither of these results is captured in the model currently used by the Los Angeles MTA nor by similar cost-allocation models used by most other public-transit systems.

Comparison of Fully Allocated Model with Typical Cost-Allocation Model

The time-of-day cost variations estimated are similar to those found by others in that the peak periods account for more than half of all costs (*15, 21, 29*). Figure 6 shows that the fully allocated model esti-mates the total cost of operating peak-period bus service in 1994 at $151.01 per in-service vehicle hour, which is 35.9 percent higher than the per-hour cost of $111.10 estimated by the Los Angeles MTA model. Figure 6 also shows that the fully allocated model estimates base-period costs to be $94.96 per in-service vehicle hour, or 14.5 per-cent below the Los Angeles MTA model estimate. It is important to note that these base-period costs are estimated to be lower than those of the Los Angeles MTA model, despite the inclusion of annualized vehicle and nonvehicle capital costs.

Overall, the systemwide bus costs estimated by the fully allocated model vary by $56.05 per in-service vehicle hour, or 59 percent
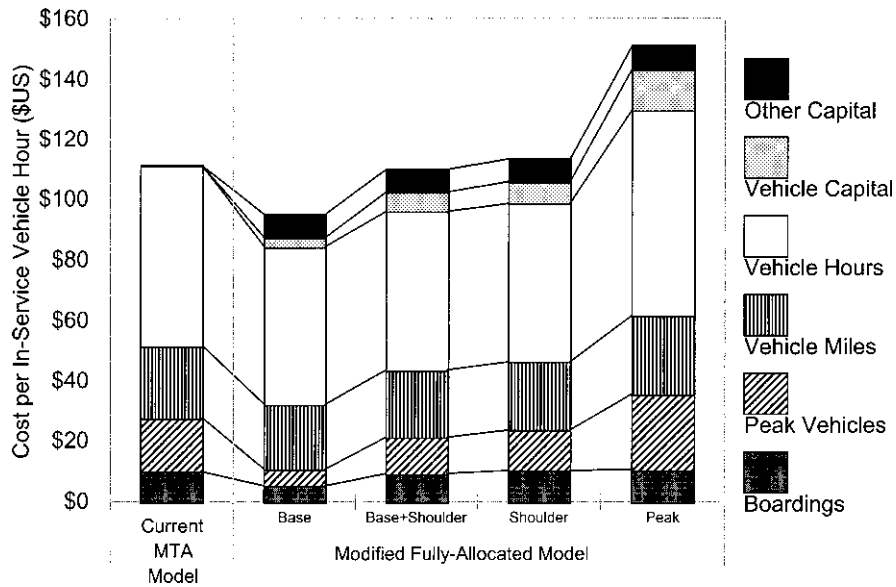
FIGURE 6   Comparison of estimated systemwide costs between Los Angeles MTA model
and fully allocated model.

between the base and peak periods. This substantial difference in peak- and base-period costs is all the more remarkable given that the Los Angeles MTA has the third-lowest peak-to-base vehicle ratio of any major U.S. transit operator (Figure 7). The relatively large peak-to-base cost differential estimated for a transit operator with a very low peak-to-base vehicle ratio suggests that the inclusion of time-of-day cost estimates in the cost-allocation models used by other U.S. transit systems would produce time-of-day cost differentials even greater than those observed here.

The fully allocated systemwide bus costs described earlier then were compared with similar cost data for the one Los Angeles MTA LRT line in operation at the time that these data were collected. This comparison, summarized in Figure 8, shows that considering (*a*) the annualized vehicle and nonvehicle capital costs, (*b*) the higher seat-

