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**MEASURING THE EFFECTS OF PEAKING, VEHICLE CAPITAL,
AND PASSENGER CAPACITY
ON THE COST OF PROVIDING TRANSIT SERVICE**

Working Paper

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by

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ABSTRACT

The cost of producing public transit service is not uniform, but varies by trip type (such as 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. The exclusion of cost variability in most public 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 developing a set of models that account for marginal variations in vehicle passenger capacity, capital costs, and time-of-day costs using FY 1994 capital and operating data for the Los Angeles MTA. This analysis is unique in that it combines a number of previously and separately proposed improvements to cost allocation models. In comparison to the model currently used by the MTA, we find that the models developed for this analysis estimate: (1) higher peak period costs and lower base period costs, (2) significant variations in costs by mode, and (3) substantially lower costs for incremental additions in bus service. While this study uses Los Angeles MTA data, the focus of this analysis is not on the MTA *per se*, nor is this work intended as a critique of MTA practice. Rather, the focus of this study is on the limitations of the rudimentary, average cost allocation models employed by most transit operators. Toward that end, this analysis shows quite clearly that an array of factors addressed separately in the cost allocation model literature can be simultaneously and practically incorporated into a usable transit cost allocation model to provide transit systems with far better information on the highly variable costs of producing transit service.

Keywords: Transit Costs, Cost Allocation Models, Peaking

I. OVERVIEW

Many transportation managers in the private sector might be surprised to learn that their public sector counterparts often have very limited 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 passengers or freight varies by season, day-of-the-week, time-of-day, direction, and mode. By contrast, public transit managers often have only rudimentary information linking budgetary inputs to service outputs. One might argue that, as publically subsidized services, 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 may often have limited or incomplete information regarding the cost or savings from such changes.

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 operators to serve these trips -- paratransit vans, buses, rail operating as demand response, local, or express service -- varies significantly. 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, nor are they 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 output, and most moderately-sized and large transit systems use cost allocation models of one form or another (Carter, Mundle, and McCollom 1984). Such models can, for example, aid managing in tracking cost-efficiency over time or in estimating the costs or savings of changes in service (Levinson and Conrad 1979). In a more limited fashion, the models are used by policy makers and funding agencies to inform choices over the deployment of services and allocation of funding (Peskin 1982). A number of researchers over the years 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, yet transit operators have generally been slow to adopt such improvements into practice (Cohen et al. 1988).

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

models.

We compare the results of the models developed for this analysis with the current MTA model, which is typical of those used by U.S. transit operators. In this comparison, we separately estimate the total systemwide costs of bus and rail. We then compare the estimated variations in costs among individual bus lines. Finally, we compare the estimated costs of incremental additions of bus service on a sample of five lines. These comparisons clearly reveal substantial deviations in estimated modal and time-of-day costs between the models developed for this analysis and the standard 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 practically implemented using data normally available to transit operators to produce a more fine grained analysis to better inform decision making.

II. 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 only include operating costs. These costs can be differentiated into variable, semi-fixed, and fixed costs (Arthur Anderson & Co. 1974; Taylor 1975; Levinson and Conrad 1979; Kemp, Beesley, and McGillivray 1981):

X **variable costs** - costs directly linked with vehicle operations such as driver wages and fringe benefits, and non-driver variable costs such as fuel and vehicle maintenance;

X **semi-fixed costs** - costs not directly linked to service changes but influenced by the level or pattern of service such as rolling stock, revenue collection, and marketing;

X **fixed costs** - costs insensitive to marginal changes in service levels such as 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 costs. 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 such as 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 (Cervero 1982). Additional variables such as the number of revenue passengers or peak-period vehicle “pull-outs” (vehicles leaving the yard to begin revenue service) can also be added to the model (Cervero 1982; Talley 1988).

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/variable costs, will not typically have any expense items assigned to them, while others such as vehicle hours/fixed overhead costs may or may not depending on the particular costs estimated by the model.

Figure 1. Relationships between Cost Inputs and Service Outputs			
	Variable Costs	Semi-fixed Costs	Fixed Costs
Vehicle hours	Strong	Strong	Moderate
Vehicle miles	Strong	Moderate	Weak
Peak vehicles	Weak	Strong	Strong
Source: Adapted from Taylor (1975)			

To calibrate a model, system-wide 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 (Lem, Li, and Wachs 1994):

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

C	:estimated costs
i	:a particular measurable service characteristic which represents the scale of operations
n	:number of service characteristics included in the model
U_i	:unit cost of characteristic i
X_i	:quantity or value of characteristic i in the analysis

There are two forms these models commonly take. *Partially* allocated models generally include only variable costs and some semi-fixed costs, and are used to estimate the costs of marginal or incremental service changes (Carter, Mundle, and McCollom 1984; Li 1997). *Fully* allocated models include variable and most or all fixed costs (though in practice they commonly exclude capital costs), and are mainly used 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 (Cherwony, Gleichman, and Porter 1981). 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 semi-fixed and fixed costs such models tend to overestimate the costs or savings associated with small changes in service (Kemp, Beesley, and McGillivray 1981; Stopher et al. 1987; Talley 1988; New York City Transit Authority 1988). On the other hand, by excluding most capital costs (land, vehicles, buildings, etc.) they significantly underestimate the full cost of transit service (since, 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, semi-fixed, and fixed costs, and considers only those costs that in fact vary with service outputs over the scope and scale of the analysis. Cherwony (1981) has 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 (Cervero 1980) or between different modes (Li 1997). One explanation for the exclusion of capital expenses in most cost allocation models is that transit operations in the U.S. are usually funded primarily through farebox revenues and local subsidies, while capital costs are more often funded by state and, especially, federal subsidies which 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 can also be a problem in comparing the costs of publically operated and privately contracted transit services (Chomitz, Guiliano, and Lave 1985).

Modal Variations in Passenger Capacity

In comparing system performance between different modes, operators do not normally consider differences in vehicle passenger capacity among various transit modes (Li 1997). In other words, a vehicle hour of transit service is not directly comparable between paratransit, bus, and rail. Failure to account for vehicle capacity can bias modal comparisons against higher vehicle capacity modes like rail.

The 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 counter-direction traffic resulting in an increasing temporal and directional concentration of transit demand (Jones 1985; Wachs 1989). Studies have clearly shown that it costs significantly more per unit of output to provide service in the peak periods than in the off-peak (Cherwony and Mundle 1978; Kemp, Beesley, and McGillivray 1981; Cervero 1982; Charles River Associates Incorporated 1989; Parody, Lovely, and Hsu 1990). 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 (Jones 1985; Pickerell 1986; Wachs 1989). Although many of these excess wage expenditures occur during off-peak periods, a reasonable argument can be made for attributing them to the peak since they would not be incurred but for peak service levels (Cervero 1980).

Moreover, during peak periods many vehicles carry passengers predominately 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 (Pickerell 1986; Tomazinis and Takyi 1989). In addition, peak period-only service runs proportionally increase the costs of “deadheading” vehicles to and from storage yards. Since fixed costs are generally scaled to peak level service, average unit cost models that are temporally insensitive may not capture actual cost differences where different

routes have similar peak vehicle requirements but different off-peak requirements (Savage 1988).

A survey of thirty transit agencies conducted by Cohen *et al.* (1988) found that none used cost allocation models that distinguished between the cost of providing service by time of day or day of week. The survey also 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 on which output measures best reflect changes in cost (Biemiller and Munro 1981; Stopher et al. 1987; Li 1997). Some cost items may be related to more than one measure (Kemp, Beesley, and McGillivray 1981). The various output measures used, such as vehicle hours and vehicle miles, are not independent but in fact highly correlated (Kemp, Beesley, and McGillivray 1981; Talley 1988). Finally, since these models are usually based on systemwide costs, they do not fully account for cost variations on individual routes (Cervero 1982).¹

III. DEVELOPMENT OF COMPREHENSIVE COST ALLOCATION MODEL

This study uses data collected by the Los Angeles Metropolitan Transportation Authority (MTA) for the 1994 fiscal year.² Contrary to the popular perception of Los Angeles as the most automobile dominated metropolitan area in the U.S., the MTA is the second largest public transit system in the country in terms of unlinked passenger trips, operating 131 bus and three rail lines serving 391 million passengers annually. While the Los Angeles MTA cost allocation model has been modified and improved over the years, it is typical of most such models used in practice in that it does not account for variations by in capital costs, vehicle passenger capacity, or time of day. The MTA model relates operating costs to vehicle hours, vehicle miles, peak vehicles, and the number of passenger boardings as shown below (Lem, Li, and Wachs 1994).^{3,4}

¹ See Appendix A for further discussion of these issues.

² See Appendix B for details of service output data obtained from the MTA reports.

³ See Appendix C for actual values of coefficients of the MTA model and detailed description of the model development.

⁴ To develop the model sensitive to cost variation by time of day, we estimated variables such as scheduled vehicle hours, in-service vehicle miles, etc. by time of day. See Appendix D for detail description of this estimation.

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

equation (2)

<i>OC</i>	:estimated operating costs
<i>j</i>	:unit of analysis in question — system, line, etc.
<i>U</i>	:unit cost per service output
<i>VH</i>	:scheduled vehicle hours
<i>VM</i>	:scheduled vehicle miles
<i>PV</i>	:PM peak vehicles
<i>TP</i>	:total passengers
<i>F</i>	:fixed overhead cost factor

This model allocates costs for labor to scheduled vehicle hours; fuel, maintenance, and repair equipment to scheduled vehicle miles; fixed non-maintenance labor and administration costs to peak vehicles; and overhead costs, such as customer service and ticket sales, to passenger boardings. The model also includes a constant multiplier to allocate indirect expenditures such as 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 the 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 semi-fixed operating and capital cost allocation generally allocate a higher percentage (or all) of these costs to the peaks. In this study, we combine both operating and capital costs and disaggregate service into multiple time periods to better reflect the changes in transit demand and service throughout the day.

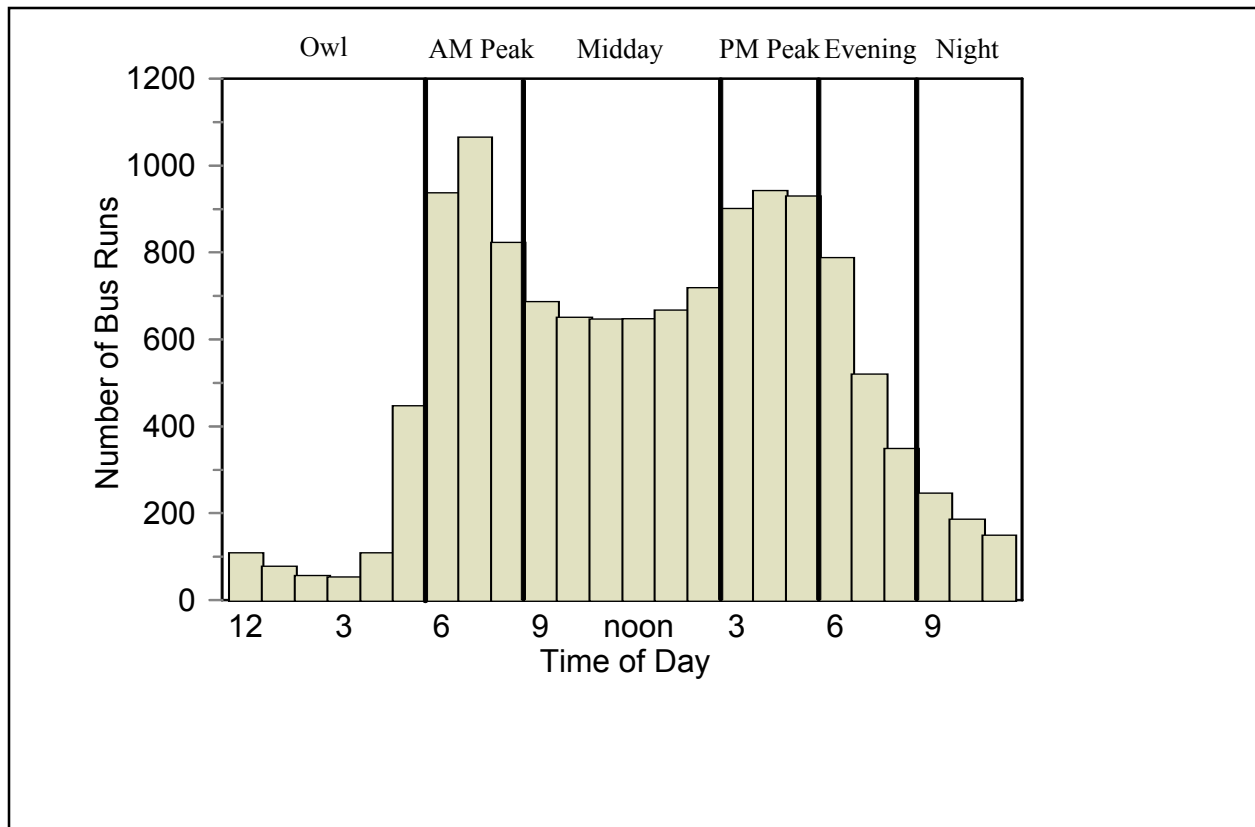
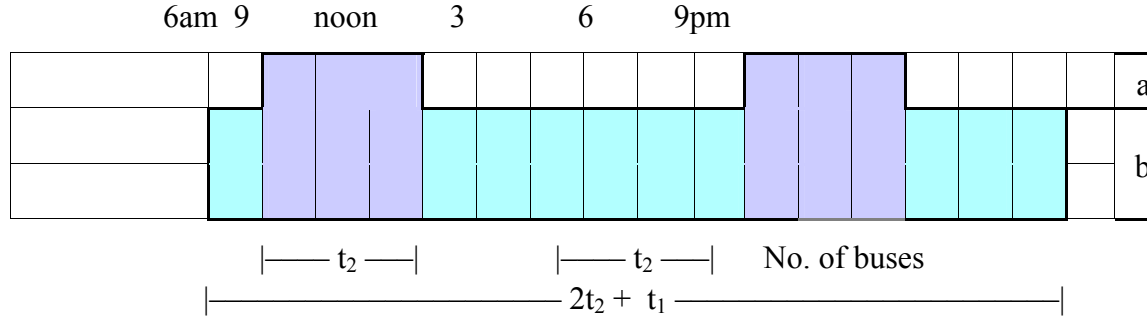


Figure 1. Time-of-Day Variation in Service Levels: Los Angeles MTA

Figure 2 shows the number of MTA service runs occurring in a typical 24-hour period. Based on this service profile, the service day can be divided into six periods: Owl (12 am - 6 am), AM Peak (6 - 9 am), Midday (9 am - 3 pm), PM Peak (3 - 6 pm), Evening (6 - 9 pm), and Night (9 pm - 12 am). To determine operating costs during these six service periods, we substituted appropriate values for vehicle hours, miles and passenger boardings as shown in Figure 3, which diagrammatically illustrates the variation in service and costs during a 16-hour portion of a typical weekday. While our initial service cost calculations were made for all six periods (to more accurately capture the temporal variability of service), for simplicity we have aggregated the total costs to three periods: *base* (Night plus Owl), *shoulder* (Midday plus Evening), and *peak* (AM Peak plus PM Peak). In comparison to 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.



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:

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

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

U :unit cost of service output

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

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

Source: Adapted from Cervero (1980).

Figure 11-10. Cost-Related to Operating Costs of Public Transit
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 (McClenahan et al. 1978). A second, *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 (Cherwony, Gleichman, and Porter 1981).⁵

A third, *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, we distinguish between costs that vary by service level at different times of day and those costs that are generally invariant with respect to time.

Accounting for Labor Utilization

To account for time-of-day differences in labor utilization, we multiply the vehicle hours factor by a labor utilization factor derived for each period representing the relative share of the ratio of pay hours to scheduled vehicle hours. The basic form of the model is given by Yu (1986):

$$LUF_i = \left(\frac{PH_i}{VH_i} \right) \frac{\sum_i VH_i}{\sum_i PH_i} \quad \text{equation (6)}$$

LUF_i :Labor Utilization Factor for period i

PH_i :pay hours for period i

VH_i :vehicle hours for period i

Cherwony and Mundle (1978; 1980) 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)):

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

⁵ See Appendix E for further description of the statistical and the resource-based approaches.

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

where $0 < LUF_B < 1 < LUF_P$

U_{PVH} :vehicle hour unit cost estimate for the peak
 U_{BVH} :vehicle hour unit cost estimate for the 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
 $VH_{P \text{ or } B}$:vehicle hours for peak or base period

Studies by Kemp (1981), Cervero (1980; 1982), Charles River Associates (1989), and Parody *et al.* (1990) 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 based on 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 upon a determination whether the pay hours were “caused” by demands in the peak or 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 % more pay hours than vehicle hours in the peak and 7 % more in the base) (Cervero 1980). Since 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 (Reilly 1977; Levinson 1978; Cohen et al. 1988).⁶

Using a method similar to the *Peak-Base Model* discussed above, we adjusted the vehicle hour coefficients in the MTA model 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 we used Cervero’s (15) average labor productivity factor and data on the peak to base ratio of vehicle hours for each bus line (s) to calculate *peak* and *off-peak (base plus shoulder)* unit costs for each line using equations (6) and (7). For the *off-peak* we used the sum of vehicle hours in the Midday, Evening, Night, and Owl periods, and for the *peak* period we used vehicle

⁶ See Appendix F.

hours in the AM and PM Peak periods.⁷

Accounting for Vehicle Utilization

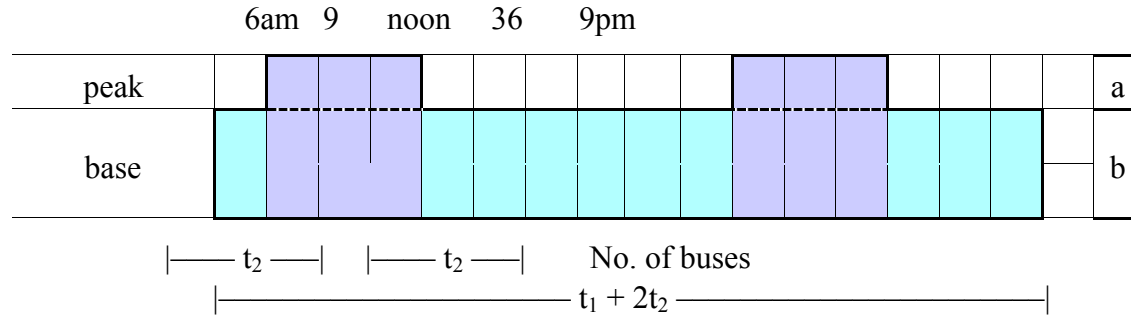
Nearly all transit vehicles “deadhead” to and from storage facilities or maintenance yards at the start and conclusion of revenue service. For vehicles operated in peak period only service, the ratio of out-of-service vehicle miles to in-service vehicle miles is greater than for vehicles in revenue service 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, we allocated costs on the basis of total (or “scheduled”) vehicle miles, but used in-service vehicle miles and hours to develop our unit cost measures. Doing so, in effect, applied a vehicle utilization factor comparable to the labor utilization factor described above.

Including Fixed and Semi-Fixed 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 (1989) and Parody *et al.* (1990) reviewed studies that examined capital cost allocation to the peak and off-peak periods, classifying the prior studies into two groups: (1) those where all capital costs were assigned to the peak on the assumption that these resources would not be needed but for the peak period demand (Meyer, Kain, and Wohl 1965; Mohring 1972; Taylor 1975; Reilly 1977; Cherwony and Mundle 1978), and (2) those where 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 (Boyd, Asher, and Wetzler 1973; Levinson 1978; Cervero 1980; Cervero 1982; Lee 1986; Charles River Associates Incorporated 1989; Savage 1989; Kerin 1989). Acknowledging this split in the literature, Charles River Associates (1986) 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 (1980) 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 non-capital overhead costs as described in Figure 4.

⁷ Cervero defined peak vehicle hours at those occurring between 6:15 - 8:45 am and 3:15 - 5:45 pm and off-peak vehicle hours as those occurring during the remainder of the day. For purposes of this paper, we consider these equivalent to the *peak* period (6 - 9 am and 3 - 6 pm) and the *off-peak* period (the rest of the day) in this study.

Service layer



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

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

U : unit cost of service output

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

$$C_2 = 2t_2a * U \quad \text{equation (10)}$$

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:

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

Source: Adapted from Levinson (1978) and Cervero (1980).

Figure 4: Bradford Bus Study Approach to Allocating Costs by Service Layer

In a more refined application of the principles shown in Figure 4, the Bradford Bus Study allocated overhead costs, including vehicle facility costs, non-maintenance 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 utilized in any other periods that have higher vehicle requirements. Based on 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 can then be further disaggregated to individual lines (within each time period) by the relative number of buses for each line (Savage 1989).

In this study, we used the Bradford Bus Study method to allocate fixed operating, vehicle capital, and non-vehicle capital costs to individual lines by time period. For the allocation of vehicle capital costs, Figure 5 shows 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 (12 midnight - 6 am) requires 58 buses, Night service (9 pm - midnight) an additional 207 buses, Evening service (6 - 9 pm) another 638 buses, and so on. Buses in the first service “layer” (I) run for 24 hours a 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 one hour of service for the whole system in this layer can be obtained by dividing the daily capital cost of a bus (\$94.14) times the number of required buses, 58, divided by 24 hours. Capital costs were annualized using generally accepted accounting principles; space limitations do not permit a full description of these calculations, though the details are available from the authors.⁸ Similarly, buses added for use in the *shoulder* period are also available for service during the *peak* and their capital costs are spread over the *shoulder* and *peak* periods. Buses assigned exclusively to the highest peak period (AM Peak) run for only 3 hours. The capital cost for one hour of service exclusively during the AM 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 hours of service. These hourly figures were multiplied 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.

⁸ See Appendix C for actual calculation, and G for discussion of annual capital cost calculation methods.

Service layer /																			
# Buses					3am		6		9		noon		3pm		6		9		
					\$565														
					\$31,207						\$31,207								
					\$3,954		\$7,908				\$3,954								
					\$12,012		\$24,024				\$12,012		\$12,012						
					\$3,248		\$6,496				\$3,248		\$3,248			\$3,248			
\$1,365					\$682		\$1,365				\$682		\$682			\$682			
					Owl	AM Peak		Midday		PM Peak		Evening		Night					
Total Cost/Day					\$1,365	\$51,668		\$39,792		\$51,103		\$15,942		\$3,930					

Similar assignments were made for the operating overhead costs assigned to peak vehicles (to account for the fact that some of these costs properly should be attributed to weekend service, we adjusted the weekday totals by a factor representing the relative shares of weekday and weekend service for each period).⁹ These values were then distributed to each individual line in proportion to the number of required vehicles on each line during that time period.

Allocation of LRT Operating and Vehicle Capital Costs

Operating and capital costs of the MTA's light rail service were allocated in a similar fashion to that for bus service as described above.¹⁰ Due to 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.

⁹ See Appendix C.

¹⁰ See Appendix C.

Resulting Models

Using the modifications described in the preceding sections, we developed three variants of comprehensive cost allocation model – a *Fully-Allocated Model*, and two *Partially-Allocated Models*, as defined below:

1. *Fully-Allocated Model*

$$\begin{aligned} FAC_{ij} &= OC_{ij} + CC_{ij} \\ &= (LUF_{ij} * U_{VH} * VH_{ij} + U_{VM} * VM_{ij} + PVC_{ij} + U_{TP} * TP_{ij}) * (1 + F) \\ &\quad + VCC_{ij} + OCC * (IVH_{ij} / IVH_{day,system}) \end{aligned}$$

equation (12)

$$(LUF_{ij} = 1, F = U_{TP} = 0 \text{ for LRT})$$

2. *Partially-Allocated Model I*

$$\begin{aligned} PAC_{ij} &= OC_{ij} + VCC_{ij} \\ &= (LUF_{ij} * U_{VH} * VH_{ij} + U_{VM} * VM_{ij} + PVC_{ij} + U_{TP} * TP_{ij}) * (1 + F) \\ &\quad + VCC_{ij} \end{aligned}$$

equation (13)

3. *Partially-Allocated Model II*

$$\begin{aligned} PAC_{ij} &= OC_{ij} + VCC_{ij} \\ &= (LUF_{ij} * U_{VH} * VH_{ij} + U_{VM} * VM_{ij}) + VCC_{ij} \end{aligned}$$

equation (14)

- FAC* :costs estimated by the fully-allocated model
- PAC* :costs estimated by the 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 the modified model
- VCC* :vehicle capital costs
- OCC* :non-vehicle 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 :PM peak vehicles
TP :total passengers
F :fixed overhead cost factor