ing capacity of LRT vis-à-vis bus, and (*c*) the time-of-day cost differentials, the cost per seat hour of service is substantially higher on LRT. This is due mostly, though not entirely, to the much higher annualized nonvehicle capital costs. Buses operate on streets and highways paid for largely by others—property owners (via property taxes) and private vehicle operators (via motor-fuel taxes). For the LRT line, in contrast, the costs of right-of-way, track, catenary, and stations were paid for by the transit operator. These costs, when annualized using generally accepted accounting principles, make up 49.1 percent of fully allocated costs per seat hour of LRT service. Other LRT unit costs are higher than bus costs as well because of higher per-seat vehicle capital costs and higher per-seat expenditures by the Los Angeles MTA on LRT operations, such as those for security.
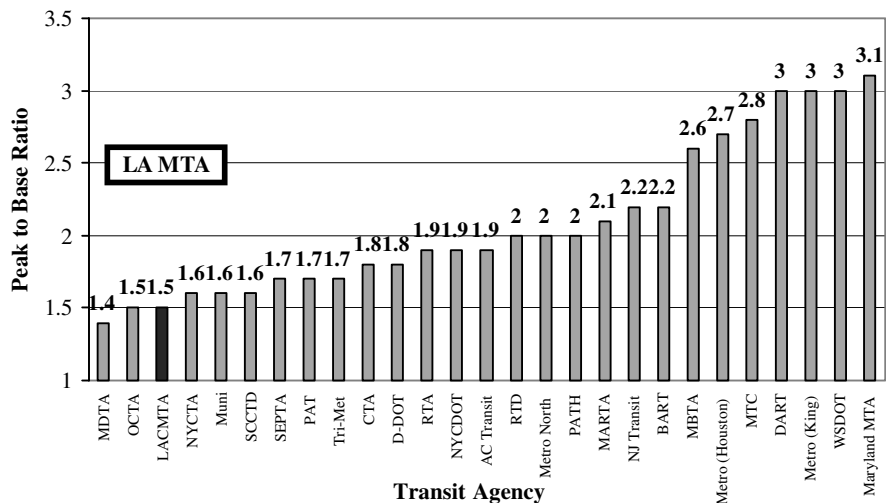

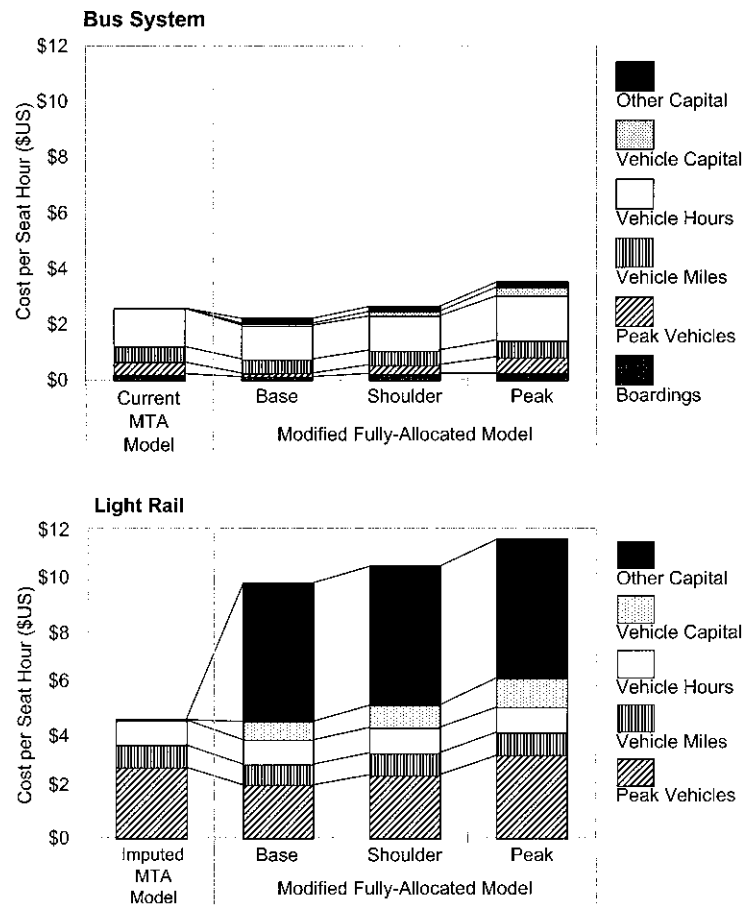FIGURE 7   Peak-to-base ratios of 27 largest transit operators.

FIGURE 8   Comparisons of estimated bus-system and LRT costs using Los Angeles MTA model and fully allocated model.