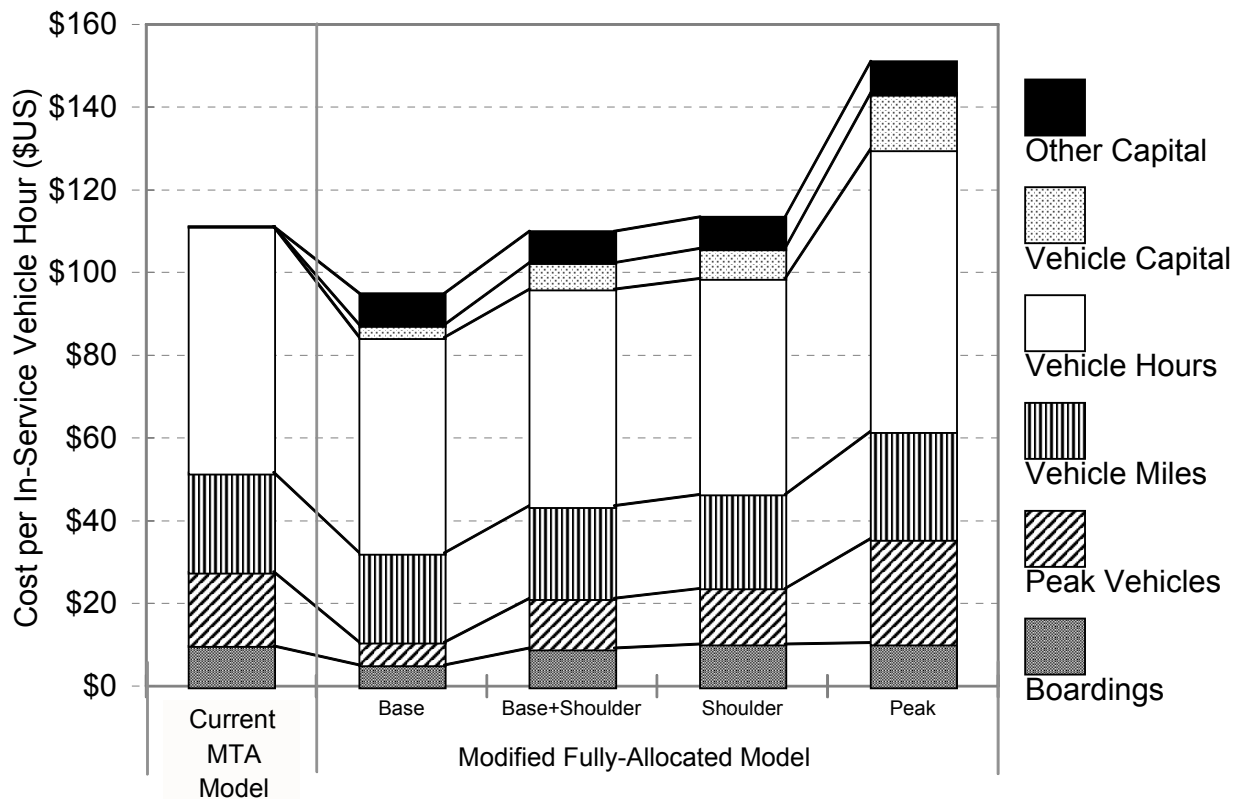
IV. FINDINGS

After developing a new cost allocation model to account for variations in capital costs, vehicle passenger capacity, and time-of-day costs, we then used operating data compiled by the Los Angeles MTA to compare these three variations of this new model with the model currently used by the MTA. The *Fully-Allocated Model* was used to examine systemwide costs and to compare costs between the bus and light rail (LRT) modes. The *Partially-Allocated Models I and II* were used to compare costs between bus lines within the 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 differences in costs between modes, neither of which is captured in the model currently used by the MTA, nor by similar cost allocation models used by most other public transit systems.

Comparison of the *Fully-Allocated Model* with a Typical Cost Allocation Model

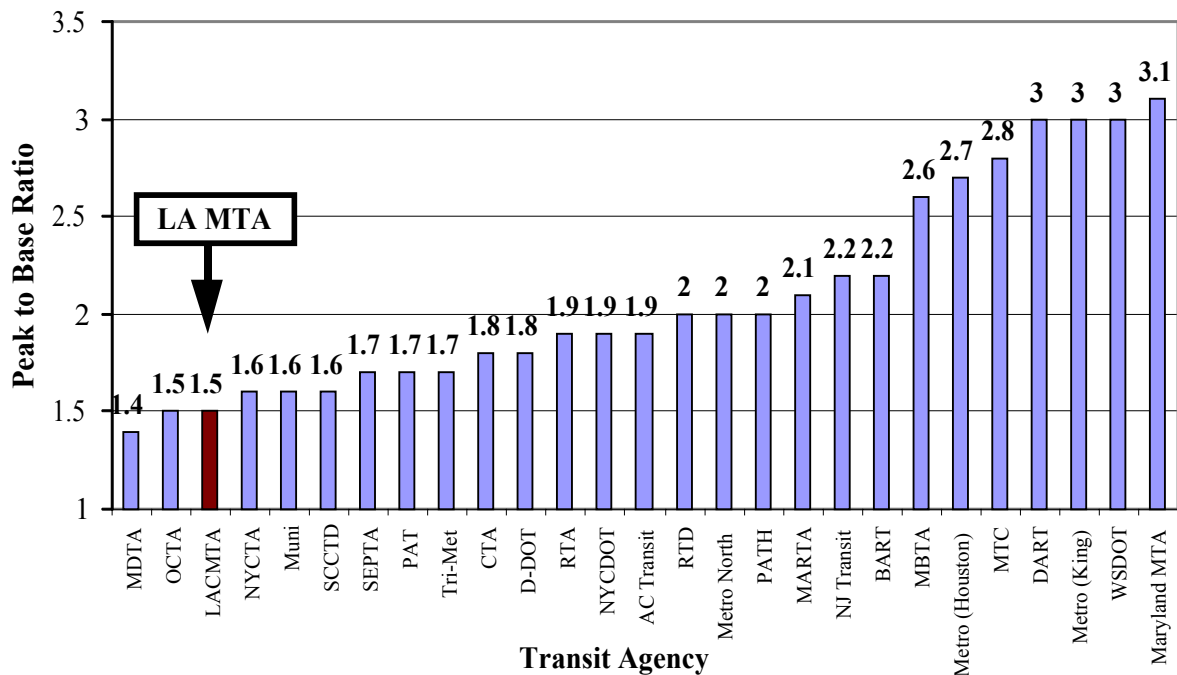
The time-of-day cost variations estimated in this analysis are similar to those found by others, in that the peak periods account for over half of all costs (Levinson 1978; Cervero 1980; Parody, Lovely, and Hsu 1990).¹¹ Figure 6 below shows that the *Fully-Allocated Model* developed for this analysis estimates 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 MTA model. This figure also shows that the *Fully-Allocated Model* estimates base period costs to be \$94.96 per in-service vehicle hour, or 14.5 percent below the MTA model estimate. It is important to note that these base period costs are estimated to be lower than those of the MTA model despite the inclusion of annualized vehicle and non-vehicle capital costs.

¹¹ For a simple comparison of the results of our study to other studies, we computed the peak period shares of operating, vehicle capital, and non-vehicle capital costs. See Appendix H.



5. Comparison of Estimated Systemwide Costs Between the MTA Model and the *Fully-Allocated Model*

Overall, the systemwide bus costs estimated by the *Fully-Allocated Model* vary by \$56.05 per in-service vehicle hour, or 59.0 percent 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 (see 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.



6. Peak/Base Ratios of the Twenty-Seven Largest Transit Operators

We then compared the fully allocated systemwide bus costs described above with similar cost data for the one MTA LRT line in operation at the time these data were collected. This comparison, summarized in Figure 8 below, shows that, considering the (1) annualized vehicle and non-vehicle capital costs, (2) higher seating capacity of LRT *vis-a-vis* bus, and (3) time-of-day cost differentials, the cost per seat-hour of service is substantially higher on the LRT, due mostly, though not entirely, to the much higher annualized non-vehicle capital costs. Buses operate on streets and highways paid largely others: property owners (via property taxes) and private vehicle operators (via motor fuels taxes). For the LRT line, by contrast, the cost of right-of-way, track, catenary, and stations were paid by the transit operator. These costs, when annualized using generally accepted accounting principles, comprise 49.1 percent of fully allocated costs per seat hour of LRT service. Other LRT unit costs are higher than bus costs as well, due to higher per-seat vehicle capital costs and to higher per-seat expenditures by the MTA on LRT operations, such as for security.¹²

¹²

See Appendix I.

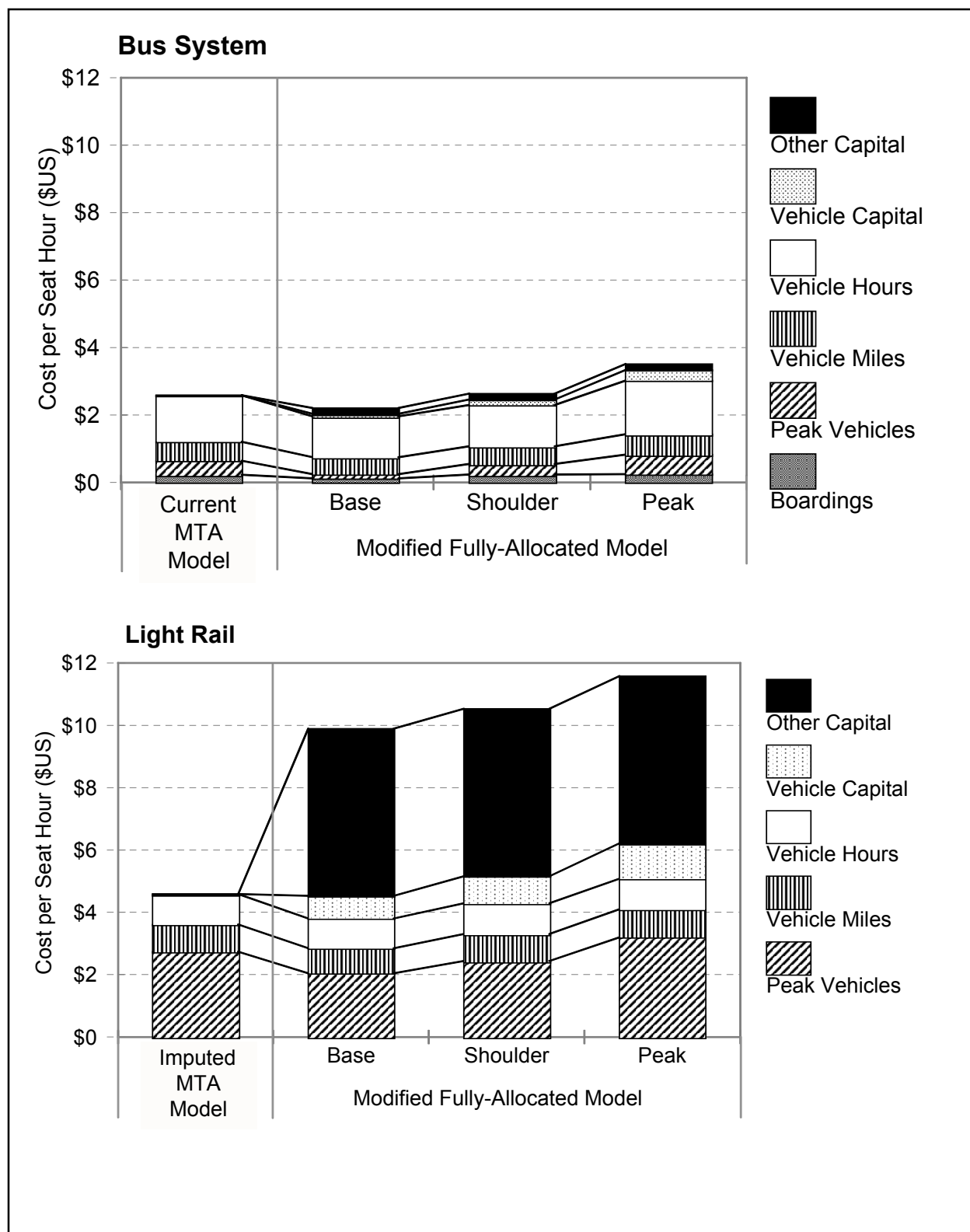
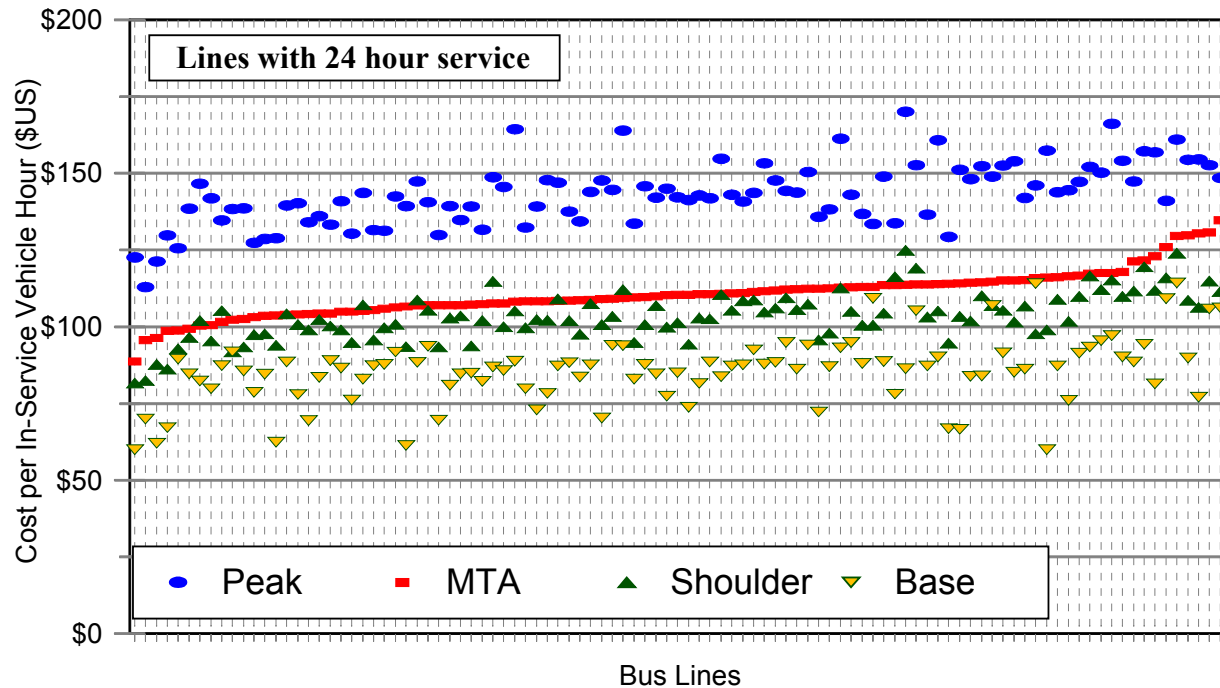


Figure 7. Comparison of Estimated Bus System and Light Rail Costs Using MTA Model



8. Comparison of Individual Line Costs Using *Partially-Allocated Model I*

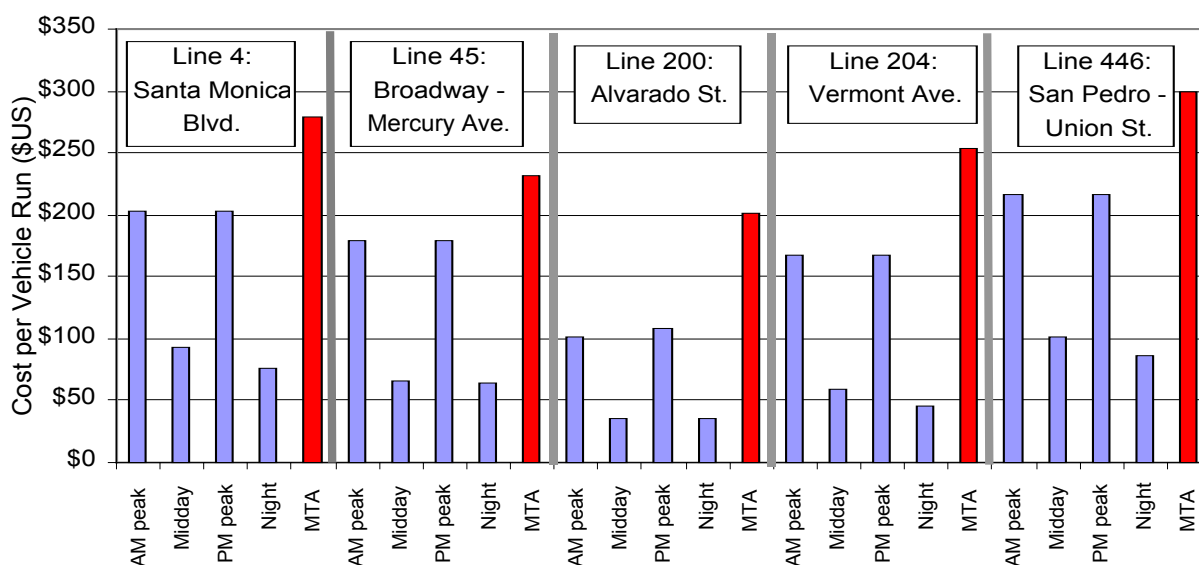
Comparison of the *Partially-Allocated Models* with a Typical Cost Allocation Model

As noted in the opening discussion of fully- and partially-allocated models, marginal or incremental additions or deletions of service are most appropriately evaluated using partially-allocated models which include only variable operating and vehicle capital costs (like driver compensation, fuel, and vehicles) which vary with incremental changes in service, but exclude most fixed and semi-fixed costs (like facilities, planning, and administration) which do not. Accordingly, *Partially-Allocated Model I* excludes non-vehicle capital costs, but includes all semi-fixed and variable costs — both operating and capital. *Partially-Allocated Model II*, excludes, in addition to non-vehicle capital, all fixed and semi-fixed operating costs (administration, marketing, etc.). In contrast, the MTA model includes all operating costs — both variable and fixed — but no capital costs, nor does it separately estimate costs by time-of-day.

To evaluate line by line variations in costs, we compared the costs per in-service vehicle hour estimated by *Partially-Allocated Model I* to the MTA model for each of the 122 bus lines in the MTA system. Figure 9 below displays the results of this comparison for the 101 MTA lines that operate around the clock, sorted by the hourly cost estimated by the MTA model. This figure shows that, as expected, the *Partially-Allocated Model I* consistently estimates higher peak-period costs — by an average of \$32.55 per hour — than the 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 MTA model. On another line, the base period costs are estimated to be 48.3 percent (\$56.01) lower per hour than the 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 per hour.

To explore how using a temporally sensitive cost allocation model might affect service planning decisions, we selected five MTA lines representing a cross-section of operating conditions and calculated the cost of adding one additional vehicle run for four different time periods.¹³ Figure 10 below shows that the added costs of including variable capital costs in *Partially-Allocated Model II* are outweighed by the inclusion of semi-fixed and fixed operating costs in the MTA model. For each of the five lines examined, the 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 MTA model estimates the costs of an additional vehicle run to be three to five times higher than *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 (such as route length) of each line.



9. Cost of Additional Vehicle Run for Five Sample Bus Lines by Time Period

The results suggest that erroneous cost estimates for different times of day can result in

¹³

A map of the five sample lines is in Appendix J.

inefficient service scheduling and reduced efficiency. Since the cost of providing additional service during off-peak periods is normally less than the system-wide 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 to increases in peak service that are costlier than anticipated (Cherwony and Mundle 1978).

V. CONCLUSION

The cost of producing public transit service is not uniform, but varies by trip type (such as 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 has long been noted in the literature, particularly with respect to time-of-day variations in costs (Cherwony and Mundle 1978; Kemp, Beesley, and McGillivray 1981; Cervero 1982; Cohen et al. 1988; Charles River Associates Incorporated 1989; Parody, Lovely, and Hsu 1990). But the exclusion in most models of variations in vehicle passenger capacity, capital costs, and directional peaking have been noted by others as well (Cervero 1980; Chomitz, Guiliano, and Lave 1985; Lem, Li, and Wachs 1994; Li 1997). 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 us to account for directional peaking in these models).

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

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

While the modified *Fully- and Partially-Allocated Models* developed in this analysis 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:

1. Accounting for the directional peaking of demand by distinguishing peak direction service in the analysis;

2. Taking weekend operation directly into account in computing vehicle and capital costs;
3. Applying a “cost centers” approach to differentiate unit costs to discrete parts of the system such as operating divisions (Cervero 1980; Bell, Blackledge, and Bowen 1983); and
4. 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, while this study uses Los Angeles MTA data, the focus of this analysis is not on the MTA *per se*, nor is this work intended as a critique of MTA practice. The four-factor cost allocation model currently used by the MTA is more sophisticated than the one- and two-factor models used by many transit operators. As noted earlier, the observed time-of-day cost differentials, while significant, are probably smaller than those of most other transit operators, given the 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 of this study is on the limitations of the rudimentary, average cost allocation models employed by most transit operators. Toward that end, this analysis has clearly shown that an array of factors — namely capital costs, vehicle passenger capacity, and time-of-day variations in costs — which have generally been addressed separately in the cost allocation model literature, can be simultaneously and practically incorporated 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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APPENDIX A

Limitations of Cost Allocation Models

There are a number of shortcomings apparent in using any cost allocation model. One is the assumption that each operating expense can be appropriately assigned or allocated to a specific output measure.

In addition, assigning particular expense items to individual output variables is also difficult. For example, overhead costs, such as administrative costs, insurance, vehicle repairs, and storage, may be related to more than one output variable (Kemp, Beesley, and McGillivray 1981). In such cases, it is necessary to determine the proportion to be allocated to each variable. Another difficulty lies in the implicit assumption in cost allocation models that model variables are independent with respect to each other and do not influence the magnitude of other variables (Talley 1988). That is, changes in one output measure does not cause any changes in the other outputs. In fact, vehicle miles and vehicle hours are in general highly correlated; Kemp (1981) has noted this problem of multicollinearity and autocorrelation of variables in cost allocation models. Talley (1988) argues that modelers should use vehicle miles but not vehicle hours because vehicle miles is the better measure of transit service outputs in statistical cost studies.

There is little agreement among researchers regarding how many and which output variables to use in the model. Biemiller and Munro (1981) reviewed a number of cost allocation model studies, in which most models use three or four variables, and found 18 different variables used to estimate operating costs for individual lines or systems. Stopher (1987) developed a four factor model for the Southern California Rapid Transit District (SCRTD) using vehicle miles, vehicle hours, peak vehicles, and passenger boardings. Li (1997) used vehicle miles, vehicle hours and peak vehicles to allocate operating costs in a comparative study of bus and rail performance using data from Los Angeles MTA.

Another concern has been how to apportion costs that do not vary directly by level of service output but are nevertheless typically included in fully allocated cost estimates. Since not all costs are linearly related to specific service changes, some researchers have chosen to identify cost items that vary only when a change in an associated variable exceeds specified threshold values. For example, in a fixed-variable model developed by the New York City Transit Authority, semi-fixed costs such as mechanical repairs, body repairs, vehicle cleaning, and graffiti removal were allowed to vary stepwise with either vehicle miles or fleet size, while driver wages, fuel, tire wear, and scheduled maintenance costs were assigned to vehicle hours and vehicle miles in direct proportion to each incremental change of output (New York City Transit Authority 1988). Stopher (1987) also used a step approach to apportion costs in his study of the SCRTD, where changes resulting in increases or decreases of less than 853 vehicle hours — representing the annual cost of hiring one half-time operator — were ignored.

Very large changes in service present additional issues. While some have suggested that U.S. bus operations are likely to experience both economies and diseconomies of scale (Kemp, Beesley, and McGillivray 1981), the standard model assumes that the unit cost of a change in service remains constant irrespective of the size of the service expansion or contraction (Talley 1988).

Most cost allocation models are based on system-wide unit costs, and therefore they do not account for variations in cost profiles on individual routes. It would be possible to assign individual expenses directly to the specific routes where the costs were incurred, though this would require detailed data and would likely be time consuming. In yet another study of the SCRTD, Cervero (1982) developed a “cost-centers” model that produced separate cost allocation equations for each operating division on the assumption that buses operating within each division would share reasonably similar cost characteristics. He found that the division cost coefficients varied considerably around the systemwide values. His research also suggested some economies of scale for longer routes and express buses but also higher unit costs for high volume routes serving predominately inner city areas.

APPENDIX B

Service Output Data Drawn from the MTA Reports

The service output data on individual bus lines used in this study were obtained from three types of MTA reports: Line Performance Trends Reports (LPTR), Consolidated Transit Service Policies Reports (CTSPR) and Schedule Quality Reports (SQR). The LPTR provides data for daily total bus miles and bus hours (scheduled, revenue, and in-service), daily boardings, and the peak number of vehicles during the AM Peak, Midday, PM Peak, and Owl periods for weekday, Saturday, and Sunday service. The CTSPR provides detailed information on the number of daily weekday outbound and inbound vehicle trips, passengers, and loading ratios for every 10 to 60 minutes, depending on time of day. It also provides data on passenger boardings, in-service hours, and revenue hours. The SQR provides data on vehicle runs, in-service vehicle miles, and passenger miles for most hours of a day.

Table B-1 (next page) presents a comparison between the time periods used in each of the MTA reports, and this study. Due to these differences it was necessary to re-apportion variables for certain period in the MTA reports into the time periods used in this study.

Table B-1. Development of Time Periods for Cost Calculations

Data Source	Time Periods							
Consolidated Transit Service Policies Report	Early AM ¹	AM Peak	Mid-Day	PM Peak	Night			
	4-5am	5-9am	9am-3pm	3-7pm	7pm-4am			
Line Performance Trends Report			AM Peak	Mid-Day	PM Peak			Owl
			6-9am	9am-3pm	3-6pm			12mid-6am
Schedule Quality Reports								
				Every Hour			9pm-5am	
This Study			AM Peak	Mid-Day	PM Peak	Evening	Night	Owl
			6-9am	9am-3pm	3-6pm	6-9pm	9pm-12mid	12mid-6am
			peak	shoulder	peak	shoulder	base	

Table B-2 (next page) summarizes the data available in each report for the time periods shown in Table B-1.