Comparison of Partially Allocated Models with Typical Cost-Allocation Model

As noted in the opening discussion of fully and partially allocated models, marginal or incremental additions or deletions of service most appropriately are evaluated using partially allocated models. Such models include only variable operating and vehicle capital costs (e.g., driver compensation, fuel, and vehicles) that vary with incremental changes in service, but they exclude most fixed and semifixed costs (e.g., facilities, planning, and administration) that do not vary. Accordingly, partially allocated model I excludes nonvehicle capital costs but includes all semifixed and variable costs—both operating and capital. Partially allocated model II excludes, in addition to nonvehicle capital, all fixed and semifixed operating costs (administration, marketing, etc.). In contrast, the Los Angeles MTA model includes all operating costs—both variable and fixed—but no capital costs. In addition, it does not estimate costs separately by time of day.

To evaluate line-by-line variations in costs, the costs per in-service vehicle hour estimated by the partially allocated model I were compared with those of the Los Angeles MTA model for each of the 122 bus lines in the MTA system. Figure 9 displays the results of this comparison for the 101 MTA lines that operate around the clock, sorted by the hourly cost estimated by the Los Angeles MTA model. Figure 9 shows that, as expected, the partially allocated model I consistently estimates higher peak-period costs—by an average of

$32.55/h—than does the Los Angeles MTA model. On one bus line, peak-period costs are estimated to be 49.6 percent ($56.37) higher per hour than the costs estimated by the Los Angeles MTA model. On another line, the base-period costs are estimated to be 48.3 percent ($56.01) lower per hour than those of the Los Angeles MTA model. On some lines, the time-of-day variations in costs were very large. The estimated variance in peak- and base-period costs ranged up to $97.46/h.

To explore how a temporally sensitive cost-allocation model might affect service-planning decisions, five Los Angeles MTA lines, representing a cross section of operating conditions, were selected, and the cost of adding one vehicle run for four different time periods was calculated. Figure 10 shows that the added costs of including variable capital costs in partially allocated model II are outweighed by the inclusion of semifixed and fixed operating costs in the Los Angeles MTA model. For each of the five lines examined, the Los Angeles MTA model estimates substantially higher costs to add a single-vehicle run, even in the peak periods. For off-peak periods, when vehicles and labor are likely on hand to add service, the Los Angeles MTA model estimates the costs of an additional vehicle run to be three to five times higher than those estimated by the partially allocated model II. In addition, Figure 10 also shows that the estimated costs of a service addition vary substantially from line to line, reflecting the differences in operating characteristics (e.g., route length) of each line.
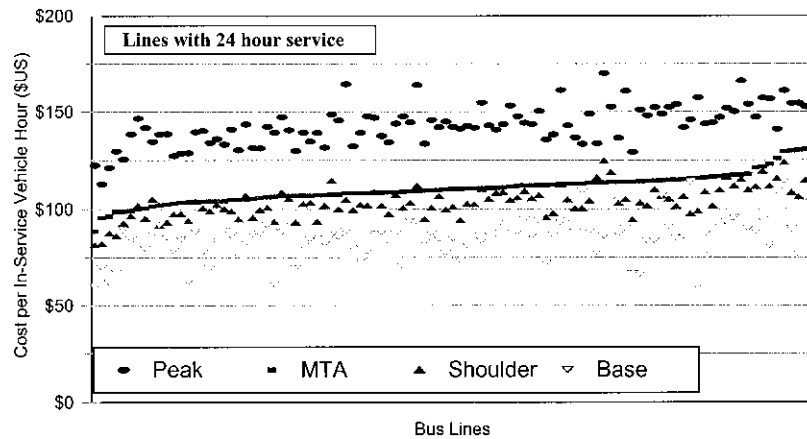
FIGURE 9   Comparison of individual line costs using partially allocated model I.

The results suggest that erroneous cost estimates for different times of day can result in inefficient service provision and reduced efficiency. Because the cost of providing additional service during off-peak periods is normally less than the systemwide average, the failure to consider temporal and directional variation in costs may lead to off-peak service cuts that save less money than hoped or lead to increases in peak service that are costlier than anticipated (*19*).