Table B-2. Summary of Available Data

Line Performance Trends Report	Consolidated Transit Service Policies Report	Schedule Quality Report
Data by Day vehicle runs scheduled vehicle mile scheduled vehicle hours revenue vehicle miles revenue vehicle hours in-service vehicle miles in-service vehicle hours total operating cost passenger boardings Data by Time Period peak vehicles	Data by Time Period passenger boardings in-service vehicle hours revenue vehicle hours Data by Day/Night scheduled vehicle hours scheduled vehicle miles peak vehicles passenger boardings cash revenue monthly pass revenue tickets/tokens revenue Data by Hour vehicle runs passengers	Data by Day vehicle runs Data by Hour in-service vehicle miles

Some data were not available for certain time periods. For instance, the LPTR provides data on the number of daily scheduled vehicle miles, vehicle hours, and peak vehicles for the AM Peak, Midday, PM Peak, and Owl periods, but does not provide information for the Night and Evening periods. Nor does the report include any information on passenger boardings by time period. Some data necessary for this analysis, but unavailable in any report were estimated using the procedures described in Appendix D.

APPENDIX C

I. MTA Cost Allocation Model for the Bus System

The MTA's cost allocation formula for the fiscal year (FY) 1993-94 was expressed for each line (j) as a daily operating cost:

$$\begin{aligned} OC_j &= (U_{VH} * VH_j + U_{VM} * VM_j + U_{PV} * PV_j + U_{TP} * TP_j) * (1 + F) \\ &= (36.52 * VH_j + 1.14 * VM_j + 139.64 * PV_j + 0.120 * TP_j) \\ &\quad * 1.2481 \end{aligned}$$

<i>OC</i>	:estimated operating costs
<i>j</i>	:unit of analysis in question — system, line, etc.
<i>U</i>	:unit cost per service output
<i>VH</i>	:scheduled vehicle hours
<i>VM</i>	:scheduled vehicle miles
<i>PV</i>	:PM peak vehicles
<i>TP</i>	:total passengers
<i>F</i>	:fixed overhead cost factor

For the fiscal year 1993-94 (FY 94), the year used in our study, labor costs, allocated to vehicle hours (*VH*), account for 42.8 percent of systemwide operating costs, while maintenance costs, allotted to vehicle miles (*VM*), make up 17.3 percent. Fixed operating costs, allocated to peak vehicles (*PV*), and administrative expenses, assigned to passenger boardings (*TP*), amount to 12.9 percent and 7.1 percent respectively. The fixed cost factor (*F*) accounts for 19.9 percent of the total operating overhead costs. The MTA uses this formula to evaluate line performance for weekdays, Saturday, and Sunday.

To obtain annual costs for each line in the system we substituted data for each of the variables for individual lines into equation (C.1). In FY 94, the MTA operated 131 lines, though nine lines were deleted from the analysis due to lack of available data. During this period, the MTA collected operating data based on a sampling of bus runs on a typical weekday, and for Saturday and Sunday service. In FY 94, there were 258 weekdays, 52 Saturdays, and 55 Sundays (some holiday service falling on a weekday was counted as Sunday service). Thus, in order to calculate total annual costs it was necessary to multiply the average weekday and weekend costs by the number of such days in the year:

$$C_{YEAR} = 258 * C_{WK} + 52 * C_{SAT} + 55 * C_{SUN} \quad \text{equation (C.2)}$$

C_{YEAR} :cost of the entire fiscal year 1993-94
 C_{WK} :cost of a typical weekday
 C_{SAT} :cost of a typical Saturday
 C_{SUN} :cost of a typical Sunday

II. Imputed MTA Cost Allocation Model for the Light Rail Transit System

In order to compute operating costs by time period for Light Rail Transit (LRT) system,¹⁴ we assigned the LRT operating expenses in the MTA's UMTA Section 15 report for FY 93-94 to three service output variables: vehicle miles, vehicle hours, and peak vehicles as shown in Table C-1. This resulted in the following cost allocation model for the LRT:

$$\begin{aligned}
 OC_{LRT} &= U_{VH,LRT} * VH_{i,LRT} + U_{VM,LRT} * VM_{i,LRT} + U_{PV,LRT} * PV_{i,LRT} \\
 &= 64.26 * VH_{i,LRT} + 3.02 * VM_{i,LRT} + 2817.94 * PV_{i,LRT}
 \end{aligned}
 \quad \text{equation (C.3)}$$

OC :estimated operating costs
 LRT :Light Rail Transit system
 i :time of day
 j :unit of analysis in question — system, line, etc.
 U :unit cost per service output
 VH :scheduled vehicle hours
 VM :scheduled vehicle miles
 PV :PM peak vehicles

¹⁴ In the fiscal year 1993-94, only the Blue Line was in operation. Another LRT line, the Green Line, started its operation in August 1995.

Table C-1. Light Rail Transit Operating Cost Allocation

	Operating Expenses	Basis for Assignment		
		Vehicle Miles	Vehicle Hours	Peak Vehicles
501	Labor			
	Operations	\$0	\$6,744,037	\$0
	Maintenance	\$2,513,699	\$0	\$0
	Non-maintenance	\$0	\$0	\$2,654,867
	Administration	\$0	\$0	\$1,980,953
502	Fringe Benefits			
	Operations	\$0	\$3,414,865	\$0
	Maintenance	\$1,272,820	\$0	\$0
	Non-maintenance	\$0	\$0	\$1,344,300
	Administration	\$0	\$0	\$1,003,062
503	Services	\$205,758	\$0	\$15,463,218
504	Materials & Supplies			
	Operations	\$48,134	\$0	\$0
	Materials	\$1,347,754	\$0	\$0
	Non-maintenance	\$473,326	\$0	\$0
	Administration	\$0	\$0	\$38,754
505	Utilities	\$3,184,343	\$0	\$508,849
506	Casualty/Liability	\$0	\$0	\$1,679,301
507	Taxes	\$0	\$0	\$32,476
508	Purchased Trans.	\$0	\$0	\$0
509	Miscellaneous	\$0	\$0	\$207,875
510	Expense Transfer	\$0	\$0	(\$386,282)
	Expenses Sub-total	\$9,045,834	\$10,158,902	\$24,527,373
	Service (Form 406):	2,997,000	158,096	34
	Unit Cost:	\$3.02	\$64.26	\$721,393 / 256 = \$2817.94*

*Peak vehicle unit cost per day is obtained by dividing the total costs assigned to peak vehicles by the number of trains, 34, and the number of weekdays of service, 256.

III. Adjustment of Vehicle Hour Costs

Incorporating the labor utilization adjustment factors into the MTA cost allocation model results in the following general equation for calculating peak and base costs for each line:

$$C_{VHi} = LUF_i * 36.52 * VH_i \quad \text{equation (C.4.1)}$$

$$LUF_P = \frac{n(1+s)}{(1+ns)} \quad \text{equation (C.4.2)}$$

$$LUF_B = \frac{(1+s)}{(1+ns)} \quad \text{equation (C.4.3)}$$

where $0 < LUF_B < 1 < LUF_P$

- C_{VHi} :vehicle hour cost estimated for the period i
- U_{PVH} :vehicle hour unit cost estimate for the peak
- U_{BVH} :vehicle hour unit cost estimate for the base
- i :time of day
- n :relative labor productivity ($= (PH_P / VH_P) / (PH_B / VH_B)$)¹⁵
- s :vehicle hour coefficient ($= (VH_P / VH_B)$)
- $PH_{P \text{ or } B}$:pay hours for peak or base period
- $VH_{P \text{ or } B}$:vehicle hours for peak or base period

IV. Allocation of Peak Vehicle Costs

We allocated the costs associated with the peak vehicle factor to the six time periods used in this study for each line using Vehicle Usage Apportionment Factors (VUAFs) to reflect the proportion of vehicle usage for each service “layer” by line. The VUAFs were then multiplied by the peak vehicle unit costs for each individual line to obtain allocated costs for each period. For the system as a whole, the number of required vehicles increases in the order of Owl, Night, Evening, Midday, PM Peak, and AM Peak periods. To calculate the VUAF for each period, first the incremental number of required vehicles (dPV) in each period was calculated:

¹⁵ We used the constant value, 1.302, for the relative labor productivity (n) on all lines in the analysis. This value was obtained from Cervero’s study (Cervero 1980).

$$\begin{aligned}
dPV_{Owl} &= PV_{Owl} && \text{equation (C.5.1)} \\
dPV_{Night} &= PV_{Night} - PV_{Owl} && \text{equation (C.5.2)} \\
dPV_{Evening} &= PV_{Evening} - PV_{Night} && \text{equation (C.5.3)} \\
dPV_{Midday} &= PV_{Midday} - PV_{Evening} && \text{equation (C.5.4)} \\
dPV_{PMpeak} &= PV_{PMpeak} - PV_{Midday} && \text{equation (C.5.5)} \\
dPV_{AMpeak} &= PV_{AMpeak} - PV_{PMpeak} && \text{equation (C.5.6)}
\end{aligned}$$

dPV :the incremental number of required vehicles
 PV :the number of required vehicles

In each successive time period the number of required vehicles increases, and the number of hours in which vehicles are in service, decreases from 24 hours to 3 hours, as shown in Table C-2.

Table. C-2 Hours in Bus Operation in Each Time Period

Service Layer	<i>Base</i>		<i>Shoulder</i>		<i>Peak</i>	
	Owl	Night	Evening	Midday	PM Peak	AM peak
Increment of Peak Vehicles	dPV_{Owl}	dPV_{Night}	$dPV_{Evening}$	dPV_{Midday}	dPV_{PMpeak}	dPV_{AMpeak}
Hours	6	3	3	6	3	3
Hours in Vehicle Operation (VOH)	24	18	15	12	6	3
Apportionment Factors	AF_1	AF_2	AF_3	AF_4	AF_5	AF_6
Cost Apportionment	CPV_1	CPV_2	CPV_3	CPV_4	CPV_5	CPV_6

For example, buses in the Owl period are available to provide service in all of the other five periods. Buses added for runs in the Midday period run a maximum of 12 hours a day. Buses added for AM Peak run a maximum of only 3 hours a day. The incremental number of required vehicles for each service layer are divided by number of hours those vehicles are in operation to obtain apportionment factors (AF_i) representing the proportion of fleet vehicles required by the entire system in each layer.

The apportionment factors for each service layer are further allocated to individual bus

lines in proportion to the number of required vehicles on each line. Apportionment factors are summed up within each time period for each line to obtain VUAF on each line in each period. Finally, VUAFs are multiplied by the peak vehicle unit cost to obtain the costs on individual lines in different time periods.

We modified the peak vehicle unit cost (U_{PV}), based on the number of the PM peak vehicles, since the number of required vehicles in the AM peak is larger than in the PM Peak. The modified peak vehicle unit cost (U'_{PV}) is computed as:¹⁶

$$U'_{PV} = U_{PV} * (PV_{PM\ peak} / PV_{AM\ peak}) \quad \text{equation (C.7)}$$

U'_{PV} :the new unit cost based on the number of peak vehicles in the AM peak
 U_{PV} :the original peak vehicle unit cost based on the number of peak vehicles in the PM peak in the MTA cost allocation model
 $PV_{PM\ peak}$:the number of peak vehicles for the system in the PM peak period.
 $PV_{AM\ peak}$:the number of peak vehicles for the system in the AM peak period

In summary, the adjusted cost associated with the peak vehicle factor ($CPV_{i,j}$) on individual lines in each period can be calculated as:

$$CPV_{i,j} = VUAF_{i,j} * U_{PV}$$

$$= \left[\sum \left(\frac{dPV_i}{VOH_i} * \frac{PV_{i,j}}{PV_{i,system}} \right) \right] * U'_{PV}$$

equation (C.8)

¹⁶ Missing data for four lines required that data from fiscal years 1992-93 and 1994-95 be used for two bus lines each. The modified peak vehicle unit cost is computed by dividing the systemwide peak vehicle costs by the number of required vehicles in the AM peak.

$CPV_{i,j}$	:cost associated with peak vehicles in the period i on the line j ,
$VUAF_{i,j}$	:vehicle Usage Apportionment Factor in the period i on the line j ,
U_{PV}	:modified peak vehicle unit cost.
dPV_i	:increment of peak vehicles in the period i in the system
VOH_i	:hours of vehicle operation for incremental vehicles in the period i
$PV_{i,j}$	:total number of peak vehicles in the period i on the line j .
$PV_{i,system}$	:total number of peak vehicles in the period i in the system.

Vehicle Utilization Apportionment Factors were calculated for the LRT in the same manner as for the bus system (Table C-3). The number of required LRT trains and train cars and the hours of operation for the six time periods were obtained from the MTA's Section 15 reports and printed time schedules for FY 1994.