CONCLUSION

The cost of producing public-transit service is not uniform but varies by trip type (i.e., local or express), trip length, time of travel, and direction of travel, among other factors. Yet the models employed by public-transit operators to estimate costs generally do not account for this variation. These limitations in the cost-allocation models used in practice significantly hinder the management, planning, and policy oversight of public-transit systems. Accurate, fine-grained cost information is essential in setting service levels, determining fare structures, and selecting transit modes. The limitations of most

public-transit cost-allocation models have long been noted in the literature, particularly with respect to time-of-day variations in costs (*4, 7, 8, 19–21*). But most models' exclusion of variations in vehicle-passenger capacity, capital costs, and directional peaking has been noted by others as well (*10, 11, 15, 16*). The models developed for this analysis are unique in that they simultaneously account for variations in capital costs, vehicle-passenger capacity, and time-of-day costs (unfortunately, data limitations did not allow accounting for directional peaking in these models).

This analysis used FY 1994 operating and capital data for the Los Angeles MTA to develop three related fully and partially allocated cost-estimation models. In comparison with the model currently used by the Los Angeles MTA, these models estimated the following:

- Peak-period bus costs to be higher by 35.9 percent;
- Base-period bus costs to be lower by 14.5 percent;
- LRT unit costs to be higher than bus costs by an average of 266 percent; and
- The cost of small additions of bus service to be substantially lower regardless of time of day.
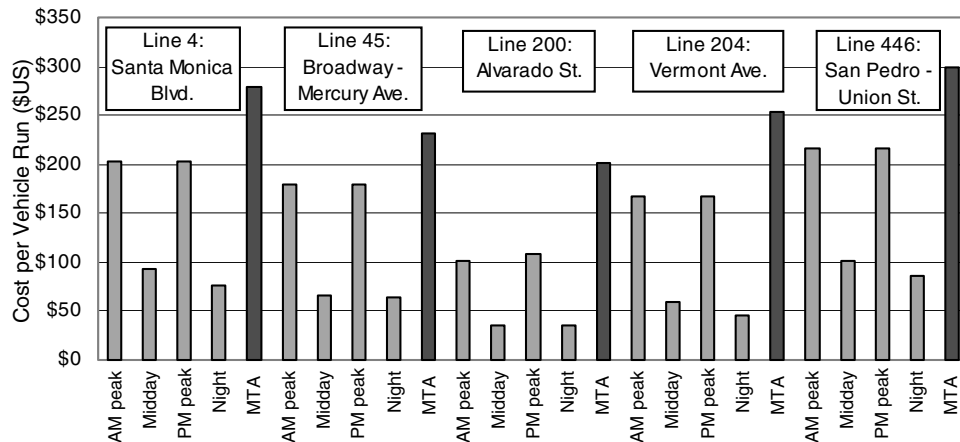

FIGURE 10   Cost of additional vehicle run for five sample bus lines by time period.

Whereas the modified fully and partially allocated models are more comprehensive than most previously developed in the literature and substantially more sensitive than the models typically employed in practice, these models could be further improved by the following actions:

• Accounting for the directional peaking of demand by distinguishing peak-direction service in the analysis,
• Taking weekend operation directly into account when vehicle and capital costs are computed,
• Applying a cost centers approach to differentiate unit costs to discrete parts of the system such as operating divisions (*15, 38*), and
• Computing relative labor-productivity factors on individual lines from the ratio of pay hours to vehicle hours by time of day to more accurately estimate vehicle-hour unit costs.

To incorporate these refinements, however, additional data, not typically collected by transit operators, would be needed.

Finally, although Los Angeles MTA data were used, the focus is not on the Los Angeles MTA per se. In addition, this work is not intended as a critique of the Los Angeles MTA practice. The four-factor cost-allocation model currently used by the Los Angeles MTA is more sophisticated than the one- and two-factor models used by many transit operators. As noted, the observed time-of-day cost differentials, although significant, are probably smaller than those of most other transit operators given the Los Angeles MTA's very low peak-to-base vehicle ratio. Finally, estimated modal differences in costs are not likely unique to Los Angeles. Except for exclusive-busway facilities, right-of-way and capital costs are typically higher for rail transit than for buses. Rather, the focus is on the limitations of the rudimentary, average-cost-allocation models employed by most transit operators. Toward that end, it has been shown that an array of factors—namely capital costs, vehicle-passenger capacity, and time-of-day variations in costs—that generally have been addressed separately in the cost-allocation-model literature can be incorporated simultaneously and practically into a usable transit-cost-allocation model to provide transit systems with far better information on the highly variable costs of producing transit service.

ACKNOWLEDGMENTS

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