It should be noted that while the total operating costs associated with the peak vehicle factor for the entire system remain the same after applying the VUAFs, the costs on individual lines varied to reflect line-by-line differences in vehicle utilization.

Table C-3. Computation of Vehicle Usage Apportionment Factors for the LRT

Service Layer	<i>Base</i>		<i>Shoulder</i>		<i>Peak</i>		Total
	Night	Owl	Evening	Midday	AM Peak	PM Peak	
	9pm-12:30am	4:30-6am	6-9pm	9am-3pm	6-9am	3-6pm	
Trains	6	11	11	15	17	17	-
Train Cars	12	22	22	30	34	34	-
Increment of Train Cars	12	10		8	4		34
Hours of Operation	20	16.5		12	6		-
Apportionment Factor	0.60	0.61		0.67	0.67		-
Sum of AF	2.10	1.81	11.24	11.24	7.62	7.62	34

V. Allocation of Vehicle Capital and Non-Vehicle Capital Costs

To allocate vehicle and non-vehicle capital costs for the bus and the LRT systems, we computed

the annual capital costs of the rolling stock and other capital assets using data on asset values, cumulative depreciation, years of expected life, from the MTA's Section 15 Report for 1994 as shown in columns (1), (2), and (4) respectively, in Tables C-4 and -5. The net value in column (3) is obtained by subtracting the cumulative depreciation from the asset value. The remaining expected life in column (6) is obtained simply by the years of expected life multiplied by the ratio of the net value to the asset value. Using the capital recovery method¹⁷ with a 7 percent discount rate, we computed the annual capital cost of each asset as shown in column (8). The annual vehicle capital cost, \$ 46.4 million for buses and \$ 8.7 million for LRT cars, was divided by the peak number of required vehicles, 1,912 for the bus system, and 34 for the LRT system, to obtain the vehicle capital unit cost per year: \$24,288 for the bus system and \$256,241 for the LRT.¹⁸

The annual cost of non-vehicle capital assets sum to \$47,258,646 and \$57,305,281 for the bus system and for the LRT respectively. Annual vehicle capital costs were divided by the number of weekdays, 258 days for the bus system and 256 days for the LRT, to obtain daily capital costs and to take into account differences in vehicle usage on weekdays and weekends. The daily vehicle capital cost is \$94.14 per bus and \$1,000.94 per light rail vehicle. In contrast, the annual costs of non-vehicle capital assets are divided by 365 days to obtain the systemwide daily capital costs: \$129,476 and \$157,001 for the bus system and for the LRT respectively. Finally, after obtaining the daily vehicle capital costs, VUAFs were applied to compute costs for different time periods on individual lines for each system. The annual costs of non-vehicle capital assets were then allocated to each time period in proportion to the number of in-service vehicle hours.

¹⁷ See Appendix G for methods to compute annual capital costs.

¹⁸ The numbers of vehicle for the bus system were obtained from the MTA's Section 15 Report for FY93-94, and do not match the total number of vehicles used to allocate costs associated with peak vehicles and vehicle capital in this study, since we took into account only those lines analyzed in this study.

Table C-4. Annual Capital Cost Estimation of the Metro Bus System

Expense Item	Asset Value	Cumulative Depreciation	Net Value	Expected Life	Discount Rate	Remaining Expected Life	Annual Cost	Total Output	Unit Cost
	(1)	(2)	(3) = (1) - (2)	(4)	(5)	(6) = ((3) / (1)) * (4)	(7) = (3) * (CRF(5)&(6))	(8)	
Revenue Vehicles	\$471,288,619	\$312,652,441	\$158,636,178	12	7.00%	4.04	\$46,437,990	1,912	\$24,288
Service Vehicles	\$15,510,730	\$11,091,748	\$4,418,982	5	7.00%	1.42	\$3,366,645		
Buildings & Structures	\$168,072,224	\$52,171,029	\$115,901,195	30	7.00%	20.69	\$10,769,623		Other Capital
Equipment	\$139,466,671	\$91,867,623	\$47,599,048	10	7.00%	3.41	\$16,159,322		Cost Total
Office Equ. & Furnishing	\$10,052,352	\$7,661,286	\$2,391,066	10	7.00%	2.38	\$1,125,953		\$47,258,646
land	\$88,140,680	\$0	\$88,140,680	100	7.00%	100.00	\$6,176,966		
Work In Process - Capital Project	\$119,873,030	\$0	\$119,873,030	30	7.00%	30.00	\$9,660,136		
Total	\$1,012,404,306	-	\$536,960,179	-	-	-	\$93,696,637		

Table C-5. Annual Capital Cost Estimation of the Metro Light Rail Transit System

Expense Item	Asset Value	Cumulative Depreciation	Net Value	Expected Life	Discount Rate	Remaining Expected Life	Annual Cost	Total Output	Unit Cost
	(1)	(2)	(3) = (1) - (2)	(4)	(5)	(6) = ((3) / (1)) * (4)	(7) = (3) * (CRF(5)&(6))	(8)	
Revenue Vehicles	\$78,913,000	\$28,689,428	\$50,223,572	12	7.00%	7.64	\$8,712,193	34	\$256,241
Service Vehicles	\$144,609	\$16,817	\$127,792	5	7.00%	4.42	\$34,618		
Buildings & Structures	\$648,114,855	\$74,003,312	\$574,111,543	30	7.00%	26.57	\$48,165,473		Other Capital
Equipment	\$32,498,862	\$11,717,949	\$20,780,913	10	7.00%	6.39	\$4,141,963		Cost Total
Office Equ. & Furnishing	\$0	\$0	\$0	10	7.00%	0.00	\$0		\$57,305,281
land	\$67,265,000	\$0	\$67,265,000	100	7.00%	100.00	\$4,713,983		
Work In Process - Capital Project	\$3,092,873	\$0	\$3,092,873	30	7.00%	30.00	\$249,244		
Total	\$830,029,199	-	\$715,601,693	-	-	-	\$66,017,474		

VI. Allocation of Vehicle Capital Cost to Weekend Service

While costs associated with peak vehicles are computed for weekdays,¹⁹ we also took into account weekend service to allocate vehicle capital cost to different times of day. As shown in Table C-6, the total number of buses required for the Owl period was 59 (weekdays), 62 (Saturday), and 61 (Sunday). The total number of vehicles in the Night, Evening, and Midday periods on weekdays are 287, 861, and 1051 respectively, while the number of vehicles required on Saturday ranges from 895 to 1016. Therefore, all Saturday operations can be covered by the vehicles used for Midday service on weekdays. Similarly, the number of peak vehicles required on Sunday ranges from 652 to 813, so the number of vehicles in service during the Evening period on weekdays is large enough to cover Sunday operations.

Table C-6. Vehicle Requirements for Weekday and Weekend Bus Service by Time Period²⁰

	Owl	Night	Evening	Midday	PM peak	AM peak
Weekday	59	287	861	1051	1934	1940
Saturday	62	-	-	895	1016	1016
Sunday	61	-	-	652	813	813

We spread the costs of service for all Owl, Night, and Evening service over 365 days, assuming that the number of vehicles in each of these three periods remains constant over the year. Since peak vehicle data are not available and cannot even be estimated in the weekend Evening and Night periods, we assumed that the number of peak vehicles in these periods would be the same as weekdays, though this assumption probably overestimates the apportionment of costs in the Evening and Night period for some lines and underestimates the costs in other periods. We also spread the costs incurred during the Midday period over 306 days on the assumption that the number of vehicles in service for this period is the same on weekdays and Saturday. The cost of vehicles operating in the peak periods is not affected because these vehicles are not used on weekends. As a result, while the daily depreciation costs in the peak period remain the same, the daily capital costs were reduced by a Weekend Operating Factor (*WOF*) equal to $258/365$ ($= 0.71$) in the Owl, Night, and Evening periods and $258/306$ ($= 0.84$) for the Midday period.

¹⁹ This is based on the original MTA model that allocates none of costs associated with peak vehicles to weekends.

²⁰ For some lines, the number of required vehicles on Saturday and Sunday is obtained from years different from FY 94 due to limited data availability.

For the LRT system, the number of required train cars on weekdays was 34 in the two Peak periods (5 am - 9 am and 3 pm - 7 pm), 30 in the Midday (9 am - 3 pm), and 22 for the rest of day, as shown in Figure C-7. Since the number of required train cars on Saturday and Sunday is 26, we assumed that train cars in the weekday Midday period can cover the weekend operation. Since train cars in the *base* and *shoulder* periods on weekdays are operated also on weekends, the daily vehicle capital cost in these two periods were modified by multiplying these costs by 256/365 (= 0.70).

Table C-7. Vehicle Requirements for Weekday and Weekend LRT Service

	Weekday				Saturday	Sunday
	AM Peak	Midday	PM Peak	other		
No. of Vehicles	34	30	34	22	26	26

VII. Final Equations of the Temporally Sensitive Cost Allocation Model

The capital costs for each time period i on each line j of the bus system (CC_{ij}) is given by:

$$CC_{ij} = VCC_{Bus} * WOF_i * VUAF_{ij} + OCC_{Bus} * (IVH_{ij} / IVH_{day,system})$$

equation (C.9.1)

VCC_i	:the annual vehicle capital cost of buses divided by 365 days
WOF_i	:weekend operation factor in the period i (= 258/365 for the Owl, Night, Evening; 258/310 for the Midday, and 1 for the AM and PM Peaks)
$VUAF_{ij}$	:vehicle usage apportionment factor in the period i on the line j in the bus system
OCC_{Bus}	:non-vehicle annual capital costs of the Metro bus system divided by 365 days
IVH_{ij}	:in-service vehicle hours in the period i for a day and on the line j or in the system.

Similarly, the capital costs for each time period i on each line j of the bus system and LRT (CC_{LRT}) are given by:

$$CC_{LRT} = VCC_{LRT} * WOF_{i,LRT} * VUAF_{i,LRT} + OCC_{LRT} * (IVH_i / IVH_{day})$$

equation (C.9.2)

VCC_{LRT}	:the annual vehicle capital cost of the LRT train car divided by 365 days
$WOF_{i,LRT}$	:weekend operation factor in the period i (= 256/365 for the <i>base</i> and <i>shoulder</i> periods; 1 for the <i>peak</i> period)
$VUAF_{i,LRT}$	:vehicle usage apportionment factor in the period i in the LRT system
OCC_{LRT}	:non-vehicle annual capital costs of the LRT system divided by 365 days
IVH_i	:in-service vehicle hours in the period i or for a day.

Total cost in each time period (i) for each line (j) ($TC_{i,j}$)²¹ is the sum of the adjusted marginal operating cost plus adjusted marginal capital cost.

For the bus system:

$$\begin{aligned}
 TC_{i,j} &= OC_{i,j} + CC_{i,j} \\
 &= (LUF_{i,j} * U_{VH} * VH_{i,j} + U_{VM} * VM_{i,j} + U'_{PV} * VUAF_{i,j} + U_{TP} * TP_{i,j}) \\
 &\quad * (1 + F) + VCC_{Bus} * WOF_i * VUAF_{i,j} + OCC_{Bus} * (IVH_{i,j} / IVH_{day,system})
 \end{aligned}$$

equation (C.8.1)

For the LRT system:

$$\begin{aligned}
 TC_{i,LRT} &= OC_{i,LRT} + CC_{LRT} \\
 &= U_{VH,LRT} * VH_{i,LRT} + U_{VM,LRT} * VM_{i,LRT} + U_{PV,LRT} * PV_{i,LRT} \\
 &\quad + VCC_{LRT} * WOF_{i,LRT} * VUAF_{i,LRT} + OCC_{LRT} * (IVH_i / IVH_{day})
 \end{aligned}$$

equation (C.8.2)

TC	:total cost estimated by the fully-allocated model
i	:time of day (base, shoulder, and peak) or daily
j	:unit of analysis in question — system, line, etc.
OC	:estimated operating costs

²¹ This is equivalent to the *Fully-Allocated* model in the main text.

<i>CC</i>	:estimated capital costs — vehicles, buildings, equipment, land, etc.
<i>LUF</i>	:labor utilization factor
<i>U</i>	:unit cost per service output
<i>U_{PV}</i>	:modified peak vehicle unit cost for the bus system
<i>VH</i>	:scheduled vehicle hours
<i>VM</i>	:scheduled vehicle miles
<i>PV</i>	:PM peak vehicles
<i>TP</i>	:total passengers
<i>F</i>	:fixed overhead cost factor
<i>OCC</i>	:non-vehicle daily capital costs
<i>VCC</i>	:the vehicle capital cost for a typical weekday
<i>IVH</i>	:in-service vehicle hours
<i>WOF</i>	:weekend operation factor
<i>VUAF</i>	:vehicle usage apportionment factor

APPENDIX D

Estimation of Operation Variables by Time of Day

In several cases it was necessary to estimate data required for this analysis, unavailable in any report described in Appendix B. These estimates are described herewith:

Estimation of Scheduled Vehicle Hours by Time of Day

Scheduled vehicle hour data were available from a breakdown in the Consolidated Transit Service Policies Reports (CTSPR) for two time periods, 5 am - 7 pm (daytime) and 7 pm - 5 am (nighttime), but not for three periods used in this study. Therefore, scheduled vehicle hour data were estimated based on the number of revenue vehicle hours and the ratio of scheduled hours to revenue hours.²² The ratio of scheduled hours to revenue hours was also obtained from the CTSPR for the daytime and nighttime periods. After re-apportioning revenue hours for the five time periods in the CTSPR by the proportion of vehicle runs in each of the six periods used in this study, we obtained revenue hours in the *base*, *shoulder*, and *peak* periods. Revenue hours in each period were adjusted so that the daily total of adjusted revenue vehicle hours equaled the daily total in the Line Performance Trends Report (LPTR). The nighttime ratio of scheduled vehicle hours to revenue vehicle hours was multiplied by revenue hours in the *base* to obtain an estimate for scheduled hours in the *base*. The daytime ratio was multiplied by revenue hours in the *shoulder* and *peak* to obtain an estimate of scheduled hours in these two periods.²³ Finally, scheduled vehicle hours in each period were adjusted so that the daily total of adjusted scheduled vehicle hours equaled the daily total in the LPTR. In addition, all scheduled vehicle hours were included in the *peak* for twelve peak-period service only lines, although some vehicle runs do not fall entirely within the *peak* period.

Estimation of In-Service Vehicle Hours by Time of Day

Although the CTSPR provides data on in-service vehicle hours for five different time periods (see Table B-1), it does not provide data for all lines. In-service vehicle hours for the three time periods used in this study (*base*, *shoulder*, and *peak*) were obtained for 99 of the 122 MTA bus

²² In-service hours exclude deadhead and layover. Revenue hours exclude deadheading but include layover. Scheduled hours include deadhead and layover. (MTA Line Performance Trends Report.)

²³ Due to data limitations, for the Base period, the ratio of scheduled hours to revenue hours for the nighttime period (7 pm - 5 am) was used to estimate scheduled hours. For the *shoulder* and *peak* periods, the same ratio for the daytime period (5 am - 7 pm) was used.

lines using the same method to apportion revenue vehicle hours described in the previous section. For the remaining 23 lines, in-service hours were estimated based on the reported number of revenue vehicle hours in each period on each line. Three regression equations were calculated relating revenue hours and in-service hours on those lines:

$$IVH_{base} = 0.861 * RVH_{base} - 0.204 \quad \text{equation (D.1.1)}$$

$$IVH_{shoulder} = 0.864 * RVH_{shoulder} - 1.239 \quad \text{equation (D.1.2)}$$

$$IVH_{peak} = 0.862 * RVH_{peak} - 1.095 \quad \text{equation (D.1.3)}$$

IVH_i :in-service vehicle hours in the period i

RVH_i :revenue vehicle hours in the period i

These equations were used to estimate in-service hours for the additional 23 lines. The estimated number of in-service vehicle hours in each time period on all lines was adjusted, so that in-service vehicle hours in the *base*, *shoulder*, and *peak* periods equaled the daily total of in-service vehicle hours reported in the LPTR. In addition, all in-service vehicle hours were included in the *peak* for twelve express lines with only *peak* period service although some of their vehicle runs do not fall entirely within the six-hour *peak* period defined in this study.

Estimation of Scheduled and In-Service Vehicle Miles by Time of Day

Data for the number of scheduled vehicle miles by time of day were not available in the MTA database so scheduled vehicle miles were estimated from reported in-service vehicle miles. The difference between scheduled and in-service miles for a day on each line was apportioned to the *base*, *shoulder*, and *peak* periods by using the vehicle usage apportionment factors (VUAF) described in Appendix C on the assumption that peak service involves a higher proportion of vehicle miles to revenue-producing miles than off-peak service. For example, more buses deadhead to assigned run starts in the peak. Also, additional short runs, known as trippers, are frequently added to handle peak loads. Since the degree of deadheading and trippers also vary by line, vehicle utilization also varies on different lines. In addition, for twelve express lines with only peak period service all scheduled vehicle hours were included in the *peak* although some vehicle runs do not fall entirely within the *peak* period.

In-service vehicle miles data were available for 96 of the 122 MTA bus lines in the Schedule Quality Reports (SQR). For the remaining of 26 lines, in-service mileage was estimated based on the reported number of vehicle runs in each period multiplied by the average trip distance for each line. The average trip distance was obtained by dividing the daily total in-service miles by the daily total number of vehicle runs reported in the LPTR. Three regression equations were calculated relating this estimated mileage to reported in-service miles for lines for which data were available:

$$IVM_{base} = 0.894 * (T * D) + 4.219 * Dummy^{24} + 6.187$$

$$IVM_{shoulder} = 1.005 * (T * D) + 21.5489 \quad \text{equation (D.2.2)}$$

$$IVM_{peak} = 0.974 * (T * D) + 16.382 \quad \text{equation (D.2.3)}$$

IVM :in-service vehicle miles

T :number of trips

D :ratio of in-service vehicle miles to reported number of vehicle trips

These equations were used to estimate in-service mileage for the additional 26 lines. The number of vehicle runs in each period obtained from the CTSPR were adjusted, so that vehicle runs in the *base*, *shoulder*, and *peak* periods equaled the daily total vehicle runs reported in the LPTR. Likewise, in-service mileage in each period was adjusted so the total daily in-service mileage equaled that in the LPTR.

Estimation of the Number of Required Vehicles by Time of Day

As stated above, the MTA's LPTR provides data on the number of required buses only for the AM Peak, Midday, PM Peak, and Owl periods. To estimate the number of peak buses assigned on each line during the Evening and Night periods, we computed a coefficient for each of the four periods for which data were available relating the number of vehicle trips to the number of required buses:

$$K_i = \frac{VT_i / t_i}{PV_i} \quad \text{equation (D.3)}$$

i :AM Peak, Midday, PM Peak, and Owl

K_i :coefficient for time period i

VT_i :number of vehicle trips in time period i

PV_i :number of peak vehicles in time period i

t_i :number of hours in time period i

We then calculated the coefficient for the Evening period (6 - 9 pm) by taking the average of the AM Peak, Midday, and PM Peak coefficients. Since it is reasonable to assume that the maximum number of vehicles in the Night period is much less than that in the earlier periods of the day, we included the coefficient for the Owl period to compute a coefficient for the Night period.

²⁴ For the *base* period, a dummy variable is included to differentiate cases with no *base* period trips.

$$K_{Evening} = (K_{AMpeak} + K_{Midday} + K_{PMpeak}) / 3 \quad \text{equation (D.4.1)}$$

$$K_{Night} = (K_{AMpeak} + K_{Midday} + K_{PMpeak} + K_{Owl}) / 4 \quad \text{equation (D.4.2)}$$

K_i :coefficient for time period i

We then estimated the number of peak vehicles on each line during the Evening and Night periods by substituting known values for the number of trips in these periods back into equation D.3. The number of required vehicles were set to zero outside the *peak* period assuming there are no vehicle runs although some vehicle runs do not fall entirely within the *peak* period.

Estimating the Number of Passenger Boardings by Time of Day

Boarding data were not available for the six time periods used in this study. Operating costs associated with total boardings on each line were apportioned by time period according to the relative proportion of passengers per hour obtained from the CTSPR. For example, the reported number of boardings in the AM Peak (5 - 9 am) on line 1 is 4,239. The number of passengers on the line from 5 - 6 am and from 6 - 9 am, were 63 and 634 respectively. Thus, the number of boardings from 6 - 9 am (AM Peak) was calculated as $4,239 \times (63/(63+634)) = 3,856$. Similar allocations were made for the PM Peak, Evening, Night and Owl periods. These costs were then combined to obtain values for the *base*, *shoulder*, and *peak* periods. For twelve express lines with only *peak* period service lines, the number of passengers were allocated only to the *peak* period, although some boarding counts do not fall entirely within the *peak* period.

Estimating Vehicle Hours and Vehicle Miles by Time of Day for the LRT

Costs associated with vehicle hours were apportioned to each time period in proportion to the number of scheduled vehicle hours in each period. Since scheduled vehicle hour data were not available by time period, they were estimated based on revenue vehicle hours in each time period. Revenue vehicle hours and in-service vehicle hours were estimated from the printed time schedule in 1997.²⁵ The difference between scheduled vehicle hours and revenue vehicle hours was apportioned to each line by time period using the VUAFs on the presumption that the distribution of non-revenue hours would be similar to the distribution of the VUAFs. Scheduled and revenue vehicle hours in each period were adjusted, so that the daily total equaled those obtained from the Section 15 report.

The costs associated with vehicle miles were apportioned to each period in proportion to

²⁵ The time schedule in FY 1994 was not available.

scheduled vehicle miles in each period. Since scheduled vehicle miles were not available by time period, the number of scheduled vehicle miles was estimated based on in-service vehicle miles adjusted by the VUAFs. In-service vehicle miles in each period was estimated from the printed time schedule and the distance between LRT stations. The systemwide difference in the daily total between schedule miles and in-service miles was apportioned to each period using the VUAFs as described above. Scheduled and in-service vehicle miles in each period were adjusted, so that the daily total equaled those obtained from the Section 15 report.

APPENDIX E

Cost Estimation Approaches

Statistical Approach

The *Statistical Approach* uses sample data on productivity levels from different run types to relate costs to the proportion of peak to off peak service. The Arthur Anderson Model (McClenahan et al. 1978) uses a fixed-variable model and plots the cost of straight, evening, split shift and overtime runs. Coefficients are calculated by regressing the ratio of driver pay hours to vehicle hours against the proportion of peak period vehicle hours. The London Transport Model is similar; direct driver costs are a function of the number of split shifts and straight shifts.

Resource-Based Approach

Some studies have used a *Resource-Based Approach* that modifies the 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 types of service runs. These models include the Northwestern model, Bradford model, and Adelaide model examined in the study by Cherwony *et al.* (1981). The Northwestern model uses rules based on labor assignment practices to estimate labor requirements reflecting time of day variations. The Bradford Model uses an “audit month” to estimate unit costs by shift type based on the ratio of pay hours to worked hours. Pay hours include penalty and excess spread time. The model defines three “layers” of service similar to the Levinson model discussed above. They are peak only (7 - 9 am and 4 - 6 pm), working day (7 am - 6 pm) and all day service (roughly 6 am - 12 pm). Buses in service all day operate for 18 hours, working day shifts last 11 hours and peak period service is for four hours. Using a scheduling algorithm labor costs are calculated on the basis of the number of shifts needed to add one additional layer of service. Peak-only service requires one split shift. A pair of working day runs take two straight shifts and one split shift while two day runs need four straight shifts and one split shift.

APPENDIX F

Other Vehicle Hour Cost Adjustment Approaches

Levinson and Wilbur Smith & Associates (1978) developed a method similar to the Cherwony and Mundle model to calculate the proportion of daily operating costs to be allocated to peak periods. Their cost estimation approach also used higher per-hour cost coefficients for peak bus hours than for base bus hours based on the ratio of pay hours to bus hours. Rather than using average peak and base period unit costs, the authors separated the costs of service during the base period from the additional costs of service associated with operating extra buses during the peak periods. They allocated all costs to provide the additional peak service to the peak period, and apportioned costs of the base service to both base and peak periods using the number of vehicles in service and vehicle operating hours as shown in Figure 4 in the main text. The relative share of the daily operating costs attributed to the peak hours can be given by the following formula:

$$S = \frac{\frac{2t_2}{2t_2 + t_1} C_1 + C_2}{C_1 + C_2} \cong \frac{1 + xy}{1 + xy + z} \quad \text{equation (F.1)}$$

x :ratio of additional peak buses to base buses = a/b

y :ratio of peak to base pay hours per vehicle hour = $(PH_P/VH_P)/(PH_B/VH_B)$

z :ratio of non-peak to peak period duration = $t_1/2t_2$

Other cost adjustment models account for the variations in labor costs between peak and off-peak periods based on wage rates and the different mix of straight time and overtime runs in peak and off-peak periods (Reilly 1977). The Pay-to-Platform Ratio (PPR) method computes the driver cost based on the ratio of pay hours to platform (vehicle) hours for different types of runs (straight, split, trippers, etc.) and the different mix of types of runs by hour of the day and day of the week (Cohen et al. 1988). Pay to platform ratios for split runs and trippers are higher than for straight runs. The Schedule-Based method incorporates information on how schedulers handle service increases and decreases for different time periods by defining separate unit cost factors for weekday peak periods, weekday off-peak periods, and weekends and holidays and applying these to changes in vehicle hours. During peak runs, schedulers will generally increase service by adding split runs and trippers while during the off-peak period they will respond to service demand by increasing the number of straight runs and decreasing the number of split runs and trippers. Both methods take into account vacancy rates (the ratio of pay-hours from the payroll distribution to the pay-hours of the work assignments) and fringe benefit multipliers (the ratio of total compensation to wages).

The Worksheet Method, also incorporates assumptions about how schedulers use different types of runs by time period, as well as assumptions about the utilization of part-time versus full-time drivers and differences in their compensation. Data required include pay-hours by category for weekdays and weekends, fringe benefits, guarantee hours of pay per run, average report, turn-in and travel time per run, number of vehicles in weekday peak periods and vehicle hours per weekday and weekend day. The model specifies service changes in terms of changes in the number of weekday vehicle-hours, the number of weekend vehicle-hours, and in the maximum number of buses operated during weekday AM and PM peak periods. Costs are determined by applying incremental cost factors to the changes in each of these service measures. In a comparative study of these models the Schedule-Based Method outperformed the others in terms of accuracy, however, all three were reasonably accurate and sensitive to temporal variations in operating costs. For agencies with relatively flat peaking profiles, though, Cohen *et al.* (1988) concluded that the Schedule-Based Method would not differ much from the typical two-variable model which is easier to calibrate and apply. However, even more advanced models than these have been developed using more complex run cutting algorithms.

APPENDIX G

Calculation of the Annual Depreciation Cost

To allocate systemwide capital costs to individual lines and to different time periods we computed annual capital costs for the system. Two methods are commonly used. The first is to calculate the depreciation costs of each capital expense item per year plus interest. Under present federal regulations in the U.S., vehicle life is fixed at 12 years regardless of mileage. Many larger bus operators, particularly those that are financially strapped, operate buses well beyond 12 years. Full cost accounting suggests that actual life is a better indicator of costs irrespective of federal accounting regulations, which can result in accelerated depreciation. The second method uses a capital recovery method to amortize the net value of capital (original cost minus accumulated depreciation and scrap value) over an asset's entire service life using an interest rate which reflects the true opportunity cost of resources. Cervero (1982), Tomazinis *et al.* (1989), Kerin (1989) and Li (1997) use this approach:

$$R = [P - S(1+i)^{-n}] * \frac{i(1+i)^n}{(1+i)^n - 1} \quad \text{equation (G.1)}$$

	R	:equivalent annual capital cost for an item
	P	:purchase price for an item
S		:scrap value for the item
	i	:assumed discount rate
	n	:expected economic life of the capital item

In a recent study of intermodal performance indicators,²⁶ Li (1997) allocated the annual capital cost of Los Angeles MTA buses in seven categories: revenue vehicles, service vehicles, buildings & structures, equipment, office equipment and furnishings, land, and work in process-capital project. Using a 7 percent discount rate and a 12 year useful life for buses, Li calculated the net capital cost and used a two variable cost allocation formula based on peak vehicles and vehicle miles to allocate these costs by line. Li chose peak vehicles and vehicle miles to account for capital costs on the basis that vehicle costs constitute a large proportion of the capital costs

²⁶ Intermodal performance indicators represent full costs for service provision, and incorporate vehicle capacities in order to better reflect the effects of transit subsidy policy changes on transit performance. The analysis showed that more capital intensive modes such as light rail are more costly and less effective than less capital intensive modes such as buses.

and the depreciation of buses and maintenance costs are mainly related to the number of miles buses travel.

Others have suggested that using a fixed life for capital equipment is not appropriate since many bus companies employ their rolling stock well beyond its accounting life span. Kerin (1989) argued that vehicle life (“*n*”) should be a function of the number of miles driven. Thus total capital costs depend not only on the size of the fleet, but also on the relative number of vehicles run in the peak and off-peak periods:

$$n = \frac{L}{M} = \frac{L}{S * [b + a * (PV_B/PV_P)]} \quad \text{equation (G.2)}$$

<i>L</i>	:bus life in miles
<i>M</i>	:average vehicle miles per year
<i>S</i>	:average vehicle speed
<i>b</i>	:peak hours
<i>a</i>	:off-peak hours
<i>PV_B</i>	:off-peak buses
<i>PV_P</i>	:peak buses

More service in the off-peak increases average annual vehicle mileage, decreases average vehicle life, increases vehicle replacement frequency, and therefore increases annual capital costs of each vehicle. Total capital costs and marginal capital costs vary inversely with the peak to base vehicle ratio under this approach.

Applying the capital recovery method using a 12 year expected life and a 7.00 percent discount rate to data on vehicle asset values and cumulative depreciation obtained from the National Transit Database Section 15 report, we calculated the annual capital cost of a standard bus to be \$24,288.²⁷

²⁷ See Appendix C.

APPENDIX H

Allocation of Transit Costs to the Peak Period

Levinson *et al.* (1978) report that peak periods account for a higher proportion of total operating and vehicle capital costs than the off-peak, and that the higher the degree of peaking, the higher the share of costs attributable to the peaks. Using a hypothetical model incorporating various assumptions about typical operator characteristics, they concluded that while peak service typically constitutes 25 percent of total service hours, such peak service accounts for about 52 percent of operating costs and 63 percent of vehicle capital costs. Using a multi-stage cost allocation process with empirical data from the Southern California Rapid Transit District (SCRTD), Cervero (1980) determined that the agency's five hours of peak service accounted for 55.8 percent of the system's total daily costs.²⁸ He found similar results for Alameda-Contra Costa Transit District (AC Transit) in the San Francisco Bay Area and San Diego Transit Corporation (SDTC); AC Transit's four hour peak and SDTC's six hour peak account for 58.5 percent and 52.5 percent respectively for each system's total cost. Parody *et al.* (1990) also found net costs in the peak period to be consistently higher on both a per passenger trip and per passenger mile basis.

We computed peak period costs for the MTA bus system and for the MTA LRT, a 22-mile light rail line running between downtown Los Angeles and the downtown Long Beach. The proportion of operating, capital, and total costs for the six hours of peak service for the bus system and the LRT, which operate 24 hours and 18.5 hours per day respectively, are shown in Table H-1. The results for the bus system in Table H-1 are consistent with data from other studies. With respect to the marginal costs of peak period service, we found that the cost of providing six hours of peak service consumes 52.2 percent of operating costs, 62.7 percent of vehicle capital costs, and 52.5 percent of total costs for the bus system. As shown in Table H-1 below, these results are quite similar to the findings of earlier studies by Levinson *et al.* (1978), Cervero (1980), and Parody *et al.* (1990). The LRT has slightly lower figures for the proportion of costs in the peak period due primarily to the lower peak to base ratio of vehicles compared to the bus system (1.1 to 1.5 respectively) (FTA 1994).

²⁸ Cervero also found that the SCRTD's average cost/passenger-mile was 17.6 cents in the peak and 14.6 cents in the base - a 10 percent differential - due to more passengers in the peak and longer average trip lengths.

Table H-1. Allocation of Transit Costs to the Peak Period

	Operating Costs	Vehicle Capital Costs	Non-vehicle Capital Costs	Total Capital Costs	Total Costs
This study -	52.2%	62.7%	44.6%	55.2%	52.5%
This study -	50.8%	53.7%	45.9%	47.1%	48.7%
Levinson	52%	63%	N/A	N/A	N/A
Cervero -	N/A	85%*	85%*	85%*	55.8%
Cervero - AC	N/A	85%*	85%*	85%*	58.5%
Cervero - SDTC	N/A	85%*	85%*	85%*	52.5%

* Estimate

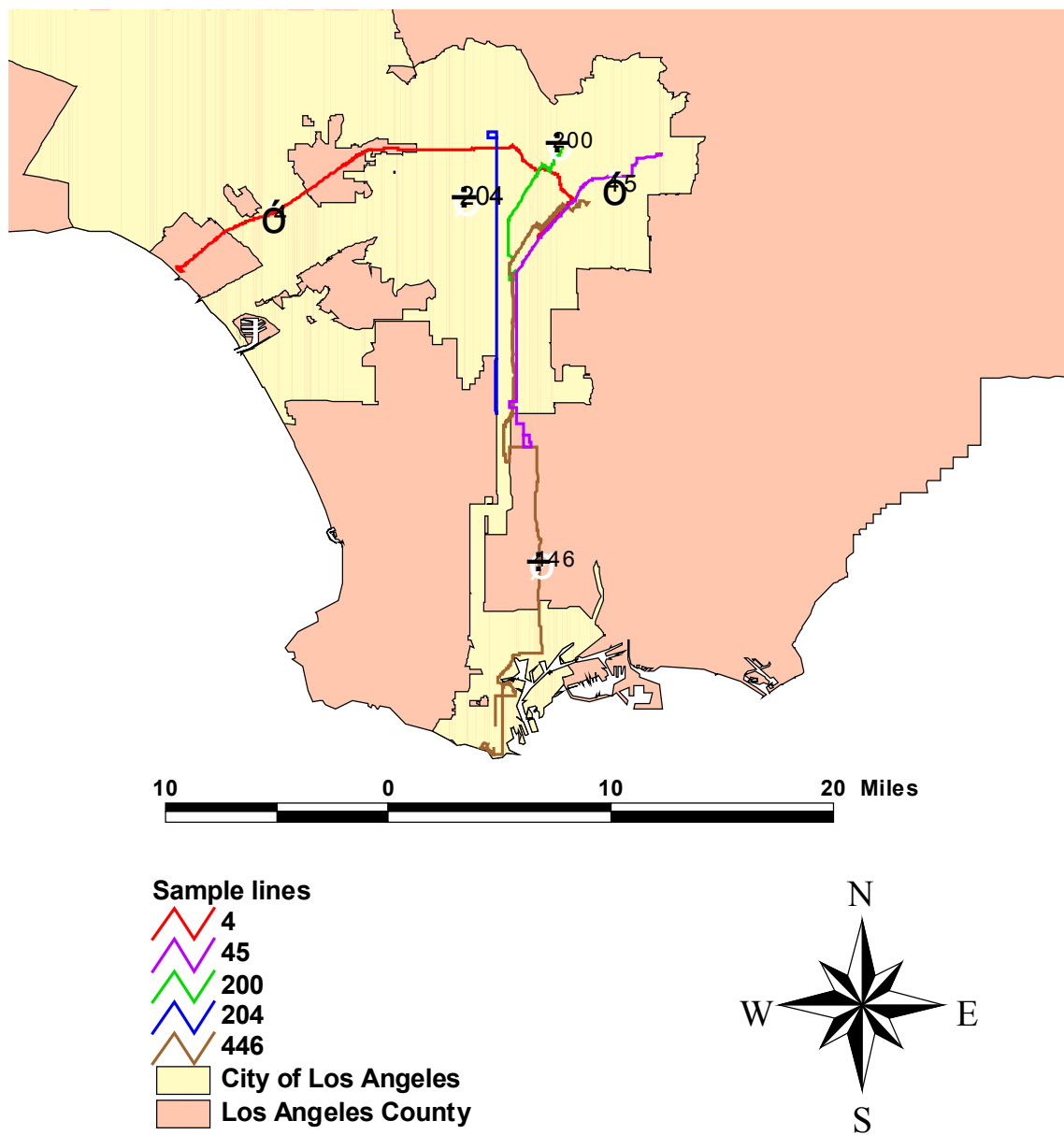
APPENDIX I

Allocation of Transit Costs to the Peak Period

Because light rail vehicles are normally configured to accommodate a lower-proportion seats to standees than buses, one could also compare fully-allocated costs by mode on the basis of overall (seat plus standee) capacity (Lem, Li, and Wachs 1994; Li 1997). Los Angeles MTA buses are currently configured for a seats-to-standee ratio of 1.45:1 (43 seated passengers and 19 standees), while the LRT has a seats-to-standee ratio of 0.5:1 (76 seated passengers and 154 standees). Thus comparing bus and rail costs on the basis of overall passenger capacity would narrow the fully-allocated gap in costs by 266 percent in comparison to the costs shown in Figure 8 below. But these reduced differences in costs are largely a function of policy choices regarding seating configurations and not necessarily differences between buses and trains. Seats could be removed from buses to replicate the 0.5:1 seats-to-standees ratio on the LRT, but the LRT cars cannot (due to the number of doors on each car) be configured to replicate the 1.45:1 seats-to-standees ratio on MTA buses. Since the Los Angeles MTA has chosen to generally maximize the seats-to-standees ratio on both buses and LRT cars, and since the agency has adopted aggressive policy goals to reduce the proportion of standing passengers, comparing modal costs per seat-hour is more appropriate than passenger capacity-hour comparisons. Given that passenger capacity is at least in part due to policy choices over seating configurations, the ideal control for capacity might be by the passenger compartment floor area. Unfortunately, such comparable data were not available for all of the vehicles examined at the time of this analysis.

APPENDIX J

Figure I-1. Sample MTA Lines



1.Counts trips for buses beginning service between 4 am and 5 am. Some lines may have trips between 4 am and 5 am that are completed by buses that are already in service.